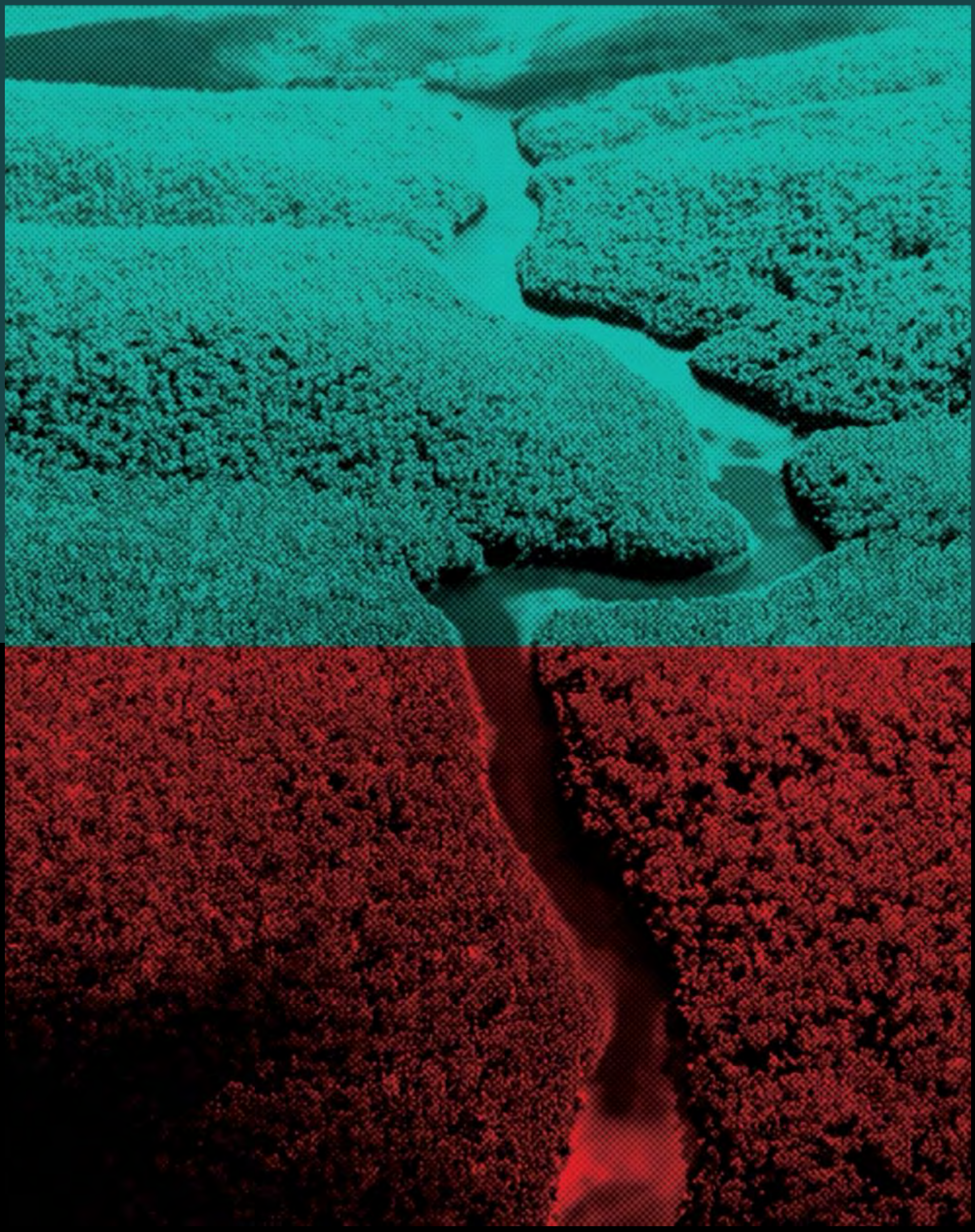
Science Panel for the Amazon

Amazon Assessment Report 2021

PART II



THE AMAZON WE WANT

Science Panel for the Amazon

SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK

A GLOBAL INITIATIVE FOR THE UNITED NATIONS

About the Science Panel for the Amazon (SPA)

The Science Panel for the Amazon is an unprecedented initiative convened under the auspices of the United Nations Sustainable Development Solutions Network (SDSN). The SPA is composed of over 200 preeminent scientists and researchers from the eight Amazonian countries, French Guiana, and global partners. These experts came together to debate, analyze, and assemble the accumulated knowledge of the scientific community, Indigenous peoples, and other stakeholders that live and work in the Amazon.

The Panel is inspired by the Leticia Pact for the Amazon. This is a first-of-its-kind Report which provides a comprehensive, objective, open, transparent, systematic, and rigorous scientific assessment of the state of the Amazon's ecosystems, current trends, and their implications for the long-term well-being of the region, as well as opportunities and policy relevant options for conservation and sustainable development.

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Part II

Social-Ecological Transformations: Changes in the Amazon

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FOREWORD

The Amazon Assessment Report is a marvel of scientific accomplishment and collaboration. Most of all, it is a result of the profound dedication of more than 200 scientists from the Amazon Basin nations to the well-being of the peoples and biodiversity of this unique part of the world. The Amazon merits every superlative thrown its way: unique, irreplaceable, mega-diverse, invaluable, and gravely endangered. The Science Panel for the Amazon has not only provided us with the most comprehensive and compelling scientific portrait of the Amazon ever produced, but has also provided a roadmap to the Amazon's survival and thriving. They show us, in short, the pathway to the Amazon We Want.

My colleague Emma Torres and I, and our fellow members of the UN Sustainable Development Solutions Network (SDSN), are deeply grateful and indebted to the scientist-authors of this volume for the profound care, scientific knowledge, and dedication that they put into this remarkable volume. When Emma and I helped to launch the Science Panel for the Amazon more than a year ago, in the midst of the COVID-19 pandemic, we envisioned that the region's leading scientists would produce a policy report to set guidelines for the Amazon's sustainable development. The scientists of course produced that, but they also produced something vastly greater. They delivered a *magnum opus*, a compelling narrative that begins with the ancient and formative geology of the Amazon Basin and that brings us to the present day, with powerful policy proposals for a new Amazon bioeconomy based on a Living Amazon Vision that "aims to transform the 'life-blind' economic system into one that is 'life-centric.'

Along the way they include a dazzling array of topics to ensure a comprehensive treatment of the Amazon from every major perspective, including the Amazon as a "regional entity of the Earth System," the "anthropogenic changes in the Amazon" including deforestation, and the "solution space" of sustainable pathways for the Amazon Basin. The solutions include bioeconomy strategies, protection of Indigenous lands, restoration of degraded lands, and stronger sustainable relations between the Amazon forest and Amazonian cities.

Both the urgency and timeliness of the report must be emphasized. The urgency is apparent from the core scientific message of the study: the Amazon's ecosystems are not only invaluable but are also gravely imperiled. Because of past deforestation and land degradation, the Amazon may well be close to a tipping point in which major ecosystems of the Amazon would irreversibly collapse or be persistently degraded.

The timeliness results from the fact that the world's nations are finally recognizing the imminent dangers facing the Amazon and the tropical rainforest regions of Africa and Asia. At COP26, more than 130 national governments signed on to a Glasgow Leaders' Declaration on Forests and Land Use, in which they promise to "halt and reverse forest loss and land degradation by 2030." At the same time, public and private sources together pledged more than $10 billion for this cause, with yet more funding to be mobilized. These governments have recognized, finally, that there can be no solution to climate change without ending deforestation and restoring degraded lands, in conjunction with transforming the global energy system to zero-carbon energy sources.

Even as the Assessment Report is being launched, the transformative importance of the Science Panel for the Amazon is already being recognized by governments in the region and by key international development agencies and institutions. This report and the ongoing work of the SPA will be taken up by the Leticia Pact that brings the region's leaders together to protect the common heritage of the Amazon, and by the

Amazon Cooperation Treaty Organization. Also, leading scientists working in other critical ecosystems, including the Congo Basin and the tropical forests of southeast Asia, are looking to the SPA for inspiration and guidance on how to carry out similar scientific collaborations and initiatives in those ecosystems as well.

Let us therefore savor the remarkable scientific insights gathered in this study, and commit as well to act upon the urgent messages of the SPA. If we act decisively and cooperatively, with the Amazon Basin countries cooperating closely and the rest of the world joining in urgent support of the Amazon, we can achieve the SPA's vision of "a healthy, standing forest and flowing rivers bioeconomy based on exchange and collaboration between local and Indigenous knowledge, science, technology, and innovation."

Jeffrey Sachs
SPA Convener

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We are profoundly grateful to the SPA Strategic Committee. Your distinguished leadership has been most valuable in providing strategic guidance to the work of the panel.

We are grateful to the members of the Technical Secretariat. This Assessment would not have been possible without their diligent efforts and dedication.

We also wish to express our profound gratitude to the peer reviewers who helped improve and clarify the Report, and to the many stakeholders who provided invaluable input through the public consultation as well as by other means.

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In gratitude,

Jeffrey Sachs	Emma Torres	Carlos Nobre	Andrea Encalada
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Contributing Authors: Rebecca Abers, Ana Paula Aguiar, James S. Albert, Claudio Almeida, Rafael Almeida, Vera Maria F. Almeida-Val, Angelica Almeyda-Zambrano, Lincoln Muniz Alves, Cecilia S. Andreazzi, Luiz E.O. Aragão, Caroline Arantes, Alessandro C.de Araujo, Julia Arieira, Eduardo D. Assad, Tasso Azevedo, André Baniwa, Daniel Baniwa, Camila Sobral Barra, Marivelton Barroso, Luana S. Basso, Denise Humphreys Bebbington, Aoife Bennett, Carla Jaimes Betancourt, Richard A. Betts, Bibiana Alejandra Bilbao, Laura S. Borma, Paulo M. Brando, Sonia Bridi, Eduardo Brondizio, Paulette Bynoe, Nadino Calapucha, Derek Campos, João Paulo Ribeiro Capobianco, Thiago Cardoso, Ana Carolina Carnaval, Patrick Caron, Juan D. Carrillo, Zienhe Castro, Michael T. Coe, Sandra B. Correa, Sandra Costa, Mily Crevels, Francisco Cuesta, Liliana M. Davalos, Luisa Esther Diaz Arriola, Luis Donisete Benzi Grupioni, Carolina Rodrigues da Costa Doria, Amy E. Duchelle, Fabrice Duponchelle, Ana Margarida Duran Calisto, Juan Alvaro Echeverry, Marco Ehrlich, Andrés Escobar, Jhan-Carlo Espinoza, Adriane Esquivel-Muelbert, Ana Euler, Doris Fagua Rincon, Fander Falconí, Jorge Figueiredo, Matthew Finer, Suzette G.A. Flantua, Alexander Flecker, Carlos Eduardo Frickmann Young, Rong Fu, Laura P. Furquim, Silvia de Melo Futada, César Rodriguez Garavito, Roosevelt García-Villacorta, Rachael Garrett, Camilo Guio, Sandra Hacon, Sebastian Heilpern, Bernardo Herrera, Catarina C. Jakovac, Christopher Jarret, Clinton N. Jenkins, Juan-Carlos Jimenez Muñoz, James Junior, André B. Junqueira, David Kaimowitz, Michelle Kalamandeen, Mapulu Kamayurá, Jürgen Kesselmeier, Eduardo Kohn, Alexander C. Lees, Isabella Leite, Andrés (Willy) Lescano, Carolina Levis, Lúcia G. Lohmann, Marcia Macedo, Carla Maldonado, Luz Marina Mantilla, Jose Daniel M. Marra, Carlos (Uldarico) Matapí, Anderson Mattos, David McGrath, Gustavo Henrique Coelho Melo, Diego Meneghelli, Fernando Miralles-Wilhelm, Guido Miranda, Anna G. Mombiola, Encarni Montoya, Mariana Montoya, Edel Moraes Tenório, Claide P. Moraes, Gaspar Morcote-Ríos, María de los Ríos Almandoz Moreno, Federico Mosquera Guerra, Nathália Nascimento, Pedro Meloni Nassar, Ismael Nobre, Felipe Nunes, Valeria Ochoa-Herrera, Gustavo Oliveira, Maria A. (Tina) Oliveira-Miranda, Rafael S. Oliveira, Jean Pierre Ometto, Fernando Ozorio de Almeida, German Palacio, Sunitha R. Pangala, Daniela Peluso, Henrique dos Santos Pereira, Davi Pereira Junior, Stefan Peters, Oliver L. Phillips, Eduardo Pichilingue, Natalia Piland, Miguel Pinedo-Vasquez, Camille Piponiot, Paulo dos Santos Pompeu, Visnu Posada, Carlos Alberto Quesada, Raoni Rajão, Ying Fan Reinfelder, Natalia Restrepo-Coupe, Diana Alvira Reyes, Camila C. Ribas, Humberto Ribeiro da Rocha, Douglas Riff, Gloria Amparo Rivera, Luciana Rizzo, Daniel Robison, Bruna C. Rocha, Carlos Rodriguez, Herve Rogez, Oscar

R. Román-Jitdutjaaño, Eduardo Roxo, Boris Sakschewski, Norma Salinas, Jochen Schöngart, Tatiana Schor, Glenn Shepard, Myrtle P. Shock, Miles Silman, Celso H. L. Silva Junior, Roberto Donato da Silva Júnior, Maria Aurea Pinheiro de Almeida Silveira, Divino V. Silvério, Charlotte Smith, Britaldo Soares-Filho, Atossa Soltani, Carlos Souza, Gasodá Wawaeitxapôh Surui, Tod D. Swanson, Gabriella Tabet, Eduardo K. Tamanaha, Leonardo Tello, Emiliano Terán, Laurent Troost, Fernando Trujillo, Luis Angel Trujillo, Ermeto Tuesta, Carmen Ulloa Ulloa, Manari Ushigua, Judson F. Valentim, Clara van der Hammen, Richard van der Hoff, Silvia Vidal, Martin von Hildebrand, Robert B. Wallace, Jennifer G. Watling, Stefan Wolff, Markos Zangas-Tsakiris, and Stanford Rhode Zent

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Public Consultation Contributions: Cassio Bernardino (WWF Brazil), Paula Bueno (WWF Colombia), Joaquin Carrizosa (WWF Colombia), Joao Paulo de Soares Cortes (UFOPA), Brian Crnobrna (RedCons-Ucayali), Carlos de la Torre (University of Florida), Filipe Machado França (Lancaster University), Clarissa Gandour (Climate Policy Initiative and PUC-Rio), Deborah Goldemberg (WWF Brazil), James Gordon (WWF United Kingdom), Tarsicio Granizo (WWF Ecuador), Pia Escobar Gutiérrez (WWF Colombia), Consuelo Hernandéz (Fundación Humedales), Gerbrand Koren (Wageningen University), Claudia Leal León (Universidad de las Andes), Juan Carlos Ledezma (Conservation International), Bette Loisette (University of Florida), Bruno Garcia Luize (Unicamp), Anastassia Makarieva (Petersburg Nuclear Physics Institute), Stephanie Mansourian (University of Geneva), Dean Muruven (WWF International), Luis German Naranjo (WWF Colombia), Miguel Pacheco (WWF Peru), Sandra Petrone (WWF Mexico), Nigel Pitman (Field Museum of Natural History), Silvya Benitez Ponce (The Nature Conservancy), Thomas Ratican (University of Florida), María Inés Rivadeneira (WWF Ecuador), Carlos Rodríguez (Tropenbos Colombia), Jordi Surkin (WWF Bolivia), TR (Tinde) van Andel (Wageningen University), Michiel van den Bergh (WWF Suriname), Analiz Vergara (WWF), Hermani Vieira (EPE), Daphne Willems (WWF International), Mark Wright (WWF United Kingdom)

Interviews: Kleber Abreu, Dirceu Barbano, Andreia Bavaresco, Nurit Bensusan, Marcello Brito, Antônio Britto, Thaís de Carvalho, Mariano Cenamo, Claudia Galvez Durand, Kleber Franchini, Ruth Salzar Gascon, Deborah Goldemberg, André Guimarães, Jorge Hoezl, Kate Horner, Camilo Jaramillo Hurtado, Simão Jatene, Carlos Koury, Fany Kuiru, Riikka Kaukonen Lindholm, Pablo Lloret, Mauricio López, Lars Lovold, Elcio (Toya) Manchineri, Carlos Eduardo Marinelli, Elio "Wayu" Matapi, João Meirelles, Antônio Mesquita, Denis Minev, Paola Minoia, Berta Lina Murillo, Jhusely Danesy Navarro Patiño, Carina Pimenta, Marcos da Ré, Carlos Rezende, Jaír Rincón, Jaime Siqueira, Roberto Smeraldi, Bruna Stein, Izabella Teixeira, Eduardo Trigo, Daniela Trivella, Sineia Bezerra do Vale, Tuija Veintie, Roberto Waack, Luke Weiss

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Communication Senior Advisors: Pilar Calderon, Coimbra Sirica, Ilona Szabo

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INTRODUCTION

The Amazon Basin holds the most extensive rainforest in the world (~5.8 million km^2), and the largest river, which flows four thousand kilometers from the Andes to meet the Atlantic, carrying more water than any other river (~220,000 m^3/s). Billions of years of geologic and climatic changes and millions of years of biological evolution resulted in a highly heterogeneous region sheltering an unparalleled, vast, but still mostly unknown biodiversity. The Amazon rainforest is a vital ecosystem for the entire planet and part of the irreplaceable heritage for all humanity. The Amazon Basin is also home to Indigenous peoples that co-evolved with biodiverse ecosystems for more than ten thousand years, driving the emergence of a vast biocultural diversity.

Notwithstanding, the Amazon and its inhabitants have been historically threatened by a resource-based development model with a monetary-centric vision that causes ecosystem destruction while maintaining inequalities and violence. This model has been associated with a tremendous loss of intact, diverse forests and degradation of terrestrial and aquatic ecosystems by deforestation, non-natural fires, logging, natural resources exploitation, and pollution. Together with global climate change, these activities are pushing the Amazon towards a tipping point beyond which lies irreversible loss of the rainforest and its biodiversity, severely compromising human well-being. Halting deforestation and ecosystem degradation and finding alternative pathways towards the sustainable development for the Amazon are a priority under this critical scenario.

Despite the existing wealth of scientific and socio-environmental knowledge on the Amazon, there are still significant gaps in our understanding; this affects our ability to guide conservation strategies and support science-based decision-making processes, and demands great scientific and technological efforts to overcome. For instance, although scientists have described thousands of species in the Amazon, the full dimensions of Amazonian biodiversity remain vastly underestimated. Furthermore, despite the great effort of scientists to quantify carbon emissions and ecosystem productivity, limited data on the potential effects of CO_2 fertilization on photosynthesis and water use by trees restrict our understanding of forest resilience in the face of climate change. Finally, notwithstanding the enormous diversity of knowledge systems connected to the Amazon´s cultural and biological diversity, there are limited investigations into how these systems generate, transmit, and use such knowledge.

Under the auspices of the UN Sustainable Development Solutions Network (SDSN), over 200 scientists from the Amazon and who study the Amazon have come together to form the unprecedented Science Panel for the Amazon (SPA). They brought together their knowledge and experience to produce a Scientific Assessment of the state of the diverse ecosystems, land uses, and environmental changes in the Amazon and their implications for the region and other parts of the world. The challenge was unprecedented, to produce the first full-fledged scientific report carried out for the entire Amazon Basin and its various biomes, including an opportunity to develop a new, sustainable paradigm that ensures that the forest is worth far more standing than cut down, and that freshwater resources are managed sustainably. The well-being of those who inhabit the planet today and of generations to come depends on conservation of the Amazon.

This Report is divided into three main parts, each containing four Working Groups and together totaling 34 chapters:

I - The Amazon as a Regional Entity of the Earth System
II - Social-Ecological Transformations: Changes in the Amazon
III - The Solution Space: Finding Sustainable Pathways for the Amazon

Part I addresses an undisturbed - or with very low human-induced disturbance –Amazon Basin through the geologic, climatic, and ecological evolution of terrestrial and aquatic ecosystems and biodiversity. It explores why the Amazon rainforest is an important contributor to regional and global biogeochemical cycles, such as the carbon cycle and major nutrient cycles, and synthesizes the main mechanisms which operate in the physical hydroclimate of the Amazon. Part I ends by exploring human presence in the Amazon, highlighting the critical role of Indigenous peoples and local communities (IPLCs) in the sustainable use and conservation of Amazonian biodiversity and the consequences of European colonization for these populations.

Part II focuses on increasing anthropogenic changes in the Amazon, mainly from the 1960s to the present day. From the 1960s onwards, the Amazon experienced the most profound socio-environmental transformation in its history. Part II starts by reviewing the current situation of the diverse peoples who live, move, and work in the Amazon region, putting into context the changes in global policies and deep regional integration into the world economy. Such integration moved the Amazon to the top tiers in global exports of beef, iron, gold, timber, cocoa, and soy, which occurred in the context of highly unequal societies, threatening the rainforest, aquatic ecosystems, and the survival of IPLCs. National conservation policies are discussed as a counterforce to protect biodiversity, cultural diversity, and the territorial rights of IPLCs. Next, the chapters analyze the current reality of a highly complex and dynamic mix of rural and urban activities, including the formal, informal, and clandestine economies that drive deforestation. This includes the expansion of pastures and croplands, and ecosystem degradation such as pollution and forest fires. The cumulative impacts of multiple drivers of forest loss and terrestrial and aquatic degradation on biodiversity, climate, and the carbon cycle are described from the local to the global perspective, including their cascading effects on agriculture, hydropower generation, and human health and well-being. Last but not least, Part II ends with a warning of the imminent risk of crossing a tipping point due to ongoing land conversion and climate change; beyond this point, continuous forests can no longer exist and are replaced by highly degraded ecosystems.

Part III of the report focuses on solutions, presenting recommendations based on scientific and traditional knowledge, guided by the principles and values of the *Living Amazon* vision. This vision proposes a sustainable development model for the Amazon that is socially just, inclusive, and ecologically and economically flourishing. It recognizes the role of the Amazon in the 21st Century and the need for economies that can sustain ecological integrity and diversity, protect terrestrial and aquatic ecosystems, restore and remediate impacted ecosystems, empower Amazonian people, protect human rights and the rights of nature, and promote human-nature well-being. The solutions proposed are based on three pillars:

1) Conservation, restoration, and remediation of terrestrial and aquatic systems
2) Development of an innovative, healthy, standing forests, flowing rivers bioeconomy; addressing policies and institutional frameworks for human-environmental well-being and biodiversity protection; ingenuously combining the knowledge of IPLCs and scientific knowledge; and investing in research, marketing, and production of Amazonian socio-biodiversity products
3) Strengthening Amazonian citizenship and governance, which includes the implementation of bio-regional and bio-diplomatic governance systems (environmental diplomacy) to promote better management of natural resources and strengthen human and territorial rights

More than ever, the SPA Assessment is a timely opportunity to show the connection between human well-being and nature to a broad audience, including decision makers. The sustainable functioning of the Amazon's ecosystems guarantees the safety of the people who live in the Amazon and its surroundings, and supports planetary health. The SPA Report urges decision makers and all societies to act now to prevent further devastation in the region. Key outcomes of this unprecedented scientific report are new recommendations for a sustainable Amazon, which can serve as models for all tropical forests. Given the rapid transitions experienced by the Amazon and the world, there is great need for better communication between policy makers and the scientific community, including consensus on several key issues. Although threats and their administration fall first and foremost to Amazonian nations, the responsibility of saving the Amazon is global. What transpires in the Amazon in one country affects the Amazon in all countries, and what happens in the Amazon affects the entire world. Therefore, actions within the Amazon itself convergent with global actions to stop human-induced Amazon crises are urgent.

Carlos Nobre	Mercedes Bustamante
SPA Co-Chair	*SPA Science Steering Committee*

Amazon Assessment Report 2021

Chapter 14

Amazon in motion: Changing politics, development strategies, peoples, landscapes, and livelihoods

Caminhão sem placa e carregado com toras de madeira (Foto: João Paulo Machado /Amazônia Real)

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Graphical Abstract

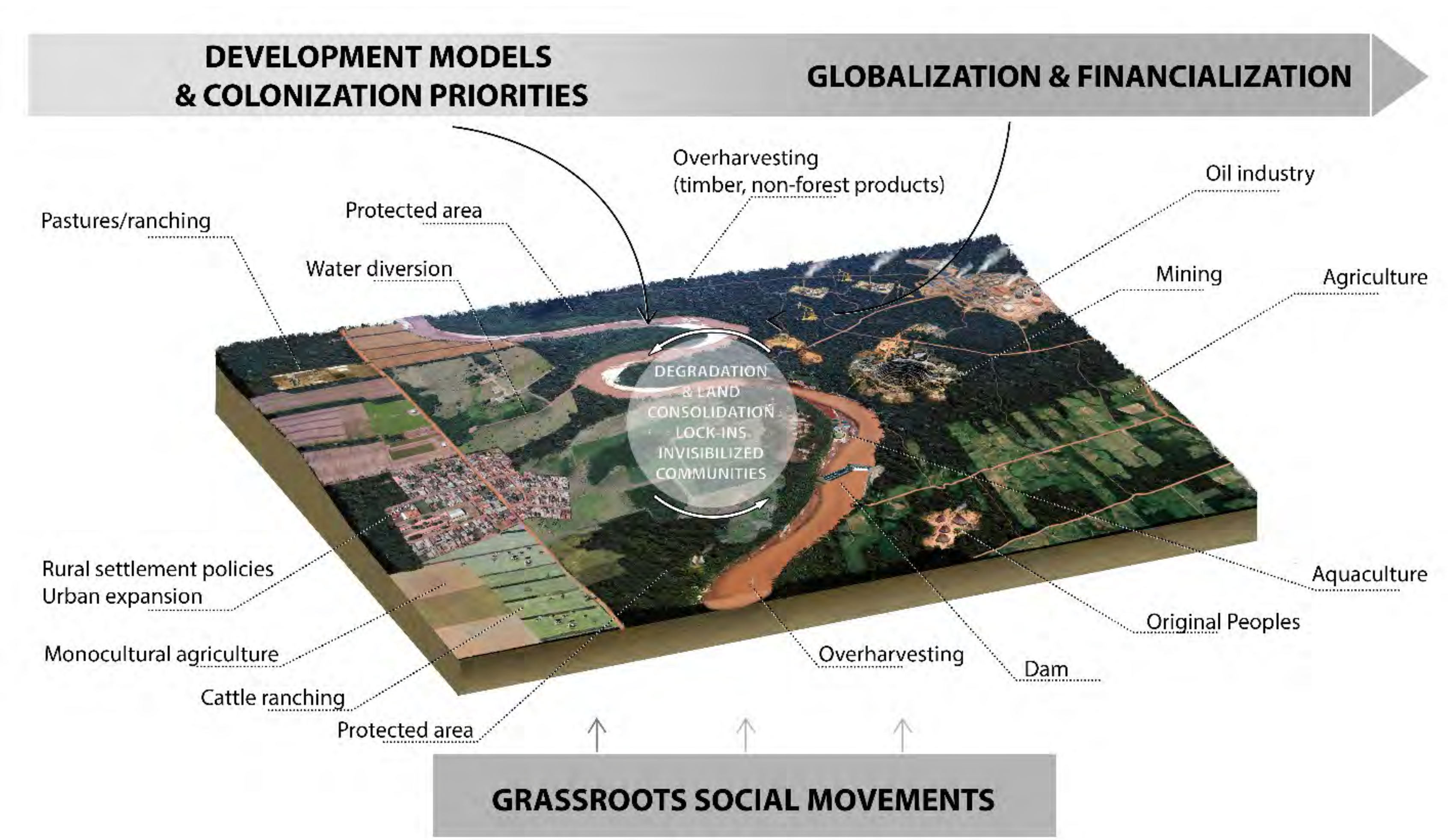

Figure 14.A Amazonian landscapes are shaped by development policies, globalization, financialization, and grassroots social movements

The Amazon in Motion: Changing Politics, Development Strategies, Peoples, Landscapes, and Livelihoods

Susanna Hecht[1], Marianne Schmink[2]*, Rebecca Abers[3], Eduardo Assad[4], Denise Humphreys Bebbington[5], Eduardo Brondizio[6], Francisco Costa[7], Ana María Durán Calisto[8], Philip Fearnside[9], Rachael Garrett[10], Sebastian Heilpern[11], David McGrath[12], Gustavo Oliveira[13], Henrique Pereira[14], Miguel Pinedo-Vazquez[15]*

Key Messages

- The Amazon has been treated as an experimental laboratory for modernization and development policies and politics since World War II. The undifferentiated green on maps belies the complexity of regional economies, social and cultural diversity, accelerated dynamics of land use change, rapid urbanization, and structural changes that have accompanied Amazonian integration into national and international politics and economies. The current context includes accelerated globalization and international commodity demand, rising inequality, expanding environmental concerns, and planetary change.
- Modernization policies and large-scale regional planning initially unfolded under mostly authoritarian Pan-Amazonian regimes, emphasizing national integration and Cold War politics. This stimulated early infrastructure investment (1960s) and state, informal, and private colonization programs to physically occupy the Amazon and serve as alternatives to agrarian reform in more settled and contested areas. In addition, a series of targeted and highly subsidized regional corporate economic programs and growth poles were advanced to promote mining, hydrocarbons, energy, agroindustry, and livestock. These settlements often impinged on Indigenous peoples and local communities (IPLCs)' territories.
- The idea of "modernization" emphasized deep structural change supported by an understanding of nature, and especially forests, as inert platforms, obstacles to development, evidence of backwardness, and largely lacking in value. This was the basis for development policies and planning in the Amazon, approaches that were largely indifferent to its ecologies, and perceived the Amazon as a demographic void.
- Yet, the Amazon was not empty. It has been inhabited for at least 12,000 years and is currently occupied by a diversity of people with multiple livelihood strategies. However, land-use in the Amazon is

[1] University of California Los Angeles, USA, Luskin School of Public Policy, and Graduate Institute for International Development Studies, Geneva, Switzerland, sbhecht@ucla.edu
[2] University of Florida, Center for Latin American Studies, USA, schmink@latam.ufl.edu
[3] University of Brasília, Political Science Department, Brazil
[4] Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), São Paulo, Brazil
[5] Clark University, Department of International Development, Community and Environment Massachusetts, USA
[6] Indiana University Bloomington, Department of Anthropology, USA
[7] Federal University of Pará, Centre for High Amazonian Studies and Postgraduate Program in Economics, Brazil
[8] Yale School of Architecture, New Haven, CT and Estudio A0, Quito, Ecuador
[9] National Institute for Research in Amazonia (INPA), Department of Environmental Dynamics, Manaus, Amazonas, Brazil
[10] ETH Zurich University, Switzerland
[11] Cornell University, Cornell NY, USA
[12] Earth Innovation Institute, San Francisco, CA, and Graduate Program on Society, Nature and Development of the Federal University of Western Pará, Brazil
[13] University of California, Global and International Studies, Irvine, USA
[14] Federal University of Amazonas (UFAM), Agricultural Ecology, Brazil
[15] Columbia University, Earth Institute, New York, USA; Earth Innovation Instituto (EII), San Francisco, USA; and Universidad Intercultural de la Amazonia (UNIA), Pucallpa, Peru

increasingly dominated by simplified monocultural systems, and mineral, hydrocarbon, and timber extraction, largely export-oriented.

- Amazonians live in ranches, farms, mining camps, Indigenous and traditional territories, forests, and villages, but most live in the region's cities. Complex dynamics of circular migration, multi-sited households, and polyvalent income strategies including state transfers and intra-family remittances underlie strong rural-urban interactions and widespread dependence on forests and rivers in the Amazon.
- Erratic public policy, limited technical support, uncertain tenure, and violence, combined with the volatility of small farm prices, have contributed to the emergence of multiple forms of clandestine economies. Rural instabilities and contested land rights have also been instrumental in fueling migration throughout the region.
- The insights and interests of local people, both urban and rural, native and migrant, are often overlooked. But these groups are generating alternative approaches to manage and restore landscapes, giving rise to new marketing systems and forms of governance. These systems can serve as models for a necessary shift in the approach to and practices of sustainable development in the Amazon.

Abstract

This chapter reviews the often-invisible, powerful processes that drive social and ecological change in the Amazon, and the diverse peoples who inhabit its landscapes. It explores the large-scale development ideologies of modernization, and the policy tools that were deployed to carry them out. Outlining general periods of macro policy shifts, it shows the evolution of the framework for today's complex interactions between large-scale agroindustry, mining, and hydrocarbons; diverse small-scale livelihoods; the clandestine and illicit economies of land grabbing, gold, coca and timber; and their operation in globalized and regional economies. While Pan-Amazonian governments have oscillated between authoritarian and more or less democratic forms of governance since the mid-20th century, more democratic transformations and trade have led to interactions among a wide array of new civil society actors; including non-governmental organizations (NGOs), social movements, rural syndicates, and urban social movements; and powerful actors such as national and international technical, financial, and corporate groups and international conservation organizations. New international sources of funding expanded well beyond multilateral or traditional bilateral aid; this includes financing from China and hedge funds, and new forms of both informal and corporate production lending. Integration into numerous globalized markets and finance have had enormous effects on Amazonian politics and economies at all scales. These dynamics have generated new kinds of policies, political framings, institutions, and economies, and restructured old ones; reshaped forms of urbanization, settlements, and land regimes; and stimulated extensive and controversial infrastructure development. On the ground, diverse Amazonian peoples have largely suffered the impacts of these processes, and have continued to adapt to changing circumstances while fighting to advance their own proposals for alternative forms of Amazon conservation and development.

Keywords: Development policy, globalization, urbanization, settlement, clandestine economy, deforestation, roads, dams, social movements

14.1 Big Processes and Invisible Amazonian Peoples and Landscapes

Far from being a homogenous forested river basin, the Amazon is home to diverse peoples and landscapes, often hidden from the outside perspective that tends to see the region as a vast forest devoid of human inhabitants. People on the ground make livings from the forests, rivers, lakes, wildlife, trees, crops and livestock they produce after clearing the forest, and minerals and oil they dig from under the ground. They also have urban livelihoods and depend on a variety of kin and state support networks. They live in ranches, farms, logging and mining camps, large project labor depots, Indigenous territories, and villages – but mostly in the region's cities and towns, invisible in the public's imagination of the Amazon as an untouched forest. Meanwhile, politicians, businesses, environmentalists, researchers, and financiers exert their influence over the region and extract its wealth, remaining hidden from sight in cities and countries far removed from the forest itself. Unnoticed, Amazonian people's ways of living, the places they live, and their quality of life have been transformed, swept up in nation-building projects and global development and processes of planetary change in recent decades.

Powerful outside forces and their results interact in complicated ways with the complex circumstances in each different corner of the Amazon, where particular histories and landscapes have evolved over millennia. This chapter sheds light on the major ideas, actors, and practices that have shaped its current dynamics to bring into better focus Amazonian people, how and where they live, and how that is changing under the impact of globalization, large-scale deforestation, land degradation, agro-toxics and mercury pollution, massive fires and rapid urbanization, accelerating and often erratic change regional politics, and planetary change. The chapter clarifies what forces and actors turned the Amazon into a place in crisis in terms of climate, species extinctions, and development inequalities and contradictions.

We begin the chapter by discussing the ideas of development and the politics that from the 1940s to the end of the 1980s actively shaped theoretical and political approaches to Amazonian transformation (Section 14.2). Subsection 14.2.1 introduces theories of development and modernization that have shaped recent Amazonian history in the context of the Cold War, the Amazon's emergent properties and large processes, and problems which remain "off the radar" (i.e., poorly studied and somewhat invisible) but which are major features of the Amazon's socio-economic and socio-environmental dynamics. Section 14.2.2 focuses on large-scale development policy approaches that have changed Amazonian regional economies since the 1960s and large-scale infrastructure programs that structure the current development trajectory. They establish the preconditions for the economic, ecological, and social dynamics that have shaped new and continuing processes of settlement, urbanization, infrastructure, state expansion, globalization, new forms of investment and finance, and rising social movements.

Section 14.3 deals with more recent dynamics evolving since the 1990s. The structure of regional economies in different parts of the Amazon varies a great deal, as will be discussed later in this chapter, and in Chapters 15, 17, and 18. What most country data suggest, however, is that there have been significant structural changes in agricultural and regional economies since the accelerated integration of the Amazon into regional, national, and global economies. These reflect the privatization of public lands and expropriation of commons; deforestation of protected areas and the lands of Indigenous peoples and local communities, and displacements by large scale infrastructure development, as will be discussed in Section 14.3.1. While human development indices have improved in many areas (e.g., schooling, access to water and health care) through the extension of national programs and basic income programs, such as Bolsa Familia, inequality has also increased (Richards and VanWey 2015; Guedes *et al.* 2012; Torras 2019), a situation brought to the fore during the COVID-19 pandemic.

Differing national contexts and politics reflect a wider role of the Amazon and its commodities in planetary politics and national economies. To understand this, Sections 14.3.2 and 14.3.3 focus on emergent drivers, such as new forms of globalization, new types of financing for projects and commodities, new kinds of export dependency, and clandestine economies, highlighting the hidden properties that are inherent in the current transformations (Box 14.1). We also discuss urbanization, settlement patterns, and infrastructure development as emergent processes, both as new drivers and outcomes of change. We end in Section 14.3.4 with a discussion of changing patterns of urbanization and settlement, the complex livelihood systems Amazonian people have developed in response to the massive transformations underway in the region, and the social movements these people have organized to push back against current conservation and development policies to propose promising alternative paradigms for Amazonian governance and sustainability.

14.2 Modernization and its Discontents

14.2.1 Development and modernization paradigm

The Amazon, like much of the tropical world in the 1950s, was the object of "meta" thinking about development. The post-World War II (WWII) world seemed malleable to transformation from its existing systems of wealth and poverty into the modern world. The idea of "development" or, as a more colonial idiom had it, "improvement," as applied to the tropical world, implied a transformation via "modernization," meaning a pathway from underdeveloped or traditional societies towards a uniform kind of modernity, characterized as essentially urban, industrial, largely secular, and organized by laws, institutions, and markets based largely on those of the North Atlantic World. This paradigm required modern bureaucratic states framed by nationalist identity rather than colonial administrations or societies structured by bonds of kinship, identity, patronage, or tradition, and many policies were put into place to disrupt them. Modernization was also seen as a mechanism to counter the unevenness of regional economies within nations, since the sleek modernism of Latin America's urban capitals was regularly contrasted with imagery of depressing poverty in its rural societies (Albuquerque 1999; Buckley 2017).

The modernization paradigm involved a shift from relatively non-capitalist, mercantile or traditional forms of society and institutions into modern economic, social, and political structures: non-waged labor to waged and monetized forms; emphasis on private property regimes and institutions over collective property; shifts in structures and economic "engines" from rural to urban; cultural change in terms of individualization, secularization, and new values and forms of consumption; monetization and privatization of what had been collective resources; and finally, industrialization. This modernization process depended on strong state intervention in the economy and many other social structures.

At least until the early 1990s this modernization paradigm was seen as the dominant way that the issues of so-called Third World poverty, understood to be expressions of underdevelopment, could be resolved through the powers of technocratic science and planning (Rostow 1971). Regional inequalities and poverty could be overcome by constructive means through accelerating economic growth and structural change. These would be part of *national projects* rather than colonial programs, with revenues accruing to national coffers rather than foreign metropoles, thus developing state capacity, institutions, and the economy, and moving beyond natural resource dependency as central economic drivers. This narrative, put simply, was countered by "Dependency" theorists in the 1960s, who argued that peripheral areas were sites of systematic extraction of resources, goods, and wealth to major economic centers (metropoles) (Frank 1966; Bresser-Pereira 2011; Cardoso and Faletto 2021). This framing has reemerged, and now forms part of the discussions about development in the idioms of extractivism, which we discuss further on.

Box 14.1 The hidden (and not so hidden) processes of Amazonian transformation

Invisibilities

One central problem in understanding the Amazon is that of invisibilities. These include invisibilities associated with socio-economic systems: illicit economies (timber, gold, and coca; and land grabbing) whose economic values, social, and environmental costs are enormous; and invisibilities associated with informal economies (in-kind exchanges in informal markets); the use and subsistence value of forests and rivers to local populations; the large scale flows of populations as they travel in daily, periodic, and seasonal movements in the shaping of their livelihoods, especially given the high degree of insecurity that prevails in Amazonian livelihoods; and the invisibilities of the costs of many population displacements associated with enclosures, land seizures, infrastructure development, and violence (Fearnside 2006, 2014; Jaichand and Sampaio 2013; Bratman 2014; Atkins 2017; Ioris 2017; Randell 2017; Calvi *et al*. 2020). Also invisible are the ecological and social costs of corruption, resource theft, and speculation, and the costs of the losses of cultural diversity, knowledge systems, and value systems that have been central to maintaining ecosystems integrity and livelihoods.

Informal institutions, "tradition," and access and tenurial regimes also operate in ways that are often invisible to outsiders but obvious and trenchant in the operation of daily lives. "New" social mapping is now being used to reveal forms of urban dependencies on ecological resources and territories (UEA 2010; de Almeida *et al*. 2019). Among the most dramatic of these has been the emergence of the importance and extent of *Quilombola* settlements (see Chapter 13), both urban and rural (refuge territories whose existence was largely unnoticed by most development agencies until the turn of the 21st century). Other ubiquitous, but largely invisible populations are the "*caboclo*" river dwellers, lake-side dwellers and fisherman, forest collectors, and swidden cultivators (Harris and Nugent 2004; Brondizio 2009; Silva 2009). About 25% of Indigenous populations are at least part-time urban residents (Alexiades 2009; Eloy and Lasmar 2011; Alexiades and Peluso 2015; Campbell 2015a,b; Nasuti *et al.* 2015; Sobreiro 2014) relying on urban access for markets, communication, education, healthcare, and political organization, in sharp contrast to the uniquely forest-based images of Indigenous people.

Other invisibilities are related to environmental impacts, including the environmental consequences of Amazonian land use transformations such as hydro-bio-climatic changes (discussed in Chapters 19-24), and regional, national, and global impacts such as changing rainfall patterns and increased local temperatures. The shift in some areas of the Amazon turning into CO_2 emitters versus carbon sinks (Gatti *et al*. 2021), and the methane release associated with hydrocarbon extraction are serious cumulative unseen impacts, while increased ecological fragmentation and enhanced vulnerabilities to fires also change landscapes for many species whose declining numbers go unnoticed. New forms of pollution associated with agro-toxics linked to large scale monocultures, and mercury and arsenic pollution associated with gold mining, contaminate Amazonian waters and bioaccumulate through the food chain.

Subsidy from nature

Another less visible factor is the importance of the "subsidy from nature." Like fish, forest products are freely collected in support of both rural and urban livelihoods. In many cases, this "no cost" subsidy for smallholders involves extensive resource management, knowledge, and labor inputs into the reproduction of the resource. The subsidy provided by free goods amounts to about a third of people's income, a result that for small-scale forest collectors is remarkably widespread. This means that typical ways of looking at rural and urban livelihoods often overlook the importance of collected goods in the economic portfolio.

The "subsidy from nature" also applies to externalities, through the simple extraction of value from nature with no attention to replacement costs, mediation, or remediation of environmental and social effects, or of impacts on ecosystem trajectories at local, regional, and planetary scales. For example, a natural product that was destructively harvested, such as commercial logging with no remediation or replanting, involves capturing and monetizing a resource embedded in ecological processes, incarnated in wood, without incurring any costs relating to the reproduction of the resource. In complex systems like the Amazon, while there were costs of logging (roads, trucks, labor), the timber resource itself - the main source of value - is often collected at little to no cost to loggers, or through corrupt capture of concessions, in contrast to other kinds of forestry and land-use systems where there are management costs that accrue to the profiter. Another key example is monocrop replacement of complex forests, collapsing their conditions and systems of recuperation, destroying their capacity to provide environmental services, and changing hydraulic, climatic, and ecological regimes (Coe *et al*. 2013; Laurance *et al*. 2018; Lovejoy and Nobre 2018). In this case, both the costs of "producing" an ecosystem product - say a mahogany tree - and the impacts of the externalities associated with its extraction increase system vulnerabilities, cause loss of resilience, and drive the loss of ecosystem services that are priced at zero. Social dislocations and conflicts also are not part of the calculus.

Path Dependency

Path dependency is the *dependence* of economic outcomes on the *path* of previous actions rather than decisions focused uniquely on current conditions. With path dependency, "history matters" and has an enduring influence on economies, livelihoods, institutions, and politics, reflecting choices made at one time that affect the conditions and possibilities available at a future time. Path dependence involves embedded institutional, political, and economic commitments to a particular technological regime, or in the case of the Pan-Amazon, particular technological landscapes, with considerable barriers to "switching regimes." For ecological and environmental reasons, such landscapes may involve not just political or technical regimes, but may produce what might be called "quasi-irreversibility" because ecological change can undermine ecosystem functionality and resilience once the forests are gone. These changes can be revealed in deflection of successional pathways of vegetation, soil toxins that limit re-establishment of local species, soil compaction, and the impacts of ecosystem fragmentation, local extinctions, and microclimate barriers to recuperation, to mention just a few. These can produce degraded lands that are usually very expensive to recover, and provide the background of scrubby brush visible next to every roadway in the Amazon (Laurance *et al*. 2002, 2018). These ecological changes can align with political blockages or institutional barriers that limit the capacity to support more resilient and/or complex social or ecological states. Land-use decisions and practices can preclude other options and development paths because they are so transformative of the natural base of production and/or the institutionalities that support them, or the people involved with them.

14.2.2 The modernization imperative and its toolbox: Development planning, programs, and processes

Putting this modernization vision into practice involved an array of instruments that had worked in rebuilding Europe via the Marshall Plan, and for poverty alleviation in the United States via The Tennessee Valley Authority (TVA) and New Deal, which very specifically focused on natural resource zoning and hydropower development (Miller and Reidinger 1998; Ekbladh 2002; Ekbladh 2011; McMahon *et al.* 2017). This fit well with both authoritarian and civil governments in the region because of the luster of technocratic approaches compared to the more personalist trajectories that had characterized the first half of the 20th century (Burns *et al.* 1979; Skidmore 1986). Large-scale plans promulgated throughout the Andean and Brazilian Amazon mimicked the more general five-year planning models of Europe and the Communist bloc. Bureaucratic states would expand their territorial powers, with the Amazon a development planning "laboratory" along capitalist lines, and a bulwark against communism, a key concern in the Cold War period (Klein and Luna 2016).

The forms of intervention involved the coordination of banking, investment, and infrastructure through regional planning agencies that would override coteries in favor of national project and national political control. These regional frameworks would provide a kind of geographical coherence to the development enterprise and remove control from local actors and their patronage circles (León *et al.* 2015; Sudério 2020). A second important strategy was "growth poles," inspired by the ideas of French economist Henri Perroux; these were sites for specialized investment and supporting infrastructure in the Amazon, accompanied by development corridors between specific poles and regions (Perroux 1955; Mønsted 1974; Hite 2004). Scientific assessment of natural resources and land suitability served as guiding mechanisms in the development of resource and land capability zoning inspired by the large-scale resource planning of the TVA. Targeted social investment (agro-industrial and mining development, and later agrarian reform or its kindred programs) would be used to ameliorate uneven development, and state-legitimating social programs such as agrarian reform efforts.

Facing the Amazon, regional and military planners focused on the idea of national integration as the first step of what would become a larger concern with river basin planning. Brazilian military and US planners dreamed of transforming the Amazon through a kind of tropical TVA (Hecht and Rajão 2020; Garfield 2013; Buckley 2017). The integration of the TVA approach with its basin-wide scale and organizing, and centralized management agencies for regional growth poles, became the model for much of the river-basin planning in Latin America. This is best exemplified by Cuidad Guyana and the huge Macagua Dam in Venezuela, and broadly inspirational for tropical planning and agricultural development more generally, as in Bolivia with the planning agency Cordecruz, in Colombia with the Corporación Araraquara, and in Ecuador and Peru. In Brazil, the powerful agency SUDAM (Superintendência do Desenvolvimento da Amazônia), in many ways the model for the rest of the Pan-Amazon, was the coordinating agency.

In these modernization approaches, the ecosystem was simply classified as natural resources; a platform on which the development visions of modernity were gridded out. Ecological simplicity was created through land transformation, as diverse ecological and livelihood systems, mostly illegible to the state and outsiders, were mapped into large scale grids and planning spaces to be occupied by ranching and colonist monocultures. This kind of modification depended on what anthropologist James Scott has called the "drive for legibility" by authoritarian modernist states (Scott 1998).

The technocratic strategy also involved resource assessment for new development planning. While there had been some cartographic endeavors dur ing WWII by US and Brazilian aircraft, the scale and frequent cloud cover required a different technology, one which, in the end, would become the main means through which the Amazon was apprehended by the states that claimed its territories. This new technology of remote sensing, which began with *Projeto RADAM* in Brazil and culminated in reports in the early 1970s, represented a fundamental shift in Amazonian studies and resource assessment via remote sensing, a central technological change whose impact is apparent throughout this report. In many ways, *Projeto RADAM* was foundational for understanding the scale of the Amazon.

14.2.2.1 Resource assessment, remote sensing, and modernization: the rise of land use suitability zoning, and conservation set-asides

Environmental degradation was of limited relevance in modernization discourse, and was more or less perceived as a technology problem, related to issues of efficiency, regional planning, and a few remote National Parks. Resource assessments, such as *Projeto RADAM* (1972), were carried out to provide a comprehensive survey, largely focused on minerals, soils, and forest types, and to examine the physical geography in order to upgrade the regional cartography of resources and boundaries (Herrera Celemin 1975) and to orient development enterprises. Remote sensing was employed by the Brazilian military government as a strategic input to national integration, and also followed TVA practices. The rich information provided set the stage for massive remote sensing initiatives upon which all Amazonian countries embarked (and have come to depend), especially when satellite remote sensing and computational capacities expanded. These produced the development of national remote sensing and land-use change monitoring laboratories such as Brazil's world-class INPE (National Institute for Space Research) and the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) that was instrumental in deciphering the dynamics of the Amazonian climate (Nobre *et al.* 2009). Remote sensing, and the models developed from satellite data, have become key in understanding the spatial dynamics of land-use change and its implications (e.g., fragmentation, carbon dynamics). Powerful remote sensing and computational technologies meant that significant analyses could take place remotely, with some ground truthing, displacing what had previously been the *sine qua non* of Amazonian research: fieldwork. While many scholars continued to explore the Amazon from the ground up, and continued to contribute to understanding of the historical importance of people's co-evolution with Amazonian natural systems, much of the environmental research continued to focus on "pristine" Amazonian nature, without humans.

Remote sensing projects like *Projeto RADAM* were unable to capture many aspects of human occupation, especially those of Indigenous peoples and local communities (IPLCs), whose livelihood was based on trees, tubers, bushmeat, and fish, until much later in the development of remote sensing technologies. The images of a vast agglomeration of resources and an unlimited forest underscored the idea of a demographic void and, fundamentally, of an experimental space that could be transformed into something more scientific, uniform, and ordered, according to a centralized vision (Silva 1957, 1967, 2003; da Costa Freitas 2004). This dynamic set into play a continuing contest for control of regional resources between existing populations, the state, and immigrants; and new regional aspirations by local inhabitants through claims for land, rights, and citizenship; along with the ambitions of more distant coteries.

14.2.2.2 ISI and military modernizations in the Amazon (1960-1990): Geopolitics, agro-industry and agrarian reform alternatives

Import Substitution Industrialization (ISI) was the main meta-policy framing for much of the mid- century period in the Pan-Amazon.[1] The initial phase, exemplified by Brazilian president Kubitschek's promise to modernize "50 years in five," included the first major Amazon infrastructure project, the Belém-Brasilia highway, built between 1958-60. This became the prototype for the Trans-Amazon highway which was also part of the system of "highways of integration" that formed part of strategic plans elaborated by the military. These infrastructure ambitions continued after the period of military rule in Brazil (1964-1985), when the focus shifted from national integration to the integration of the Amazon into large-scale export corridors, as we discuss further on.

Military developmentalism unfolded in a series of five-year plans across the Brazilian Amazon, stressed integration through road building, supported large-scale rural enterprises (especially minerals and ranching, with significant subsidies), ramped up the technical and scientific institutions for agriculture and tropical research (Dalmarco *et al.* 2015; Klein and Luna 2018), developed growth poles and instruments for regional development coordination, and provided significant but also erratic credit lines for regional occupation, a highly subsidized export assembly, and a duty-free hub in Manaus (Kanai 2014; Wilson *et al.* 2015). For reasons of legitimation, regional food supply, and geopolitical occupation, and also to deflect the demands for agrarian reform, significant colonization projects were implemented in Brazil, Peru, Colombia, Ecuador, and Bolivia, engaging state-run, private, and spontaneous colonization, which we expand on later (Brazil 1976; Barbira-Scazzocchio 1980; Becker 1982; Kohlhepp 2001; Jepson 2006a,b; Intrator 2011). Supported by bilateral international funding from Europe and the US, and multinational funding, the early interventions development process also produced extensive deforestation, environmental degradation, human rights abuses, and invasion of Indigenous peoples and local communities' lands, as the Brazilian Amazon exploded into land conflicts (Almeida 1992; Hecht and Cockburn 1989; Schmink 1982; Schmink and Wood 1992; Jepson 2006a; Osorio 1992; Fearnside 1986). This period, from the mid-1960s until the 1990s (a generation), evolved with minimal environmental regulation and enforcement of the few laws there were.

Migrant colonist agricultural systems, in general initially based on rice production, were also problematic, plagued by production and marketing problems, labor issues, and agronomic failure, with real problems of soil nutrient decline and low yields, using varieties and practices not adapted to local conditions, largely as a function of faulty extension and unadapted practices. These issues were exacerbated by titling insecurities, rural violence, very high colonist attrition rates, and high turnover (Hall 2000; Murphy 2001; Etter *et al.* 2008; Fearnside 2009; Pacheco 2009; Acker 2014; Carrero *et al.* 2020; Yanai *et al.* 2017).

Large-scale deforestation was increasingly becoming an international issue throughout Amazonian terrains from the 1970s forward, as scientific literatures explored in greater detail the dynamics of standing forests, and the local, regional, and, increasingly, planetary level consequences of forest clearing. This linking of social issues with environmental concerns became increasingly acute

[1] Evolving from a critique of natural resource exports which we discussed earlier, it was argued that such economies condemned countries to a skewed role in the international division of labor and underdevelopment. ISI promoted policies that were meant to expand the national industrial base through four main stages: (1) domestic production of previously imported, simple, nondurable consumer goods; (2) the extension of domestic production to a wider range of consumer durables and more complex manufactured products; (3) the export of manufactured goods and continued industrial diversification as part of a modernization strategy; and 4) modernization of agriculture to free up labor for emerging industrial sectors. A range of policies around fiscal incentives, floating currency rates, and new infrastructure that favored industries and sectors guided by growth poles would drive the economy and its linkages forward, shifting development from its heavy emphasis on natural resources and international markets, to industrialized goods for local consumption, and manufactures in its export mix.

and internationalized in the controversies associated with the development of Brazil's *Polonoroeste* program, the paving of the Cuiaba-Porto Velho highway (BR-365), continuing problems with the Transamazon highway, and in Ecuador, Peru, and Bolivia's active colonization zones (Well 1980; Eastwood and Pollard 1985; Santos-Granero and Barclay 1998, 2000; Barbieri *et al*. 2009; Pinto-Ledezma and Mamani 2014; Orta 2015). These controversies allied international environmental and human rights groups with national groups and movements. Coinciding with urban industrial unrest, corruption within the military, distress over torture and political killings, and the clamor for democracy, these movements eventually led to the fall of authoritarian regimes and spread of democratic governments (Luciak 2001; Hagopian and Mainwaring 2005; Hecht *et al*. 2006; Zimmerer 2006; Hochstetler and Keck 2007). Military developmentalism in the Pan-Amazon had many different variations, but similarities included ideas of territorial integration and/or occupation via early infrastructure development, large-scale transfers of public land to private owners (discussed in Chapter 15), promotion of colonization programs, support to leading sector(s) (oil, mines, sugar, livestock), Cold War politics, and supporting massive land-use changes and highly conflictual regional processes of territorial expropriation and local repression (Alvarez-Berrios *et al*. 2013; Bebbington 1993; Brondizio *et al*. 2009; Andersson and Gibson 2007; Arrueta Rodríguez 1994; Assies 2002; Blanes Jiménez and Flores Céspedes 1983; Bottos 2008). In most cases the environmental problems, human rights abuses, and other forms of repression and serious corruption problems stimulated national mobilization and alliances with other parts of civil society, including labor unions, urban social movements, and national and international environmental organizations, and were instrumental in the region's rise to democracy and the writing of new constitutions (Hecht and Cockburn 1989; Schmink and Wood 1992; Kingstone and Power 2000; Hagopian and Mainwaring 2005; Hochstetler and Keck 2007).

There was also military environmentalism, as far as it went. Generally indifferent to deforestation *per se*, the Brazilian military regime was sensitive to international pressure, and to the issues raised by rising conditionality in international loans starting in the mid-1980s, that raised concerns about human rights, Indigenous territorial rights, traditional people's resource rights, species extinction, and climate change. In part this was reflected in the creation of National Parks during the 1970s, so that until the early 2000s and the new presidential administration, the military period had been considered the golden age of Amazonian National Park creation (Foresta 1991; Padua and Quintao 1982). Indigenous lands also had to be demarcated, although at a leisurely pace, in order to diminish concerns about human rights abuses during the period of military developmentalism.

Our review of the political economies of the 20th century and political ecologies of different Amazon interventions helps us understand what we might call "Amazon Ascendency" (Box 14.2), or how a region that had been seen as a backwater became a crucial economic presence in national accounts, and increasingly a driver of national social, economic, and environmental policy issues beyond gross domestic product (GDP). New concerns with legitimacy, social inequalities, and uneven patterns of development could be attenuated by intervening with Amazonian programs of multiple types, paving the way for both large and small-scale producers.

14.2.3 Transition, constitutionalism and early neoliberalism

The late 1980s are often used as a marker of the shift from authoritarian to nominally democratic politics and regimes in Latin America, although modernization ideas did not actually recede. Instead, approaches were augmented by new scientific framings of environment, history, ethnography, and social movements that challenged the technocratic orientation and planning models

Box 14.2 Amazon ascendency: Complex shifts in Amazonian resource conservation

The late 20th century Amazon was seen as a solution or resolution to several kinds of national problems with international implications. These included 1) national integration; 2) geopolitical concerns over boundaries; 3) problems of political insurgencies, whether real or imagined; 4) issues relating to Indigenous populations in ways that nominally satisfied international observers; 5) political potential for economic gains and exploratory resources; 6) agrarian issues without engaging structural reform in other, more politically delicate, regions, and where reform was vigorously resisted by national elites; 7) a means of “modernizing traditional agriculture” in new spatial contexts that would not antagonize landed oligarchs, a critical element of national political alliances and important to development agencies; 8) the elaboration of technologies that would fuel the agro-industrial sectors of economies via innovations in soy/corn rotations, new pasture grasses ,and the introduction of oil palm; and 9) rhetorical and actual environmental policies and institutional development that was of special interest to trading partners, multilateral organizations, and bilateral funders.

We can perhaps summarize aspects of these shifts in the following points that evolved in the post-authoritarian period, in terms of conservation, development approaches, and regulations. There were, as part of this process of economic change and increasing national engagement in civil societies, a series of other shifts which, although contested, suggested a new form of politics. These can be summarized as “Epistemic Shifts” in institutional development at the level of the states, and new market dynamics. These also produced emergent properties and new drivers that now shape the Amazon.

Epistemic shifts

1. In a profound change from the set-aside conservation model, inhabited landscapes were recognized as having conservation value as well as economic value, and their stewards deserved rights and recognition, substantively changing land rights for Indigenous peoples and local communities (Simmons *et al*. 2010; Fontana and Grugel 2016; BenYishay *et al*. 2017; Bebbington *et al*. 2018a). These rights are currently under attack almost everywhere in the Amazon.
2. Agroecological and socioecological critiques of monoculture agriculture and livestock development models have been accompanied by the rise of agroecological experiments and sustainable alternatives as a response to externalities, and to enhance the subsidy from nature and support of environmental services. There is a substantial literature on this, as evidenced in the bibliography.
3. Nature has standing and legal rights, at least at the level of rhetoric. The *Pachamama* Earth mother has legal standing in the constitutions of Ecuador and Bolivia. A river has rights in Colombia. This incorporation of respect and rights for nature represents at least an ideological counterweight to the view of nature as a mere commodity.
4. Traditional tenurial regimes and territories become legally and constitutionally-recognized through historical rights and ancestral use (i.e., Afro-descendant *quilombos*, *Palenque* or Maroon lands; traditional and extractive reserves). These also ratified Indigenous rights and autonomy. Again, these rights are under informal attack via land grabbing and formal legislative threat.
5. The Amazon was increasingly recognized as a “socio-environment” constructed through people’s historical geo-biotic transformations of forests and soils, and engineering works, based on archeological, ethnographic, and historical research (Balée 1998; Fausto and Heckenberger 2007; Heckenberger *et al.* 2007; Parssinen *et al.* 2009; Clement *et al.* 2015; Athayde *et al.* 2017; Watling *et*

al. 2017; de Souza *et al.* 2018; Levis *et al.* 2018; Maezumi *et al.* 2018). These were analyzed with current enthographies and provide an alternative source of technologies for longer term ecosystem and social resilience in the current moment, and a kind of epistemological bridge to the future.

Legislative, regulatory, and analytic/technology regimes emerged as States evolved systems for environmental management

1. New ministries were created in all Pan-Amazonian countries, allied to ideas of sustainability and resilience and with new regulatory powers. Existing ministries (such as those in agriculture) took on expanded environmental portfolios.
2. Environmental legislation expanded, and Pan-Amazonian countries were integrated into international environmental agreements at national and local jurisdictional levels (Paris Climate Agreement 2015, Aichi 2017).
3. National "socio-environmental" politics, in Brazil and elsewhere, created insights into pathways and strategies for controlling deforestation. This included enhanced international support for alternative development models (Amazon Pilot project) and other sustainable research and practices which also ramified through regional research institutions. It included active demarcation of protected areas of all kinds, including inhabited forests. Moratoria on products from newly deforested areas were enacted, community organizations of many kinds were supported, credit black outs were applied in illegally deforested areas, state regulatory agencies were given support and funded, and real time monitoring and assessment, including fines and sanctions for illegal deforestation, occurred. This alignment of actions at all levels provided an unusual constraint on illegal clearing. Other processes were also at play, including low commodity prices, and producers' regulatory flight (leakage) to the Cerrado, Bolivia, and the Chaco.
4. Enhanced deforestation and land use monitoring, as well as land use modeling scenarios, emerged and provided powerful new scientific, policy, and regulatory tools.
5. New technologies for land demarcation, such as CAR (Brazilian Cadaster of Rural Areas), social mapping, and validation of historical claims were used to mediate and regularize land claims (Oliveira and Hecht 2016; Arima *et al*. 2014; Azevedo *et al*. 2017; Oliveira 2013). However, this geolocated land system required access to GIS systems that might not be available to many rural people, and increasingly these systems have been used to regularize illegal holdings (Ferrante *et al*. 2021).

Emergent Market Dynamics

1. Increased integration into global markets, especially China and the EU, for non-traditional Amazonian commodities (e.g., soy, Palm oil) and timber, gold, and beef. This accompanied a decline in US trade (formerly the Pan-Amazon's main trading partner). Strong international demand has increased, making the Amazonian agroindustry one of the largest sources of foreign exchange.
2. Expansion of clandestine markets, one of the main regional economic activities. Clandestine markets are an important source of both seasonal and continuous employment.
3. Expansion of green and fair-trade markets (e.g. *Açai, cacau/cacao*, rubber, Brazil nuts) has been important for valorizing native Amazonian crops and the populations that know how to produce them best. Increasingly, these products are branded (e.g., the "superfoods" maca and guarana) and move into global niche markets which show continuing growth potential, as do markets for basic food stuffs for Amazonian towns and cities.

4. Certification schemes have been important as marketing devices for food products, but problems of corruption remain, especially with timber (Clark and Kozar 2011; VanWey and Richards 2014; Brancalion *et al.* 2018).
5. Expanded demand for fast-growing timber from small farms (Sears *et al.* 2018).
6. Leakage of large-scale producers into less-regulated forested systems triggered significant deforestation in non-Amazonian forests (Meyfroidt *et al.* 2020).

that had dominated Amazonian interventions for a generation. This meant the end of the Import Substitution Industrialization model of development, which had been highly centralized; focused on internal markets, urbanization, and industrial expansion; with tariff and currency controls. Problems of cronyism, human-rights violations, and the marginalization of an emerging new entrepreneurial class undermined the legitimacy of these kinds of rules and rulers (Guidry *et al.* 2000; Hochstetler and Keck 2007). This shift produced Constitutional Conventions and an emphasis on the more market-oriented, decentralized, privatized economic exigencies of the Washington Consensus, a necessity for international finance, and early neoliberalism throughout the Amazon countries. Through the recognition of historical rights to territories, these constitutions laid the foundation for a rights-based approach to natural landscapes that was to be known as "Socio-environmentalism," ideas that took inhabited forests (and their complex tenurial regimes) as part of a conservation and land management strategy.

During the 1988 Brazilian Constitutional Convention, the articulation of inhabited landscapes as conservation spaces and the idea of forest peoples as forest guardians and defenders gained salience, and were incorporated into land laws and the creation of legislative frameworks and institutional development for agro-extractivist reserves, sustainable development settlements, historical communities and their territorial claims, and better recognition of Indigenous land rights. Indigenous people and local communities successfully pushed for conservation approaches, laws, and institutions that recognized the important role of historical Amazonian populations in both creating the Amazon's ecological complexity as well as in protecting forested landscapes (Balée and Erickson 2006; Nepstad *et al.* 2006; Vogt *et al.* 2015; Levis *et al.* 2018; Maezumi *et al.* 2018; Brondizio *et al.* 2021). New ways of thinking about the role of Amazonian forests focused on global and regional climate dynamics, environmental services, expanded ecological economics, recognition of the rights of nature, and concerns over environmental justice (Conklin and Graham 1995; Nogueira *et al.* 2018). In addition to new constitutions, this period saw the creation of new national environmental agencies, the emergence and institutionalization of the idea of socio-environmentalism, and radically reconfigured Amazonian conservation strategies (see Chapter 16). Socio-environmental politics have been part of every constitution of every Amazonian country since the early 1990s, articulated through concepts like the rights of nature, and the substantive recognition of the conservation value of inhabited landscapes.

14.3 Recent Development and Politics

14.3.1 The influence of political opening, mobilizations, and environmental politics, and the fall and rise of deforestation

The politics of the 2000-2020 period reflected the integration of many emergent factors that stimulated new social, institutional, and political structuring. The response to these complex pressures and changes was not uniform in the Pan-Amazon, but it produced new ideologies and strategies that moved beyond both traditional conservation modes and standard development frameworks. As mentioned in Box 14.5, the importance of new forms of land rights for Indigenous peoples and local communities, especially Afro-descendants, forest product extractors, river and lake communities, and others legitimized by long historical occupation, created both cultural and political spaces, a kind of forest citizenship. In Bolivia and Ecuador, ideas such as the Rights of Nature (the *Pachamama*) and ways of living focused on well-being over accumulation (*Buen vivir)* were incorporated into constitutional and political language (see also Chapter 25). While certainly mostly rhetorical, it articulated an Indigenous moral language into a nation-defining document.

Yet, while socio-environmentalism increasingly influenced Amazonian policy, macro-development economic policies associated with the Washington Consensus or neoliberalism worked counter to these approaches through their deregulatory stances, limitations on state actions, privatization, extensive national opening to international investment, political decentralization, and tariff-free trade. The neoliberal period in the Amazon coincided roughly with the rise of Chinese and European engagement and investment in the economy, including as well a "China /Asia shock," as inexpensive, high-quality Chinese and other Asian-manufactured imports undermined and effectively dismantled many national industries. This caused economies to again focus on natural resource exports. China and the EU became more involved in the economies of Amazonian countries. This was also reflected in accelerated demand for raw materials, especially soy and beef (de Waroux *et al*. 2019). The 1990s and post-authoritarian transition period reflected the institutional weakness of a rising civil society that had been sharply repressed during authoritarian times, and the undermining of the state as part of macro policies, which more or less left markets as the central organizing institution.

Instability in the manufacturing sectors triggered a more erratic policy context, and shifted the ideas of the economy away from what had been import-substitution thinking with industrial efforts for internal markets, to export-led development based on raw or minimally processes materials - what was later called the "commodity consensus" (Svampa 2019), "extractivism," or "neo-dependency." This expansion coincided with a commodity boom largely led by demand from Asia, and increased national and global environmental concern, as environmental justice issues animated local politics and IPLCs, including Afro-descendent communities, whose lands and livelihoods were increasingly threatened. These contradictory dynamics were reflected in greater activism in both rural and urban domains, and pressure for social investments and new institutions for socio-environmental support. This produced a shift into a development regime now called "Neo-Extractivism," which involved continuing to expand exports while implementing fiscal transfer schemes as a means of poverty alleviation, and a movement away from structural change. These anti-poverty initiatives included conditional cash transfers throughout Latin America; such as *Bolsa Familia* in Brazil, a social transfer that provides a guaranteed income to mothers conditioned on children's schooling and child vaccination; and funded retirements, higher minimum wages, access to credit, and expanded social services.

In this context, "socio-environmentalism" represented a rethinking of the nature of conservation, which could include inhabited environments of many kinds oriented to sustainable and resilient forms of development. Because of its environmental and social justice components, and increased international concerns over climate change and deforestation, international conservation and environmental activists began large scale investments oriented towards maintaining standing forests as social and biotic places. This represented novel forms of rural investment that went well beyond the production credits previously provided for small farmers. These macro-changes in development models had significant policy impacts throughout the Amazon, but perhaps the most closely studied has been the Brazilian case (see Chapter 17). Figure 14.1 illustrates these dynamics.

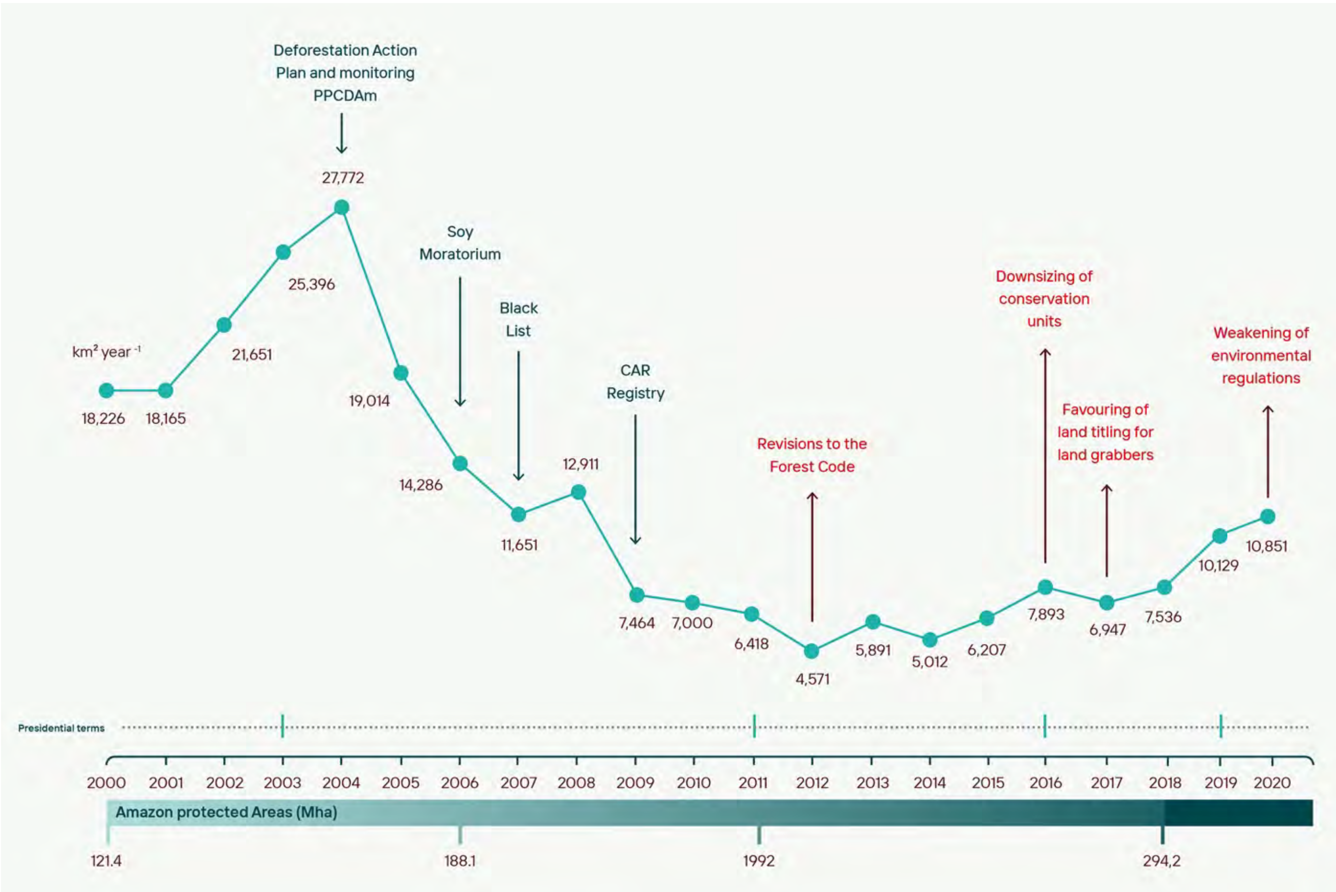

Figure 14.1 Deforestation in the Brazilian Amazon in response to policy changes, 2000-2018. Adapted from: PRODES 2020, Soares-Filho and Rajão 2018.

Figure 14.1 shows how important political and policy changes in Brazil led to dramatic declines in deforestation after a peak in 2004, and how subsequent policy reversals since 2016 have been accompanied by rising deforestation. Annual deforestation rates in the Amazon dropped by approximately 80% from 2005 to 2012, due to commodity price decreases, unfavorable currency exchange rates, policy interventions, significant institution development at local and national levels, wide participation of civil society in sustainable development initiatives, voluntary market agreements, expansion of protected areas, international support for forest-based initiatives such as the Pilot Project for the Amazon, much better monitoring of deforestation, and significant "leakage" (displacement of major deforestation processes to the Brazilian Cerrado, Bolivia, and the Chaco of Argentina), which all aligned to reduce Amazonian clearing in Brazil (Fearnside 2007; Hecht 2012, 2014a; de Waroux *et al.* 2016; Davenport *et al.* 2017; Duchelle *et al.* 2017; Lambin *et al.* 2018; Nogueira *et al.* 2018; de Waroux *et al.* 2019; Silva *et al.* 2020). Nevertheless, by 2016, with the impeachment of the President, and the emergence of a powerful agribusiness coterie who gained control over institutional and rural policy (the *Bancada Ruralista*) in Brazil, deforestation began to climb. By 2019 the annual deforestation rate in the Brazilian Amazon had increased by 122% since the

2012 low (Carrero *et al.* 2020), and continued to increase throughout 2020. By the first half of 2021, deforestation alerts rose to the highest in six years (Dantas 2021). A new law legalizing illegal seizures of public land was making its way through the legislature, threatening to regularize previously illegal land grabs and stimulate new waves of land grabbing (Fasolo 2021).

The current development model, Neo-extractivism, with its minimal diversification and processing within the main export sectors, has been usefully summarized by McKay (2017); (1) large volumes of materials extracted, destined for export with little or no processing; (2) value-chain concentration and sectoral disarticulation; (3) high-intensity environmental degradation; and (4) deterioration of labor opportunities and/or conditions. McKay and others argue that "agrarian extractivism" is a politically and analytically useful concept for understanding new landed dynamics and trajectories of agrarian change. "Rather than a form of industrial agricultural development; which implies value-added processing, sectoral linkages, and employment generation; agrarian extractivism challenges this dominant discourse, revealing … its negative implications for rural development" (McKay and Colque 2016; McKay 2017).

Pan-Amazonian deforestation is volatile for a number of reasons, both intrinsic to the region, and reflecting interactions with broader national ambitions and international processes. It clearly responds to policy and to national and international economic and political pressures, but it also reflects how these unfold on the natural resource base and through socio-environmental systems at different scales. While deforestation is the central concern now, it cannot be addressed without understanding the larger frameworks that justify and drive forest clearing and that contribute to larger instabilities. We emphasize the variation in Amazonian regional economies, structures, logics and production systems; the political coteries that have benefited; and the forms of resistance and economic alternatives that have emerged, both legal and illegal, in the construction of the current Amazon, as old pathways give way to multiple new drivers of change.

14.3.2 Old pathways, new drivers

14.3.2.1 New circuits of globalization

Globalization refers to the integration and movement of multiple commodities, capital, people, technologies, ideas, ideologies, discourses, and forms of representation that can structure and transform localities and economies, but also hybridize with local, regional, and national spaces. At the current moment, the expansion of soy, oil palm, beef, exotic pasture grasses, eucalyptus, new mining concessions, and oil and gas blocks that have proliferated in the Andean Amazon are forms of modern "ecological imperialism" in the Amazon, transforming national and global ecologies, commodities, and economic transfers.[2] The Amazon, however, has been integrated into large-scale circuits in the movement of goods for thousands of years, with the transfer of Amazonian germplasm, feathers, medicinal plants, stones, gold artifacts, metals, and technologies throughout Latin America (Whitehead 1990, 1994; Whitten *et al.* 1997).

Since the 2000s, global markets, rather than internal development strategies, have increasingly driven land-use processes in the Amazon. In particular, global markets for timber, pulp and paper, meat, drugs, oil, gold, and oilseeds have driven larger and faster transformations of the Amazonian Basin than in any other period. More industrialized countries have "off-shored" their environmental footprints toward the Amazon, as with the expansion of oil palm for Dutch biofuels, soy for China, and beef for Asia, choosing to exploit the Amazon in place of further degrading their own

[2] Ecological imperialism is a concept developed by Alfred Crosby (2004), who argued that settlers were successful in colonizing other regions because of their accidental or deliberate introduction of plants, animals and diseases that deeply shifted local ecologies.

resources (see for example Rajão *et al.* 2020; Austin 2010; Rudel 2007; Klinger 2018).

While certain forms of agro-industrial production can generate development where they involve value-added processes (Garrett and Rausch 2016; Richards *et al.* 2015; Richards and VanWey 2015), they generally perform poorly in terms of generating increased employment and improved access to services, and tend to exacerbate inequality (Weinhold *et al.* 2013). In this same vein, 'model municipalities' emerged as nodes in the evolution of a governance frontier in the Amazon, advancing a neoliberal paradigm that replaced more direct democratic measures (such as participatory budgeting) with municipal governance that regulated and stabilized 'green' agro-industrial development (Schmink *et al.* 2017; Thaler *et al.* 2019). The re-democratizing "wave" of governments of Amazonian countries, and the ascension of socio-environmental policies protecting IPLCs and the region's natural resources, appear to have been largely played out by 2020, with clear signs of political setbacks as the region as a whole has become more integrated into global economies, and national politics drifted toward coterie dynamics.

While new forms of financialization and globalization were unfolding in the context of powerful economic forces shaping export markets in agricultural commodities, failures in other development arenas, especially as regards employment, as occurred so broadly elsewhere in Latin America, caused clandestine economies to surge forward in part because of their relatively high labor demand.

14.3.2.2 New Amazonian financialization

An important new aspect of Pan-Amazonian dynamics has been the transformation of the financial sector. The role of South American development banks and state-owned commercial banks has decreased in providing loans and investment capital for agriculture, agroforestry, timber, other forest product extraction, mineral extraction, and even infrastructure construction. New, private financial actors have started to play an increasingly large role in production, consumption, and conservation practices. This includes not only greater participation of private commercial bank lending in the region, but also, and even more importantly, the role of new financial actors, such as hedge funds, sovereign wealth funds, pension funds, and new financial instruments in shaping the development trajectories and historical geography of the Amazon. By 2021, illegal Amazonian lands (including Indigenous lands) were being sold on Facebook (Fellet and Pamment 2021), and digital technologies had come to play an important role in facilitating illegal market transactions.

In agricultural production and ranching, state-owned commercial banks (such as *Banco do Brasil*) were the most important financiers of agriculture and ranching in the Amazon until the 1980s (Torres 1996). As soy monocultures expanded in the southern Brazilian Amazon during the 1990s (see Chapter 15), particularly over degraded pastures cleared from the Amazon forest in the states of Mato Grosso, Rondônia, and Pará, farmers started to rely increasingly upon seed and agrochemical trading companies such as Monsanto, Bunge, and others for credit – often pre-negotiating a third or more of their future harvests at the moment of purchasing their inputs for the year (Wesz Jr. 2016). In turn, this financialization of agribusiness trading companies provided them with more dynamism in generating profits, even making speculative gains from commodity trading and farmland investment (Salerno 2017). This process unfolded alongside deregulation of the banking sector in South America since the 1990s (Studart 2000), and the rise of private equity funds, hedge funds, local investment circles, and investment banking worldwide (Wójcik *et al.* 2018), which began to see natural resources and agribusiness in developing countries (particularly those with potential for growth, such as Brazil) as ideal targets for investment (Visser *et al.* 2015). Consequently, when soy displaced ranching in the southern fringes of the Amazon (especially in Mato Grosso), private equity funds, pension funds, and other new financial actors became the leading providers of capital (both from South America and beyond the region) to large-scale "land development" and farm management companies (Oliveira and Hecht 2016).

Similar transformations have taken place with regard to finance for infrastructure construction, including not only roads and ports, but also, very significantly, hydroelectric dams in the western (Ecuador, Peru, and Bolivia) and southern (Brazil's Tapajós and Xingu basins) Amazon (Bebbington *et al.* 2018a). Many of these infrastructure projects involve Brazilian construction companies, especially the transnational giant Odebrecht, and were recently swept up in corruption scandals that reached into other Amazonian countries, toppling governments in Peru, Bolivia, Ecuador, and Brazil (Branford 2016). Historically, large-scale infrastructure projects have been financed by state-owned or multilateral development banks, among which Brazil's National Economic and Social Development Bank (BNDES) has played an outsized role in the region, including in neighboring Pan-Amazonian countries such as Peru, Ecuador, Colombia, and Venezuela (Rivasplata Cabrera *et al.* 2015; Hochstetler 2014).

There has been a notable shift in international development finance away from the Inter-American Development Bank (IDB) and the World Bank (WB) towards the China Development Bank and the China Export-Import Bank (Ray *et al.* 2019), in part because of the limited environmental or social conditionality on their loans. The latter are newcomers not only to the Amazon, but also to the realm of international development finance, and there has been concern that the entrance of Chinese development banks may destabilize perceived gains in the best practices for environmental protection and social responsibility adopted by the BNDES, IDB, and WB (BankTrack and Friends of the Earth 2012; Dussel Peters *et al.* 2018).[3]

Chinese finance is more responsive to government-to-government articulations and national-level policies than to bottom-up social movements and NGO interventions (Ray *et al.* 2019). Consequently, this shift transformed the balance of power among Amazonian actors, empowering national elites and others outside the Amazon who might benefit from infrastructure construction projects, while avoiding the direct negative effect of these projects, and weakening the relative strength of Amazonian Indigenous peoples, social movements, and NGOs in the face of such mega-projects. In this way, China is becoming a major force in Amazonian deforestation and environmental degradation (Fearnside *et al.* 2013; Fearnside and Figueiredo 2015), and is now the main trading and lending partner in Amazonian Latin America (see also Chapter 18).

Perhaps the most notable change regards the creation of new instruments for generating financial dividends from conservation itself. At the 2006 United Nations Framework Convention on Climate Change Conference of Parties, the Brazilian government was able to launch a partnership with European donors to establish (in 2008) the Amazon Fund (*Fundo Amazonia*), a USD 1.1 billion financial vehicle for sustainable development and conservation. The Norwegian government was the main contributor, while the German development agency KfW and Brazilian state-owned oil company Petrobras made smaller contributions. The crux of the project was that financial transfers from the Amazon Fund were conditional upon reducing deforestation and GHG emissions, while exploring and supporting alternative land uses.

[3] This is somewhat ironic given the troubled history of BNDES in the Amazon (Bergamini Junior 2003, Gallagher and Yuan 2017), even as recently as the 2000s, with high-profile disputes about the Belo Monte dam on the Xingu River (Fearnside 2006, 2017a; Diamond and Poirier 2010; Jaichand and Sampaio 2013; Bratman 2014). The rise of Chinese development finance has been accused of provoking a "race to the bottom" in international standards and perceived best practices (Gerlak *et al.* 2020). The lack of concern for impacts is illustrated by the 2014 Chinese purchase of a 33% interest in the notorious São Manoel Dam in Mato Grosso, located only 700 m from the Kayabí Indigenous Land, where the Indigenous people were not consulted (in violation of Brazilian law and International Labour Organization [ILO] Convention 169). The São Manoel reservoir was filled in 2017, despite multiple licensing irregularities, and it is the scene of continuing tensions with the Indigenous people it impacts (Fearnside 2017b, 2020).

The Amazon Fund became the world's largest financial instrument for deforestation control, and a lynchpin of the strategy of mobilizing finance and trade mechanisms for reducing emissions from deforestation and forest degradation (i.e., REDD or REDD+). Nonetheless, the implementation of REDD+, the activities of the Amazon Fund more broadly (including mechanisms for monitoring and calculating deforestation and emissions), and the economic quantification of these processes are the subject of intense scrutiny and heated debate (van der Hoff *et al.* 2018; Correa *et al.* 2019; Pinsky *et al.* 2019; West *et al.* 2020). Beyond technical questions about how to monitor and measure deforestation, degradation, and carbon emissions/sequestration, and how to calculate these phenomena in economic terms (Fearnside 2012a), the most important debates pertain to the political struggle over *who* sets the terms for and benefits from development in the Amazon (McAfee 2012; Corbera 2012; Mahanty *et al.* 2013; Klinger 2018). These political tensions became especially clear in 2020 as European donors withheld funds destined for the Amazon Fund due to rising deforestation in Brazil, while the federal government of Brazil publicly rejected the idea of other nations imposing conditions on Brazilian policy, and tensions increased over Mercosur agreements as a function of rising deforestation.

14.3.2.3 Clandestine economies

Clandestine economies emerge alongside, and converge with, regulated, lawful, and formalized economies. Working in the economies of gold, timber, and coca is often part of a livelihood strategy for many people in the Amazon. These economies form part of a portfolio strategy that works in tandem with larger household livelihood approaches in agriculture, urban or rural waged labor, petty commerce, non-timber forest products, and family cash income from formal sources like conditional cash transfers, pensions, agricultural or product sales, and remittances. As we will discuss below, both rural and urban incomes exhibit a high degree of precarity, and this is also reflected in the relatively high number of workers in illegal activities, at least periodically. However, all these types of income generation "subsidize" relatively low wages paid in all livelihood sectors for relatively unskilled labor. The expansion of clandestine economies reflects new technologies, expanded transport infrastructure, new geolocation technologies, new or expanding markets, and failed national development policies that produce few income opportunities and very high levels of employment and income precarity.

Legal and illegal systems often operate side by side, melding into each other in both space and products, as in the timber industry. Illegal land acquisition can be laundered through livestock, fake title, and land clearing amnesties or, as mentioned above, even sold on the internet. Traditional land tenure and access regimes were held by communities that often had limited legal standing if not demarcated under new laws, and hence community lands frequently are legally appropriated in spite of their new constitutionally legal status. The long history of fraudulent land grabbing in the Amazon often depended on simple forged documents, or failing that, setting fire to land registry offices, or simply using violence to intimidate or kill occupants (Schmink and Wood 1992).

The revenue generated from clandestine economies is substantial; for example, the United Nations estimates the value of the coca economy at half a billion USD globally (UNODC 2015), but returns often carry severe environmental and social costs, and may or may not produce much by way of local development linkages over time. A recent study by the Escolhas Institute compared gold-mining municipalities to those without; they showed that the economic impacts and well-being were highly ephemeral, since for many goods processing, adding value, and lucrative markets occurred elsewhere. The commodity value increases with the distance from the site of production, as is so typical of Amazonian commodities.

14.3.2.3.1 Gold

Peru is the largest gold producer in Latin America and the seventh largest in the world. Yet, over half of Peruvian gold is extracted by unregulated artisanal and small-scale gold mining (ASGM) operations (Caballero Espejo *et al.* 2018; Rodrigues 2019). Significant proportions of the gold extracted in Amazonian countries is extracted illegally (Table 14.1). Virtually all the gold mining in the Madre de Dios region of the Peruvian Amazon is "informal," in violation of state environmental and labor regulations, a situation that essentially criminalizes all small-scale mining, despite its importance for livelihoods in the region (Bird and Krauer 2017). Efforts to formalize small-scale miners and induce them to shift to alternative agricultural activities have largely failed, because alternatives cannot match the higher incomes available through gold mining, due to high global prices for gold (currently almost USD 2,000/ounce; Monex 2021).

Mining is responsible for about 10% of deforestation in the Brazilian Amazon (Soares-Filho and Rajão 2018). Mineral soils that underlie tropical forests of the Amazon basin contain diffusely distributed gold deposits. Extracting this gold, which requires a combination of forest removal, soil pit mining, and the use of liquid mercury, poses a major threat to Amazonian biodiversity, water quality, forest carbon stocks, and human health (Diringer *et al.* 2019). The Pan-Amazon's major rivers are subject to sediment mining on tributaries, which affects aquatic systems. Further, regional roads for one product (like timber) permit broader access to formerly isolated environments, although a great deal of gold moves by small planes and on rivers (Bebbington and Bury 2013; Caballero Espejo *et al.* 2018).

Relatively limited and controlled exits points, such as gold through Lima, have been reconfigured to move almost entirely though the Amazon. This regionalization of the Peruvian ASGM trade reveals the flexibility of the gold production system, and particularly ASGM, in reacting to pressures emanating from the Peruvian state to eradicate illegal mining. This leakage mimics in many ways the shift of soy to less regulated venues. The Global Initiative Against Transnational Organized Crime (2016) notes that illegal gold mining is rapidly spreading across the Pan-Amazon.

Table 14.1. Percentage of gold considered 'extracted illegally'

Country	%
Brazil	36
Peru	28
Bolivia	30
Ecuador	77
Colombia	80
Venezuela	80-90

Source: Escolhas Institute 2020

These mining systems are organized in multiple ways, ranging from cooperatives or semi-cooperatives in the "Garimpeiro Reserve" in Pará and Mato Grosso, Brazil, to mines managed by Maroons in Surinam or elsewhere by Indigenous groups, and through debt peonage and other forms of forced labor and waged or product payment (Asner *et al.* 2013; Caballero Espejo *et al.* 2018; Cortés-McPherson 2019). Gold mining often provides an important complement to people's livelihood systems, and has also provided a form of economic upward mobility for some (Cleary 1990; Escolhas Institute 2020). Miners often become politically active in defense of the practices, and have in some cases made arguments in favor of informality and its redistributive and access features, as compared with large scale, formal mining which often involves large international companies and state subsidies (Bebbington and Bebbington 2018; Bebbington and Bury 2013; Schmink and Wood 1992).

In the realm of precarious states and illegal extraction, Venezuela deserves special mention. The Orinoco Mining Arc (*Arco Minero*) is the product of a national policy established in 2012; operations began in 2016 (Rendon *et al.* 2020). El Callao, an historical gold mine (begun in 1853) was exploited by the formal mining company Minerven since the 1970s. With the economic crisis, the mine stopped working, and was taken over by informal armed groups and the Venezuelan military. Armed forces controlled the *Arco Minero*; they extorted illegal miners and controlled commercial routes. Planes took minerals to international markets (for exam ple, Curaçao, taking advantage of the free trade zone). Indigenous communities were forced into labor (mining or prostitution), but the mine itself also attracted a desperate diaspora from other parts of Venezuela. While the Yanomami were periodically given respite and Brazilian miners expelled from their lands, the Venezuelan situation remained complicated, especially in light of the precarity of the state itself and the ambiguous nature of its regional actors. Illegal mining can affect Indigenous groups through direct land invasion, but also through the contamination of fish and aquatic birds, a main source of protein in many Amazonian communities, and trafficking of goods and people.

14. 3.2.3.2 Land grabbing

In Brazil, "land grabbing" is known as "*grilagem*," involving land claiming through showing effective use (see also Box 15.3, Chapter 15).[4] For centuries it has been a major part of Brazil's land-tenure practice by large actors, and invasion and later legalization by small homesteaders (*posseiros*) through various system of traditional land recognition (Benatti *et al.* 2006; Moreno 1999; Schmink and Wood 1992). The 54 to 65 million hectares of "undesignated lands" (*terras devolutas*) of Brazil are the major targets, but substantial unclassified lands also exist in Loreto in Peru, and in the former Revolutionary Armed Forces of Colombia (FARC) territories (Azevedo-Ramos and Moutinho 2018; Reydon *et al.* 2020). Indigenous lands and other forms of land claiming, such as Afro-descendent communities and other traditionally recognized, but not yet demarcated, lands are also increasingly under threat, apparently encouraged by the current Brazilian administration's discourse (HRW 2019).

In Colombia, various dynamics associated with the interactions of paramilitaries, and shifts in FARC governance, have also stimulated land grabs in the absence of mediating authorities. Maroon lands in the Chaco have been targeted for expropriation as well (Armenteras *et al.* 2013; Ballve 2013; Gomez *et al.* 2015; Grajales 2011, 2015). It is exactly at these zones of shifting territoriality where deforestation is most likely to occur as a "hotspot," since land clearing works to help establish definitive land claims in places where they are contested. The situations in Colombia, Peru, Ecuador, and Bolivia are complicated by the hydrocarbon industry, which operates with subterranean concessions, even as above ground land or resource concessions accrue to others. The hydrocarbon sector, like the infrastructure sector more generally, provides access roads into extensive areas that can become sites of land appropriation.

While the legal dynamics across the Amazon vary, dynamics of land claiming can be quite similar.[5] Land grabbing involves deforestation, because

[4] The use of the term "land grabbing" in the Amazon is different from the way it is commonly used in other contexts. Particularly since 2008, this term usually refers to the purchase of large areas by outsiders, such that the local population is excluded, especially small farmers producing for local consumption (Borras Jr. *et al.* 2011). More recently, however, more complex notions of "land grabbing" have come to the foreground that do not necessarily amount to "foreignization," as the process was characterized in Brazil, such that it can encompass more clearly the historical and ongoing processes of *grilagem* in the Amazon (Oliveira 2013, 2021; Oliveira and Myers 2021).

[5] The Terra do Meio is an area in the Brazilian Amazonian state of Pará the size of Switzerland, that has long been essentially outside of the control of the Brazilian government, dominated by land grabbers, drug traffickers, and others (e.g., Fearnside 2008). The southern part of the state of Amazonas is now also an active land-grabbing frontier, including the claiming and clearing of Brazil nut groves used by traditional extractivists in the municipality of Boca do Acre, and other vulnerable regions (Maisonnave and de Almeida 2020). Beginning in 2009, Brazil enacted a series of laws that allowed "legalization" or "regularization" of illegal land claims larger than 100 ha, which had been the maximum that could be legalized in practice (despite a 2005 law allowing legalization of up to 500 ha that was not put into practice by the Brazilian National Institute for Agrarian Reform [INCRA]) (Barreto *et al.* 2008). Law No. 11,952, known as the first "land-grabbers' law" (*lei da grilagem*), increased the area that could be legalized to 1,500 ha (Brazil PR 2009). In 2017, the second "land-grabbers' law" (Law No. 3465) increased this to 2,500 ha. (Brazil PR 2017). In December 2019 Brazil's federal government issued MP-910, a temporary executive order (*medida provisória*) valid for 120 days, allowing 2,500 ha land claims to be legalized based on "self-declaration" without requiring any onsite inspection (Fearnside 2020). This measure was

clearing land for cattle pasture is the best way to demonstrate "productive use" and justifying a land title. Clearing also discourages other potential claimants from invading the area and eliminates forest resources for those who might depend on them (Fearnside 2008). This kind of "conjuring property" (Campbell 2015a) is critical for understanding the expansion of livestock as a mechanism of valorizing land claim, a means of asset creation rather than necessarily a production input (Hecht 1993), and a key element in the continuing private expansion of roads, which facilitate forest conversion (see Chapter 19).

14.3.2.3.3. Logging

In the highly biodiverse forests of the Amazon, logging is always selective, marketing only species that are commercially valuable, in contrast to temperate and boreal forests where logging often involves clearcutting. Illegal logging has been and still is rampant in the Brazilian Amazon, and supplies more timber to the market than legal logging (Brindis 2014; Butler 2013; Greenpeace 2003; IMAZON 2017). Much of the timber that appears in official statistics as coming from areas being deforested legally or from legal forest management projects is actually being "laundered" from illegal logging; Brancalion *et al.* (2018) show that the volume of high-value species declared in supposedly legal timber sales far exceeds the volumes of these species originally present in the forest areas from which the timber supposedly came. An estimated 47% of wood sold in Colombia is illegal (EIA 2019), while in the Peruvian Amazon, illegal wood is extracted in Loreto, Ucayali, Madre de Dios, the Marañon River, Yurimaguas, Ucayali River, and Ucayali/ Contamana, legalized in Colombia, and sold in Tabatinga, Brazil (Praeli 2019).

Licensed forest management systems can be unsustainable due to various loopholes that have been created, and frequent violation of regulations both by government licensers and by those who receive the licenses. Bribes can be paid. More fundamentally, economic contradictions make unsustainable behavior financially rational due to the widespread availability of wood from predatory and unsustainable sources (see also Chapter 27). Moreover, because forest trees grow at rates up to around 3% per year, while other investments can produce returns on the order of 10% per year (in real terms, independent of inflation), it makes financial sense to cut and sell the potentially sustainable forest resource as fast as possible, and invest the proceeds elsewhere. This fundamental contradiction has been shown to lead to unsustainable harvesting of potentially renewable biological resources throughout the world (Clark 1973), and it applies strongly to Amazonian forest management (de Jong *et al*. 2014; Fearnside 1989, 1995).

14.3.2.3.4. Coca

Coca leaf chewing can alleviate hunger, cold, and fatigue, and coca is also a psychotropic with a vast international market. It is a crop that can be flexibly produced; it is processed locally into a paste, and production can easily move from one area to another in coca producing zones, to avoid political pressure or state repression; this has occurred with frequency (Gootenberg 2017; Gootenberg and Dávalos 2018).[6]

Over four million Peruvians continue to practice

allowed to expire and was transformed into a proposed law (PL No. 2633/2020), which is currently passing through the committee process in the Chamber of Deputies (Brazil Câmara dos Deputados 2020). Note that all of these laws apply to each claimant or taxpayer identification number (CPF), making it possible to legalize substantial areas either by a family with various members or by a land grabber using "*laranjas*" (literally "oranges," or people whose identities are used by others, with or without consent). This means that land grabbers and squatters assume that they can illegally occupy other areas, and eventually a new law will grant yet another "amnesty," pardoning the violations and granting land titles.

[6] The source of all cultivated coca are two closely related South American shrub species, *Erythroxylum coca* and *Erythroxylum novogranatense* (Plowman 1984), adapted to environmentally distinct regions in Colombia, Bolivia, Peru (Ehleringer *et al*. 2000), and, more recently, Brazil (Duffy 2008). Each species has an additional variety, *E. coca var. ipadu* and *E. novogranatense var. truxillense*, with the former known for its traditional use by lowland Amazonian groups (Plowman 1981, 1984) and the latter a drought-resistant variety

traditional use of the coca leaf (Rospigliosi *et al.* 2004) as they have done for perhaps as long as 5,000 years (Piperno and Pearsall 1998). Coca has been an object of international harassment since Richard Nixon's War on Drugs, and William Clinton's Plan Colombia, which invested billions in coca eradication, with limited success (Bradley and Millington 2008). Justifications for coca eradication programs have also included political discourses on anti-insurgency, anti-communism, and the War on Terror.

A highly valuable traditional crop, coca is an ideal product for small farmers, since it generates considerable employment and revenue, is locally processed, and integrates well into agroforestry systems. United Nations data from coca cultivation on the Ucayali River indicate that one hectare could conservatively produce approximately 860 kg of sun-dried coca leaf at an average farm gate price of USD 2.8 per kg in 2004 (UNODC 2005) or USD 2,350 per hectare, without the farmer even having to leave his farm. This estimate dwarfs the income potential of alternative crops farmed close to the regional market city of Pucallpa (even as the USD 2,350 per hectare accounts for as little as 2% of the US street value for the same amount of leaf in cocaine form) (Salisbury and Fagan 2011).

The indirect impact of coca production on deforestation is considered to be much larger than the actual area used for cultivation, since abandoned plots tend to convert to sites used for small-scale agriculture, cattle ranching, and further land clearing in the surrounding area (Davalos *et al.* 2014). As a means of money laundering, investment, and land speculation, coca often works in tandem with livestock, land claiming, and speculation in coca zones (Gootenberg 2017; Negret *et al.* 2019). While for a considerable time coca was eradicated manually, the expansion of the use of herbicides (glyphosate) has resulted in it drifting onto legal household and subsistence croplands, where it is quite toxic to small stock, has marginalized producers, and often exacerbated political tensions, threatening Indigenous areas (Arenas-Mendoza 2019). However, repressive measures have not succeeded in eliminating coca plantations in the region; the area from the southern Andean-Amazonian foothills to the Ecuadorian border is still one of the major coca-producing regions in Colombia (UNODC 2015). Current hotspots of cultivation include the Ucayali, the Putumayo, Caquetá, the border areas between Bolivia and Peru, and more generally the fluid tri-border region (Cuesta Zapata and Trujillo Montalvo 2009).

14.3.2.4 Infrastructure

Rising global demand for commodities, particularly grains and beef but also minerals and fossil fuels, and the seemingly unquenchable imperative of regional and global integration, are driving large scale land-use change and dramatically reshaping the physical and human environment of the Amazon region. Access and energy infrastructure projects dominate the investment portfolios of all Amazonian governments and are the projects whose spillovers generate the most environmental and social impacts. Lands are cleared to build transoceanic multi-modal transport networks to support agro-industrial expansion, to construct hydroelectric dams and transmission networks, and to develop mega-mining projects and assist in the extraction and transport of hydrocarbons. These investments interact and support each other, enabling each project's financial viability. However, the significant environmental and social impacts unleashed by multiple projects are rarely if ever assessed for their potential cumulative and synergistic effects (Bebbington *et al.* 2020; Van Dijck 2008).

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grown largely for commercial purposes in arid to semi-arid inter-Andean valleys. Although *E. coca var. ipadu* has been cultivated in the lowland Amazon for many centuries, historically its low alkaloid content made it a poor choice for cocaine production; nevertheless, recent research on coca cultivated illegally in the Colombian Amazon indicates farmers are increasingly cultivating high producing hybrids of *E. coca var. ipadu* (Johnson *et al.* 2003), in part as a response to climate change. These hybrids would be well-adapted and easily diffused to other parts of the Amazon (Duffy 2008).

Governments across the Pan Amazon, and from across the political spectrum, now pursue export-oriented economic policies that prioritize large-scale infrastructure projects in support of natural resource and agroindustry expansion, and also because they are increasingly a necessary employment program in light of the contraction of small-scale agriculture and stable urban employment. Such investments both attract large amounts of foreign investment, and fuel bursts in employment and economic activity in more remote geographies. They form part of a longstanding development paradigm that promotes centralized urbanization, connectivity, and economic growth over more local, resilient, and participatory strategies. These investments are also important for the support of mineral and fossil fuel extraction that finance social policy and other expenditures that give viability to their "Neoextractivist" political projects (Bebbington *et al.* 2018a). Throughout the Pan-Amazon, roads became primary sites of land speculation (see Chapter 19). Construction companies saw lucrative infrastructure as key sites for contracts awarded though the dynamics of corruption. One Brazilian company, Odebrecht, became famous for corrupting almost every national government in the Pan-Amazon (Campos *et al.* 2019; Morales and Morales 2019; Lagunes and Svejnar 2020).

Large-scale infrastructure projects are justified on the grounds of job creation and economic benefits for priority sectors of the economy (soy, livestock, mining, oil and gas), but smallholders can be equally eager for better transportation access and the land valorization that it produces. We discuss some of three of these dynamics further on.

Beginning in 2000, and led by Brazil, an ambitious, coordinated infrastructure initiative, IIRSA (*Initiative for the Integration of the Regional Infrastructure of South America)*, now managed by COSIPLAN *(South American Council on Infrastructure and Planning*), prioritized and promoted select sectors and geographies to receive infrastructure investment (Box 14.3). IIRSA/COSIPLAN's proposed hubs traversing the Amazon Basin are especially contentious given their high costs in terms of human rights, threats to Indigenous peoples and local communities, land expropriation, forest clearance, and forest degradation (Bebbington *et al.* 2018b; Bebbington 2020; Ferrante and Fearnside 2020; Ferrante *et al.* 2020).

How infrastructure decisions are made, in practice, does not necessarily reflect the magnitude of these consequences, but in many cases reflects the political power of coteries, especially in the absence of more participatory forms of planning, even if these are legally mandated, and better "full cost accounting." Pressure groups can include the military, economic interests, corporate groups, grassroots social movements, and other actors, and the influence of corruption and the personal interests of political leaders. Decisions are not taken in the manner that one might imagine, but rather reflect a great deal of political expediency and largely follow the autocratic practices of the military period.[7] In Brazil, information on broader socio-environmental impacts is not even gathered before critical decisions are made; this comes later during the licensing process that serves to justify the decisions that have already been made for political reasons (Fearnside 2012b). Even when involving the Chinese government and state-owned companies, the latter often play to

[7] In Brazil, as in other Amazonian countries, infrastructure projects are normally part of "pluriannual plans" (PPAs), which are sets of projects (including many investments in addition to infrastructure) that are proposed for implementation over a four- or five-year period (Fearnside *et al.* 2012). The president collects suggestions from the different ministries and is responsible for submitting a proposal for the PPA to the congress, where there is plenty of room for lobbying by interested parties, and "horse trading" among political groups. The 2020-2023 PPA was approved by the Senate with 326 amendments (West and Fearnside 2021). High-level plans such as IIRSA (see Killeen 2007; Zibechi 2015) have little influence, although they can be used as arguments for justifying projects wanted for other reasons. In Ecuador for example, projects that had remained on the books were taken off the COSIPLAN system, mainly to assure more national autonomy. Once included in the PPA, further political struggles determine the priority a project receives for inclusion in the annual budget.

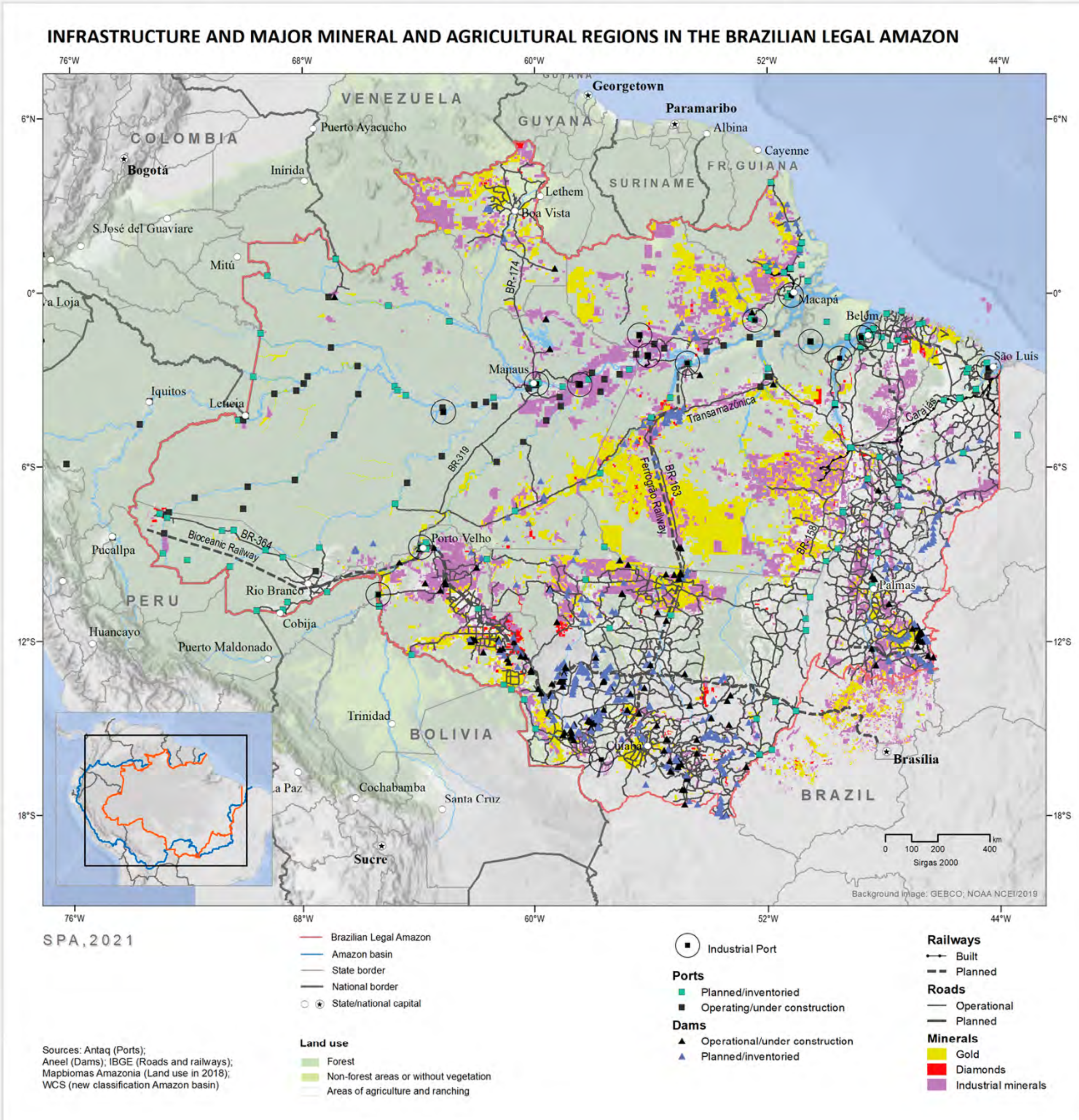


Figure 14.2 Map of infrastructure and major mineral and agricultural regions and projects.

Box 14.3: IIRSA/COSIPLAN

The Initiative for Regional Infrastructure Integration in South America, created in 2000 and managed by the South American Council of Infrastructure and Planning since 2009, established a framework to promote a series of coordinated, strategic mega-infrastructure investments at a continental scale. The initiative breathed new life into longstanding development narratives of connectivity, integration, and economic growth, but now combined with the urgency of increasing competitiveness in a globalizing world.

IIRSA/COSIPLAN proposed to support the transformation of the Amazon through a series of ten strategic, integrated development corridors or hubs connecting countries in the region with each other and to global markets (Simmons *et al.* 2018; Walker *et al.* 2019). The portfolio of projects included some 544 priority investments totaling over USD 130 billion (Little 2014). The larger vision included the creation of navigable waterways, a system of ports and logistical centers, a transcontinental railway with over 15,000 km of new track, and improvements to ~2 million kilometers of roads, in addition to modernizing the telecommunications systems and standardizing and harmonizing regulations in support of the efficient flow of goods and services. The initiative also encourages private sector participation and introduces innovative financing arrangements to overcome the types of bottlenecks experienced by publicly funded infrastructure projects. The creation of integrated development corridors offers governments and financiers of infrastructure big vision projects around which they can link purported benefits (jobs and economic growth, increased access) to secure the support of subnational authorities and local populations.

One of the greatest challenges to continental integration has been the construction of terrestrial transport corridors connecting Atlantic and Pacific ports. The Southern Interoceanic Highway, spanning over 2,600 kilometers and connecting Brazilian and Peruvian ports, was inaugurated in 2011 to great fanfare. More recently, the highway has drawn criticism for overstating the amount of commerce it would carry, the lack of social and environmental safeguards, and the significant deforestation and illegal gold mining that it has induced. In addition to the Southern Interoceanic Highway, Peru continues to develop a Northern Interoceanic route involving a combination of investments in road building, river navigation (the proposed Amazon waterway), and port development. Finally, a third route, the Central Interoceanic Highway, has improved the road network linking Lima to Pucallpa, leaving open the possibility of a terrestrial connection to Cruzeiro do Sul in Acre.

In Brazil, national infrastructure plans complement and reinforce larger regional integration objectives. Brazil's Agenda for Priority Integration Projects earmarked nearly 70 percent of its USD 20 trillion budget to support the construction of multi-modal systems of transport (roads, rail, and waterways) (Bebbington *et al.* 2018b). Investments in these systems of transport are attractive because they are high-value projects and create synergies with other potential investments.

The vast infrastructure network envisioned for the Amazon is intended to connect remote production and extraction sites, reduce transport costs, and increase the efficiency of transporting commodities destined for foreign markets, but especially China. Improving access infrastructure in the Pan-Amazon is clearly a priority for both subnational and national governments; however, a recent study found that many of the proposed roads – the researchers analyzed a portfolio of 75 - did not include sufficient impact assessments of social and environmental impacts, nor were the projects found to be economically viable (Vilela *et al.* 2020).

distinct interests and priorities, and compete for capital and political support for divergent infrastructure projects, such as the north-south *Ferrogrão* railroad connecting Mato Grosso state to the Amazon Basin ports on the Tapajós, the east-west Bi-Oceanic railroad crossing the Amazon and the Andes (Oliveira and Myers 2021), or the recent *Ferro-Pará*.

Availability of funds and expertise from outside sources can be important in determining which projects get priority. In the past this has included major projects financed from multinational development banks (Fearnside 1987), Korea, and especially China, now a critical player in various planned railways, dams, and waterways (Ascensão *et al*. 2018; Branford and Torres 2018; Fearnside and Figueiredo 2015; Serrano Moreno *et al*. 2020; Oliveira and Myers 2021; Oliveira 2021).

State-owned companies, and their managerial agencies, can significantly influence decisions on major infrastructure projects. Examples include the Carajás railway, which was completed in 1984 by Companhia Vale do Rio Doce, a Brazilian government mining company that was later privatized and is now called Vale. The railway carries iron ore 890 km from the Carajás mine to a port near São Luis, Maranhão. State-owned oil companies in Ecuador (PetroEcuador), Colombia, and Brazil (Petrobrás) have significant control and financing over forms of regional development and extraction. Another example is the Tucuruí Dam, which blocked the Tocantins River in 1984. The dam was built by ELETRONORTE (the government electricity company for northern Brazil) to supply aluminum factories in Barcarena (Pará), and São Luis (Maranhão) (Fearnside 1999, 2001a, 2016). Construction companies are famous for pressuring for access and energy infrastructure development. The soy transport corridor from the interior of Mato Grosso to the Cargill Terminal in Santarem was promoted by soy growers and infrastructure firms (Torres and Branford 2018). The effect of corruption on infrastructure decisions can also help explain why expensive projects can gain priority, as the Odebrecht case reveals so trenchantly.

14.3.2.4.1. Roads

In recent decades, significant investment has been directed to building new and upgrading existing highways that form part of a series of strategic transport corridors promoted under IIRSA/COSIPLAN. These plans echo the large-scale road building projects of previous eras, such as the construction of the Belem-Brasilia highway (1960) and the *Carretera Marginal de la Selva* (1963) which was intended to connect the Amazon regions of Bolivia, Peru, Ecuador, Colombia, and the Venezuelan *llanos*.

In subsequent decades the Trans-Amazon highway was started in the early 1970s, followed by the Cuiaba-Porto Velho road in the 1980s, and a burgeoning set of formal and informal road building since the opening of the major trunk roads (Fearnside 2015). Current formal and informal roads are discussed further in Chapter 19. One outcome of this dynamic has been continuing deforestation and forest degradation, except in periods of deep civil strife, as in Peru with Shining Path, and in Colombia with various occupying rebel groups (Negret *et al*. 2019; Clerici *et al*. 2020), only to increase deforestation afterwards.

One of the truisms of infrastructure could be the axiom “have road, have deforestation.” There are numerous scientific articles that have documented this dynamic everywhere in the Amazon for decades (Arima *et al*. 2008; Armenteras *et al*. 2006; Baraloto *et al*. 2015; see also Chapter 19), usually accompanied by images of deforestation flanking the road (see Figure 29.5, Chapter 19). A recent article reviewing road-associated clearing (Vilela *et al*. 2020) found the rapidly-expanding Amazon network to be permanently altering the world’s largest tropical forest through forest fragmentation, sub-canopy processes (selective logging, hunting, and increased fire vulnerability), and sub-canopy cutting in preparation for more extensive clearing and eventual land claiming.

This kind of forest degradation now rivals deforestation. Most proposed road projects lack rigorous impact assessments or even basic economic justification, reflecting the habits of bureaucratic practice. The Vilela *et al.* (2020) study cited above analyzed the expected environmental, social, and economic impacts of 75 road projects, totaling 12 thousand kilometers of planned roads. All projects, although in different magnitudes, would negatively impact the environment, and involved deforestation of some 2.4 million ha. Forty-five percent would also generate economic losses, even without accounting for social and environmental externalities. Canceling economically unjustified projects would avoid 1.1 million hectares of deforestation and USD 7.6 billion in wasted funding for development projects (Vilela *et al.* 2020). The fragmentation, ecological loss of connectivity, degradation of landscapes used mainly for speculation, and the constant threat to protected areas of many types, threatening the integrity of significant areas and ecologically important landscapes, remain part of the massive externalities associated with roads. Chapters 19 and 20 outline the environmental effects in more detail.

Most of the environmental impacts of infrastructure development are elaborated in more detail in Chapter 19. Both the construction of new roads and the paving of existing secondary roads also have dramatic effects on the human population of the area along the route. When a new road is built in an area of the Amazon that previously lacked road access, the residents of the area are likely to be traditional groups such as Indigenous peoples, riverside dwellers (*ribeirinhos),* or forest extractivists collecting non-timber forest products. The advantages of the road in allowing more rapid access to hospitals and other urban services can often be far outweighed by the negative effects, as new migrants, loggers, and land grabbers move into the area, often displacing earlier populations (Schmink and Wood 1992; Yanai *et al.* 2017).

New roads attract actors of various types. Individual families can migrate to the area to occupy land (*posseiros*) (e.g., Simmons *et al.* 2010). With the passage of time, these migrants may be expelled violently by more powerful actors who convert the area into large ranches, as occurred along the Belém-Brasília Highway (Foweraker 1981; Valverde and Dias 1967) and along BR364. Initial settlers may be "regularized" by the Brazilian National Institute for Colonization and Agrarian Reform (INCRA), or granted lots elsewhere in official settlement projects (Fearnside 2001b; Schmink and Wood 1992). Brazil's "*Terra Legal*" (Legal Land) program, which was intended to curtail advancement of the agricultural frontier into the Amazon, actually consolidated agribusiness and extractivism in the Amazon-Cerrado transition zones (Oliveira 2013) as small farmers sold lots with legalized title. This process has been widely repeated throughout Amazonian settlement projects (Ferrante *et al.* 2020).

A parallel process occurs in government settlement projects, where, even if not legally permitted, the original settlers sell their lots to others who concentrate them into medium and large ranches (e.g., Carrero and Fearnside 2011; Yanai *et al.* 2020). Initial occupation can also occur as large areas are appropriated by land-grabbers (*grileiros*), who then subdivide the claims and sell the land in smaller parcels, or alternatively, land consolidators who use multiple names to acquire larger holdings.

14.3.2.4.2. Ports

Nearly 100 major industrial river ports have been built on the Brazilian Amazon's major rivers over the past two decades (Andreoni 2020). Many have been internationally financed and built by commodities companies with little government oversight, such as the former Minister of Agriculture's port in Porto Velho (Brazil) or the Cargill port in Santarem (Bratman 2019). These ports have transformed the region, further opening it to agribusiness and reducing transport costs for export commodities, especially soy, to China and the rest of the world. However, this boom in port infrastructure often came at the expense of the environment and traditional riverine communities. Today, more than 40 additional major river ports are planned in the Amazon biome; on the Tapajós, Tocantins, and Madeira rivers; proposed port development in Peru; and the Ichilo-Mamoré-Madeira-Amazonas waterway in Bolivia. These projects are again being pursued largely without taking into account cumulative socio-environmental impacts (Silva *et al*. 2008; Leal *et al*. 2012; Alves *et al*. 2015; Barbosa and Moreira 2017).

14.3.2.4.3 Dams

The construction of dams and hydro-electric plants remains a major development strategy across the region. Decisions on logistical infrastructure, such as roads, dams, railways, ports, and waterways, are critical, both because they represent major government investments and because their social and environmental consequences are enormous (see Chapters 19 and 20).

While the social impacts of dams vary from site to site, some of the major and well documented social effects include displacement of populations, loss of livelihoods from fisheries, downstream effects, impacts on Indigenous populations, and impacts on human health and migration, as detailed in Box 14.4 (Fearnside 2016; Andrade 2021).

14.3.3 Export dependency & precarious states

As the previous sections have shown, Pan Amazonian states have become increasingly dependent on global exports of enormously valuable natural resources from Amazonian forests, waters, lands, and sub-soils, part of a wave of Latin American "neoextractivism" combining commodity exports with the deployment of social welfare programs to address persistent poverty in the face of limited economic opportunity and virtually no structural change (Baletti 2014; McKay 2017; Svampa 2019). Some writers have labeled this current phase of development a new incarnation of dependent development (Svampa 2019).[8] At the same time, however, there are new innovative economies based on traditional Amazonian crops like *açai, guarana*, animal products, and medicines that circulate in national and globalized markets.

The extraction of industrial ores and hydrocarbons and agroindustry are not especially labor-absorbing activities, and most export products leave the Amazon as raw or minimally refined products. Other systems of capital accumulation include multiple forms of resource capture that take place through direct appropriation (land grabbing, wild animal commerce, resource theft), and a variety of institutional rents that depend on political positioning (credit lines, speculation, corruption), regulatory and institutional capture, and illegality and violence. That is, a great deal of economic activity and profit making is related to positioning, access, and to a degree, impunity.

Amazonian states suffer from continuing issues of political instability regardless of political format (authoritarian, illiberal, or democratic), which has given a "stop-start" quality to Amazonian development initiatives, with frequent policy reversals or shifts in emphasis that increase volatility in processes, prices, and policy implementation. Most Amazonian nations are young states with new constitutions only a few decades old that emerged after authoritarian regimes or illiberal democracies collapsed, and remain characterized by intense factionalisms if not insurgencies (such as in Colombia and Peru), succession movements (Bolivia, Ecuador), and the complex political scenar-

[8] Dependency theory argued that over-reliance on natural resources made economies vulnerable to volatilities in global markets for reasons of price and politics, global competition and technical change in the sectors, and declining terms of trade in raw materials versus industrialized products. This actually "underdeveloped" countries rather than developing them, by structuring institutions and infrastructure around sectors which were often, and still are, largely dominated by large international corporations who garnered most of the benefits, and national coteries allied to them. This idea was elaborated further by Bunker (1985), who placed environmental degradation as another element in the "development of underdevelopment".

Box 14.4 The social impacts of dams

Displacement of population

Displacement of population is the most dramatic human consequence of hydroelectric dams. The full weight of this impact falls on those who have the misfortune of living in a place chosen for flooding by a dam, while the benefits of the dam go to people and industries in distant cities, making environmental justice one of the primary concerns with Amazonian dams (Fearnside 2020). The 23,000 people displaced by Brazil's Tucuruí Dam in 1984 still suffer the consequences of their displacement (Fearnside 1999, 2020; Santos *et al*. 1996). Those displaced by the Madeira River dams are also suffering (Baraúna 2014; Simão and Athayde 2016). At Belo Monte, a large population of riverside dwellers was displaced and moved to "urban settlements" distant from the river, with dramatic consequences both from the loss of livelihood and from the loss of the physical and social environment (Magalhães and da Cunha 2017). Meanwhile, a massive influx of migrants moved into the region.

Loss of livelihoods from fisheries

Dams have severe impacts on natural ecosystems (see Chapter 20). These changes lead to a loss of the fisheries that sustain much of the human populations in areas flooded by reservoirs, and in the river stretches both below and above the reservoir where fisheries are also negatively impacted. In the case of Tucurui, the fisheries below the dam declined precipitously, both for fish and for freshwater shrimp, eliminating the fishing fleet at Cametá (the main city in the lower Tocantins) (Fearnside 1999, 2001a; Odinetz-Collart 1987). Fish-landing data along the length of the Tocantins River show that the fish production in the Tucuruí reservoir never compensated for the loss of fish production in the natural river (Cintra 2009). Fish production in Amazonian reservoirs is minimal. At Balbina, commercial fishing was banned beginning in 1997 due to the fish population's precipitous decline (Weisser 2001). The Santo Antônio and Jirau Dams on the Madeira River destroyed one of the world's most productive fluvial fisheries that had supported large populations of fishers in Brazil, Bolivia, and Peru. Impacts come from blocking fish migration, including the famous "giant catfish" of the Madeira River, from impeding the descent of fish larvae spawned in the river's headwaters, from the reservoirs' unfavorable environment for many species, and from reduction of nutrients associated with sediments (Fearnside 2014; Forsberg *et al.* 2017; Faleiros and Isensee e Sá 2019). Hydropower development can negatively affect perceptions of fishery sustainability and exacerbate existing weaknesses in fisheries governance (Doria *et al*. 2021).

Indigenous populations

Indigenous peoples suffer the same impacts as other dam-affected people, plus some that are unique to Indigenous groups. The loss of sacred sites is particularly serious, and this is not even considered as an impact in environmental impact assessments (EIAs), as in the case of the proposed São Luiz do Tapajós Dam, which would flood the site where the great ancestor of the Munduruku people created the Tapajós River (Fearnside 2015). Most traumatic for the Munduruku was the dynamiting in 2013 and flooding in 2014 of the Sete Quedas falls to make way for the Teles Pires Dam (Branford and Torres 2017). This is the place where the spirits of deceased tribal elders reside, or the equivalent of Heaven for Christians. Sacred sites were also destroyed in 2017 by the São Manoel Dam 40 km downstream, and tensions with the residents of the Kayabi Indigenous Land, located only 700 m from the dam, have resulted in Brazil's

National Force still being deployed to the site to protect the dam (Fearnside 2017a; *Neo Mondo* 2018). These cases illustrate the problem of sites located outside of Indigenous lands being vital to the Indigenous groups, in this case destroying both fisheries and sacred sites.

Dam impacts can result in severe losses of Indigenous cultures. In the case of the Balbina Dam, the two largest Waimiri-Atroari villages were flooded, and the displaced population moved to the roadside of the BR-174 (Manaus-Boa Vista) Highway, where they were on their way to physical and cultural elimination. After a disastrous delay, the hydropower company (ELETRONORTE) financed a program that convinced the group to leave the roadside and build a new village in the forest (Fearnside 1989). The group has survived and increased in population, but has paid a heavy price in cultural loss under the influence of the power company's program (Rodrigues and Fearnside 2014).

The Belo Monte Dam did not flood Indigenous land, but it diverted 80% of the water in the Xingu River to flow to a powerhouse 100 km downstream from the main dam, leaving the "Big Bend of the Xingu" (*Volta Grande do Xingu*) with very little water. Two Indigenous lands are located along this stretch, and a third group on a tributary that joins the Xingu in this stretch also lost the fishery on which they depend (de Oliveira and Cohn 2014; Villas-Bôas *et al.* 2015). As severe as these impacts were, they were dwarfed by the impacts of planned dams on the Xingu River upstream of Belo Monte (Fearnside 2006). Belo Monte is completely unviable economically without water stored in upstream dams, making it clear that official denials of the original plans for these dams represent disinformation (de Sousa Júnior *et al.* 2006; Fearnside 2017a). The first priority would be the Babaquara Dam (officially renamed as the "Altamira' Dam, but best known by its original name). This would flood 6,140 km², twice the size of Balbina or Tucuruí, almost all of which is Indigenous land (Fearnside 2006).

Health impacts

Dams have health impacts on the people who live around reservoirs or eat fish from them. Mercury is naturally present in the soils in the Amazon because the soils are millions of years old and have been receiving mercury via rain – the result of volcanic eruptions that inject mercury into the atmosphere, where it spreads around the globe. Additions of mercury from its use in alluvial gold mining can also occur, but they are not necessary to have substantial amounts of mercury present at the bottom of reservoirs. The water in reservoirs like Tucurui or Balbina stratifies into layers based on temperature, and the cold water at the bottom does not mix with the warm water near the surface. The result is that oxygen in the water at the bottom is soon depleted as leaves and other forms of organic matter are converted to CO_2. This provides an anoxic environment (without oxygen) in which mercury is converted into highly toxic methylmercury. The methylmercury in the water is absorbed by plankton, and passes up the food chain to fish, increasing approximately ten-fold in concentration with each link in the food chain. High concentrations of mercury have been found in reservoir fish and in the hair of people who eat these fish at Tucurui (Arrifano *et al.* 2018; Leino and Lodenius 1995) and Balbina (Forsberg *et al.* 2017; Weisser 2001).

Insects represent another health risk from reservoirs. The dramatic "mosquito plague" at Tucuruí was an enormous explosion of mosquitos of the genus *Mansonia* that were breeding in the floating macrophytes in the reservoir (Tadei *et al.* 1991). Mosquitos have a painful bite, but the main disease they can transmit (filariasis or "elephantiasis") is not yet present in Brazil, although it is present in Surinam and French Guiana. Other mosquitoes, such the *Anopheles* species that spread malaria, can also breed in reservoirs (Sánchez-Ribas *et al.* 2012).

Downstream impacts

The river downstream of a dam changes in ways that have negative impacts for the many human residents of these areas. These include fish die-offs, and retention of sediments in dams that deprive the downstream river of the nutrients associated with these particles, thus jeopardizing the base of the food chain for fish production. The Madeira-River dams reduced downstream sediments (Latrubesse *et al.* 2017), and downstream fish catches have declined markedly (Santos *et al.* 2020). Sediment retention by dams planned in Peru and Bolivia will impact fisheries along the entire length of the Amazon River in Brazil (Forsberg *et al.* 2017). Ironically, almost all planned dams are to be financed by BNDES and built by Brazilian construction firms. The loss of sediment affects nutrient distributions in flooded forests and floodplains which may be used for collection and floodplain agriculture. Another impact of dams on downstream communities occurs during construction, when the river flow is temporarily halted or reduced to near zero as the dam begins to fill. Ironically, when the spillways are first opened, the water level in the downstream river can rise far above its normal high-water mark, causing flooding damage to downstream residents.

Social effects of migration

Social effects of migration to the dam construction area are notable. While a few entrepreneurs can earn fortunes from the local economic boom during the construction phase, most of the population loses heavily. Altamira, the city nearest to the Belo Monte Dam, experienced an explosion in the prices of housing and basic household needs, making the city unaffordable for many of the original residents. There was also an explosion of violence, with Altamira being rated the most violent city in Brazil (Sales 2017). A long list of urban problems accompanied dam construction (Miranda Neto 2015; do Nascimento 2017; Gauthier and Moran 2018).

ios in the “Caribbean Amazon” of Guyana, Suriname, and French Guyana.

All Amazonian governments have had serious corruption scandals (Fogel 2019). Six of the last Peruvian presidents have been indicted for corruption associated with cronyism and personal payoffs, often associated with infrastructure development. Peru cycled through three presidents in a one-month period in 2021. Corruption concerns also emerge around concession systems for hydrocarbons, minerals, and timber. The lack of transparency and favoritism in many contracts and bidding processes have generated distrust of the national state and supported a dynamic of illegality around land acquisition, infrastructure concessions, production certifications, clearing moratoriums, invasions of protected areas, forms of bribery, and political patronage. All these add distorting elements to regional dynamics, and foster distrust of government and broader, lower-level societal corruptions (Bulte *et al.* 2007; Campos *et al.* 2019; Fogel 2019).

While GDP has increased across the Pan-Amazon, inequality and precarity remain central issues, and COVID-19 has driven poverty, inequality, and vulnerability to new heights. Peru, Colombia, Bolivia, Ecuador, and Brazil have some of the highest per capita infection and death rates. The COVID-19 crisis has diverted some attention away from forest destruction and protection, made illegal incursions easier by paralyzing state actions to control clearing (Silva Junior *et al.* 2021), and in some states led to implicit *carte blanche* to go forward with semi-legal and destructive practices.

In spite of the current "commodity consensus" framework and its agro-industrial emphasis and widespread environmental destruction, there are new innovative economies based on traditional Amazonian crops like *açai, guarana*, cacao, and other traditional Amazonian goods and medicines (see Chapter 30). These remain largely niche crops, whose value and value chains are quite different from large-scale commodity dynamics. Of the major export items, coca and gold go through significant processing in Amazonian localities, and might be considered more "industrialized exports" than many of the other export commodities (Gootenberg and Campos 2015; Gootenberg 2017; Hilson and Laing 2017; McKay 2017; Betancur-Corredor *et al*. 2018) even though the local value added is often ephemeral (Escolhas Institute 2021).

In the midst of these powerful and often hidden forces and processes shaping Amazonian development and conservation, the diverse people who live there continue to respond as best they can to increasingly precarious options for making a living in the forests, rivers, and lands of the Amazon. They draw on Indigenous cosmologies and practices dating back millennia (see Chapters 8 and 10), and the unique cultural identities and systems of management of natural resources that have evolved in each Amazonian country and locality, while adapting to rapidly-changing new drivers and processes that increasingly constrain their possibilities (Athayde *et al.* 2017; Vadjunec and Schmink 2012). Far from passive and invisible, these Amazonian people in motion have continued to mobilize to protect their territories, livelihoods, and cultural identities by defending their own proposals for a future characterized by new forms of governance, social innovation, land uses, and goods. This is done through traditional national political channels, and seeking cross-basin partners and international allies.

14.4 Amazonian People on the Ground

The settlement patterns of Amazonian populations are highly complex and dynamic, including diverse patterns and forms of migration by peoples internal and external to the region, and between urban and rural areas. Contrary to the general understanding of the Amazon as a large, natural forest, the population is highly concentrated in urban areas, including large numbers of Indigenous peoples with complex links to the rural hinterland, a pattern that dates to antiquity. We first examine urbanization as a settlement form of significance in Amazonian antiquity, and the historically-rooted complex linkages between rural livelihoods and urban settlements (Sobreiro 2014; Campbell 2015b; Peluso 2012, 2017; Hecht *et al.* 2015). Finally, we examine broader settlement and migration patterns.

14.4.1 Amazonian urbanization in antiquity

Although the Amazon is perceived as a wild place with a biotic rather than human history, earlier sections of this Report (Chapter 8) have shown that humans have occupied the Amazon for at least 12,000 years, with very large populations (in many places much greater than they are today). Evidence of these populations includes extensive areas of ring ditch construction, numerous mounds, central plaza villages, extensive engineering works, widespread anthropogenic soils, humanized ecologies and biogeographies, celestial observatories, and extensive mastery of long-distance integrated water-based travel. Material culture included artistic masterpieces, gold metallurgy, ceremonial burial sites, a complex suite of domesticated and semi-domesticated plants, and a sophisticated pharmacopeia, all evidence of complex civilizations. The populations of the Amazon declined by more than 90% due to epidemic diseases after contact with Europeans (Denevan 1992, 2003; Clement *et al.* 2015), obliterating knowledge systems and tropical ways of being that also included complex polities and urban life (Whitehead 1994; Heckenberger 2009; Rostain 2009).

During the colonial period, Amazonian urban settlements included a mix of Indigenous, religious, military, and commercial models, reflecting geopolitical and economic strategies. Mission towns stretched from the mouth of the La Plata River up through much of the Amazon territories, especially the Bolivian Amazonia, to the mouth of the Amazon and Orinoco Rivers (Block 1994). Missions; often built on the ruins of past villages, trading centers, and towns; brought together native populations, profiting from their use in forced labor regimes. Trading centers established at river conjunctures became commercial entrepots, multiethnic urban sites that often included substantial Indigenous populations (Roller 2014). Many Indigenous populations never left these enclaves, and native, traditional populations continued to move back and forth between towns and cities and hinterlands and home villages. The persistence of this pattern today may reflect much deeper cultural roots.

Later, at the end of the 18th and beginning of the 19th century, the Brazilian Amazonian trade in enslaved people through the ports of Belém and Sao Luis rivaled the slave trade in Bahia and Rio de Janeiro (Salles 1971; Hawthorne 2010). Fugitive slave communities of Afro-descendant people sprang up deep in forests, the *Quilombos* that stretched throughout the lower Amazon, and all the way up into the Guyanas (Agostini 2002; Cavalcante 2011; De la Torre 2012; Florentino and Amantino 2012a,b; Hecht 2013; dos Santos Gomes 2015). The mercantile system, the military outposts that attended it, and ethnically complex towns and villages made up webs of "informal" trading networks, especially in the lower Amazon (La Torre López and Huertas 1999; De la Torre 2012). This provided the framework for the rubber-boom period of economic expansion that, for some decades, built on and expanded these settlements, and internal transportation systems, further disrupting Indigenous settlements and economies (see also Chapter 11). The towns established during these historic periods continued to dominate mostly riparian settlement patterns until the post-WWII period and the shift to terrestrial transport.

The extractive cycles that sustained frontier development in the Amazon after the 19th century contributed to a characteristic "disarticulated urbanism" (Godfrey and Browder 1997), with multiple urban centers dispersed within a shifting frontier economy. This focus on the global system in its modern form may obscure pre-existing Amazonian systems of livelihoods and also supporting agricultural systems and non-timber products that flowed into households and markets (Hecht 2007; Schmink and García 2015). Many Amazonian cities have undergone periodic cycles of expansion and contraction, export versus local orientations reflecting population movements into and from the countryside, following fluxes in global demand for particular forest products and the emergence of new local types of demand for local construction woods, Amazonian foods, and new export systems for products like *açai* (Sears *et al*. 2007; Uriarte *et al*. 2012). The durability of household and individual engagement within commercial, waged, and subsistence frameworks of the older pattern of urban-rural livelihoods, with traditional circular migration or multi-sited households, is a model of urbanism that differs from much of the temperate zone patterns of urbanization, although this polyvalence is also widespread in tropical Africa and Asia (Hecht 2014b).

After WWII, dynamic relationships between urban and rural spaces became increasingly shaped by the influence of nation-building and state-driven formalist planning. This involved new "showcase cities" like Ciudad Guyana (in Venezuela) and, after 1989, towns such as Palmas and the redo Goiania (Correa *et al*. 2019) designed as agro-industrial service towns and planned rural cities in private colonization projects (Jepson 2006b). These corporate planned cities complemented planned agrarian reform village settlements in Bolivia, Colombia (Caquetá), and Peru (San Martin) (Eastwood and Pollard 1985; Redo *et al*. 2011). A largely bifurcated Amazonian model of new settlement unfolded in which large-scale capital was encouraged by extensive subsidies, largely following the growth pole spatial planning ideas for areas of mineral extraction and specific urban areas like

Manaus (Hite 2004), while spatially extensive agrarian reform using a different territorial settlement model was expanding, linking poles through settlement corridors with road infrastructure. A fantasy of planned urbanization as part of infrastructure arrangements and the idea of orderly settlement has been attended by massive spontaneous settlement, a striking fluidity in boom towns, and their abandonment after resources are depleted or the speculative cycle in land runs its course. Rural settlement has gone hand in hand with new urbanization, expansion of illegal side roads, and the increased importance and growth of medium-sized towns that can permit interaction with rural resources, while continuing access to banking, health, and education systems, and periodic employment that reflects changing rural economies. While road and infrastructure development has "triggered" some spontaneous "infrastructure" towns, these settlements are notorious for their lack of urban and social infrastructure.

Migration flows in the region are largely characterized by the rural-urban shift of population (Maia and Buainain 2015). With nearly two-thirds of the population living at least part time in urban areas, the Amazon presents one of the highest rates of internal migration in Peru and Brazil; roughly 10% of the population migrated between 2005 and 2010 (IBGE 2018). The Amazon's emergence as the next energy frontier also changed the social and spatial composition of the Andean Amazon, as northern Peru, Ecuador, and Bolivia have become sources of employment and road speculation based on hydrocarbons, timber, gold, and coca production, whose labor demand is often seasonal.

14.4.2 The rural-urban continuum

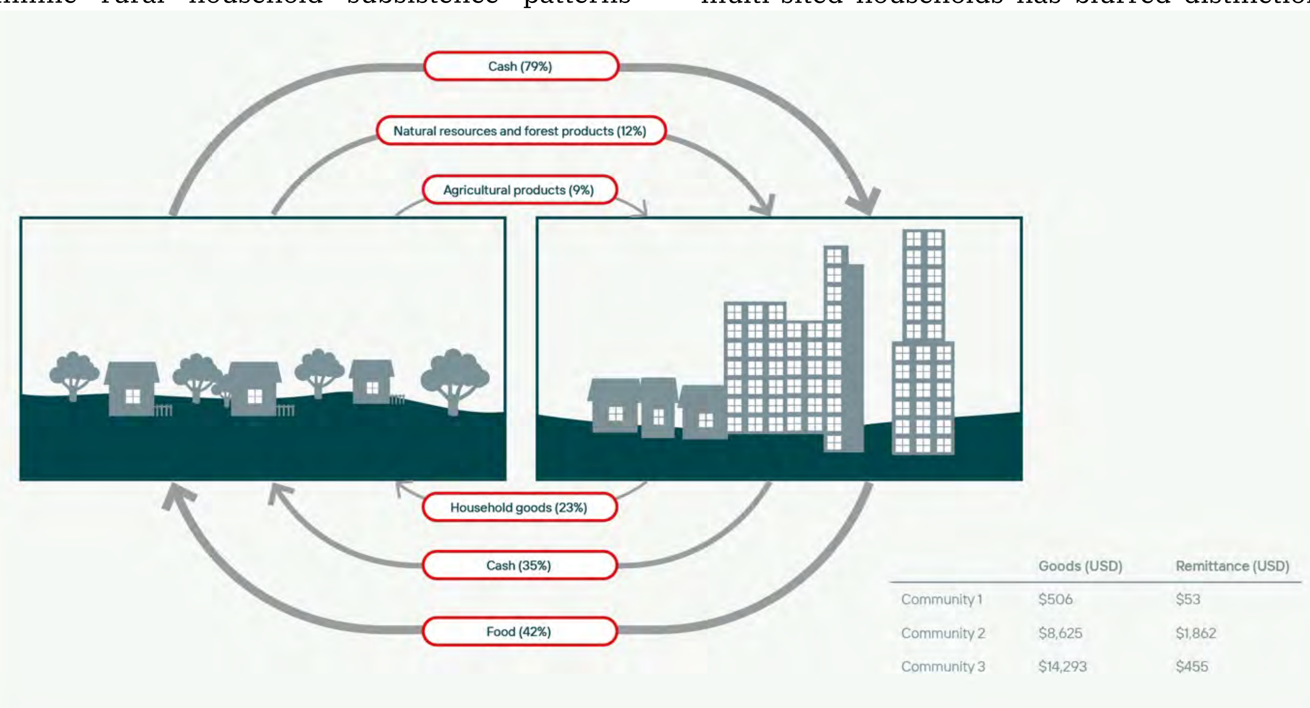
Of roughly three million Brazilian inhabitants in 1960, only about 36% resided in urban areas; by 2010, 74% of the Amazonian population resided in towns and cities. A similar pattern is found in Peru (Menton and Cronkleton 2019), Colombia, and Ecuador. Current urban transitions in the developing world have several features that differ from the Euro-American pattern:

1) They have occurred extremely quickly (in a decade or two as opposed to centuries.
2) They were underpinned by different kinds of urban, rural, or forest functionalities from most European systems.
3) They reflect strong exogenous pressures at least as much as endogenous dynamics; that is, land wars, economic displacement, globalization, political violence, road development, and in some cases climate change (Brondizio *et al.* 2011; Hecht 2014b; Hecht *et al.* 2014; Kanai 2014; Mansur *et al.* 2018).
4) Rural areas, in areas with a deep settlement history, often have high population densities, strong relations to historical and current forms of family or small-scale agriculture and forest livelihoods, and deep regional histories. Examples include the estuary areas and the environs of Iquitos (Sears *et al.* 2007; Brondizio 2008, 2009; Pinedo-Vasquez and Padoch 2009; Brondizio *et al.* 2011).
5) Current urbanization processes are generally more globalized in terms of commodities, financial flows, and often labor (or its lack), and shaped by new production ideologies.
6) Urban export corridors and mega project labor depot construction sites; such as those near Maraba, Carajás in Pará, Ciudad Guyana, and Jari; are examples of the spontaneous urban expansion (i.e. unplanned satellite cities or peri-urban expansion) that accompanies planned cities. These settlements are often labor depots and informal service centers (Roberts 1995; Randell 2017; Weißermel 2020; Ulmer 2021).

Urbanization that builds on older livelihood mobilities involves newer forms of transport and communication (although Amazonian towns often still rely on their aquatic systems), while increasing dependency on state services for cash transfers, pensions, health and education services, and periodic work, local markets, and a complex platform for livelihood construction, in a context of an often "wageless world" with high degrees of precarity. About 40% of Amazonian residents now fall below World Bank poverty lines (Verner 2013). This in turn has contributed to a need for enhanced levels of mobility and migration, a regular re-engagement with cities and markets, and to intensified rural-urban links and exchanges, often through the use of complex, informal social networks of kinship, clientelism, and patronage (Peluso and Alexiades 2005; Pinedo-Vasquez *et al.* 2001; Brondizio *et al.* 2011; Eloy *et al.* 2014; Tritsch and Le Tourneau 2016). Rural conflict, violence, and in some cases, climate change also contribute to this complex reengagement with a new kind of urbanism and new rurality, where both city and country engage in forms of production that may mimic each other, with increasing similarities in production and consumption patterns. The urban growth of *açai* palms and other foods, and the complex of products generated in the dooryard garden, a kind of "open-air laboratory," often mimic rural household subsistence patterns (WinklerPrins 2002; WinklerPrins and de Souza 2005; Lewis 2008).

14.4.3 Living and livelihoods in the urban-rural matrix

Amazonian urban studies are in their infancy, especially compared to the mass of research on Latin American coastal cities and capitals. Urban processes clearly have profound implications for regional development, conservation, and livelihoods. The complex dynamics of circular migration, multi-sited households, and strong rural-urban interaction and dependence are widespread in the Amazon and throughout the tropics, as depicted in Figure 14.3 based on a study in Iquitos, Peru. Several insights help characterize current dynamics we see in "embedded urbanization" (towns and cities historically rooted in their regional livelihood systems) versus "service centers" (labor depots and export cities linked to mega development construction sites, oil camps, and export enterprises). First, the increase in multi-sited households has blurred distinctions



	Goods (USD)	Remittance (USD)
Community 1	$506	$53
Community 2	$8,625	$1,862
Community 3	$14,293	$455

Figure 14.3 Remittances and Gift Flows Between Iquitos, Peru, and Rural Communities. Adapted from Gregory and Coomes 2019, 298.

between rural and urban areas, making peri-urban areas and peripheries the intersection of new forms of livelihood construction. This includes forest, agricultural, urban and rural waged livelihoods, and petty commerce and state transfers. When observed from the perspective of families, the Amazon region is indeed a 'rural-urban continuum.' Family networks shape the urban and rural landscapes of the region, supporting intense patterns of circulation and exchanges across short and long distances. However, interactions between people and families in rural and urban areas vary significantly in the region, as a function of geography and transportation, with the density and frequency of interactions proportional to proximity to cities and the type of transportation available (Padoch *et al*. 2008; Parry *et al*. 2010; Eloy *et al*. 2014; Nasuti *et al*. 2015). Independently, rural/resource economies are intrinsically connected to urban hubs, involving social networks between extended families, intermediaries, market brokers, and corporations (such as *açaí* or Brazil nut exporters); these interactions, depicted in Figure 14.3, are behind large segments of the regional economy and social life, generating high-value regional economic chains in fishing, fruit, and regional and international non-timber forest products.

Rural-based extractive activities such as logging, gold mining, and fisheries are now important sources of employment and income for urban residents. Life in most rural communities has become a reflection of life in low-income urban neighborhoods and vice-versa. Seasonal economies are especially important to families (e.g., *açai* and fish commercialization along the floodplains, mining, harvesting, construction work); seasonal mobile economies tend to be highly gendered, predominantly dominated by men. Almeida (2011) has documented the dependence of Brazilian urban populations on resource configurations for Belém and Manaus, showing the extent of travel, seasonality, and gender division in these systems.

Several factors affect rural-urban interactions and urbanization in different parts of the region, including the increasing availability of inter-municipal transportation and personal transportation (motorcycles, small boats, cars), kinship networks, access to market opportunities and market niches, access to cellphones and communication technology, availability of public services and education, and life-style. A continuing dynamic is the marginalization of small farm agriculture in the Amazon except in peri-urban areas, areas with traditional tenurial regimes, more traditional regional settlements, and those close to historic urbanizations. More recent colonist settlements have been characterized by very high levels of landownership turnover, close to 72% (Yanai *et al*. 2012, 2020), high deforestation, and continuing rural violence. Infrastructure development, such as dams, continues to displace people from rural areas (Chiavenato 1993; Sousa Júnior and Reid 2010; Carrero and Fearnside 2011; Fearnside 2016; Atkins 2017; Ferrante *et al*. 2020).

The peri-urban and peripheries have become new, central forms of livelihood construction in the Amazon's low-income urban neighborhoods, such as in Belem, Santarem, Tefe, Rio Branco, Manaus, Macapa, Coca, Leticia, Iquitos, Pucallpa, boom towns in the ambit of the oil axis of Ecuador (Lago Agrio), the smuggling town of Leticia, infrastructure development hubs like Marabá, and drug entrepots like San Jose de Guaviare (Cuesta Zapata and Trujillo Montalvo 1999; Armenteras *et al*. 2013), and ports on the Putumayo. These peri-urban and household agroforests are increasingly important for food security and petty commerce under conditions of precarity (Emperaire *et al*. 2012; Madaleno 2000), the low wages that accrue to both urban and rural waged work, and the volatile and generally low prices for agricultural or forest products.

Another key finding is that local ecological knowledge and complex production systems support rural and peri-urban livelihoods and agro-diversity in the Amazon**.** Multifunctional agroforestry, forest, and aquatic management systems form both rural and peri-urban production systems. These multi-strata and multi-species systems of natural resource exploitation can incorporate small stock, stagger harvest times, have labor flexibility, engage local fisheries, and cycle materials (Pereira *et al.* 2015; Coomes and Barham 1994; Pinedo-Vasquez *et al.* 2002; Padoch *et al.* 2008; Perrault-Archambault and Coomes 2008; Manzi and Coomes 2009; Coomes *et al.* 2010, 2015; Vogt *et al.* 2015, 2016). The different, varied forms of rural, peri-urban, and urban agriculture are important providers of agro-diversity conservation, and other forms of ecosystem services (Padoch and Pinedo-Vasquez 2010; Beyerlein and Pereira 2018). Under-recognized, but increasingly important, are the roles these agroforestry-urban ecosystems play in the larger issue of environmental services support, such as in moderating heat island effects, which are certain to become more severe in the future, or wind and water infiltration (de Souza and Alvala 2014; Fernandez *et al.* 2015; Livesley *et al.* 2016), and, increasingly, food security. Urban-rural connections could be enhanced with better participation in local actions to support linkages for both urban and rural agroecological and production activities, as further discussed in Chapter 34.

Historically, Amazonians were defined by a one-dimensional occupation---such as farmer, fisher, rubber tapper, or wage worker, even as their identities and livelihoods were always more complex. Rural income has become more varied, reflecting changes in agricultural economies, and encompassing employment in urban areas, commerce, and various forms of cash transfer/benefit programs. Amazonian incomes come from agriculture and resource markets, but the role of remittances is increasingly important, including money sent to Amazonian kin from other cities or rural areas and, increasingly, internationally. About one fifth of Ecuador's population resides overseas, as does a similar proportion of Venezuelans, and their remittances often exceed regional direct foreign investment funds (Hecht 2014b; Hecht *et al.* 2015). Almost 4 million Colombians live outside the country, which has also had very high rates of internal displacement (Ibáñez and Velez 2008; Ibáñez and Moya 2010; Sánchez-Cuervo and Aide 2013). Incomes come from different combinations of agricultural/resource-based activities, access to urban employment and market-niche opportunities, education, health services, and other arrangements (Eloy *et al.* 2014; Padoch *et al.* 2008). Substantial numbers of Brazilian families depend on conditional cash transfer programs such as *Bolsa Familia* and *Bolsa Floresta*. As cash benefits have to be collected in urban centers, this has further strengthened connections between rural areas and cities. These conditional cash transfers have become a central poverty alleviation practice in the region.

Rural populations remain stable in some parts of the region while aging in others, with different patterns of gender balance in out-migration. Geography/distance make a difference in terms of the frequency of rural-urban interactions and mobility. There is increasing movement from more distant tributaries and roads towards the peri-urban areas of medium to large urban centers, with growing population density in peri-urban areas as sites of settlement for small scale production and positioned for access to urban financial, medical, and educational services (also related to accessing cash transfers programs). The extent to which these processes are leading to the aging (or elder/children predominance) of rural areas is still unclear. In many rural areas, the "feminization" of the rural is discussed, as women remain in rural areas (Zimmerer 2014), but gendered patterns of migration require deeper analysis. In areas of Ecuador and Colombia, female migration into domestic service and prostitution dominates (Barbieri and Carr 2005; Massey *et al.* 2006; Tacoli and Mabala 2010; Abbots 2012; Paerregaard 2015). Women sometimes dominate in rural-urban migration as domestic servants, teachers, and public functionaries; migrate with their children for schooling, leaving men behind in the rural areas; or migrate to facilitate government transfers (Schmink and García 2015; Padoch *et al.* 2008, 2014; Brondizio *et al.* 2011).The intersection of economic and infrastructural precarity, high rates of violence and crime, and the effects of climate change particularly impact low-income populations in rural areas and urban peripheries. These vulnerabilities have been enhanced by COVID-19 impacts on local cities and circular migration.

14.4.4 Urban environmental issues

Urban sanitation infrastructure in the Amazon is precarious at best (Brondizio 2016; Mansur *et al.* 2018; De Lima *et al.* 2020). Vast majorities of municipalities have less than 20% sewage collection (Mansur *et al.* 2016), and these issues are becoming more complex, with increasing patterns of climate related "deluge rains" that cause extensive flooding, overwhelming the infrastructure that does exist, and hammering settled areas near storm and flood-vulnerable waterways. Strong droughts can undermine rural production of various kinds, and with their associated high heat island temperatures make urban areas lethally hot, more than 5°C degrees above adjacent nonurban areas (de Souza and Alvala 2014). As urban areas grow, issues of pollution become more extreme, and these are reflected in increased indices of waterborne disease, such as recent outbreaks of cholera, and mosquito-borne illness like dengue, Zika, and malaria. In addition, worrisome problems like mercury contamination, oil contamination, and industrial pollution are on the rise, as is concern over COVID-19 (Howard *et al.* 2011; Bourdineaud *et al.* 2015; Webb *et al.* 2016; Arrifano *et al.* 2018). Air quality questions are becoming more important as vast fires proliferate in the dry season. Limited visibility is only part of the problem; respiratory problems such as asthma worsen and hospitalizations increase (Irga *et al.* 2015; Butt *et al.* 2020). Long term impacts of prolonged forest fire smoke are now a large public health question, and again enhance vulnerability to COVID-19.

The shift into aquaculture in the form of tilapia ponds near Peruvian towns is also raising concerns about resurgences of malaria (Maheu-Giroux *et al.* 2010). Sea level rise is affecting the lower Amazon estuary settlements with "sunny day" flooding and worsening water quality (Mansur *et al.* 2016; De Lima *et al.* 2020). These problems are compounded by high levels of criminality. Amazonian urban areas experience a great deal of crime and violence, reflecting the dynamics of poverty and clandestine economies, including the presence of drug traffickers or organized crime. A recent report by a Mexican-based NGO (*El Consejo Ciudadano para la Seguridad Pública y la Justicia Penal*) places the Amazonian capitals of Manaus (23rd), Belém (26th), and Macapá (48th) among the 50 most violent cities in the world (41 of which are in Latin America) (Seguridad, Justicia y Paz 2021).

This section has summarized the "embedded urban-rural Amazon," its livelihood dynamics, and some of its vulnerabilities. The complex interactions between urban waged work and natural resources livelihoods in subsistence, exchange and commerce, city services, state transfers, and the dynamics of rural survival are linked to multivalent forms of income and identities. These dynamics suggest that there are many ways that Amazonian peoples' resources and environmental services can be simultaneously supported to improve welfare. Recent panel studies of welfare in the Brazilian Amazon in urbanizing and rapidly deforesting areas show that urbanization does not lead to positive changes in human welfare, and that state agricultural investments also undermine welfare as they marginalize small scale producers (Silva *et al.* 2017). This information, coupled with recent studies on the socioeconomic impacts of gold mining (Escolhas Institute 2021) and large-scale agro-industrial development, suggest a problematic set of paths of Amazonian transformation in terms of their development benefits, while their environmental and social costs are high; a huge development externality. The poor infrastructure conditions of many towns, and the precarity of incomes, may make integration with rural life both an economic necessity (a safety net in the formal absence of one, and indicative of a new kind of rurality [Rivera and Campos 2008; Hecht 2009; Pinedo-Vasquez and Padoch 2009]) and also important for overall health by reducing exposures to pathogens.

14.4.5 Migration: Formal, private, and spontaneous

To western eyes, the Amazon has stood as an El Dorado to adventurers and to the state, a refuge from *minifundia*, a place for new beginnings, of insurgencies and prisons, of opportunity and its negation (see Figure 25.1 on Amazon worldviews over time, Chapter 25). There are now literally thousands of planned and unplanned settlements, ranging from formalized private colonization, corporate planned cities, and state-led colonization, to informal settlement, boom town explosions, landless occupations, and do-it-yourself *de facto* agrarian reform (Perz *et al.* 2010; Simmons *et al.* 2010).

Early phases of Amazonian colonization involved the importation or dislocation of labor at the regional level through Indigenous peonage, indenture, and slavery; and African slavery for forest collection and plantation agriculture (MacLaughlin 1973; Acevedo and Castro 1997; Salles 2005; Roller 2010, 2014). This instigated another form of "hidden urbanism," begun initially around Afro-descendant communities located deep in forests, the *Quilombos* that stretched throughout the lower Amazon, and all the way up into the Guyanas (Agostini 2002; Cavalcante 2011; De la Torre 2012; Florentino and Amantino 2012a,b; Hecht 2013; dos Santos Gomes 2015). The rubber period stimulated formal state and private colonization in Bolivia (Lavalle 1999), and state-organized movements into Peru's Selva Central (Santos-Granero and Barclay 1998). Colombia's Putumayo became especially infamous for its Indigenous slavery and the international political fallout that this occasioned (Taussig 1984; Goodman 2010; Hecht 2013). Brazil, and especially the western state of Acre, which was a key supplier of rubber for the global market, relied on massive relocation from Brazil's northeast, Indigenous enslavement, and even involved workers from the US. More than a million people were resettled in the Amazon under various labor regimes, spatial configurations, forms of coercion, and labor migration of multiple types, including US workers to assist with railroad construction (Weinstein 1983; Coomes and Barham 1994; Ferreira 2005; Neeleman *et al.* 2013). Similar forms of settlement and labor recruitment, again from the northeast region of Brazil, were reanimated during WWII (Garfield 2010) for rubber supply for the US after Asian supplies were no longer available.

The Amazon has been open to foreign settlement since the 19th century when it embraced American slave holders (Guilhon 1987; Hecht 2013); settlers included Japanese, Mennonites, people from the former Ottoman empire, Syrians, Belgians, French, eastern bloc refugees, and in the Guyanas, South Asians (especially Indians) and Hmong, among many others. Although the Amazon shows a high degree of internal national migration, it also has a long history of cosmopolitan migration, both permanent and short term (Hecht 2013; Benchimol 1998). The Korean company towns that sprang up to support the construction of Korean-financed dams in Ecuador provide an example of a controlled, and probably impermanent diaspora, and the recent arrival of Haitian migrants and a Venezuelan diaspora into Brazil, Ecuador, and Colombia reflect the political and environmental drivers of migration.

Migration can be categorized as a combination of push and pull factors. The standard discussion of push factors emphasizes livelihood problems, the issues of *minifundia*, environmental issues faced by smallholders in Andean zones and the Brazilian northeast, political pressures from the "*Violencia*" in spontaneous migrations in the Colombian massive occupation of the Guaviare (Molano 2019), and more general displacements of up to 5 million people in Colombia. Rural instabilities and land rights were instrumental in fueling insurgencies in Latin America in the post-war period (Bolivia, Brazil, Colombia, Peru). Agrarian reform as frontier settlement would become a key social policy initiative, and a territorial strategy (De Janvry 1981; Pacheco 2009; Hecht and Cockburn 2011).

Modern colonization policies have emphasized pull factors for the most part, offering land, credit, and production assistance accompanied by large scale public relations campaigns. These programs have fed a narrative that frames the Amazon as an "empty" and "uninhabited" space, echoing hundreds of years of geopolitical and settlement language. With the idea of "he who has, keeps" ("*Uti Possedetis*" in Roman law), as awareness of resources grew and infrastructure expanded, colonization took on a geopolitical cast ("*Integrar para não entregar*" or basically "use it or lose it", "Integrate to avoid handing over"), and a continuing alternative to agrarian reform in more developed areas in virtually all Amazonian countries, to avoid expropriation of the terrains of landed elites in more settled areas where such elites maintained significant power. Further, colonization appeared to address serious social inequalities and helped frame states as modern rather than oligarchic entities actively seeking to redress inequality in access to land, which was, at mid-century, a striking feature of Latin American societies. It was this "strategic" use of colonization within the different framings and needs of national economies, from geopolitics to counter-insurgency to eco-settlement, that gave Amazonian settlement its highly erratic quality and its terrains of shifting, and often contradictory, policy. Yet, this very appealing political narrative was important, even as many colonization areas became rife with conflict. Erratic public policy, combined with volatility for small farm prices, environmental and other production problems, and a general sense of abandonment have been central in the emergence of clandestine economies of multiple types (Betancur-Corredor *et al.* 2018; Caballero Espejo *et al.* 2018; Gootenberg and Dávalos 2018; Kolen *et al.* 2018). Clandestine economies can be seen as highly labor absorbing as compared to agro-industries and livestock production, and thus are often vigorously defended, regardless of environmental or health consequences. The empty land narrative, which was foundational for all the other settlement arguments, ignored the fundamental reality that these lands were inhabited by Indigenous populations, traditional peoples, previous settlers, and Afro-descendant communities who made claim to their historical territories, sometimes based on earlier treaties signed with defunct empires, overlapping sovereignties, and to appeals to current land rights laws by previous settlers and new recognitions of territorial claims. Settlement policy and practice, as we mentioned, has undergone significant program shifts, and this is perhaps best exemplified in Brazil, which has by far the largest number of formal settlements, extensive informal settlements, and settlements declared by local states (Box 14.5). The geographic distribution of the various forms of settlement is shown in Figure 14.4

One of the most consistent outcomes in settlements has been the high degree of colonist attrition, which is marked in both formal and informal colonist settlements, with levels of turnover as high as 77% (Carrero and Fearnside 2011). Thus, because most farm lots changed hands at least once, and often many times, deforestation and farm consolidation processes do not reflect the action of one single household (defying the classic Chayanovian models of household behavior), but rather of successive households or landowners over time. The models of settlement currently on offer suggest little by way of settler security, but fulfill important ideological and aspirational functions, even as they reproduce patterns of landholding inequality in most contexts, as we also see in Chapter 15.

14.4.6 Social movements, development paradigms, and governance

Since colonial times, Amazonian social movements have struggled for rights to land, livelihood, physical security, autonomy, and ultimately more inclusive and sustainable development approaches (Box 14.6). In the 20th and 21st centuries, authoritarian, illiberal governments and regional elites severely repressed social movements throughout the region, in many cases denying rights to traditional territories and assassinating their leaders, as in the iconic case of rubber-tapper leader Chico Mendes in 1988 (Vadjunec *et al.* 2011; Hecht and Cockburn 1989) and a decade later, activist nun Dorothy Stang who also died in

Figure 14.4 Distribution of settlements by type in Brazil's Legal Amazon region. Source: Yanai et al. 2017.

Box 14.5 Traditional and environmental settlement programs in the Brazilian Amazon

Brazil's National Institute for Colonization and Agrarian Reform classifies federal settlements into two groups; the "traditional" model consists basically of gridded areas divided into distinct parcels or "*lotes*," usually part of a plan involving an *agrovila*, a kind of service center. These involve settlement projects (PAs), integrated colonization projects (PICs) and directed settlement projects (PADs). The last includes resettlement projects. These settlements permit colonists to receive formal title after a few years. The justification for these settlements usually involves social justice arguments, agrarian reform concerns, modernization arguments, and pressures for regional food production. These settlements are based on private property regimes for the most part, and are dominated by annual crops and pasture (see Chapter 15). Land rights associated with spontaneous occupation usually involve clearing land for claiming and recognition of the holding by INCRA.

Environmentally distinctive settlements arose more recently in Brazil due to the pressure from traditional populations to recognize historical land rights for forest-based populations and their livelihoods. These kinds of settlement are meant for traditional populations, to support activities with low deforestation impacts, such as agro-extractive activities and sustainable forest management (Agro-Extractivist Settlement Projects [PAEs, *Projetos de Assentamento Agroextrativista*], Sustainable Development Projects [PDSs, *Projetos de Desenvolvimento Sustentável*] and Forest Settlement Projects [PAFs, *Projetos de Assentamento Florestal*]). These can either be new kinds of settlements or involve regularization of existing holdings, which are often characterized by collective rights or long-term access rights. Environmentally distinctive settlements can be installed in areas of primary forest, whether or not the areas have previously been inhabited by traditional populations, and may be organized around *agrovilas* (planned agricultural villages) where the families live. Lots destined for the settlers' production are located elsewhere in the settlement, in some cases far from the *agrovilas* (Silveira and Wiggers 2013). Settlements with collective land rights can be divided into individual lots if settlers request an individual area, or if division into lots is needed to avoid territorial conflicts between settlers (Guerra 2002).

Environmentally distinctive settlements are infused with the language of sustainability, and they do deforest less than the tradition settlements, but the dynamics of deforestation follow the classic pattern: taking out valuable timber, clearing for annual cropping and/or pasture, fragmentation of forests, and over the long-term, shifting into pasture. These proximate drivers can also reflect indirect non-legal processes such as illegal logging, land grabbing through clearing to claim and other forms of land fraud, and single owners acquiring multiple lots. Recurrent problems include limited credit for activities other than livestock, poor levels of technical assistance, limited monitoring of ownership patterns and clearing sizes, and cutting into protected areas. The literally devastating result is that settlements contributed to 17% of the total forest clear-cutting and 20% of the total carbon lost in the Legal Amazon (Yanai *et al.* 2017). Despite only 8% (397,254 km^2) of the Legal Amazon being occupied by settlements, and despite most of the cumulative deforestation (83% or approximately 870,000 km^2) being outside of the settlements analyzed, the contribution of these settlements to deforestation rates and to carbon loss were both substantial and increased over time. Most of the carbon stock loss (2.2 Pg C or 86% of the total carbon loss in settlements) occurred in settlements situated in the Arc of Deforestation, where deforestation pressure is intense and the number of settlements is large (2,190 settlements or 80% of the total) (Yanai *et al.* 2017).

A continuing pattern of assassination of forest defenders (Staff 2007; May 2015). Far less noted, in the absence of international profiles, have been the hundreds of assassinations of peasant leaders. Brazil, and the Pan-Amazon more generally, leads the world in the frequency of murders of human rights activities, Indigenous rights leaders, and forest guardians according to Amnesty International (2020) (see also Chapter 16).

Democratization in the 1980s and 1990s allowed Amazonian civil societies greater opportunity to participate in policy debates in both rural and urban areas. A high point took place in Belém, where, between 1997 and 2001, a vibrant participatory budgeting initiative was implemented to discuss small urban infrastructure for community-determined projects (Silva *et al.* 2015). This kind of initiative lost space, however, with the expansion of national government support for large-scale infrastructure in the 2000s. Movements throughout the Pan-Amazon have increasingly mobilized to address the destabilizing impact of these projects, and to push for improved environmental governance and alternative regional development models.

In rural areas, new kinds of land claims gained traction following Brazil's 1988 Constitution, which recognized the territories of many kinds of traditional peoples, including Indigenous and Afro-descendent peoples, rubber tappers, non-timber forest product extractivists of many kinds, traditional fishers, and communities in sustainable development units as we have discussed earlier. Accompanied by better protected area legislation, this produced new conceptualizations of "socio-environmental" forms of conservation in inhabited landscapes (Box 14.6). More than 70 million hectares in Brazil alone were conserved with this model, which provided the legal basis for contesting the expansion of land grabbing associated with soy and cattle ranching, and the expanding road system. Similar language and concepts spread through the Pan-Amazon, building on previous experiences of resistance by Andean Indigenous groups, as countries shifted away from their earlier authoritarian regimes. These gains are now under threat everywhere in the Amazon, and especially Brazil.

Indigenous groups, in particular, have increasingly turned to international organizations and trans-basin organizing to pressure governments to respect human rights, citizenship, and territories in a context of increasing violence and threats to their territorial and human rights. As these words were written in 2021, thousands of Indigenous peoples and their supporters were protesting in the Brazilian capitol against the controversial law PL 490 under consideration by the Brazilian legislature, which would undermine the exclusive rights of Indigenous peoples to their lands, and impose an arbitrary time frame of occupation and demarcation at 1988 (the year Brazil's constitution was approved) to determine Indigenous land rights (Castro 2021). PL490 would permit mining and timber concessions on Indigenous lands.

14.5 Conclusions

The great Brazilian writer Euclides da Cunha noted that Amazonian countries would never really come into their own histories and identities until they began to understand the implications of their Amazonias (Cunha 1907). The Amazonian transformations presented in this chapter are framed by the complexity of the Amazon's environment, the antiquity of human co-existence with the region's natural resources as outlined in earlier chapters, and now the powerful forces that have imposed dramatic, and in many ways novel, configurations on Amazonian peoples and nature, especially over the past half a century. While forms of government have shifted among authoritarian, illiberal and liberal regimes from the left and the right, the Amazonian question remains essentially the same: What to do with a vast illegible national territory, infused with the myths and realities of riches, inhabited by largely obscure populations? What to do with an ecologically exuberant, largely incomprehensible terrain to planners, capitalists, farmers and the political classes

Box 14.6 Insurgent citizenship: Social movements and social change

While the fiscal crisis of the 1980s and 90s implied diminishing availability of funds for big infrastructure (except roads), this situation started to change in the mid-2000s, especially in Brazil. With the creation of the *Programa de Aceleração do Crescimento* stimulus program in 2007, major funds became available for both urban and regional large-scale infrastructure. These initiatives have met with massive and highly-publicized popular resistance from the lowlands to the Andes (Canessa 2014; Jerez *et al*. 2015). In the mid-1980s, social and environmental movements joined together to protest the Cuiabá-Porto Velho road (BR-364), attracting international and national attention (Hecht and Cockburn 1989; Hochstetler and Keck 2007; Schmink and Wood 1992). In Ecuador, the Waorani people have been struggling for reparations from Texaco/Chevron and PetroEcuador for the devastating impacts of drilling operations, including a lawsuit under litigation in US court since 1993 (Pellegrini *et al*. 2020). More recently, grassroots groups have protested the construction of a road in Bolivia's Isobore Sécure National Park and Indigenous Territory (TIPNIS) (McNeish 2013), the Camisea pipeline in Peru (Urteaga-Crovetto 2012), and the mega-hydroelectric power plan of Belo Monte in Brazil (Fearnside 2017a), to name just a few contentious projects.

National and subnational governments in the Pan-Amazon have generally resisted attempts to create more robust participatory institutions through which affected communities can engage in informed consent around big infrastructure projects (Bebbington *et al*. 2018a,b). In Brazil, community participation in decision-making about such projects is almost entirely reduced to environmental permitting hearings late in the process, with little practical impact on decision-making (Abers 2016; Zhouri 2011). Land-use zoning efforts, popular in the 1990s, were an opportunity to engage community participation, but these plans were frequently overturned or approved without effective participation (Bratman 2019).

In the 2000s, left-leaning national governments throughout the region promised a more participatory and sustainable approach to mega-projects. One example was the BR-163 road paving project in Pará and Mato Grosso (Brazil). The federal government approved a Sustainable Development Plan for the region designed by civil society groups through extensive consultations. Unfortunately, it was never implemented (Abers *et al*. 2017). This area was critical due to the threat of soy expansion into smallholder, Indigenous, Extractive Reserve, and *ribeirinho* lands. Similar promises were made about the Belo Monte dam, and a Regional Development Plan for the Xingu (PDRSX) was modeled after the defunct BR-163 plan. Civil society groups, however, have reported difficulties getting their proposals approved through the participatory mechanisms created to implement the plan (Pereira and Gomide 2019: 202-22), and the definitions of 'sustainability' are themselves contested (Bratman 2019). Later, with the new federal administration, the BR163 became famous for its "Fire Day" (*Dia de Fogo*) where fires were actively set in defiance of regulations against clearing and burning along the road.

In the absence of effective participatory structures, local and especially Indigenous movements have sometimes made headway through protest. The Indigenous March of 1990 (*Marcha por el Territorio y la Dignidad*) influenced Bolivia's forestry law (1996) and struggles for territorial recognition and control (Barroso 2013). In Ecuador, *La Gran Marcha* of 1992 won the recognition of Indigenous land rights. In late September 2021, lowland groups in Bolivia again marched, not only for land and autonomy, but to protest environmental destruction. Recent protest "caravans" by Indigenous populations in Europe have focused on the impacts of European consumption patterns, the encroachment on lands and violence against Amazonian Indigenous peoples, and the lack of prior consent in the implementation of mega projects. These contributed to questions raised in the EU about MERCOSUR trade agreements, in light of Amazonian destruction and human rights problems.

Another way that Amazonian movements have influenced political institutions is through the dissemination of the concept of *Buen Vivir,* which has been included in the constitutions of Ecuador, Bolivia, Colombia, and Peru. Throughout the Andes and Amazon, Indigenous cultures have concepts of a healthy life based on traditional knowledge and lifeways, and of care for the environment; this includes Quechua (Ecuador), *Sumak Kawsay;* Aymara (Bolivia), *Suma Qamaña;* in Guarani, *Teke Porã;* and in Baniwa (Brazil), *Manakai* (Cruz and Pereira 2017; IHU 2012). These ideas have been translated into Spanish as *Buen Vivir,* a paradigm that deprioritizes economic growth and puts people's lives, nature, and basic rights to education, health, and social equity at the center of development (Alcantara and Sampaio 2017: 232). These ideas reside at the heart of many Amazonian cultures and represent different kinds of "episteme," a normative and foundational principle that informs behavior. *Buen Vivir* is an important example of how social movements can contribute to debates about alternative models of development.

located in the capitals, along the coasts, interiors, and in the mountains, who were to decide its fate? And thus was the Amazonian thrust into the current world through the ideologies and practices of modernization, and the massive ecological, sociocultural, and economic simplifications that have attended it over the last 50 years or so. The simple answer about the Amazon lay in the recipes of modernization writ everywhere in its various incarnations. In the Amazon, what this meant was to shed the fabric of Amazonian lives, and turn complexity into monocultures, mines, degraded pastures, struggling small farms, and precarious cities. The largest tropical forest on the planet became among the most urbanized places in the developing world and full of hyper-simplified landscapes.

For modernization to advance, the complexity of forests had to be reduced from multiplicities, to landscapes of a few species at most, and much of this devoted to animal feed of soy, corn, and grass. Over huge areas, lands would be freed from their diversity by a kind of hellfire that would swirl their millennia of DNA and carbon bodies into choking ash, enough to darken cities hundreds of kilometers away. This was done in the name of many things and contested meanings: bringing civilization to the tribal, religion to the heathen, taming the wild, national sovereignty, nation building, geopolitics, poverty alleviation, national integration, agrarian reform, territorial governance, market triumphalism, and transformation of the means and the modes of production into a mostly capitalist idiom. It also meant that the Amazon would become one of the largest planning terrains on the planet, second only to China, and in many ways, the graveyard of failed, and largely forgotten regional plans, that had the problem of constantly remerging for bad reasons and bad results. Modernization has moved the Amazon from its traditional forms into a caricature of modernity; urban, secular, waged, and monetized, but largely lacking the distributional structural change and the larger welfare improvements that politically and economically justified ravaging Amazonian lands and waters, a failure exemplified by the current astronomical COVID-19 mortality. As nation states made their mark on Amazonian lands, gridding them out, creating new settlements, and punching roads through forests, Amazonian countries have reinvented resource dependency as national economic strategies, key elements of their foreign exchange. This has been achieved through the expansion of mining, fossil fuel extraction, monoculture agriculture, speculative frontiers and infrastructure to support the export and flight of national wealth, and the creation and re-creation of inequalities. Large, clandestine economies of plundered timber, stolen lands, illegal gold and its mercurial waters, furtive coca production, and continuing streams of migration, seasonal labor, and a bricolage of urban and rural livelihood tactics frame the contours of the precarity for much of the region's population. The modernization development model as it is currently deployed incarnates externalities (unaccounted for environmental costs) not as a "bug," but rather as an essential feature of the process, with the true costs borne at multiple scales, from local ecological destruction and extinctions, social dislocations, and immiseration, to regional and global climate change. The prevailing definitive forms of destruction lock out alternative ideas and practices that regional populations advance as "multiple" and "hybrid forms" (what is often called a "pluriverse") of modernities based in systems of local knowledge, social innovations, and equitable outcomes, that support environmental services rather than the systems of almost colonial plunder and wealth extraction which currently dominate.

In spite of their importance, cities, towns, and villages remain more or less out of the discussion, even as they are now home, at least part of the time, to the large majority of Amazonian inhabitants. How these urban areas will adapt, how they shape their hinterlands, and how people's complex livelihoods will unfold under increasing social instability is still largely off the radar. Moving forward, the insights and interests of local people, both urban and rural, native and migrant, and especially the region's diverse and highly-organized Indigenous peoples, Afro-descendants, riparian, and urban dwellers among many others, must serve as the touchstone for a dramatic shift in the approach for sustainable, resilient development and conservation in the Amazon.

14.6 Recommendations

- Most of the wealth generated in the Amazon is transferred away from it. The modernization model that has largely prevailed since the 1960s, where tropical environments and the people of the region were largely viewed as obstacles, has generated severe geo-ecological damage, social inequalities, and economic dysfunction in the form of corruption, extensive clandestine economies, and failing institutions. This model of monocultural uniformity and extractivism has entwined Amazonian development with climate change, economic vulnerabilities, and deep employment instabilities. A more just, inclusive, and resilient future for the region calls for confronting these legacies and rethinking development, not only in a regionally-integrated way but also in terms of multiple local realities (or forms of modernities or "pluriverses"). Such an approach calls for aligning regional-level policies with support for place-based initiatives addressing social and environmental problems on the ground. At the regional level, the alignment of supportive state policies, regional institutions, and national/international approaches, such as supply chain certifications and agreements, green markets, and conservation finance, can contribute to promoting clarity in environmental governance, economic incentives for sustainable production systems and value aggregation, and addressing infrastructural deficiencies. At the local level, support for place-based initiatives and organizations can contribute to sustainable resource management and value aggregation that generates employment and inclusion where resources are produced. As with previously successful efforts to control deforestation, institutional alignment from the municipal to federal level is crucial.
- Amazonian development projects need to engage in full cost accounting of the social and environmental impacts prior to licensing, should follow informed consent practices for affected communities, and should plan for realistic compensation for harms produced by projects. Implementing and requiring participatory input, through both existing and new institutional mechanisms, might also help such programs avoid pitfalls and deploy lessons learned.

- Amazonian towns and cities are neglected terrains in Amazon research and land use planning to guide their expansion. Information on the dynamics of Amazonian urbanization and its relationship to varying hinterland processes, such as land-use change, pollution, migration flows, resource demands, and impacts on biodiversity and watersheds is extremely sparse. The influence of urban areas on surrounding and distant landscapes varies significantly across historical-geographic contexts and does not follow the same conventions of urban dynamics in temperate zones. More concerted attention to understanding these processes is needed and should be shared throughout Amazonian countries.
- Most people in the Amazon live in cities with highly precarious and often ephemeral livelihoods, receiving income from multiple sources, including wages, petty commerce, state transfers, and remittances. These can include strong relations with rural and Indigenous areas, local fisheries, and subsistence or rural waged labor in agriculture, construction, illicit logging, gold mining and the coca economy. This economic bricolage is poorly understood, and policies can undermine parts of these income sources, radically enhancing already entrenched inequality. More participatory forms of urban development, and regional development more generally, and support for the inclusion of producers and resource users in value aggregation opportunities could help support complex livelihoods.
- Amazonian cities and their peri-urban areas are sites of agricultural production for subsistence as well as sale. Amazonian towns often have significant areas of agricultural and agroforestry production within them. In spite of their importance in food production and employment, both are largely “policy orphans”. Greater promotion and creation of open space and forms of urban agroforestry could enhance food security under increasingly precarious conditions. Peri-urban and close in hinterland production should be supported with credit and infrastructure for transportation, commercialization, and value aggregation. These could build on local knowledge and practices, such as support for the thousands of local associations and cooperatives engaged in such efforts.
- Given the intensity of tropical urban heat island effects, multipurpose urban arborization (which can also help with diversifying food sources, promote thermal comfort, minimize the effect of extreme weather, and enhance wildlife habitat) should be a priority. Use of local knowledge systems in tree selection and management can build on multiple strategies for urban comfort under increasing temperatures. Arborization can provide elements of an urban conservation strategy.
- Amazonian cities lack basic water and sanitation infrastructure. In light of the billions of dollars spent on Amazonian infrastructure to support export corridors, a much larger percentage should be allocated to urban systems. In addition to improving quality of life and lowering sewage loads to rivers, such investments should increase resilience to extreme heat and flooding events.
- While deforestation clearly remains a problem, the Amazon is also the site of significant toxic pollution, including mercury and arsenic from gold mining; and pesticides, herbicides, and other biotoxins from agro-industrial systems which contaminate both land and water. In ore mining areas, extensive water pollution, processing chemicals, and holding pools remain largely unregulated, and hydrocarbon extraction areas are famous for their impacts on air, water, and land. Urban port areas are also increasingly polluted. While in principle there are regulations that address these issues, for the most part they continue unabated. Better enforcement is necessary.
- One of the drivers of deforestation in the Andean Amazon is the displacement of coca producers, who move to escape enforcement of ‘war on drugs’ policies. This moves coca systems further into forests and across borders.

This fuels deforestation both through production and money laundering. The legalization of marijuana in many US states helped reduce criminality and illegal invasion of public lands, while providing taxable revenue.

- The insights and interests of local people, both urban and rural, native and migrant, are often overlooked. But these groups are generating alternative approaches to manage and restore landscapes, and elaborating new marketing systems and forms of governance. These systems can serve as the models for a necessary shift in the approach to and practices of sustainable development in the Amazon.

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Chapter 15

Complex, diverse, and changing agribusiness and livelihood systems in the Amazon

Avião aplica agrotóxico na plantação de soja localizada em Feliz Natal (Foto: Alberto César Araújo / Amazônia Real)

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Graphical Abstract

Figure 15.A Finding pathways to more sustainable agriculture and resource use from the currently unsustainable practices is among the most pressing challenges facing Amazonian countries.

Complex, Diverse and Changing Agribusiness and Livelihood Systems in the Amazon

Francisco de Assis Costa[a], Marianne Schmink[b]*, Susanna Hecht[c]*, Eduardo D. Assad[d], Denise Humphreys Bebbington[e], Eduardo S. Brondizio[f], Philip M. Fearnside[g], Rachael Garrett[h], Sebastian Heilpern[i], David McGrath[j], Gustavo Oliveira[k], Henrique dos Santos Pereira[l]*

Key Messages

- Key agrarian production systems (crops, livestock, agroforestry, fisheries, forestry and tree plantations) are complex and vary in form and dominance across Amazonian countries. The different actors involved in both wage-based and family-based systems interact in multiple ways that diverge in different countries, with important impacts on ecosystem services. These production systems are undergoing rapid change in the context of structural shifts in the economy and markets, varying policies, political contexts, accelerated urbanization, and climate change.
- The trajectory of production systems in the Brazilian Amazon region over the past two decades, the analytical focus of this chapter, reflects both the divergent trajectories and the profoundly asymmetric support and recognition given to smallholders in comparison to large-scale and corporate production systems. While larger-scale producers and agribusiness, especially livestock, soy cultivation and oil palm plantations, have benefited from favorable land tenure policies, sustained access to credit and technical assistance, and logistical infrastructure, a large number of family-based producers have moved out of agriculture. Policy continuity, institutional support, and favorable commodity markets for larger-scale commercial production structures have reinforced regional inequities in access to resources while encouraging deforestation and unleashing environmental impacts on land and rivers, undermining environmental services and possibilities for more resilient, equitable and sustainable development pathways.
- A prominent feature of Amazonian land-use change has been the transfer, both legal and illegal, of public land to private control and use, facilitated by institutional support for research focused on agro-industrial crops, by supportive credit lines, and by infrastructure development. Indigenous peoples and local communities (IPLCs) continue to grapple with erratic state policies, limited institutional support, high costs to access markets, economic uncertainties, and increasingly, threats to land rights and climate change. Expanding clandestine economies of multiple types threaten protected areas and spur forest degradation, especially IPLCs, whose lands may not be adequately demarcated, legally recognized, and protected by the government.

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[a] Centre for Advanced Amazonian Studies and Postgraduate Program in Economics of the Federal University of Pará, Belém, Pará, Brazil, francisco_de_assis_costa@yahoo.com.br
[b] Center for Latin American Studies, University of Florida, Gainesville, Florida, USA, schmink@latam.ufl.edu
[c] Luskin School of Public Policy University of California Los Angeles, USA, and Graduate Institute for Development Studies, Geneva, Switzerland
[d] Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), São Paulo, São Paulo, Brazil
[e] Department of International Development, Community and Environment, Clark University, Worcester, Massachusetts, USA
[f] Department of Anthropology, Indiana University Bloomington, Indiana, USA
[g] Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA), Manaus, Amazonas, Brazil
[h] Environmental Policy Lab, ETH Zurich University, Zurich, Switzerland
[i] Cornell University, Ithaca, New York, USA
[j] Center for Advanced Amazon Studies of the Federal University of Pará, Brazil, and Graduate Program on Society, Nature and Development, Federal University of the West of Pará, Santarém, Pará, Brazil
[k] Global and International Studies, University of California, Irvine, California, USA
[l] Agricultural Ecology, Federal University of Amazonas (UFAM), Manaus, Amazonas, Brazil

- Growing tensions over land and stagnant incomes have squeezed rural families out of rural economies and areas, in some cases leading to significant outmigration to cities and a focus on informal labor. On the other hand, family-based agriculture and agroforestry systems and fisheries have continued to persist, and in many cases to flourish, while confronting pressures and adapting to new markets and climate change. These processes also have consequences for accelerated and precarious urbanization, and other challenges. On the other hand, local livelihoods based on longstanding and diversified agroforestry and fisheries systems, that bridge rural and urban networks, remain vulnerable and largely unrecognized in regional public policies. One of the main opportunities to reconcile food production, inclusive economies, and nature conservation in the Amazon is to support the thousands of place-based initiatives promoting more sustainable and diversified agriculture and resource use practices. Throughout the region, these initiatives are providing multiple sources of employment, income and food security, supporting regional development, and enhancing and sustaining the functionality of environmental services.

Abstract

Finding pathways to more sustainable agriculture and resource use remains the most pressing challenge for Amazonian countries today. This chapter focuses on characterizing recent changes in the structure and types of agrarian production systems, including fisheries. The chapter identifies local responses to deal with both the challenges and opportunities to promote more sustainable production and extraction economies in the Amazon. While regional agriculture and resource economies rest on a rich diversity of producers, knowledge, and production systems, the expansion of agribusiness enterprises came to dominate the distribution of subsidies, institutional support, and logistical infrastructure. These trends are associated with forest loss and degradation, pollution of waterways, pressures on and/or displacement of Indigenous and rural communities, and increased greenhouse gas emissions, all of which undermine an array of ecosystem services. The impacts of socio-economic and hydro-climatic changes on livelihoods, environments and biodiversity are very diverse and complex in each one of the Amazonian countries and within them. In this chapter, we provide an in-depth quantitative case study focusing on the Brazilian Amazon, including attention to changes in key agrarian production systems (agricultural crops, cattle raising, agroforestry, and tree plantations). The chapter uses comparable agrarian census data from 1995, 2006, and 2017. The quantitative analysis is complemented by qualitative and empirically grounded discussions that provide insights into the changes and impacts of different activities, how they are interlinked, and how they differ across Amazonian countries. The final section provides recommendations towards promoting adaptive, profitable, and more sustainable smallholder production and management systems that reduce deforestation and support local communities and economies, in the context of increasing urbanization and climate change.

Keywords: Production trajectories, livelihoods, agriculture, livestock, agroforestry, fisheries, forest management, logging, land speculation, deforestation, climate change

15.1. Introduction: Complex, Diverse and Changing Structures of Production

Finding paths to transition agriculture and resource use from unsustainable to more sustainable practices is among the most pressing challenges that Amazonian countries are currently facing. This chapter focuses on recent rapid changes in the structure and systems of production by which specific types of actors in the Amazon region produce economic value (by combining labor, natural resources, and technology in different systems). It also explores the implications of these changes for the environment and society of the region, and highlights local responses to deal with the challenges and opportunities to engage in more environmentally sustainable production and use of natural resources in the Amazon.

The discussion in this chapter is heavily weighted towards the Brazilian reality due to the rich data available, which analysis reveals the rapid expansion of agribusiness over the past few decades in the Brazilian Amazon region. Favored by pro-short-run growth and export policies, the gross value of agricultural, livestock and extractive production (GVP) of the 556 municipalities that make up the Brazilian Amazon biome grew at constant 2019 prices, from USD 5.1 billion in 1995 to USD 20.2 billion in 2017, expanding over the two decades nearly fourfold.[m] This growth was due largely to the rapid expansion of agribusiness production structures and systems, which grew from 48% of the total GVP in 1995 to 80% in 2017. In contrast, the small farm sector collapsed from 52% to only 20% in the same time period.

While many of these main trends hold across national borders, the chapter also points to specific distinctions in other Amazonian countries. In the territories of the different countries that share the Amazon, agro-industrial economies have been expanding rapidly in recent decades, reflected in the increased area of the soy-corn system, livestock, and palm oil plantations. This dynamic growth, with important impacts on public lands, has been favored by pro-short-run growth policies discussed in Chapters 14 and 17. The impacts of socioeconomic and hydro-climatic changes on livelihoods, environments and biodiversity are very diverse and complex in each one of the Amazonian countries, involving distinct actors within different modes and structures of production. Historically, both traditional, long-term and recently-arrived large-scale farmers and smallholders have interacted with one another and with the highly diverse, complex natural environment of the Amazon, mediated by different institutions and alternative technical resources as discussed in Chapter 14, thus shaping a plural, multifaceted reality.

This chapter's in-depth quantitative case study in the Brazilian Amazon focuses on changes among key agrarian production systems (agriculture, cattle raising, agroforestry and tree plantations), through analysis of comparable agrarian census data from 1995, 2006, and 2017. It demonstrates the dynamic growth of agribusiness, which also entailed large-scale appropriation of about 13 million hectares of public land: land controlled by private establishments expanded from 86 million in the 1995 agricultural census to 99 million in 2017. Appropriated lands were transformed into pastures and agricultural areas in increasing proportions: in 1995, 37 million ha (43.0% of total owned land); and by 2017, 57.8 million ha (58.5%). This structural land-use shift resulted in deforestation of 20.8 million hectares between 1995 and 2017. The process also resulted in critical reductions in labor demand (from 2.3 million workers in 1995, the number of workers decreased to 1.7 million in 2017) and a massive out-migration of people from agrarian employment to jobs in infrastructure, extractive industries, and Amazon towns and cities (Table Annex 15.2 a, b).

The quantitative analysis of these changes in the Brazilian Amazon is complemented by qualitative empirical discussions that provide more in-depth insights into the changes and impacts of the different activities, production systems and structures and how they differ across Amazonian countries. The findings provide the basis for proposals, in the final section of the chapter, to document, test and promote adaptive, profitable and more sustainable production and management systems in the context of urbanization and climate change.[n] The chapter ends with a series of recommendations

[m] All values in USD were corrected to 2019 prices, the most recent year with the necessary indices, and converted into USD by the exchange rate of 12-31- 2019: BRL 4.0307/USD.

[n] Although the chapter discusses the importance and relevance of local knowledge systems, it does not provide an analysis of the agriculture, husbandry, extractive, or other types of production by Indigenous groups; insights into these activities can be found in Chapters 10 and 25.

and suggestions to transition to more sustainable production and resource use that can facilitate Amazonian countries achieving the Sustainable Development Goals (SDGs, see Chapter 26).

15.1.1. Production systems and trajectories in the Brazilian Amazon

The Brazilian Institute of Geography and Statistics (IBGE) published versions of the Agricultural and Livestock Censuses of 1995, 2006 and 2017 that included separate sets of information about "family farming" and "non-family farming landholdings". Family farming or family agriculture in Brazil has been defined (Law 11,326/2006), by four criteria followed by IBGE: 1) size of holding: a maximum land area defined regionally; 2) reliance on mostly family labor; 3) income predominantly originating from farming activity; and 4) operated by the family. These criteria describe the particular logic of family enterprises that include diverse livelihood activities (agriculture, forestry, fishing, aquaculture, and both rural and urban off-farm employment) to meet their social, economic, and environmental needs. Increasingly, such households also rely on urban incomes, state transfers of various kinds, and remittances, in the creation of multi-sited, complex systems of household income formation (see also Chapter 14). By definition "non-family farming landholdings" are establishments that do not fit these criteria, so they are agribusiness establishments with a predominance of wage labor and with larger land plots; hence, they are medium and large-farms and rural companies.

We refer to these two types of establishments as "smallholder" or "family-based," in contrast to "agribusiness" or "wage-based." As just explained, the use of the term "family-based" regards the predominance of the *labor* involved, not necessarily *ownership,* as many large-scale agribusiness companies and ranching enterprises in the Amazon might be *family-owned,* but operated as large-scale agribusiness enterprises relying predominantly on wage labor.[o]

Within these two broad categories, the census data permit the comparison over time of six key types of actors and productive structures based on the social relations of production, three of them mainly "family-based" and three mainly "wage-based". The productive structures are further identified within each of these two broad categories as "agroforestry," "crops," "plantations," and "livestock" according to the activity that has a greater share in the value of total production and greater importance in net income and investments than other types of crops and activities (following Costa 2009a, 2021).

This use of census data from Brazil and these typologies has some limitations, but nevertheless facilitates the analysis of data trends over time. These types of actors are not necessarily "specialized," since they may combine multiple activities, certainly with significantly greater diversity among the family-based types (Figure 15.1a, Annex). The great majority of smallholders make a living by a combination of agriculture, some type of livestock, agroforestry, temporary wage-labor, periodic urban migration, government welfare programs, fishing, hunting and extraction of forest resources. Part of the extraction of forest resources (primarily logging by actors not listed in the agricultural censuses), hunting and fisheries activities were not included in the quantitative analysis of key production actors because comparable census data were not available. Consequently, it was possible to discern a group of establishments in which temporary agriculture predominated, here called "family-based crops", another in which agroforestry systems predominated, named "family-based agroforestry", and still a third in which cattle raising predominated and so was denominated "family-based livestock".

[o] In this chapter we use the terms "large-scale," "wage-based," "agribusiness," or "commercial" interchangeably to refer to these larger establishments, while referring to smaller-scale family systems as "smallholders," "small-scale," and "family-based".

Within the wage-based agribusiness establishments, those in which livestock-dominated (in the same sense mentioned earlier) were grouped as “wage-based-livestock” – basically cattle ranching or livestock enterprises. Commercial agricultural enterprises were classified as “wage-based-crops,” usually in forms of agro-industrial production, especially soy and corn, and those based on homogenous plantations of permanent crops or trees, as “wage-based-plantations.”

These wage-based production structures had critical differences from family-based enterprises. In the 2017 census, on average only 8% of the workforce in all of the “family-based” structures were salaried, whereas in “wage-based” structures this proportion was 51%, with negligible variation among the respective types of production systems. With regard to property size, family-based enterprises held an average of 41.6 ha: crops 30.4 ha, agroforestry 34.2 ha and livestock 54.6 ha. The wage-based agribusiness structures, on the other hand, had an average of 670.6 ha: livestock 655.5 ha, plantation 231.2 ha and crops 1,066.8 ha (see basic data in Table Annex 15.2 a, b).

In the analysis that follows, we focus on these six actor-structure types and their evolution over time, which we refer to as “productive trajectories,” or “PTs” (Costa 2008, 2009a, 2009b, 2016, 2021). These concurrent trajectories (Arthur 1994; Costa 2013) in land use, labor absorption, income generated, institutional support, and other factors showed distinctive trends in the Brazilian Agricultural Censuses data from 1995, 2006 and 2017, and provide empirical evidence of the dramatic and significant agrarian shifts underway in the Amazon region, whose implications are explored to suggest concrete recommendations for future policies (Figure 15.1 shows the territorial domain of PTs in 2006 and 2017).

15.2. Key Family-Based and Agribusiness Sectors in Rural Dynamics in the Amazon

15.2.1 Family-based agroforestry and fisheries

Family-based agroforestry systems, which include fisheries systems, are managed by some of the oldest and most diverse livelihood groups in the Amazon region and also by other groups of immigrant smallholders who arrived in the Amazon region both before and after the rubber economy boom. They deserve extensive discussion here due to their deep historical roots, strong connection to Amazonian biodiverse resources and habitats, and their unrealized potential as a basis for more sustainable development strategies in the region (see Box 15.1).

People in the Amazon have long relied on agroforestry, hunting and fishing as sources of food and livelihoods (see Chapters 8 and 10). However, large scale exploitation of these sources started to emerge during the second half of the 18th century (see Chapter 11), and expanded during the rubber boom, when rubber tappers were joined by other groups of migrants coming from other regions of Amazonian countries in the second half of the 19th century and the first half of the following century. Some migrated into rubber estates while others supplied foodstuffs to urban centers (Weinstein 1983; de Castro 2013). With the rubber crisis triggered by plantations in Malaysia in the early 20th century, many rubber tappers released from bankrupt *seringais* (rubber estates) throughout the Amazon joined the ranks of small producers, settling along the region’s rivers (Costa 2019; Nugent 1993, 2002) and dedicating themselves to complex livelihood systems based on the management of the biome's natural resources.

These “historical peasants” (Costa 2019; Nugent 1993) were distinct from the peasants who came later as part of the moving agricultural frontier from the 1950s onwards (Velho 1976, 2009; Schmink and Wood 1992): they were heirs to Indigenous and local knowledge (ILK). Their systems of extraction, agriculture, production, management, and conservation were interconnected, complex and fundamental to both their well-being and the sustainable provision of biological resources, as well as more general environmental services (Caballero-Serrano *et al.* 2018; Sears *et al.* 2018). The multiple dimensions and functions of their forest product knowledge have been widely documented (Vogt *et al*. 2016; Reyes-Garcia *et al*. 2007). Both Indigenous and non-Indigenous Amazonians have generated a great diversity of knowledge and practices by constantly innovating and adapting their extraction, conservation and production systems and portfolios of diversified livelihoods in response to specific socio-economic and environmental changes (Reyes-Garcia *et al*. 2007; Vogt *et al*. 2016). Their systems integrate both local communities and modern knowledge to manage, produce and conserve plants, animals (including fish) and other biological resources (Thomas *et al*. 2017; Sears *et al*. 2007). Their flexibility, resilience, and linkages among extraction, conservation and (Almeida *et al*. 2016; Thomas *et al*. 2017).[4] Inhabitants of extractive communities in the Brazilian Amazon occupy over 8 million hectares of public production, have greatly facilitated the process of production of valuable terrestrial and aquatic resources and domestication of landscapes, and the use and management of a range of semi-domesticated species (Coomes *et al*. 2020; Franco *et al*. 2021; Levis 2018; Levis *et al*. 2018; Maezumi *et al*. 2018; Vogt *et al*. 2016; Erickson 2006: see also Chapters 8, 10 and 13). The flexibility and complexity of linked systems highlight the diversity found among family-based agroforestry and fisheries production systems explored here.

In Amazonian local communities, forest extractivism – the collection of non-timber and timber – is an important activity carried out by Indigenous peoples and local communities for generations forests established as sustainable use reserves, depending for their livelihoods on the extraction of marketed non-timber forest products, including

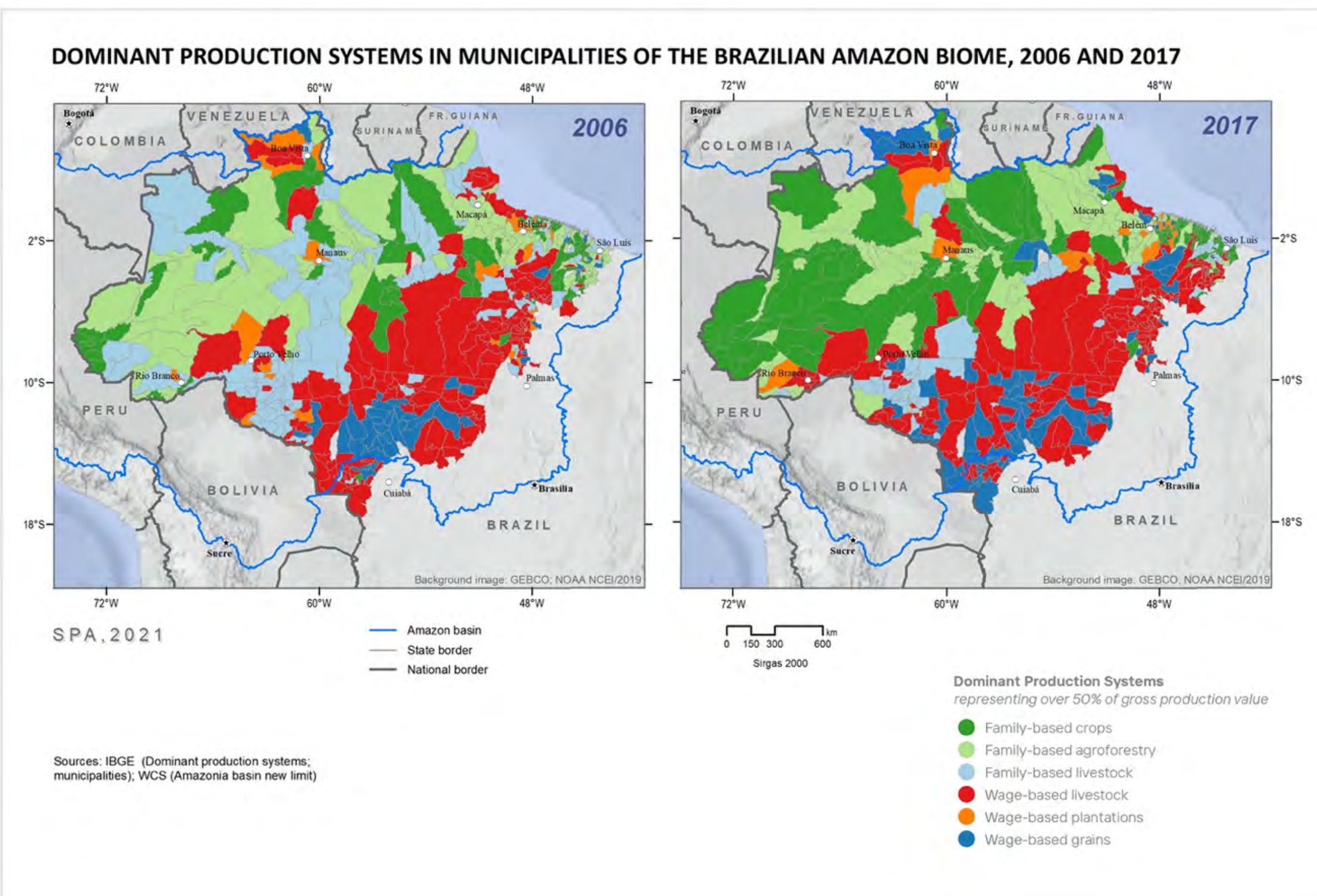

Figure 15.1 Dominant Productive Trajectories (PTs with over 50% of GVP) of Municipalities of the Brazilian Amazon in 2006 and 2017. Sources: IBGE (2006 and 2017) and LiSS- Laboratory for investigation of Socio-Environmental Systems at INPE - Project Trajectories (SinBIOse/CNPq).

those for global export such as Brazil nuts (*Bertholletia excelsa*), *açai* (*Euterpe oleracea*), and rubber (*Hevea brasiliensis),* as well as products for more regional markets such as oil from *copaiba* (*Copaifera reticulata Ducke)* and *andiroba* (*Carapa guianensis)* (Valentin and Garrett 2015; see Chapter 16). Smallholders' understanding of the impacts of extraction allows them to manage yields and avoid the risks of over-harvesting Brazil nuts (Guariguata *et al*. 2017), over-tapping of rubber trees (Almeida *et al*. 2016) and excessive hunting of game species (Ponta *et al*. 2019). Women play a prominent role in forest extractivism, especially in the Brazil nut economy (Lazarin 2002; Shanley *et al*. 2008; Stoian 2005), which accounted for nearly half of Bolivia's documented forest-related exports in 2005 and provided an estimated 22,000 jobs – including women working in urban processing of nuts – in the northern Pando region in 2001 (Cronkleton and Pacheco 2010). Other important forest products include fruits of *Mauritia flexuosa* (Peru), babassu nuts (*Attalea speciosa*) and many other tree fruits that find a niche in regional markets, and well as leaves of several palm species for thatching, artisanal and household use (*Geonoma* spp. in Bolivia) and timber (Brondizio 2008; Cronkleton and Larson 2014; Pinedo-Vasquez and Sears 2011; Porro 2019; Sears *et al*. 2007).

Within Amazonian communities, men and women have adopted multiple strategies to manage forests, generate productive house gardens and farmlands, and produce crops for their own food consumption and for market, drawing on deep cultural traditions as they adapt to changing conditions. Women's important productive work within Amazonian family enterprises is often invisibilized due to their focus on family subsistence, yet women often manage home gardens with fruits, medicinal plants, and small animals, as well as taking care of water provision and quality (Grist 1999; Mello 2014; Mello and Schmink 2017; Mourão 2008; Murrieta and WinklerPrins 2003; Schmink and Gómez-García 2015; WinklerPrins and Oliveira 2010).

They also labor in family crop fields, manage livestock and agroforestry systems, and collect and process non-timber forest products and fish; in

Box 15.1 Historic Amazon fisheries

For more than 350 years, until the second half of the 20th century, the immense fisheries resources were the major source of animal-derived nutrients, such as protein, fatty-acids, iron and zinc for Amazon populations (Crampton *et al.* 2004). Beyond providing a major source of subsistence for riverine communities, fish were a main staple of the *aviamento* (see also Chapter 30) credit and supply system through which virtually all Amazon production and trade was organized. Fish were processed in salting stations on the shores of floodplain lakes and river margins where they were cleaned, salted and dried, and stored for sale to river traders and/or transported to urban merchants who shipped dried fish upstream to rubber and Brazil nut producing areas (McGrath 2 003; Veríssimo 1895; Weinstein 1983).

This commercial system began to change with technological innovations including smaller diesel engines, synthetic fibers for nets, ice making technology, and Styrofoam for iceboxes. These innovations enabled fishers to travel further and catch and store larger amounts of fish, as well as to ship fish across larger distances (McGrath *et al.* 1993). Commercial fisheries shifted from a seasonal activity producing and selling dried, salted fish, to a year-round activity involving fresh iced and frozen fish for growing urban markets, and the developing fish processing industry (Smith 1985). Through this process, commercial fisheries developed two distinct, though overlapping supply chains, one focused on migratory catfish to supply fish processing industries that exported fish to other parts of Brazil, and the other focused on fish with scales, especially *characins*, to supply regional Amazon urban markets (Isaac *et al.* 2008; Crampton *et al.* 2004). In Peru, Ecuador and Colombia, Amazonian fisheries supply local markets, since stiff competition with well-developed marine fisheries challenges expansion of river fish into coastal and Andean markets.

effect, unpaid family labor constitutes a key household subsidy to family production systems in the Amazon (Hecht 2007). Diverse and complex livelihood strategies (drawing upon fisheries and a variety of forestry and agroforestry production and extraction) provide family-based enterprises with greater resilience to economic volatility and climate change than smallholders whose livelihoods are limited to agricultural production alone (Brondizio and Moran 2008; de Castro 2009; Nugent 1993, 2002; Nugent and Harris 2004; Porro *et al.* 2012).

A highlight among agroforestry products is *açaí*, managed in the floodplain and planted on dry land (Brondizio 2008; Costa and Costa 2007; see also Chapter 30). In 2017, 478,000 tons, or 74% of the total *açaí* produced in the Brazilian Amazon came from agroforestry. The values associated with such production increased substantially between censuses, from USD 160 million in 2006 to USD 390 million in 2017. In 2017, *açaí* represented no less than 35% of the value of the total production by family-based agroforestry enterprises. This growth in production figures probably reflects the better monitoring and commercial nature of *açaí* compared with the myriad of other products that flow through Amazonian circuits, varying throughout the basin (Padoch *et al.* 2008; Bolfe and Batistella 2011; Blinn *et al.* 2013; Vogt *et al.* 2015; Buck *et al.* 2020).

Associated with the production of *açaí* and other products of the biome economy (Costa 2020) is an urban, industrial and service economy, producing and distributing pulp, processed foods, nuts, heart of palm, oils and herbals that has grown rapidly: recent estimates suggest that in the state of Pará, total added value of thirty of such products grew by 8.2% per year since 2006, reaching USD 1.34 billion in 2019. Employment reached 234,640 jobs, including 184,128 rural and 50,512 urban, industrial, and commercial jobs (Costa *et al.* 2021). This indicates that more diversified livelihoods drawing upon complex engagements with agroforestry production, fisheries and extraction of forest products, also lead to greater synergies with activities upstream and downstream in the production chain, increasing the dynamism of local markets and generating greater opportunities for employment in the region (see also Chapter 30).

These complex agroforestry systems are prevalent through Amazonian lowlands as well as the "Andean Amazon," and the "Caribbean Amazon" reflecting the long history of extensive regional settlement history in pre-Columbian times, and the adaptation and modification of these within the contexts of relatively recent colonization in the 1970s and 1980s. These systems also reflect the different logics of small and large farmers in a context of rapid land-use change (Balée and Erickson 2006; Carson *et al.* 2016; Erickson 2006; Jacobi *et al.* 2015). Peruvian small farm agroforestry systems have been the focus of extensive research, in part because of the smallholder-focused history of much of Peruvian Amazon's development politics, the importance of the region as an "escape valve" for economic constraints in the highlands, and periodic stimulation of colonization programs where smallholders have remained an important constituency in peri-urban, rural and urban labor systems (Padoch *et al.* 2008; Putzel *et al.* 2013; Sears 2016; Sears *et al.* 2018; see also Chapter 14). As in Bolivia and Colombia, peasants farming at mid-high elevations were also subject to coca interdiction, which stimulated research on alternative cropping systems, and larger attempts at subsidizing the development of alternative production systems, largely for political but also ecological reasons (Angrist and Kugler 2008; Antolinez 2020; Dávalos 2018; Huezo 2019). As discussed in Chapter 14, the historical dynamics of coca were rooted in agroforestry systems for millennia, and in the face of precarious prices, transportation difficulties, and other kinds of vulnerabilities, coca has remained a durable smallholder commodity working through traditional, modern, as well as criminal circuits, especially in the absence of other economic opportunities.

Agroforestry systems of the upper Amazon remain integrated into multiple urban and rural networks, and typically include global niche products (coca, cacao and coffee), regional and national products, and increasingly, other kinds of medicinal plants, such as *ayahuasca* (*Banisteriopsis caapi*). However, recent transportation networks and the expansion of the hydrocarbon economies are destabilizing these systems through problems related to oil spills, expansion of access roads, other forms of pollution such as those associated with gas flaring, siphoning away of labor and also, in some cases, herbicide drift from coca eradication efforts (Bass *et al.* 2010; Brain and Solomon 2009; Finer *et al.* 2008; Huezo 2019; Lyall 2018; Sherret 2005; Suarez *et al.* 2009; Valdivia 2015; Vargas *et al.* 2020).

Fisheries are a core component of these diverse agroforestry systems, providing a major source of livelihoods as well as nutrition for many people inhabiting riverine communities – including urbanized ones - throughout the Amazon (Barthem and Goulding 2007; Begossi *et al.* 2019; Duponchelle *et al.* 2021). Fisheries in the Amazon are multi-species, with more than 90 recorded species included in the catch in individual regions, while only 6-12 species or species groups account for 80% of the local commercial catch (see Chapter 30). The composition of the catch and the importance of fisheries to local populations vary throughout the basin, associated with variations in water quality of the different sub-basins (Goulding *et al.* 2018) and river type (see Chapters 1, 3 and 4). Amazon fisheries are closely associated with the highly productive white-water rivers with their extensive floodplains, while clear and black water rivers are far less productive (Junk 1984).

Amazon fisheries are highly seasonal, and fishing activity is related to the seasonal rise and fall of the Amazon River (Junk *et al.* 1989). Along the main channel of the Amazon, high water occurs between May and June and low water in October-November. Three main groups of fish can be distinguished. Long-distance migratory catfish, several of which travel across the basin, spawn in Andean headwaters and pass their juvenile phase in the Amazon estuary (Barthem and Goulding 1997; Duponchelle *et al.* 2021). A second group of middle-distance migratory species, of which the *Characidae* are the most important, move in and out of the floodplain over their life cycle, feeding in flooded forests during the highwater season. The third group consists of sedentary species, such as the highly prized *pirarucu or paiche* (*Arapaima* spp.) that spend much of their lifecycle in floodplain lakes (Barthem and Goulding 2007; see Chapter 30).

Several types of fisheries sub-sectors, often overlapping, exist in the Amazon, from those practiced by family groups in small riverside communities and urban areas to those that are primarily large commercial enterprises centered around urban areas. Fishers located in rural communities might both subsist on fish and also supply boats (or *lanchas*) with fish that are then transported to the city, processed and sold either wholesale or directly to consumers in regional markets. Long-term information on the total amount of fish caught, sold and consumed in the Amazon is largely unavailable, reflecting the invisibility of some fisheries and ornamental fish commerce and lack of large-scale governmental support. Community-led grassroots movements sought recognition by the government for their rights to local lake fisheries developed in the 1980s. In the state of Amazonas, Brazil, these initiatives were initially fostered by the pastoral action of the Catholic Church and came to constitute the so-called “Lakes Preservation Movement,” headed by the CPT (Pastoral Land Commission) (Benatti *et al.* 2003; Pereira 2004). This social movement served as a sociopolitical basis for the development of public policies recognizing decentralized and collaborative community-based management systems based on local fisheries agreements and management of key fish species such as Arapaima spp. (see below; Campos-Silva *et al.* 2019; Duponchelle *et al.* 2021; Oviedo and Bursztyn 2017; see also Chapter 30).

In addition to historical peasantries and their long-term forged technical capacities, other groups of immigrant smallholders arrived in the Amazon region both before and after the rubber economy boom, from other regions of the Amazonian countries and from outside the region. These groups typically developed productive systems with a greater focus on agriculture, but their practices also evolved over time to agroforestry systems in response to their experience in the Amazon environment (Costa 2020).

Japanese migrant colonies are found in Brazil and Bolivia. In Brazil, beginning in the 1920s Japanese farmers settled in Tomé-Açu, Pará, where they introduced new crops such as jute and black pepper (Homma 2007). Over time, their systems shifted to agroforestry: increasingly diversified fruit crop systems that mimicked natural succession, generating 300 polyculture combinations that used 70 different species (Serrão and Homma 1993; Subler 1993; Subler *et al.* 1990; Yamada 1999; Yamada and Osaqui, 2006; see also Box 30.1 in Chapter 30).

Migrant farmers in northeastern Pará state, and agricultural colonists settled along the Trans Amazon Highway and in Rondônia state in the 1970s, also adapted their cropping systems over time, first focusing on annual crops (especially rice) using shifting cultivation methods, which led to rapid exhaustion of the soil. Farmers responded to falling productivity by diversifying their production systems through intercropping of cacao or coffee with other perennial crops, including fruits (*açai,* mango, pineapple, tangerines and other fruits) and timber trees (mahogany (*Swietenia macrophylla)*, (*Cedrela odorata*), pines (*Pinus caribawa, Schizolobium amazonicum*, and other local species) (Costa 2012a; Smith 1978; Smith *et al.* 1996).

The diversity and resilience of family-based agroforestry systems discussed here make them a key economic sector for the region's past, present and future, far beyond their importance in the statistics of production systems for the region (Franco *et al.* 2021). These statistics, however, are per se eloquent: rural agroforestry establishments in the Brazilian Amazon numbered 125,160 in 1995, and increased to 186,341 in 2017, spread over a wide area of the region (see Figure 15.1). Their contributions to the agrarian economy have grown significantly, on average, from 1995 to 2017, at 4.2% annually, increasing from USD 400 million to USD 1.1 billion (Figure 15.2). The number of people employed in 2017, in turn, remained at around 403,978 people, 92% of them family workers (Table Annex 15.2b).

A number of federal agricultural policies and programs were created in the 1990s specifically to support smallholder farmers, forest extractivists, and fishers, under the purview of the Ministry of Agrarian Development (MDA) which was established to oversee land reform in Brazil and promote sustainable practices (Niederle *et al.* 2019). The National Program for Strengthening Family Agriculture (PRONAF) provides subsidized rural credit, linked to state Rural Technical Assistance and Rural Extension agencies. The Insurance for Family Farmers (SEAF) program provided insurance to farmers who adopted certain technologies that conserved natural resources on the farm and reduced their vulnerability to climatic fluctuations. In 2010, the National Policy of Technical Advisory and Extension Services for Family Agriculture and Agrarian Reform (PNATER) was established, along with the National Program of Technical Advisory and Extension Services (PRONATER) (Valentin and Garrett 2015). However, in 2019 the MDA was demoted to the status of a Secretariat of Family Agriculture and Cooperativism, under the agribusiness-oriented Ministry of Agriculture, and in the following years many policies and programs were weakened or eliminated as resources and staff to support them were drastically reduced (Niederle *et al.* 2019).

15.2.2 Family-based annual crop systems in the Amazon

A technical focus on commercial crop specialization by credit, extension and research agencies in the Brazilian Amazon induced many family farmers to concentrate on the production of an ever-smaller number of products, especially commercial products. In fact, by 1995, nine products made up 90% of the production value of these Brazilian small farmers: cassava was the main product and 93% of family-based production focused on 5 products (cassava, soybeans, corn, sugar cane and pineapple) (see Figure 15.5a, Annex), crops that had to

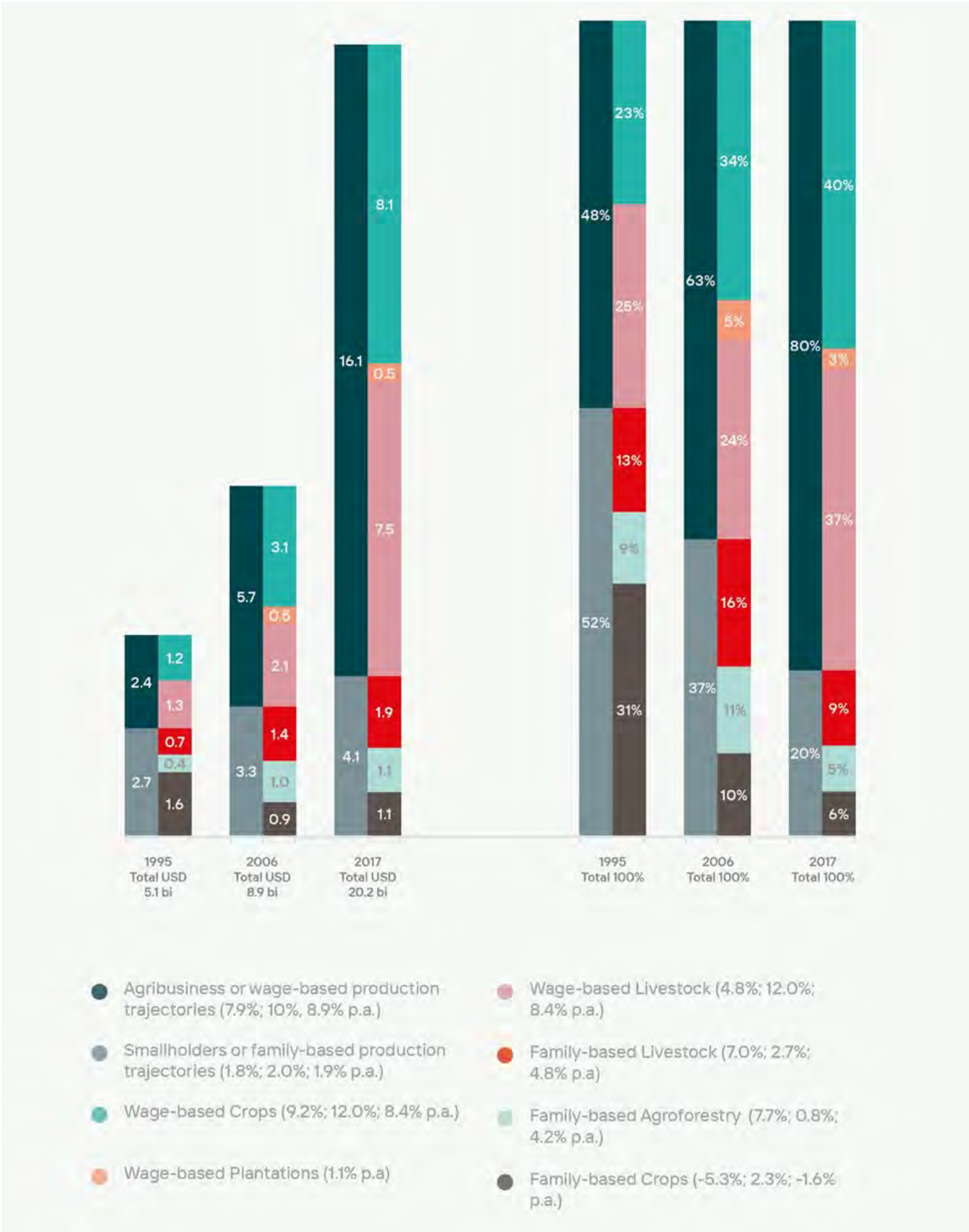

Figure 15.2 Gross Value of Production (GVP) of the rural sector by agribusiness (wage-based) and smallholder (family-based) productive trajectories within the Brazilian Amazon Biome in 1995, 2006 and 2017. The three left columns provide the absolute values in USD billion at 2019 prices, while the three right columns indicate the contribution of each PTs in % of total. In the legend, the percentages refer to the annual growth, respectively, in the periods 1995 to 2006, 2006 to 2017 and 1995 to 2017. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Table Annex15.1. Current values in BRL were restated for 2019 by the IGP-FGV and divided by the exchange rate of 12.31.2019 to get USD values.

compete with larger producers. Other products, including the ones of home gardens, represent 7% of GVP. Cassava remains the dominant commercial product in many small farms, largely serving regional markets. The family-based crops productive trajectory in the Brazilian Amazon became substantially smaller from 1995 to 2017, in terms of number of establishments (dropping from 337 to 179 thousand), amount of owned (from 9.33 to 5.44 million ha) and land area in use (from 3.99 to 2.96 million ha), along with a drastic decline in workers (from 1,179,000 to 393,000) (Table Annex-15.2a, b).

The shifts in land ownership among the family-based productive trajectories from 1995 to 2017 are presented visually in the figure that follows, which presents a perfect balance of the intermediate flows between the various productive trajectories in the segment, plus the original entries and definitive exits, respectively, from or to other segments of the agrarian economy or sectors of the whole economy (wage-based trajectories, public land stock, urban or infrastructural sectors). The original entries are represented in the left-hand first column of the diagram, by two sources:

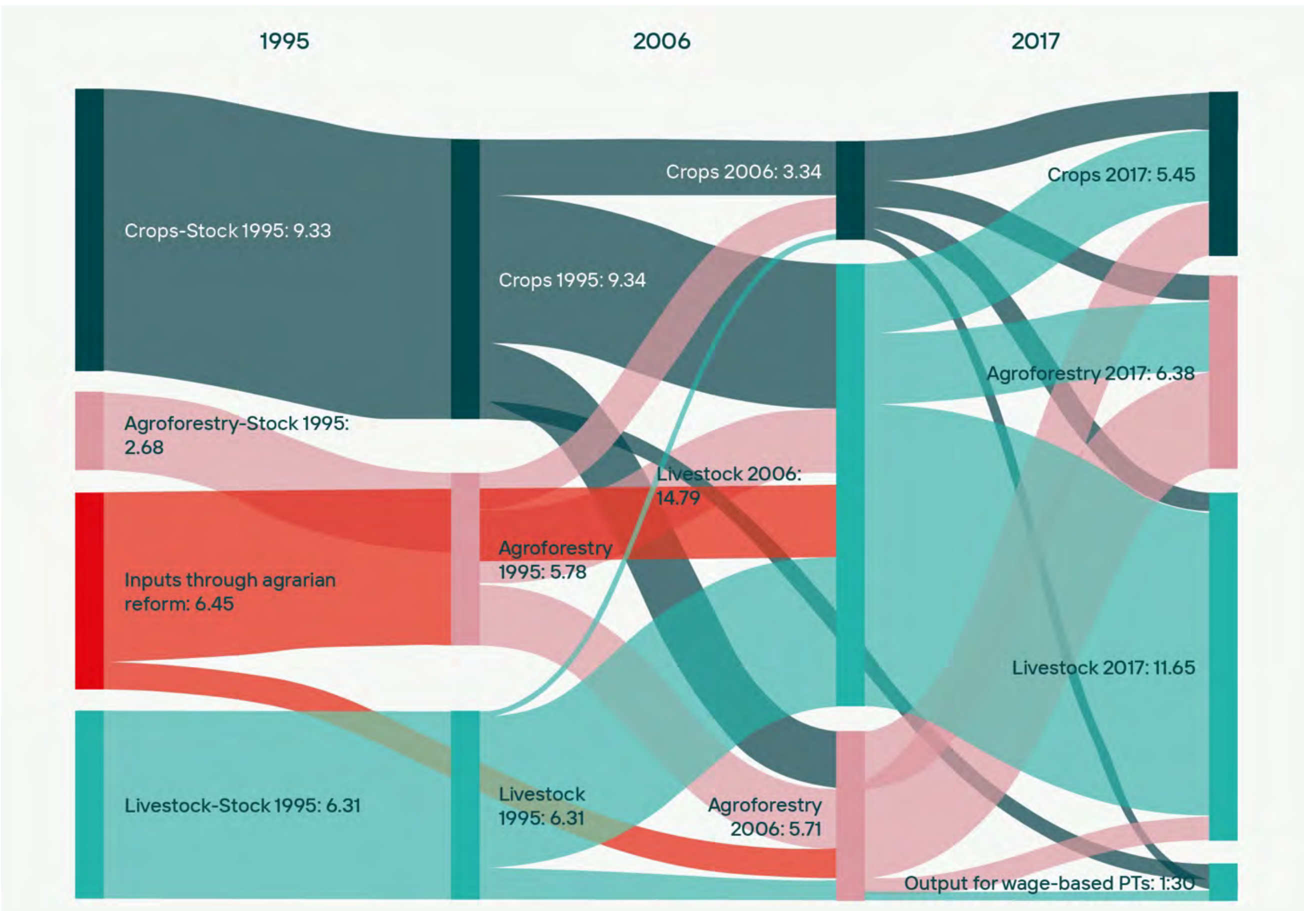

Figure 15.3 Shifts in land ownership in family-based productive trajectories, 1995-2017 (millions of hectares). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017. Table Annex-15.2a, b. The original entries are represented in the left hand first column of the diagram, by two sources: beginning "stocks" registered in the agrarian census of 1995 and the "inputs" that occurred between the censuses. The following vertical lines in the diagram represent specific "nodes" that show how the stocks increased or decreased for each production trajectory in the analyzed periods. It starts with node "1995," which result from the sum of "stock-1995" values with the "inputs" verified until the next census was carried out; continues with node "2006" which adds the stocks registered in the 2006 census with the entries verified until 2017; and so on. In this way, the diagram shows as well as how the relative share of each production type shifted as a result of these changes. Definitive outputs from the agrarian sector, if they occurred in only one period, are shown as a specific node at the end of that period. If they occurred in several periods, they are presented as a specific node in the end of last period.

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Most family-based establishments in this trajectory shifted their land resources into livestock (3.1 million ha) and agroforestry systems (0.2 million ha) throughout the 1995-2017 period (Figure 15.3). While some released workers went as well to the other family-based trajectories, about 585,000

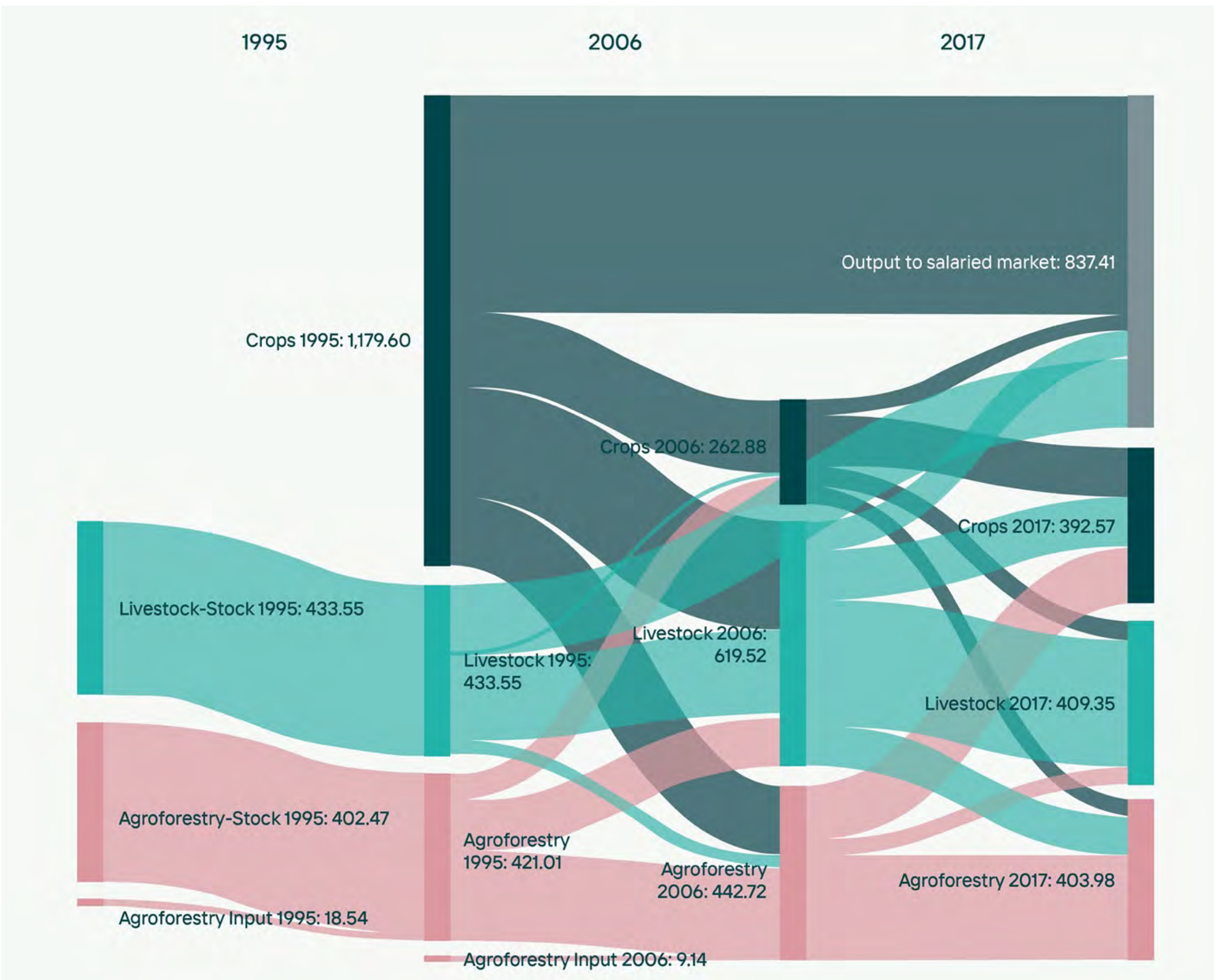

Figure 15.4 Shifts in employment among family-based production trajectories, 1995-2017 (thousand). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017. Table Annex-15.2a, b.

went to urban sectors or wage-based trajectories (542,000 between 1995 and 2006 and 44,000 in the following inter censuses interval): 70% of all released workforce from family-based trajectories to urban or rural salaried market in the period (Figures 15.4). At the end of this period in 2017, the GVP of family-based crops had shifted from 31% of total GVP in 1995 to one-fifth of its earlier value.

15.2.3 Family-based enterprises focused on livestock

Livestock ranching, introduced in the colonial period, was often dominated by ecclesiastic settlements in the 17th and 18th centuries, and has been a widespread activity in the Amazon ever since, although until the post-war period, the production was based largely on natural grasslands. Practiced in large estates since the 18th century in Marajó (Ximenes 1997), it was also present, by the 19th century, as part of productive systems of small producers in the lower and middle Amazon in Brazil (Folhes 2018; Harris 1998), where it persists today using floodplains and natural grasslands (Costa and Inhetvin 2013). Alongside the large cattle ranches that developed since the 1960s with the subsidies, land transfers, new pasture technologies, and credit policies implemented by the military governments and all subsequent governments, ranching also expanded throughout the Amazon with road construction from the 1960s onward (Hecht 1993; Costa 2000). Since the 1990s, when the *Fundo Constitucional do Norte* credit program was implemented in Brazil to support small livestock, beef and milk production, this land use has continued to expand with preferential credit lines at all scales of production, and is the dominant land use throughout the basin on natural and planted pastures; in Brazil, family-based agriculture has shifted over time to cattle systems due to their low labor demand and other advantages discussed below (Veiga and Tourrand 2000; Salisbury and Schmink 2007).

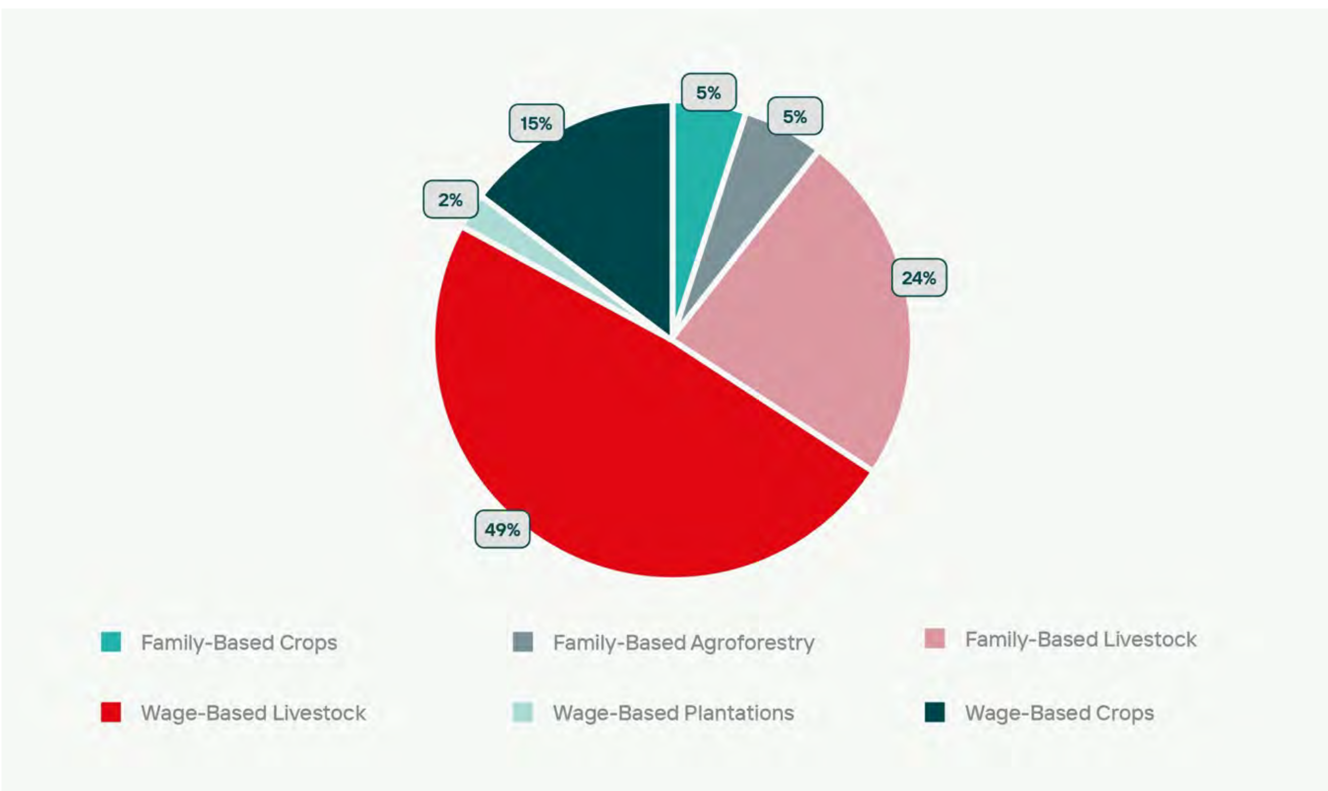

Figure 15.5 Distribution of cattle in the Amazon biome region in 2017 by PTs (% of total). Source: IBGE, Agricultural Census 2017.

As a result, Brazil stands out among Amazonian countries due to the strong dominance of livestock systems in the region. Surveys conducted by the Brazilian National Institute of Space Research (INPE) and the Brazilian Agricultural Research Corporation (EMBRAPA) in Brazil (INPE/EMBRAPA 2016) pointed to 37.7 million hectares of productive pastures (albeit at low stocking rates for the most part), out of a total of 48.4 million hectares of pastures. This is compatible with the agricultural census of 2017, which identified 45.4 million hectares of pasture in the Amazonian biome region. The cattle herd in the region has almost doubled from 28.3 million head in 2006 to 52 million in 2017 (IBGE 2017). Of this herd, 5% were held by family-based crops systems, 5% in family-based agroforestry systems, 2% in wage-based-plantations, and 15% in wage-based-crops agribusiness enterprises, while extensive commercial livestock ranching accounted for the largest proportion: 49%. Smallholder livestock raising, the subject of this section, was responsible for 24% of the cattle herd (Figure 15.5).

Family-based livestock establishments stand out as an expanding group of farmers (128,806 in 1995, 257,122 in 2006 and 198,804 in 2017), whose small farm production systems depend increasingly on livestock, mainly beef, whose share of total production value went from 32% in 2006 to 55% in 2017. Dairy cattle, in turn, increased from 16% to 20% in the same period (Figure 15.1a). Altogether, the products of cattle raising (beef and dairy) grew from 48% to 77% of the value of this small farm production trajectory during the same period, making it fundamentally a livestock sector, reflecting labor characteristics and credit availability.

With the significant shift that family-based crops underwent from agriculture into livestock, total land in family-based livestock nearly doubled from 6.3 million in 1995 to 11.6 million hectares in 2017 (Figure 15.3; Table Annex-15.2a, b). Among smallholders, it was the PT that grew fastest, 4.8% annually from 1995 to 2017. The production value basically tripled over these decades, from USD 0.67 billion to USD 1.86 billion, even though the stocking rate, about one animal unit/hectare, has remained static for decades. The labor deployment involved reduced slightly, from 433,550 in 1995 to 409,348 in 2017, 92% of which were family laborers as opposed to salaried workers. The territorial expansion and persistence of smallholder cattle ranching must be understood in the context of growing demand for beef, a decline in peasant agriculture, relative stagnation in the number of people engaged in agroforestry and fisheries, and an increase in both land area and employment in wage-based activities, both rural and urban. Ranching may continue to increase among the remaining smallholders who are unable to sustain themselves in competitive agricultural commodity chains.

Family-based livestock enterprises are much more diversified production systems compared to wage-based livestock, and more oriented towards self-consumption and local and national economies. The systems differ significantly in terms of the average size of properties, pasture~~s~~ and herd size, respectively, 58.6 ha, 40.3 ha and 61.7 heads, in family-based and 655.5 ha, 318.9 ha and 338.3 heads in wage-based-livestock - resulting in a density of 1.53 and 1.06 heads per hectare, respectively. In wage-based livestock, close to 3,000 of the 75,000 establishments have herds over 1,000 head.

Cattle ranching remains an appealing land use in more remote regions of the Amazon, where land is abundant and cheap relative to labor and capital, and where overland transport and marketing of crops are economically unviable. Even at low stocking rates and within more established agricultural regions, ranching is also extremely persistent. It is perceived as having lifestyle and social advantages over cropping, and much lower expenditures, which is beneficial to debt- and risk averse peasants who can use livestock as a highly mobile "savings account" to be sold for reliable prices when needed (Garrett *et al.* 2017; Valentin and Garrett 2015; Hecht 1993). It also has low labor demands, and stable prices, making it useful in the portfolio strategy of households, and a part of the more general allure of this sector for large holders as well. Demand for beef is strong in Brazil, unlike

Peru where beef is not as widely consumed, and where poultry consumption is growing exponentially (Heilpern *et al*. 2021; Kovalskys *et al*. 2019).

15.2.4 Wage-based livestock enterprises

Wage-based-livestock trajectory has grown rapidly: the number of establishments more than doubled in the Brazilian Amazon from 1995-2017, while their GVP increased more than five-fold (see Figure 15.2; Table Annex 15.2a, b). Indeed, there is evidence in the censuses that the intensity of land use (monetary productivity of used land equivalent to total GVP, divided by total used land area) in wage-based livestock has grown almost four-fold: from USD 67.2/ha in 1995, to USD 244.4/ha in 2017 (Figure 15.2a, Annex). However, cattle ranches remain among the lowest of all production systems in land use intensity, since their profitability depends on extensive land use and grows with the scale of that use (Costa 2016). Land use intensity grows with the potential to capture various institutional rents, and to realize land speculation and money laundering.

The history of large-scale cattle ranching presents opportunities for speculation during intense periods of land grabbing, discussed in more detail in Box 15.2 and in Chapter 14. In 1995, wage-based-livestock controlled a land stock of 45.5 million hectares, a legacy of a particularly intense period of land grabbing (Fernandes 1999). Between 1995 and 2006, 16 million hectares of this stock shifted productive trajectories: 4.8 million to wage-based plantations, 2.4 million to wage-based crops, and 8.8 million to family-based enterprises, through agrarian reform programs (Figure 15.6; Table Annex-15.1a; Costa and Fernandes 2016; INCRA 2016). Cattle enterprises bought or appropriated forested land at a relatively low market price, and, after "producing" land without forest (Costa 2012b), transferred it at the much higher price of land covered by pasture. Considering average land prices of the period 2001-2006 (Figure 15.3a, Annex), these operations may have yielded USD 400 million per year in profit, equivalent to about 20% of wage-based livestock trajectory's GVP, or 110% of its net income in 2006 (Figure 15.2, Annex; Table Annex 15.1).

Between 1995 and 2006, wage-based livestock establishments gained about 16 million ha of land that shifted away from wage-based crops, and between 2006 and 2017 land use shifted back, 12.5 million hectares to wage-based crops and 1.4 million hectares to wage-based-plantations (Table Annex-15.2a, b and Figure 15.6). This operation may have yielded, just by the inter-period price differences of pasture (Figure 15.3a, Annex), a total of USD 5.1 billion, or USD 463 million per year during this phase, equivalent to 6.2% of GVP or 87% of net income for the wage-based livestock productive trajectory in 2017 (Figure 15.2; Table Annex 15.1). In any case, land equity real value grew in the period 1995-2017 on average 7.6%/year if forested, and even faster, 7.8%/year if covered with pasture.

This indicates the centrality of wage-based livestock to the processes of expanding agricultural frontiers, forest clearing, land speculation, privatization of public lands, and displacement of alternative and more socio-ecologically sustainable livelihoods. Explaining part of the expansion dynamics, soil nutrient decline and pasture invasion by brush (the widespread "*juquira*") contributes to the pressure to clear and burn more native or secondary forest in order to use the ash from burning as a kind of fertilizer for crops, while the need for timber extraction as a form of financing also stimulates further clearing. Consequently, ranching establishments are heavily involved in timber extraction to finance pasture production (see Box 15.2).

Box 15.2 Land grabbing in the Amazon: clearing for claiming

In many places of the world land grabbing involves nation states selling off or allocating national areas to other nations or corporations for food or biofuel, plantation production or, as mining or timber concessions on lands already occupied by other claimants. These can be historical territories, as is the case with Indigenous peoples and local communities whose tenurial regimes may not be recognized by the state, or settler/peasant farmer lands that may be simply expropriated by fiat or violence.

Amazonian lands can involve such large-scale international transnational transfers for corporations for land development. The classic case here is Fordlandia, but other international land grants during the Brazil's authoritarian times included Daniel Ludwig's *Jari*, the Volkswagen ranch, the Caterpillar ranch (among many others who received fiscal incentives), as well as transfers to many large-scale national corporations. Rights over large-scale subsurface resources for hydrocarbons, minerals and concessional timber rights are common, and typically worked out through state concessions and complex sharing agreements. Because nation states typically assert subsurface rights, allocation and auction of such rights to international consortia (and sometimes with national partners) occurs widely, even if the lands and resources associated with such concessions are occupied by people whose livelihoods, lives, resources, cultures and histories can be dramatically undone by these actions (Finer *et al.* 2008; Perreault and Valdivia 2010; Valdivia 2015; Bebbington *et al.* 2018a; see also Chapter 18 on the Ecuador case study). The impacts on local populations can involve displacement, destruction of critical resources or subsistence resources like fish and tree crops, resource theft, contamination, introduction of disease, as well as cultural assaults including violence, local enslavement and attacks on women, leaders and forest guardians. Well documented cases include the Yanomami and informal gold mining, formal mining on *quilombos* on the upper Trombetas river, and pipelines on *quilombo* land near the Barcarena port in Pará State, Brazil. Indigenous land was opened for oil extraction in Ecuador, Bolivia Peru and Colombia (Oil & Gas Journal 1999; Finer *et al.* 2009; Widener 2009; Hindery 2013; Bebbington *et al.* 2018b).

Large-scale infrastructure such as dams also involves expulsion and appropriation of land and resources of current occupants, and the overflooding of catchment ponds can lead to "river murder". Displacement, flooding, alteration of access rights, loss of resources and destruction of cultural heritage and overriding of legal occupation rights are a repeating and common story (Hernández-Ruz *et al.* 2018; de Lima *et al.* 2020).

Land grabbing can also reflect overlapping tenurial regimes that are a function of land laws and property rights enacted at different historical times but that still are more or less legal, like land tenure granted in the Brazilian State of Acre and by Bolivia over the same territories before the adjudication of national territories occurred. Sometimes simple occupation rights have been validated for a period, and then new regimes change the legality of the holding, as when collection concessions were transformed into legal property (Emmi 1988). Sometimes different land agencies with different jurisdictional remits (federal and state for example) have validated claims to the same holding with competing owners. Sometimes historical rights have been validated – as in Indigenous territories and *quilombo* lands or local communities – or new categories of land categories have come into play, such as various kinds of protected areas. Because land is important as an asset, a means of production, a way to launder money from illicit or clandestine activities (Dávalos *et al.* 2014), as mechanisms for capturing institutional rents such as credit and other production subsidies, and as a vehicle for speculation with relatively low entry costs (Merry and Soares 2017), shifting forest to cleared land has been among the best ways of "conjuring property"

(Campbell 2015). Land rights have also been secured through title fraud, violence, and more recently in the current Brazilian federal regime, with amnesty. In this complexity of tenurial regimes, or the case of undesignated federal lands (*terras devolutas* as they are known in Brazil) competing surface land rights are resolved through clearing for claiming, the ancient dictum in Roman law*, uti possedetis*: he who has, keeps. Into this maelstrom of tenurial regimes, cattle ranching and the infrastructure that attends it has had a special role.

Cattle have multiple logics in Amazonian contexts: they do not need much labor, they are both an asset and a means of production of other assets (more cattle), they can be flexibly harvested, can be subsistence or market, local or regional goods, as well as a global commodity. The development of pasture itself is relatively simple and cheap: it involves cutting forest, letting it dry, and setting it on fire. Subsequent seeding with exotic pasture grasses follows, and what had been a highly diverse forest of hundreds of species is reduced to a few in order to create a habitat for one species: bovines that roam at low densities over increasingly depauperate landscapes. The creation of pasture from forest largely nullifies any alternative, forest-based or most agricultural land uses that don't employ herbicides, which is why gatherers of forest products and forest people more generally, and small scale farmers, have resisted the expansion of livestock, and why ranching has become such a central feature of land encroachment on protected and Indigenous areas, areas of road expansion and new colonization, and why this land use so often contested (Simmons *et al.* 2007; Grajales 2011; Ballve 2013; Botia 2017; Schmink *et al.* 2019).

The usefulness of cattle as a product, however, mediates a far more valuable asset which is via "clearing for claiming" –the showing of effective land use- which is an element required for the defense of land claims, and the transformation of seemingly "amorphous" lands into private property. In this context, title, however dubious, helps in real estate transfer and has given rise to a gamut of fraudulent practices, including most recently, the ability to buy georeferenced Amazonian but illegally claimed and cleared land on Facebook (Fellet and Pamment 2021).

The increase in land prices "heats up" the land market and everything it mobilizes, including the mark-up of "producing" land and expanding the land grab effort. The great growth in the volume of appropriated lands in recent years in other countries than just Brazil, corresponding to a rate of 1,2 million hectares a year, may indicate a harbinger of a new cycle of land grabbing which precedes a corresponding cycle of "producing land"--that is, turning it into a commodity (Araújo *et al.* 2009; Rajão *et al.* 2020; Campbell 2015). The expanding infrastructure programs for all of the Amazon with its vast new regional road networks and the strong association of roads and land clearing (Pfaff *et al.* 2007; Perz *et al.* 2013; Pfaff *et al.* 2018; see also Chapters 14 and 17) and with speculation suggest accelerated clearing, especially under current lax regulatory conditions, which mimic those of earlier times (Hecht 1985, 1993; Barona *et al.* 2010; Bowman *et al.* 2012; Dávalos *et al.* 2014). The speculative aspect is especially relevant in the context of land tenure uncertainty, expanded infrastructure development, and advancing crop frontiers (Bowman *et al.* 2012; Richards *et al.* 2014; Campbell 2015). Ranching can be financially appealing in the context of land speculation, as a way to cheaply secure large areas of land until land prices rise, and as a means of capturing an array of institutional rents (Hecht 1993; Miranda *et al.* 2019; Meyfroidt *et al.* 2020; Mann *et al.* 2014; Escolhas Institute 2020). By institutional rents we refer to value that comes from government infrastructure and services, including various fiscal incentives (credit lines, trade policy) research, and favorable policies.

15.2.5 Wage-based cropping production

The wage-base productive trajectory – dominated in the Brazilian Amazon by the soy-corn agro-industrial annual cropping system – responds to both comestible and industrial product demand in national economies, but remains largely export-oriented. In Brazil, its expansion would not have been possible without decades of state-sponsored research led by plant geneticists and agronomists from EMBRAPA, which led to the development of so-called "miracle" soy cultivars able to tolerate the acidic soils, uniform day length and aluminum levels in the soils (Hecht and Mann 2008; Oliveira 2013). EMBRAPA's research on biological nitrogen fixation by plants allowed the elimination of nitrogenized fertilizers in soy cultivation, reducing the costs of production, to permit Brazilian soy to compete on the international market (Dobereiner 1990).

The government promoted the expansion and modernization of Brazilian agriculture through, besides the already-mentioned supportive research, monetary and agricultural policies, providing credit to farmers at below market interest rates, and financing the building of roads and waterways, logistical centers, ports, storage infrastructure, and equipment (Garrett and Rausch 2015). In the Amazon, the private sector, especially seed companies, plays a critical role in providing credit, especially in the context of informal or contested land tenure claims (Garrett *et al.* 2013a) but more

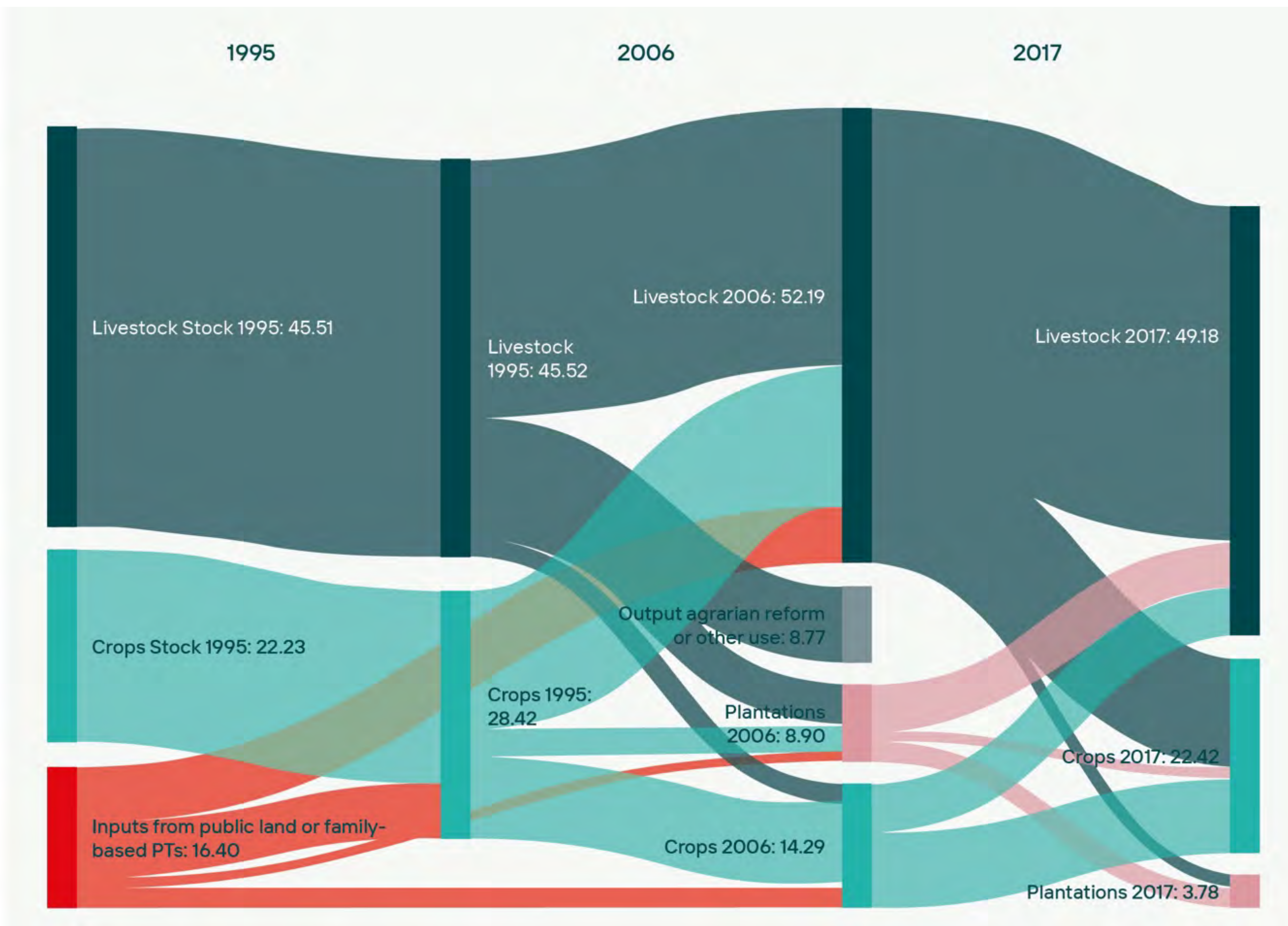

Figure 15.6 Shifts in land ownership in wage-based PTs, 1995-2017 (millions of hectares). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017, Table Annex-15.2a, b.

recently in the context of the shift from public credits to private financing as discussed in Chapter 14.

In the Brazilian Amazon, in 1995 soybeans already represented 43% of wage-based-crops' production value. Along with soy, its rotational crop, corn, grew in value, from 4.4% in 1995, to 13.6% in 2017 (Figure 15.6a, Annex). Strongly determined by this composition, the growth of wage-based crops reached 9.2% annually over the entire period, raising its GVP from USD 1.2 billion in 1995 to USD 8.1 billion in 2017 (Figure 15.2).

With the rapid growth of wage-based crops, the demand for deforested land reached 13.1 million hectares in 2017. To cover this need, 7.2 million hectares of deforested land from wage-based livestock, and 0.7 million from wage-based plantations shifted to wage-based crops in addition to 5.2 million hectares already in operation (Figure 15.7).

At the end of the period, the total land stock of wage-based crops was practically the same as at the beginning: 22.4 million hectares (Figure 15.6). However, there was a fundamental change: despite the Soy Moratorium (Box 15.3; see also Chapters 17 and 19), the proportion of the area deforested in relation to the total area of wage-based crops, grew from 43% in 1995, to and 58% in 2017 - practically the same proportions as wage-based livestock (Figure 15.4a, Annex).

Large-scale cropping systems, particularly soy and oilseed production that competes globally, require high levels of capital inputs and mechanization to achieve economies of scale, as well as the best available seed technologies and chemical inputs. Soy remains the most lucrative of the commercial annuals due to large and increasing demand globally, and substantial government subsidies, particularly in Brazil (Oliveira 2016). Double-cropping corn with soy production is increasing, due to demand for animal feed in Asia, Europe and the Middle East. Meat demand is growing in Andean regions, which import from the Amazon through the new Transoceanic highway in the western Amazon. In the Brazilian Amazon, new state aquaculture initiatives are also bolstering clusters of cropping production—largely soy for fish feed.

The evolution of soy in the Brazilian Amazon has led to a complex land possession process. At first, the entry of soy and its high level of mechanization reduced, in absolute terms, the need for land from soy cultivation. Thus, deforested lands between 1995-2006 registered large shifts of 8.8 million ha from wage-based crops to wage-based livestock, and 1.6 million to large plantations, leaving a stock of 5.2 million ha. At the same time, however, the technical and logistical requirements of soy led to a demand for land with special characteristics - areas that are flat (slope less than 12%), with well-drained soils – in specific locations, near major highways and relevant supply chain infrastructure and supporting services (Garrett *et al.* 2013b). Hence, wage-based crop enterprises also registered subsequently significant acquisitions of 7.8 million hectares of used land between 2006-2017. These either came from smallholders, associated with land conflicts and local resistance, typified by the highly publicized soy producing regions of Santarém (Steward 2007), or from previously formed stock of deforested areas by wage-based livestock, or deforestation of new areas (Figure 15.7 and Table Annex 15.2a, b). Although soy occupies a smaller proportion of the agricultural area in the Brazilian Amazon compared to cattle, it has been very important for regional development trajectories and has complex interactions with land clearing and cattle via speculation, intensification, and displacement of livestock into more “frontier zones.”

Nevertheless, soy and other annuals generate substantially more total taxable revenue than any other activity except for ranching, and participate in an expanding global market in animal feed. Moreover, when farm owners actually live in the same county where their farm is located, they spend money locally on goods and services, which can promote developments in infrastructure that benefit all memb ers of the local community and local economic linkages (Garrett and Rausch 2015).

"Agrocities" emerge in these nascent soy regions as new businesses are established to sell non-agricultural goods and services to farm and agribusiness employees, leading to new employment opportunities both related to and outside of the agricultural sector. Because of these dynamics, soy production tends to be associated with higher incomes, educational attainment, and health access, versus other wage-based land uses and even versus non-agricultural municipalities (Garrett and Rausch 2015; VanWey *et al.* 2013). This is due in part to the employment characteristics and the migration streams of relatively skilled labor into cities like Lucas do Rio Verde (Mato Grosso state, Brazil).

However, soy production is also a highly exclusionary process and tends to exacerbate inequality (Garrett *et al.* 2013b; McKay and Colque 2016; Oliveira 2016; Oliveira and Hecht 2016; VanWey *et al.* 2013; Weinhold *et al.* 2013). This means that much of the concentration of benefits within "agrocities" ac-crues to landowning elites and skilled workers in the agribusiness sector at the expense of migrant labor from other regions, as well as relative dis-investment in alternative economies (including far more sustainable and lucrative agroecological production of fruits, vegetables, and other higher-value added products), and aggravation of socio-ecological conflicts due to rising inequality and the dynamics of land appropriation. The best-paid jobs and better quality of life often flow to migrants to the Amazon from other regions, while locals are often excluded from these benefits but bear the brunt of the negative impacts, for example, of environmental contamination due to increased agrochemical use (Oliveira 2012). In Bolivia in particular, due to historical land development programs and a lack of legal protections for small landholders, much land was given away to foreign investors, mainly Brazilian companies (Hecht 2005; McKay and Colque 2016). There also is a highly active Mennonite presence in agro-industrial production in Bolivia (Hecht 2005), and they are currently very active in land transformation in Peru and Bolivia. Most soy production in Brazil and Bolivia is exported without processing, limiting the potential value-added gains and benefits to local communities (McKay 2017).

Historically cattle ranching and commodity crop production have been driven by different sets of actors, industries, and even development paradigms. However, as more farmers are looking for ways to add value to their land in light of declining expansion opportunities (Cortner *et al.* 2019), the degree of integration and fluidity between different land-use types are constricted ultimately by land-use lock-ins (path dependencies), entry costs, forms of capital scarcity, and cultural dimensions. As described in Chapter 14, past practices provide a great deal of rigidity to future transformations, by requiring "big push" policies and large upfront investments to solve collective action problems (Cammelli *et al.* 2020).

Another major rigidity stems from the cultural norms that have co-evolved with agricultural systems in the Amazon. Ranchers and croppers tend to have different backgrounds, and ranchers may look down upon cropping as an activity (Cortner *et al.* 2019). Ranching is linked to historical Iberian colonization processes and cattle cultures (Baretta and Markoff 1978; Hoelle 2015), while soy and other row crop farmers, who typically migrated more recently to the region via private colonization programs, come from German and Italian communities in the South of Brazil, and are linked to modernization and new technologies (Jepson 2006). These historical trajectories influence land users' abilities to engage in different systems, with the soy farmers generally benefiting from higher capital access from their family networks, government subsidies, private sector financing, and both financial and technological training and assistance from the United States and Japan (Garrett *et al.* 2013b; Nehring 2016; Oliveira 2016).

15.2.6 Wage-based plantations: Rubber, oil palm and other global commodities

What distinguishes wage-base-plantations is the importance of permanent tree crops in large areas

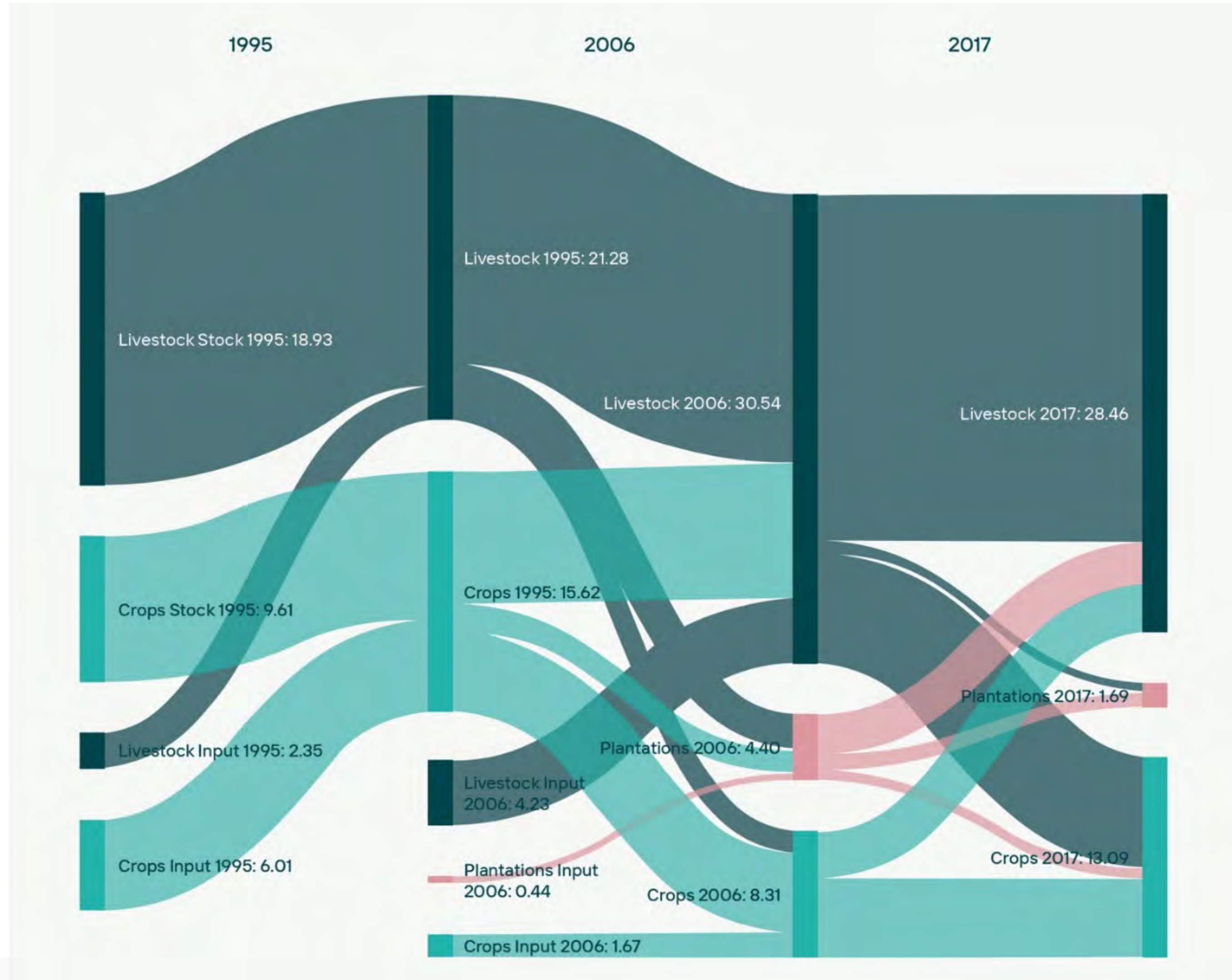

Figure 15.7 Shifts in land use in wage-based PTs, 1995-2017 (millions of hectares). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017. Table Annex-15.2a, b.

of homogeneous planting. The first such business experience in the Amazon was Henry Ford's ill-fated project for a rubber plantation in Fordlândia and Belterra, from the 1920s to the 1940s (Costa 1993; Grandin 2009). Other experiences followed with the promotion of rubber plantations by companies such as Pirelli, and public policies, such as the Brazilian Federal Government's National Program for the Development of Rubber (PROBOR) in the 1970s, with equally disappointing results (Costa 2000). In all cases, the homogeneous tree plantations in the Amazon had little resilience in the face of attacks by pathogens abundant in the hot and humid ecosystems of the region (Dean 1987).

In Brazil, the number of monocrop tree plantations and their economic contributions have declined in recent years. Currently, the most common Amazonian plantations are for oil palm and coconut. In 2017, according to the agricultural census, monocrop plantations produced 94% of the 659,800 tons of palm oil and 92% of the 124 million bay-coconut fruits. The Brazilian government actively promoted the expansion of oil palm in the eastern Amazon (Pará state). Commonly called *dendê* in Brazil,

Box 15.3. Soy Moratorium

The small number of traders who handle South American soy have made commitments to limit deforestation in the Amazon –which was called the Soy Moratorium. This agreement, which is basically non-binding, was triggered by threats by the European Union (EU) to boycott Brazilian soy, and like other global commodities ---think organic, or fair-trade goods and certifications--- involved the use of the supply chains as levers on the sources of commodities. Brazil's Soy Moratorium was the first voluntary zero-deforestation agreement implemented in the tropics, and set the stage for supply-chain governance of other commodities, such as beef and palm oil. In response to pressure from international retailers and mostly conservation NGOs, major soybean traders signed the agreement to not purchase soy grown on Amazon lands deforested after July 2006. The soy industry extended the Soy Moratorium to May 2016, by which time they expected that Brazil's environmental governance and land use monitoring would obviate the need for such an agreement. Deforestation in the Arc of Deforestation, and in the Brazilian Amazon more generally, declined by close to 80% between 2005-2012, and reflected intensification to some degree, but this decline in deforestation did not slow forest loss, but rather deflected clearing (de Waroux *et al.* 2016; de Waroux *et al.* 2019; Nolte *et al.* 2017; Hecht 2005; see also Chapters 14 and 17). This process is called leakage. In this case, deforestation exploded in the Argentine Chaco, Bolivia's Chiquitania, the Brazilian central Cerrado and the eastern Cerrado and Caatinga areas that form part of the new soy frontier known as Matopiba, an acronym composed of the first syllables of the states of Maranhão, Tocantins, Piaui, and Bahia. The dynamics of this leakage are complex, reflecting the impacts of more lax regulation (these other areas have far less monitoring), cheaper land prices, credit dynamics, promotional settlement land policies, among others, as well as displacement of livestock systems into new forest areas, speculation along roads, and pressure for paving and expanding existing road networks with their associated clearing (Meijer 2015; de Waroux *et al.* 2016; de Waroux *et al.* 2019; Nepstad *et al.* 2019; Meyfroidt *et al.* 2020).

The stickiness and concentration of market power in the hands of a few companies is subject to intense debate: some believe this opens up the opportunity to leverage private sector interventions for improved sustainability governance in the Amazon (Reis *et al.* 2020), while others maintain this consolidates unsustainable practices, enhances institutional capture, and forecloses more agroecological and socially just alternatives for rural development (Oliveira and Hecht 2016). As a partner to the Soy Moratorium, the idea of an Amazon beef moratorium also emerged. Brazil is now the world largest beef exporter, so the beef moratorium, crafted along the lines of the Soy Moratorium and relying on some super markets and the major slaughterhouses, dominated by meat packers JBS, Marfrig and Minerva, hoped to restrain ranching expansion and enhance intensification of beef production. The division of labor between cow-calf breeding operations and fattening operations, however, meant that animals reared on deforested frontier land (cow-calf) could be "finished" on deforestation free ranches, thus using the production division as a loophole to evade full compliance. JBS has been mired in multiple corruption scandals (Nishijima *et al.* 2019). The low market share of slaughterhouses that have made stringent sustainability commitments (de Waroux *et al.* 2019) is minimal compared with mostly beef cattle slaughter likely going to domestic markets, which is more difficult to track (Hoelle 2017; SEI 2018). Recent research revealed that at least 17% of beef shipments to the European Union from the Amazon region and Cerrado, Brazil's savanna, may be linked to illegal forest destruction (Rajão *et al.* 2020). According to an investigation by Global Witness, JBS, Marfrig and Minerva bought cattle from a combined total of 379 ranches between 2017 and 2019 where illegal deforestation had taken place. The firms also failed to monitor 4,000 ranches in their supply chains that were connected to large areas of deforestation in Mato Grosso state. This illegal deforestation contravenes these beef giants' public no-deforestation pledges and agreements with federal prosecutors in Brazil (Global Witness 2020). Other reviews that focused on livestock vaccination records also revealed a great deal of non-compliance (Klingler *et al*. 2018).

The period of the Soy Moratorium did show a decline in deforestation, but the over-emphasis on the moratorium as a kind of silver bullet is problematic Ascribing the decline in clearing to only the Soy Moratorium ignores the multiplicity of other processes: these included demarcation of more than 50 million ha of protected areas, declaration of extractive and Indigenous reserves along major deforestation corridors to slow active clearing frontiers, community organizations that tried to block forms of land grabbing and speculation (Campbell 2015), global commodity price slowdowns, changes in exchange rates (Fearnside 2007; Richards *et al*. 2012), acceleration of monitoring and enforcement, leakage, evasion of detection by clearing smaller lots, credit black-outs in high deforestation areas, among a broad array of other institutional and civil society initiatives (Oliveira and Hecht 2016).

oil palm was first introduced to the eastern Amazonian lowlands in 1940, and experimental plantations were established with government finance in 1968 and 1975. But until 1980, oil palms only covered about 4,000 ha in the whole state of Pará, and most production was undertaken by small-scale farmers, either organized in cooperatives or independently, supplying regional food markets.

Gradually, however, those plantations were acquired by Agropalma, currently the largest palm oil producer in Brazil, and possibly in Latin America as a whole. Agropalma (or companies that were eventually incorporated into it) continued acquiring thousands of hectares of land, mostly degraded pastures, on which to expand plantations through the 1980s and 1990s. These decades were a period of intense deforestation and violent conflicts in the region, and while Agropalma was starting to consolidate its palm oil agribusiness, the sector was also coming under pressure from international non-governmental organizations (NGOs) who condemned the deforestation, agrochemical contamination, and the displacement of smallholders and food production associated with the sector. This was particularly the case in Southeast Asia, where oil palm production had expanded the most, but concerns were also reaching the burgeoning sector in Brazil (Nahum 2011; Monteiro 2013; Alonso-Fradejas *et al*. 2016). Thus, in 2002, Agropalma reformulated a smallholder contract system mimicking those of Malaysia, through which it could promote the social and environmental benefits of oil palm production in eastern Pará, arguing it would not only diversify the local small-scale commercial farming economy, but also curtail deforestation by creating a "sustainable" economic activity on "marginal" land, primarily degraded pastures (Monteiro 2013). These arguments were adopted by the incoming Workers' Party administration in Brazil, which included palm oil production by small-scale farmers as a pillar of its National Biodiesel Production and Use Program (PNPB) in 2004. Agropalma built the first biodiesel refinery to operate with palm oil in Brazil in 2005, and a wave of investments was unleashed by Brazilian private and state-owned companies, as well as foreign agribusinesses (Monteiro 2013; Potter 2015).

Since the early years of the national biodiesel program, however, it was becoming clear that palm oil agribusinesses were unable to profitably scale-up production to operate their refineries with supplies contracted from small-scale family farmers. The new corporate investors (from the United States, Canada, Portugal, Japan, China, and Brazil itself) began establishing their own large-scale monocultures and/or acquiring oil palm plantations from smallholders who established them, but were unable to sustain operations when labor-intensive harvests began (usually two to three years after palms are planted) (Oliveira 2017). Thus, government support and encouragement for small-scale farmers to switch to oil palm were basically serving as a mechanism of indirect dispossession and land concentration among the new agribusinesses that were establishing themselves in the region (Nahum 2011; Bernardes and Aracri 2011; Monteiro 2013; Potter 2015). From the logic of agribusiness investors, self-managed large-scale plantations seemed the best instrument for palm oil production and processing in the region, despite the original intentions of the Brazilian government's biodiesel plan and the "socially inclusive and environmentally sustainable" discourse still promoted by the agribusiness corporations that were quickly gaining ground in the region. Yet there continues to be partial adoption or maintenance of some contract farming with small-scale farmers, particularly by Agropalma, ADM, and the companies in which the Brazilian state itself participated, such as Petrobras and Biovale, in order to secure subsidies from the PNPB program's support for small-scale farmers.

Similar dynamics were also present in the Ecuadoran and Peruvian Amazon, where neoliberal policies enabled company-community partnerships that captured social benefits for oil palm processors, while small-scale farmers were adversely integrated and driven to deforest additional land to remain in business. Furumo and Aide (2017) calculated land-use change for oil palm across Latin America from 2000 to 2014. They found that the Amazon region had the highest rate of forest conversion for oil palm plantations in the Americas (alongside Guatemala).

On a national scale, Peru experienced the highest rate of woody vegetation loss from oil palm expansion (76%), amounting to 15,685 ha. This was particularly striking in the vast Loreto region of the Peruvian Amazon, where 86% (11,884 ha) of local oil palm expansion occurred at the expense of forest. In the Sucumbíos and Orellana departments of the Ecuadorian Amazon, there were 15,475 ha of oil palm plantations in 2014; 3,665 ha were associated with land conversion, including 1,582 ha of woody vegetation loss in these departments (43%). The Brazilian Amazon state of Pará featured the largest area of country-scale forest loss associated with oil palm expansion in the study: 70,923 ha of oil palm expansion were detected, of which 40% (28,405 ha) replaced woody vegetation (Furumo and Aide 2017, p. 6).

Wage-based plantations' production, however, covers a wider range of permanent crops. In the order of importance of the GVP among the permanent crops, in addition to oil palm and *coco-da-baia*, with 37.4% and 11%, respectively, there are cocoa, with 20.7%, *açaí*, with 12.6%, and oranges with 4%, to name the most important (Figure 15.7a, Annex).

Homogenous *açaí* plantations started to expand in the Amazon (and elsewhere in Brazil) during the past decade, motivated by EMBRAPA's development of varieties adapted to upland soils. IBGE started accounting for homogenously planted *açaí* in 2015. According to its agricultural annual estimates (PAM), from 2015 to 2019, the area planted with *açaí* in the Northern region (mostly Pará) expanded from 136,312 ha to 194,405 ha (IBGE 2019, table 1613). The agricultural census of 2017 confirmed 129,210 ha of *açaí* plantations, of which only 12% were wage-based plantations; the most important *açaí* planters were family-based-agroforestry, with 64% of the total. Large-scale homogeneous *açaí* plantations are predominantly irrigated, but homogeneous *açaí* plantations are not necessarily more intensive than well-managed small-scale *açaí* agroforestry systems, particularly in riverine areas. The best-managed *açaí* agroforestry areas can have equivalent productivity, and comparable density of clumps/stems/ha to more recent *açaí* plantations and its value on a per hectare basis is often greater than soy (Brondizio 2008).

Between 2006 and 2017, the number of establishments in wage-based plantations decreased from 20,000 to 16,000 in the Brazilian Amazon, while growing modestly, at 1.1% annually, from a GVP of BRL 1.8 to BRL 2.1 billion. With such a performance, the PT reduced its participation in the region's rural economy from 5% to only 3%. The

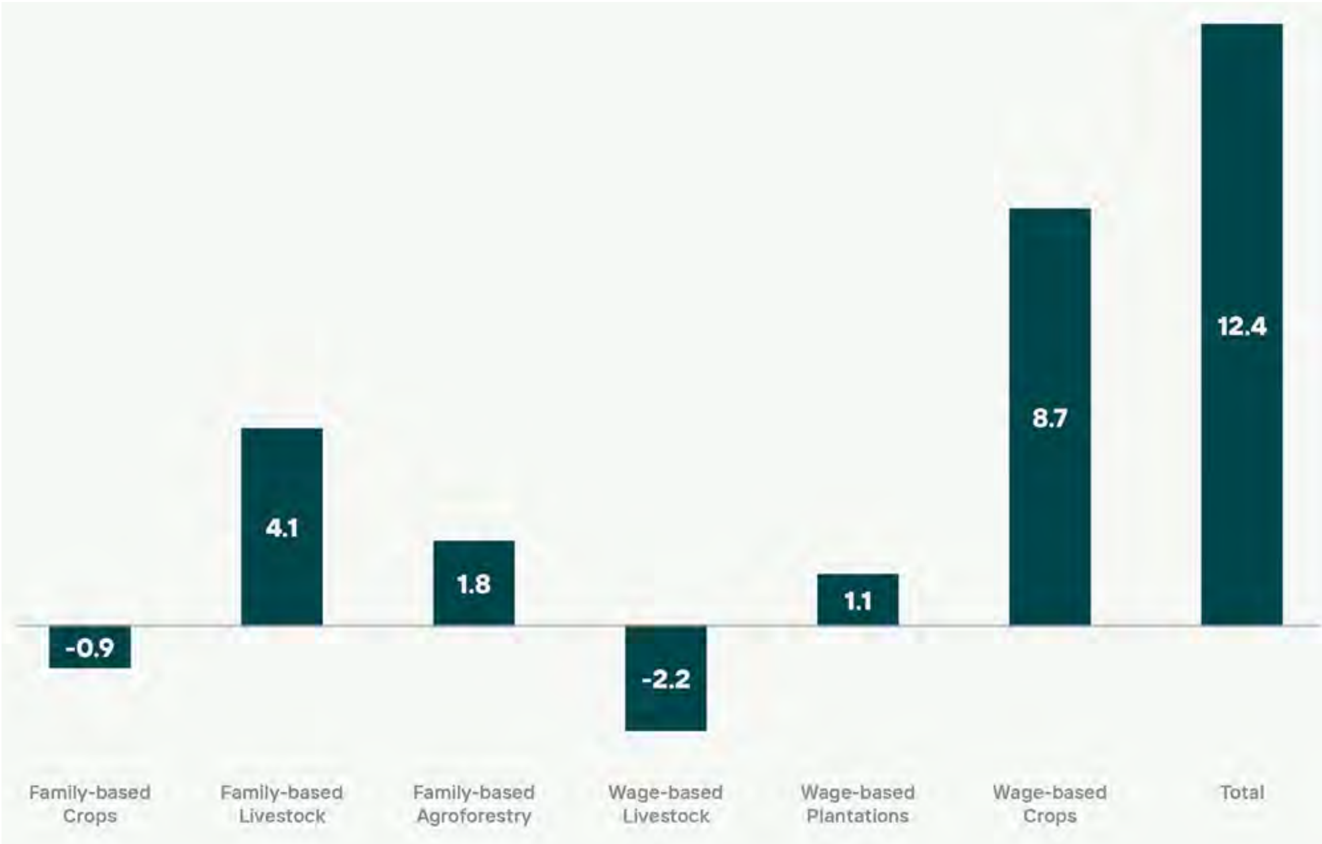

Figure 15.8 Shifts in private land tenure (million ha) in the agrarian sector of the Brazilian Amazon by production trajectories, 1995-2017. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Table Annex 15.2b, last segment.

number of workers remained constant at around 70,000, and there was a decline in land area from 7.8 to 3.8 million hectares and in lands used, from 4 to 1.7 million hectares (Figure 15.2 and Table Annex-15.2a, b).

Evidently, the expansion of commercial plantations has not taken place as fast or as widely as soy in Brazil, but they are quickly becoming a major form of land occupation in the Amazon. This is playing a role in driving direct deforestation, particularly in the lower Amazon (Pará state in Brazil) and more recently in the western Amazon (especially Peru, Ecuador and Colombia). Deforestation for oil palm expansion is one of the potential threats to forests in the "Trans-Purus" region in the western part of Brazil's state of Amazonas, as evidenced by the attempt of Malaysian oil palm firms to purchase land in this area in 2008 (Fearnside *et al.* 2020), and the purchase by Malaysian groups in the Loreto region of Peru.

15.3. Analysis of Sectoral Dynamics and their Implications

The analysis above does not include all economic sectors and livelihood strategies in the Amazon. Industry and service sector economies, concentrated in a few major cities like Manaus and Belém, for example, contribute to a significant share of the region's gross domestic product (GDP), employment, and economic dynamism. Agribusiness pressures have led to the expansion of access infrastructure (e.g., dams, fluvial ports and waterways, paved roads, and plans for additional railroads; see Chapters 14, 19 and 20). The consolidation of petroleum and large-scale mineral extraction, particularly in the western Amazon (Ecuador, Peru, and north-western Brazil) are important phenomena that attract a significant amount of labor (albeit temporarily, as discussed in Chapter 14 regarding the construction of the Belo Monte dam), and link labor and livelihood strategies in the Amazon to global circuits of capital and commodities (Klinger 2018).

In some locations, as in Madre de Dios, Peru, and the Tapajós region in Brazil, small-scale (artisanal) mining (particularly for gold) plays a determinant role in local labor markets and livelihood strategies. However, it is often associated with boom-and-bust cycles of mineral exploration, and socio-ecological ills associated with the footloose economy of mining booms and busts (e.g., trafficking, violent crimes) (Bebbington *et al.* 2018a; Kolen *et al.* 2018), and can lead to invasion of National Parks and Indigenous lands (RAISG 2020). Moreover, the socio-economic and environmental impact of infrastructure and unsustainable extractivist activities, usually associated with gold mining and timber harvesting, goes beyond the number of people employed and the area occupied; these activities literally lay the foundation for further rounds of speculative land clearing, expansion of cattle ranching and illicit crops such as coca as a means of money laundering, and stimulate agricultural production in their wake, to supply workers in these activities. They also make distant markets more accessible through the roads built to access these new infrastructure construction sites and extractivist activities in the first place.

15.3.1 Large-scale appropriation of public resource

The dynamics described above involved large-scale private appropriation of public lands in the Brazilian Amazon, generally those covered with primary forest. Data from agricultural censuses shown in the diagrams above allow us to estimate that wage-based productive trajectories incorporated 15.1 million hectares of public land between 1995 and 2017, the difference between a 16.4 million total increase (node "Inputs from public land or family-based PTs" in Figure 15.6) minus 1.3 million corresponding to the portion of these inputs that came from family-based PTs that shifted to wage-based production systems (node "Output for wage-based PT" in Figure 15.3). The composition of the flows suggests that wage-based crops accounted for 38% of the public lands incorporated in the 1995-2006 period; in the 2006-2017 period, wage-based livestock accounted for 40%, wage-based crops for 15% and wage-based plantations for 6% of the public lands incorporated into production.

A full 8.8 million ha of these lands were transferred out of wage-based livestock structures (node "Output agrarian reform or other use" in Figure 15.6), a portion of them to family-based enterprises through agrarian reform programs (6.45 million ha, node "Inputs through agrarian reform" in Figure 15.3) and another portion destined for urban, or infrastructure uses, definitively leaving the agrarian sector (the remaining 2.3 million hectares). It follows that, in 2017, around 12.4 million hectares of the public land appropriated remained in the agrarian sector, a final result that summarizes the process of shifts in the landholdings of the different production structures (Figure 15.8): wage-based-crops grew the most, by 8.7 million ha, followed by family-based agroforestry, 4.1 million, family-based livestock, 1.8 million, and wage-based plantations, 1.1 million. In turn, lands in family-based crops were reduced by about 900,000 ha, and wage-based livestock, the great intermediary in the exchange processes, by 2.2 million ha (see Table Annex 15.2b, last segment).

15.3.2 Intensification and deforestation

Ultimately, the degree of integration and fluidity between different land-use types is constricted by land-use lock-ins, capital scarcity, and cultural dimensions. Consequently, the intensification of large commercial agriculture and ranching itself becomes a driver in the further expansion of these large-scale commercial production systems, dashing the common hope that intensification can "spare land" for conservation. This belief that intensification may reduce pressure for land clearing if strict conservation regulations are established and enforced (Nepstad *et al*. 2019), overlooks how Amazonian landholders are participants in a market economy and respond to opportunities for greater profits by expanding those activities rather than limiting them (Fearnside 2002; Muller-Hansen *et al*. 2019; Thaler 2017).

The soy-livestock integrated systems (wage-based crops) may have substantially higher profits and shorter payback periods, as compared to extensive pasture systems (wage-based livestock) (Gil *et al.* 2018), but most analytics do not include the returns to land speculation. However, intensification also increases political and economic incentives for further expansion of agricultural production and ranching if it enhances productivity and profits. This is known as the "Jevons paradox" - that agro-industrial innovation can exacerbate, rather than curtail, deforestation and other forms of socio-ecological degradation (Oliveira and Hecht 2016; McKay and Colque 2016; Thaler 2017). Moreover, deforestation alone is an extremely narrow metric to gauge environmental impacts and socio-ecological sustainability, and when the intensification of agricultural production occurs through increased mechanization and application of agrochemicals (pesticides, herbicides, and synthetic fertilizers), it also significantly exacerbates ecosystem degradation through pollution of soils and waters, loss of biodiversity, soil erosion, and other impacts (Oliveira 2012).

Privatized lands were subjected to different uses in Brazil, which mainly entailed removal or impoverishment of forest and water resources. The deforested area grew from 37.2 million hectares in 1995 to 57.8 million hectares in 2017. Between 1995 and 2006, 12.6 million hectares were added to production, 2.3 million in wage-based livestock (deforested in processes that predominantly produced pasture), and 6.0 million in wage-based cropping (in processes that, in the end, produced temporary

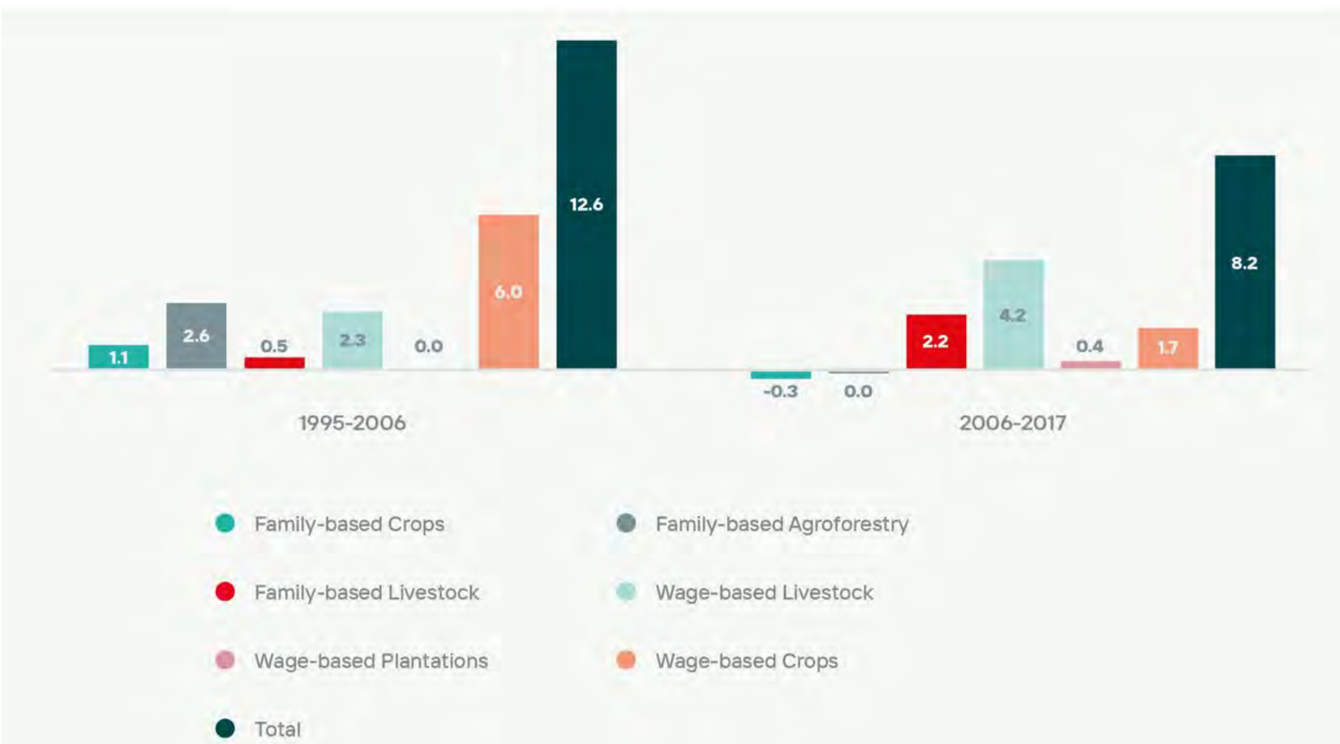

Figure 15.9 Changes in used/deforested lands in inter-census periods (in million ha). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017.

croplands). Together they represented two-thirds of the total (Figure 15.9).

Between 2006 and 2017, an additional 8.2 million hectares were converted to non-forest production, 72% of which by wage-based livestock and agriculture systems.[p] Throughout the period, a systemic cooperation was established between these two productive systems (as discussed above): the former functioned as a supplier of deforested land, the latter as its client. Among smallholder systems, only family-based-livestock deforested 2.2 million hectares. It is important to note that these figures measure only deforestation associated with land clearing, but not other forms of disturbance such as degradation, or pollution from agrochemical use (Matricardi *et al*. 2020).

15.3.3 Carbon emissions and sinks, and land degradation

Based on the census statistics from Brazil, average net CO_2 emissions (without considering emissions from equipment and tractors, fertilizer application, and subsequent soil management) were estimated to be 0.144 Gt per year between 1995 and 2006 and 0.109 Gt per year between 2006 and 2017 from forest clearing alone, which can cause an equally substantial or even larger amount of climate-change inducing emissions over time. The model applied (Costa 2016) linked the balance sheets of deforestation-linked emissions to the different production systems (PTs): between one period and the next, the contributions of emissions from wage-based livestock grew, respectively, from 60% to 65% while those from large commercial agriculture fell from 11% to 1%. The systemic cooperation between these two production systems explains these results, which should be read in aggregate (i.e., for a total of 66% in 2017), as land cleared proximately for cattle ranching typically is then turned over for soy production a few years later after pastures become degraded. The contribution to CO2 emissions by family-based-livestock also grew from 22% to. 33% in the same period.

In turn, family-based-agriculture turned into a CO_2 sink, wage-based plantations reduced their contribution from 5% to 2% of CO_2 total net emissions, and family-based-agroforestry continued to

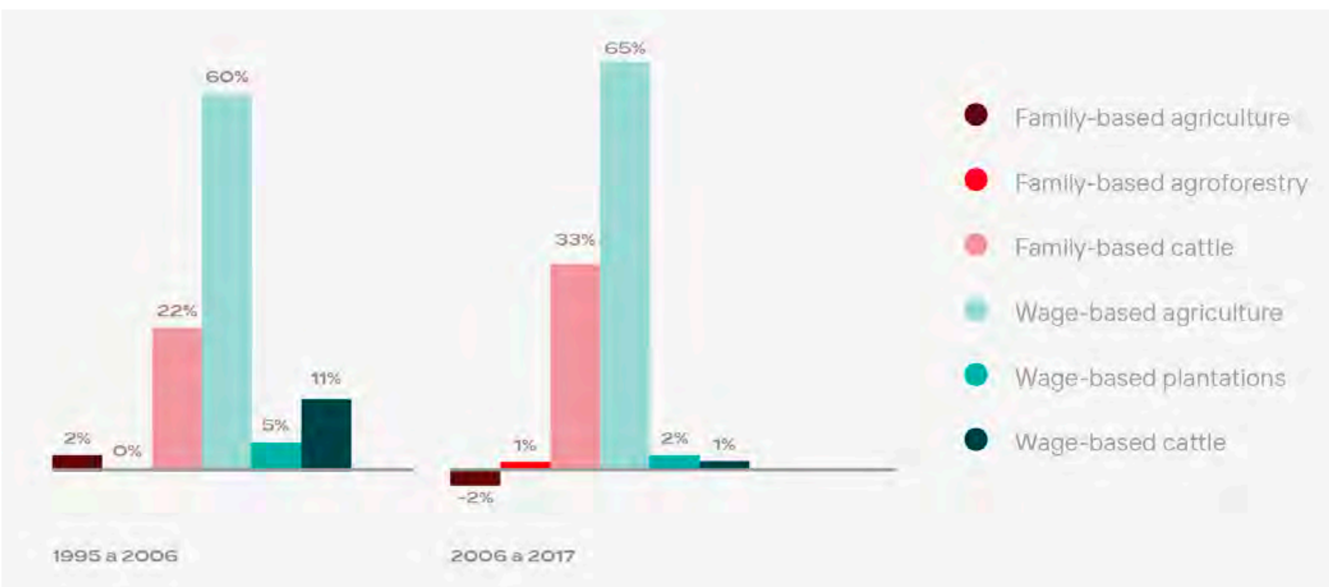

Figure 15.10 Contributions of productive trajectories to total net emission of CO2 of the agrarian economy within the Brazilian Amazon Biome, 1995-2006 and 2006-2017: % of total. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017. Costa 2016.

[p] To corroborate the census data, an equivalent area, of 8.6 million hectares, was recorded by Brazil's Amazon Deforestation Monitoring Program (PRODES) in the same period (MapBiomas 2020).

contribute virtually no CO_2 emissions through the whole period (Figure 15.10). This is because these production systems do not rely upon or drive further deforestation, and even increase the organic content in the soils, capturing CO_2 from the atmosphere and transforming it into plant nutrients, although over time cleared areas can release more carbon than native forests.

The same model, as an assumption for the calculation of CO_2 balances, estimated the area of three different forms of secondary vegetation, reaching a total in 2017 of 8.6 million hectares in the Brazilian Amazon.[q] The three types of land with secondary vegetation included: "fallow lands" associated with shifting cultivation (they totaled 580,000 hectares, distributed among the peasant production systems); "degraded land" (mainly degraded pastures – these were 2.9 million hectares, half of which was associated with cattle ranches); and finally, the largest portion was "land in unspecified reserves" of 5.1 million hectares. Half of this belonged also to commercial cattle ranches; the other half was distributed among the other land uses, without distinction of note (Figure 15.8a, Annex). One can only conjecture about the nature of these reserves: one hypothesis is that they are part of the stocks of "land producers" – they are explained by the logic of speculation with land.

Figure 15.11 Ratio of credit to GVP by productive trajectories in the agrarian economy within Brazilian Amazon Biome in 2006 and 2017: %. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017. Brazilian Central Bank. Table Annex 15.1.

[q] This estimate converges with the estimate of 8.9 million hectares of secondary forests reported in the Fourth National Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases for the United Nations Framework Convention (see BRAZIL - Ministério de Ciência, Tecnologia e Inovações 2020, Matrizes de dados de atividade e resultados de emissões e remoções de CO_2, Figure 21, Matriz de conversão de uso e cobertura da terra do bioma Amazônia de 2010 a 2016, column 3, line FSEC).

According to Walker *et al.* (2020), forest degradation accounts for a large majority of carbon loss in the Brazilian Amazon (68.8% in 2016), a proportion that was even higher in the other Amazonian countries: for Pan Amazon as a whole, forest degradation accounted for 87.3%, of carbon losses. This forest degradation is from all sources, including logging, fire, edge effects and tree death during droughts (see Chapter 19), but logging, together with the fires that occur due to the disturbance from previous logging, are undoubtedly a large part of this enormous impact.

15.3.4 Predatory commercial production and asymmetric policies

Cattle ranching and commercial agricultural enterprises occupy the largest land use category in the region, and their development has required deforestation, with also greater environmental impact expressed in the largest shares of net carbon emissions that occur in the rural sector of the Amazon. Both have been rewarded with increasing profitability, with additional returns derived from the processes of speculation with land (described above), given the dominant illicit appropriation, and through illegal timber production (Brazil 2002; Fernandes 1999; Araújo 2001; Benatti 2003; Treccani 2001). Both cattle ranching and commercial agricultural enterprises have also been the preferred recipients of favorable policies, institutions and political support, securing critical technological knowledge for homogenous agriculture and livestock establishments (Hecht and Mann 2008; Oliveira 2013; Gasques *et al.* 2011). Indeed, in 2006 and 2017 the largest volume of development credit was granted to agricultural enterprises (25% and 28% of GVP in those years), while cattle ranchers obtained financing that corresponded to 10% and 29% of its GVP in the same years, essentially tripling the support received (Figure 15.11). Access to official technical assistance corroborated precisely with what was observed with credit (Figure 15.12).

In addition, the expansion of road systems, storage infrastructure and an array of agricultural services provided a reinforcing production matrix. While these data show that agribusiness was favored in access to extension services, comparisons among regions in Brazil showed that, across all size categories, less than 15% of farmers in the North Region received extension services from the government (IBGE 2017).

Given these advantages, the competitive power of these large-scale production systems has proved overwhelming: in 2017 they represented 77% of the rural economy in the Amazon (Figure 15.2). Their considerable competitive power to shape institutions and national politics often relies upon unequal access to resources, encourages deforestation, and unleashes other environmental impacts on land and rivers that undermine environmental services and possibilities for more resilient, equitable and sustainable development pathways.

But there are issues specific to the context created by the dynamics of large-scale cattle and agricultural enterprises in the Brazilian Amazon. One problem is the antagonism generated in relation to recommended “forest management” practices. Well-intentioned management companies face competition from illegal logging and unsustainable legal forest management. From the start, there are economic impediments that stem from the widespread availability of wood from illegal, predatory and unsustainable sources (see Chapters 14 and 27). Besides, the system can be unsustainable due to various loopholes that have been created to legalize unsustainable management, as well as frequent violation of regulations both by government licensers and by those who receive the licenses. For example, various ways have been devised to allow harvesting to deviate from established cutting cycles, in which one logging compartment is harvested each year until the cycle is completed, after which logging is repeated in the logging compartment harvested in the first year. If the entire management area is harvested in the first few years (or even in the first year) and the management company or property owner is expected to remain without income for the remainder of a 30-year cycle, the theoretical sustainability of the system be-

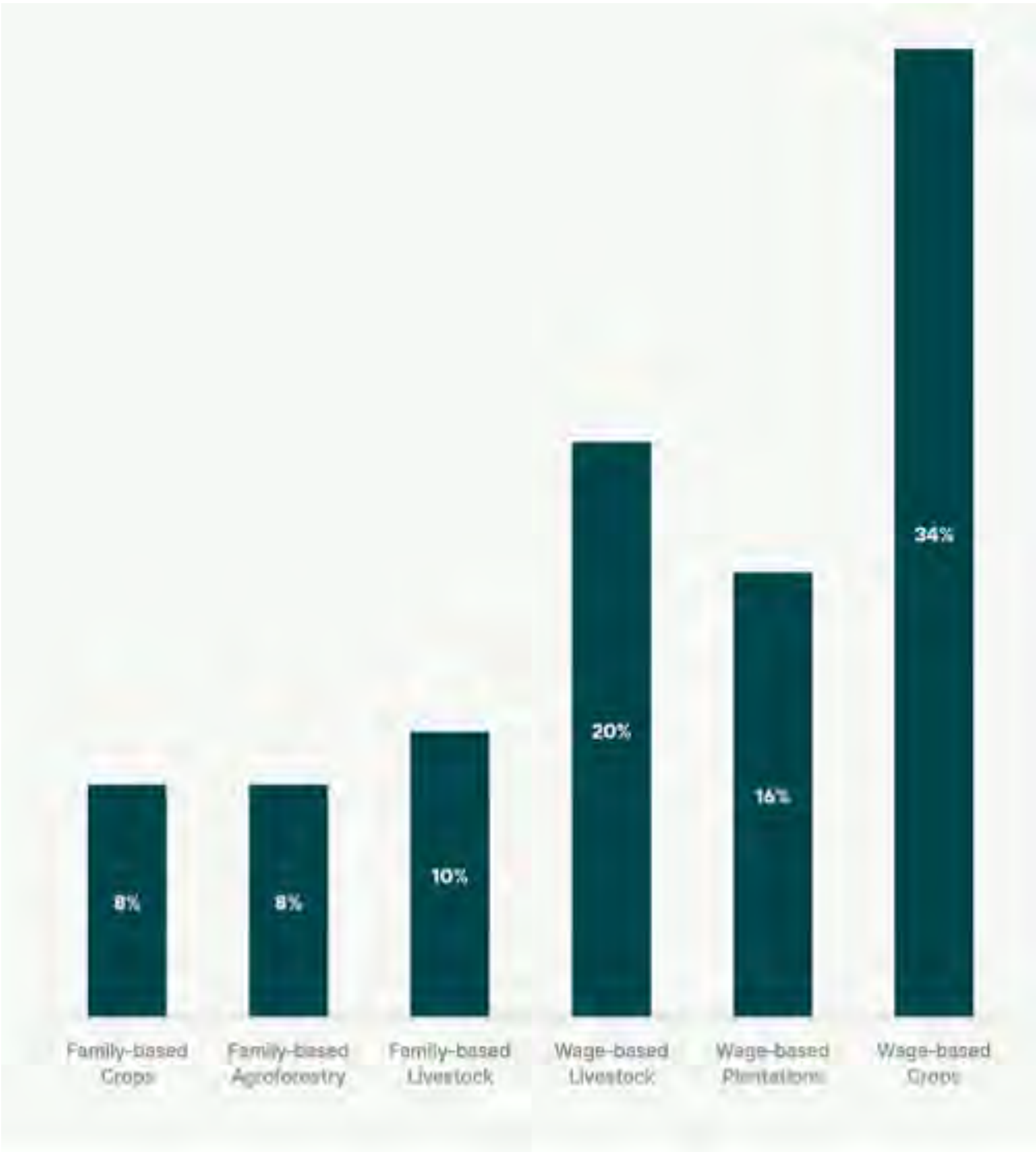

Figure 15.12 Ratio of number of establishments with technical assistance to total establishment of PTs in the agrarian economy within Brazilian Amazon Biome in 2017: % Source: IBGE, Agricultural Censuses 1995, 2006 and 2017. Table Annex 15.1 and 15.2b.

comes meaningless (Fearnside 2020).

The wage-based plantations, production systems based on permanent crops and reforestation, have recurring problems related to the vulnerability of homogeneous botanical systems that show low resilience in the region (see section 15.2.6). Also, the high opportunity cost of managed wood, resulting from the relatively low growth rate of trees in the original forest compared to the yield rates of investment alternatives from the results of the immediate liquidation of forest assets, is a problem for forest management worldwide (Clark 1973; Fearnside 1989, 1995a). However, there is a strong component in shifting cultivation systems that produce wood for local systems and construction, using fast-growing species such as *Bolaina* (*Guazuma crinita*) (Sears 2016).

15.3.5 Volatility of family-based production net income and vulnerability

As for family-based production systems in Brazil, two things stand out. Firstly, family-based-livestock followed the trend among the wage-based production systems, as it doubled net income per family worker. Also, like the latter, family-based-livestock was strongly supported with credit capital, which represented 25% of its total GVP in 2017, an increase from only 12% in 2006. In 2006, the participation of family-based cattle enterprises in credit was the most important among all family-based systems. In turn, family-based-agriculture and agroforestry had the lowest access to credit compared with other producer groups (about 4% in 2006, about 9% in 2017, Figure 15.11), and the lowest access to technical assistance (10% for family-based-livestock, and 8% for agriculture and agroforestry, Figure 15.12).

Secondly, the net income per family worker of family-based-agriculture and agroforestry, after experiencing strong growth, decreased severely for the former and stagnated for the latter: respectively from USD 1,141.20 in 1995 to USD 3,051.60 in 2006, dropping to USD 2,034.40 in 2017 (for agriculture), but increased for agroforestry, from USD 918 to USD 2,059.20 (Figure 15.13). The volatility of family-based-agriculture's income produced a crisis, certainly heightened by the tensions surrounding land, materialized in the transformation into urban or rural wage workers of over half a million workers (see Section 15.2.2), and in the reduction of their role in local supply. The income stagnation of family-based-agroforestry, notable for its sustainability attributes, indicated limits on its capacity to expand and to improve the living conditions of those involved. Considering the fact that the prices of its key products were increasing, this situation implied reductions in physical productivity. Indeed, climate change and increasing urbanization are posing new and considerable challenges to family-based-agriculture and agroforestry systems.

15.4. Key Questions and Proposals to Improve Family-Based Production Systems

15.4.1 Adaptation to climate change and urbanization

The methods by which Amazonian local communities manage landscapes and exploit natural resources are changing in response to the region's growing urbanization (Eloy and Lasmar 2012; Franco *et al.* 2021). In much of the Amazon region, originally and through the present, the economy and ways of life of the rural populations have been based on different combinations of subsistence and commercial activities of annual and perennial agriculture, gathering of forest products, fishing, and hunting (Moran 1991, 1994). This polyvalent strategy, which combines a multiplicity of primary subsistence activities, allows these populations to adapt and utilize the diverse Amazonian ecosystems, from dense forests and savannahs of drylands to the aquatic environments of the small tributaries and great river's floodplains (Witkoski 2010). This adaptability underlies the ability of diverse local production systems to persist and adapt, even under unfavorable conditions, as well as their importance for future strategies to support more sustainable production systems (Brondizio *et al.* 2021; Eloy and Lasmar 2012; Franco *et al.* 2021).

Climate variability is changing the timing as well as the frequency and intensity of heatwaves, severe storms, floods, drought spells and other hydro-climatic extreme events (see Box 15.4 and Chapter 22), which have produced catastrophic impacts on livelihoods and environments (Espinoza *et al.* 2020; Marengo *et al.* 2013). Localized short-lasting and intense hydro-climatic events have become the main constraints for farming annual and perennial crops in the Amazon, while urban expansion and the integration of the Amazon to regional, national and international markets are mentioned by policy makers, producers and experts as factors that have changed patterns of production and supply of food crops to Amazonian cities (Abizaid *et al.* 2018; Coomes *et al.* 2016).

The annual and perennial crop fields of Amazonians are highly vulnerable to short-duration and highly damaging floods, droughts and rainstorms (Espinoza *et al.* 2019; Kawa 2011; List *et al.* 2019; Sherman *et al.* 2016). Based on interviews and published information, producers in the Amazon delta are dealing with two types of extreme tidal flooding (locally known as *lava praias* and *lançantes*) and producers from upper to low Amazon are dealing with damaging out-of-season floods. These floods, locally known as *repiquetes,* are produced by fairly local extreme rainfall events causing sudden increases in river level during the dry season (Espinoza *et al.* 2019; List *et al.* 2019; Ronchail *et al.* 2018).

Climate change is interfering negatively in the production of *açaí* in hot years (Tregidgo *et al.* 2020), and productivity more generally has been affected by the erosion of diversity of *açai* varieties, resulting from the greater intensification of the management of *açaizais* (Freitas *et al.* 2015; Campbell *et al.* 2017). Amazonians are adapting in diverse ways to these challenges. They are increasingly planting cassava, corn, beans and other annual crops in upland (*terra firme*) on the highest sections of levees, locally known as *restingas altas* to protect from floods (Coomes *et al.* 2020; Gutierrez *et al.* 2014). Similarly, the data show that farmers are increasingly engaging in collective action to control fire during land preparation to avoid accidental or escaped fires (Gutierrez *et al.* 2014). In the delta, farmers are planting vegetables, spices and other annual crops in suspended platforms, locally known as canteiros or girais; in the floodplains, farmers are planting flood-tolerant varieties of rice, beans and other annual crops to attract and harvest fish in low areas of the floodplain that are vulnerable to repiquetes (Kawa 2011; Steward 2013). In the Amazon delta, the adaptive processes of farming annual crops are leading to the expansion of house gardens, enriched and managed fallows and forests for the p (List *et al.* 2019). The conversion of banana fields to enriched and managed fallows and forests, has greatly increased the production of *açai*, fruits and other perennial crops (Vogt *et al.* 2015). In the levees along the floodplains of the upper Amazon, agriculture fields have been converted into enriched fallows with fast-growing timber species, fruits and other perennial crops (Sears *et al.* 2018). Amazonians' capacity to adapt to climate changes explains why annual and perennial crops continue to be important sources in sustaining the livelihood of millions (Sherman *et al.* 2016; WinklerPrins and Oliveira 2010), and underscores the importance of their systems for the future.

While hydro-climatic disturbances are considerably impacting the yield and diversity of annual and perennial crops, Amazonian producers continue relying on a great diversity of annual and perennial crops to manage vulnerability and risks associated with changes in the market produced by the process of urbanization (Coomes *et al.* 2020; Langill and Abizaid 2020). In all Amazonian countries, producers are responding to the constraints and opportunities produced by urban expansion by: (i) changing their focus or decision making, in some cases in the direction from market-oriented to subsistence-oriented cultivation of rice, corn, beans and other annual crops and in other cases from subsistence-oriented to market-oriented production of perennial corps (Coomes *et al.* 2020); (ii) changing food processing systems, from manual to mechanical processing (Brondizio 2008); (iii) changing their sources of seeds and other planting

Box 15.4 Climate challenges faced by Amazonian farmers

Current challenges faced by farmers, particularly smallholders, of annual and perennial crops call for better dissemination of climate information and forecasting, sharing and diffusion of adaptive solutions, and better integration of existing production, processing, trading and consumption systems that improve economic return for farmers:

1) While the Amazon has experienced catastrophic flood and drought events, for producers, the main hazards are localized extreme hydro-climatic disturbances that have increased in frequency and intensity (List *et al.* 2019; Espinoza *et al.* 2019). The provision of information on timing, frequency and intensity of severe floods, droughts, strong wind and other disturbances are needed to promote sustainable production of annual and perennial crops.

2) Information on adaptive responses is as critical as information on climatic disturbances and the impact of changes in urban markets. In all Amazonian countries there are examples of families that are successfully producing annual and perennial crops by innovating and adapting farming and marketing systems. A process for documenting, evaluating and promoting alternative agricultural strategies can help to achieve the Sustainable Development Goals.

3) The fields of farmers that are successfully producing annual and perennial crops are reported to have high levels of agrobiodiversity (includes all landraces, varieties and species of annual and perennial crops) that help them to reduce the losses produced by floods and droughts. Programs such as agriculture credits should focus on promoting crop diversity rather than promoting of a single species. Experts have reported that agriculture credit programs for the production of rice, corn, *açaí*, cacao and other single crop have been demonstrated to be unsustainable and highly risky to climate changes (List *et al.* 2019; Flores *et al.* 2017).

4) Programs to foster the production of annual and perennial crops should integrate existing adapted production systems, techniques, practice and other forms of local agrodiversity (including production systems, techniques, practices and strategies used by farmers to produce, process, trade and consume annual and perennial crops) as technological resources for managing vulnerability and risks associated with hydro-climatic disturbances and changes in urban markets (Sherman *et al.* 2016; Kawa 2011; Futemma *et al.* 2020).

5) Urban expansion has attracted private investors in the food market to supply the demand for rice, beans, corns and other products of the urban Amazon. Private investors have established supermarkets that are bringing grains, vegetables and other food staples that are produced outside the Amazon. Large supermarkets often rely on more distant suppliers of products like rice and beans, while small shops sell more local products, a pattern which may have changed with the impact of small farmer declines (Roberts 1991). While urbanization has had mixed effects on the demand for locally produced annual crops, it has created markets for perennial crops such as fruits. For instance, an increase of taste and preference for rural food and diets of urban residents have created regional, national and international markets for fruits such as açaí, cupuaçu, graviola, and a variety of other perennial crops.

materials, by integrating seeds that are sold in the markets to the local seeds systems (Abizaid et al. 2018; Oliveira et al. 2020; Coomes et al. 2020); and (iv) changing trade systems, from randomly selling in all markets to directly selling to distributors or contributors (locally known as pedidos) or contracts (locally known as habilitación) mediated by social networks and cell phones (Abizaid et al. 2018).

15.4.2 Fisheries development

The expansion of modern commercial fisheries greatly increased pressure on floodplain lake fisheries, mobilizing floodplain communities throughout the Amazon floodplain network to implement collective agreements called "acordos de pesca" to regulate local fishing activity (McGrath *et al.* 1993; Smith 1985). Community management of floodplain fisheries was based on local communities' land tenure systems, which considered lakes to be collective property, and on the logic of the diversified household economy. Households employed economic strategies including various combinations of commercial and subsistence fishing, annual and perennial crops, forest management, hunting and collecting (e.g., turtles, crabs), and small and large animal husbandry (ducks, chickens and cattle). Fishing was central to these strategies, providing the main source of animal protein, cash to purchase household necessities, and working capital for investment in the other productive activities. Community management sought to maintain the productivity of local fisheries so that fishers could optimize time spent fishing, with the allocation of household labor to other productive activities (McGrath *et al.* 1999).

Among the most important innovations in fisheries management has been the development of a management system for the *pirarucu* or *paiche* (*Arapaima* spp.), one of the largest and highest-priced fish species in the Amazon. A highly successful management system that combines scientific and local fisher knowledge and skill was developed for *pirarucu* at the Mamirauá Sustainable Development Reserve (Castello 2004; Duponchelle *et al.* 2021). This system made it possible to simultaneously increase annual catch rates, numbers of fishers and populations of *pirarucu* in managed lakes (Castello *et al.* 2009). The management system has been widely disseminated in the state of Amazonas (Brazil) and in the Peruvian Amazon. In Amazonas, total catch of managed *pirarucu* increased from 20 tons in 2003 to more than 2,600 tons in 2019 (Campos-Silva and Peres 2016; McGrath *et al.* 2020). The ability to count individual fish reduced uncertainty, and motivated fisher groups to invest in sustainably managing *pirarucu*, and in the process created governance conditions that benefitted other important fish species and, more generally, aquatic biodiversity.

While some researchers have questioned the viability of community-managed fisheries, studies have shown that lake fisheries with effective management agreements can be 60% more productive than unmanaged lakes (Almeida 2006). Other studies have shown that migratory species, such as the *tambaqui* and *surubim*, which spend their juvenile phase in managed lakes, tend to be significantly larger than those in unmanaged lakes (Castello *et al.* 2011). With adequate government support and technical assistance, the community-based management system could be extended to the entire Amazon floodplain and ensure the sustainable management of floodplain fisheries (Duponchelle *et al.* 2021). Progress has been made in managing floodplain fisheries, but there has been minimal progress in sustainably managing stocks of the long-distance migratory catfish (Fabré and Barthem 2005; Goulding *et al.* 2018). While these species continue to play a major role in the Amazon's commercial fisheries, largely uncontrolled fishing and dam construction threaten their viability (Castello *et al.* 2013; see also Chapter 20).

This is a critical time for Amazon fisheries (see Box 15.5). After centuries of largely uncontrolled exploitation, important commercial fish species are overexploited. Yet, as a whole, Amazon fisheries are still productive and continue to sustain hundreds of thousands of rural and urban families. In some states, effective management systems are contributing to the recovery of regional fisheries, and if such policies were implemented throughout the floodplain system, the decline of Amazon fisheries could be reversed, improving the livelihoods of IPLCs, urban fishers and other supply chain actor groups (Duponchelle *et al*. 2021).

Beyond capture fisheries, federal and state government policy makers are enthusiastically promoting aquaculture as the modern way to produce fish and fill the gap created by the depletion of the Amazon's wild fisheries (McGrath *et al*. 2015). Aquaculture's rapid expansion in the Amazon holds the

Box 15.5 Challenges to Fisheries Development

Progress in fisheries management in the Brazilian Amazon reached its peak with the creation of the Ministry of Fisheries and Aquaculture (MPA) in 2009. However, the creation of the MPA also marked the beginning of the disruption of the government fisheries sector. With the creation of the MPA, responsibility for fisheries management was to be shared between the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) and the MPA, despite the fact that the new Ministry lacked the technical and institutional capacity to manage Brazilian fisheries (McGrath et al. 2015). Then in 2015 MPA was extinguished and its functions transferred to another agency. Over the next few years, the federal government fisheries sector became a pawn in the alliance-forming strategies of two presidents, finally ending up in a Secretary in the Ministry of Agriculture and Ranching. Subsequently, responsibility for managing fisheries was transferred to state governments with varying interest and capacity for managing their fisheries.

Contrasts in state-level commitment to fisheries management and development are illustrated by the states of Amazonas and Pará, which have the lion's share of the fisheries resources of the Amazon. Amazonas embraced its fisheries early, implementing co-management policies largely through the network of state and federal reserves. In contrast, the state of Pará has rarely invested in the fisheries sector (McGrath et al. 2015). Amazonas also developed policies for pirarucu management based on the management system developed by the Mamirauá Institute (Castello et al. 2009). As a result, while sustainably managed pirarucu production is growing in Amazonas, pirarucu populations in Pará are declining due to unregulated fishing (Castello et al. 2014).

In addition to the lack of government effort in managing fisheries, two other issues exacerbate the problem: 1) the absence of monitoring programs to collect data on commercial fish landings that can be used to analyze trends in fish stocks and fishing activity (Cooke et al. 2016), and 2) the absence of state inspection facilities to ensure that fish entering Amazon urban markets meet legal, sanitary and fiscal requirements (McGrath et al. 2015). The major exception to the latter issue is the industrial fisheries sector, which is required to register and inspect fish entering frigoríficos, and to pay any taxes and fees owed to the government. Consequently, the Amazon's small-scale fisheries are an invisible sector, with no information on the legality or quality of Amazon fish supplied to consumers, nor data to assess the economic importance of the fisheries sector to the regional economy, and inform government policies and private sector investment decisions (Bartley et al. 2015; Cavole et al. 2015).

In addition to the direct impacts of uncontrolled fishing pressure, Amazon fisheries are vulnerable to the range of impacts that have led to the decline of inland fisheries throughout the world (Cooke et al. 2016). These include large-scale land-use change that can affect water quality and discharge, and pollution from urban centers and mining, especially placer mining (garimpos) and oil extraction (Castello et al. 2013). Dams on major tributaries can disrupt the migration routes of major commercial fish species, accelerating their decline. In addition, six major Andean dams scheduled for construction could capture 70% of the sediment transported by Amazon rivers, with major long-term impacts on the productivity of Amazon rivers, their floodplains and fisheries (Forsberg et al. 2017).

potential to provide an alternative to cattle production, helping diversify local incomes and rural and urban food supplies while reducing the land footprint of animal-based foods (McGrath *et al.* 2020). However, the degree to which aquaculture will become an environmentally sustainable, nutritious, and equitable component of Amazonian food systems depends on myriad factors, including improving production efficiency, culturing a diverse set of native species, reducing initial investment costs, and ensuring that farmed fish are accessible to people who rely heavily on fish, including rural, poor and Indigenous people (Heilpern *et al.* 2021). While much uncertainty remains around the tradeoffs between aquaculture, capture fisheries, cattle and other animal-sourced foods, it is clear that well-managed fisheries, both wild and farmed, could continue to be a culturally relevant and sustainable component of the Amazon's future bioeconomy (see Chapter 30).

15.4.3 Integrating Local and Scientific Knowledge

Local or Indigenous systems integrate both local and modern knowledge to manage, produce and conserve plant, animal, fish and other biological resources (Franco *et al.* 2021; Thomas *et al.* 2017; Sears *et al.* 2007). Amazonians have demonstrated over millennia that these systems can be adapted successfully to changing conditions, persisting, and even expanding over time despite relatively weak supportive policies compared to agribusiness. They have proven their ability to support food security and promote agrodiversity through such strategies as shifting crop fields, adopting new varieties and preserving germplasm, and managing enriched fallows and home gardens. They have also successfully developed networks to collectively manage fire use, lake fisheries, processing plants and marketing, to the benefit of linked rural and urban communities in the Amazon, strengthening regional economies. The many encouraging examples of ways to reduce environmental impacts while improving the well-being of Amazonian populations provide a strong foundation for future efforts to support more sustainable production alternatives.

Rural and urban populations are increasingly linked through multi-sited households and networks across the Amazon, as discussed in Chapter 14, posing both challenges and opportunities for more sustainable development efforts. Increased urbanization can translate into stronger demand for locally produced goods of multiple types if it is accompanied by effective support for peri-urban, urban and regional small farm agricultural systems. While large-scale supermarkets now dominate urban food supply, more extensive systems of small-scale markets could enhance the viability of such systems, and preferential purchase by schools, hospitals and cafeterias can help create a more predictable demand. In addition, "niche market" chains for organic goods, cooperatives, and fair-trade items are mechanisms that can also support small-scale producers. International environmental markets for *açai*, Brazil nuts and cacao can provide significant income and employment, if supported by improved supply chain practices, branding of producer organizations, and supportive infrastructure (e.g., refrigeration, better drying and sanitation systems; see also Chapter 30).

Recently the relations of Amazonian small producers with research institutions have intensified. In Brazil, EMBRAPA has generated new drought-resistant cultivars and new technologies for family producers, as well as supporting community forest management; for example, the highly organized agroforestry systems managed by the RECA (Consortium and Densified Economic Reforestation Project) community in Rondônia produce Brazil nuts, *pupunha* (*Bacris Gasipaes*) and *cupuaçu* fruits (*Theobroma grandiflorum)* and process them into fruit pulp and palm heart to supply regional and national markets (Valentin and Garrett 2015). Furthermore, there is a growing relationship between local systems and industrial arrangements that have been rapidly building up around the processing of *açaí*, *cacao*, oils and cosmetics. De-centralized education and inter-cultural dialogue are needed for applied ecology, bio-economies and new technologies rooted in local knowledge, and oriented to equitable returns to ILK (see Chapter 32), for both local and broader markets.

For this relationship to become a positive long-term process, which protects the capacities of the Amazon biome and offers a dignified life to those who interact with it in their productive and reproductive processes, a strategy of Science, Technology and Innovation (ST&I) is needed, aiming at new competencies for economies based on, and compatible with, the Amazon biome. Rural smallholders and urban producers should participate integrally in the construction of new policies to support their evolving systems, to support food security and regional economic health. Coordinated mechanisms should integrate rural producers with already existing centers, and others yet to be formed, for the production and dissemination of appropriate knowledge for local and regional actors with alternative development approaches. In rural areas, a shift is required from a focus on specific crops, to a portfolio of diverse products and activities including forest and fisheries management, and climate change adaptation; in industrial and marketing, a shift is needed from a focus on scale to explore scope and branding economies, and to support production and consumption systems that bridge and support rural, peri-urban, and urban areas.

15.5. Conclusions

The Amazon is home to diverse populations who depend on the region's natural resources for their agricultural, extractivism, agroforestry, hunting, fisheries, and other productive activities to make a living and to generate important economic returns. The different actors involved in both larger wage-based and family-based systems of production interact in complex ways that vary across Amazonian countries, with important impacts on ecosystem services. Supportive pro-short-term growth policies regarding land tenure, agricultural credit and technical assistance, as well as the expansion of roads, waterways and other infrastructure have favored the rapid expansion of agribusiness and increasing appropriation of public lands, especially by cattle ranching and soy enterprises, with increasingly negative social and environmental consequences. These transformations have empowered agribusiness as well as speculative interests and undermined the ability of local communities to defend their own interests and practices, which are more attuned to the sustainability of the Amazon's resource base and the well-being of Amazonian peoples. The findings in this chapter point to the need to re-orient development to support small-scale, diverse production systems that provide employment and economic dynamism for local communities. Building on the rich biodiversity and local knowledge that supports many promising initiatives to adapt those systems to climate change and growing urbanization in the region, policies should focus on improving forestry, agroforestry and fishing systems managed by local communities.

15.6. Recommendations

- Amazonian communities and populations have long relied upon a combination of subsistence and commercial activities for their livelihoods. They are adopting diverse strategies and practices in response to a changing climate, including reliance on a greater diversity of annual and perennial crops for managing vulnerability and risks associated with changes in the market linked to processes of urbanization. These promising examples of more sustainable and equitable systems of production should constitute a core focus of future policies.
- Land policies and governance are required to contain the increasing appropriation of public lands for predatory uses, and to avoid the correlated negative social and environmental consequences.
- Community-managed local fisheries provide rural families with a reliable source of animal protein, cash to purchase household items and working capital that can be used to invest in other productive activities. With adequate government support and technical assistance, the community-based management system could be extended to the entire Amazon floodplain

and lake fisheries to benefit rural families, and to ensure more sustainable management of floodplain fisheries for both rural and urban families.
- Across the Amazon, Indigenous and place-based ecological knowledge integrate both local communities and modern knowledge to produce, manage and conserve plant, animal (including fish), and other biological resources. Collaborations between local producers, cooperatives, research institutes and industrial and manufacturing processing facilities around *açaí*, cacao and cosmetic oils based on native Amazon palms have shown promising results. A strategy of ST&I with participation by smallholder producers could further enhance these initiatives and support the development of diverse, local production systems that provide both rural and urban employment and economic opportunities for Amazonian populations while reducing deforestation, greenhouse gas emissions and other environmental threats.

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15.8. Annex

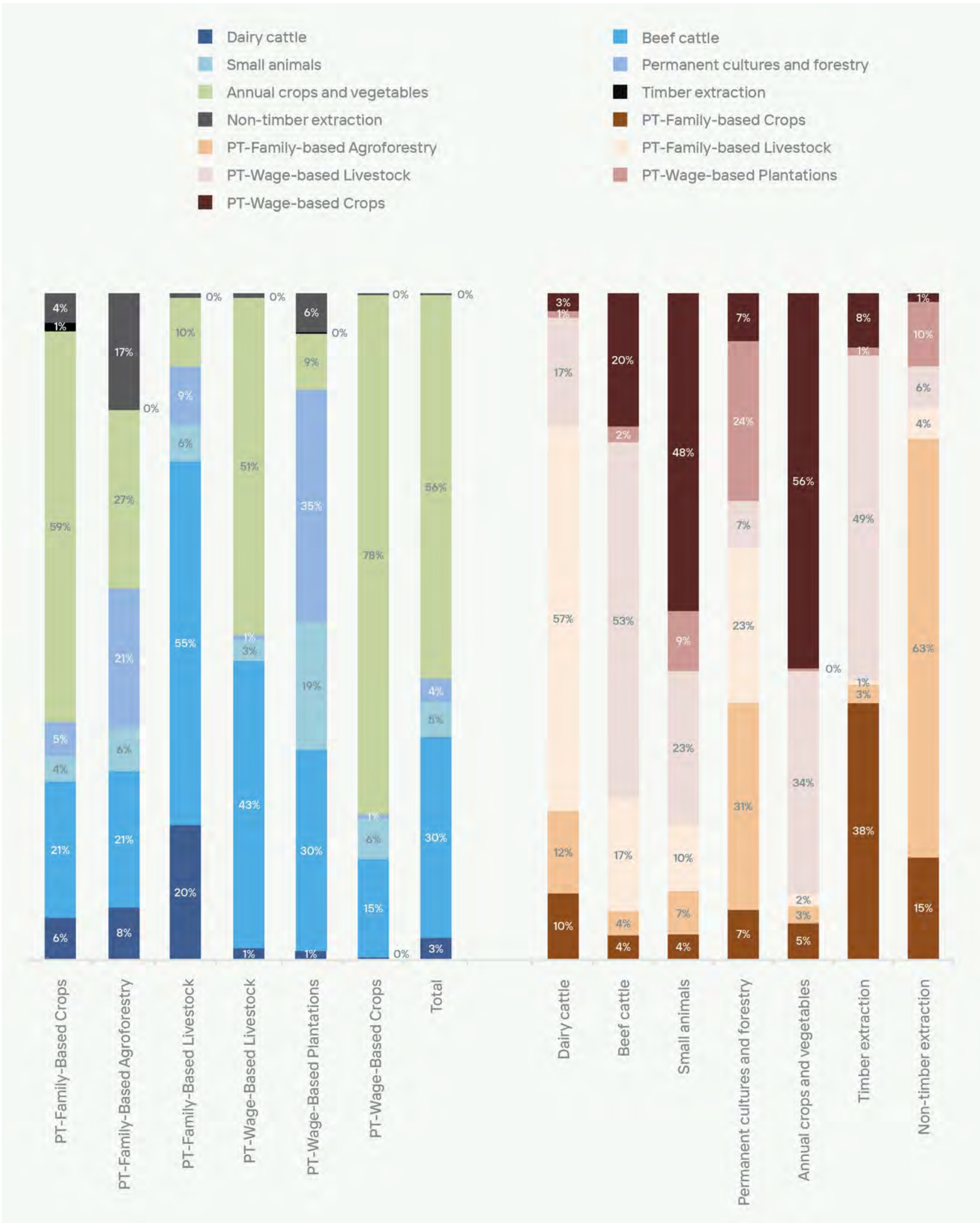

Figure 15.1a Production composition by PTs of the agrarian economy within Brazilian Amazon Biome, 2017 as % of GVP. Source: IBGE, Agricultural Census 2017; Table Annex 15.1.

Figure 15.2a Gross value of production per unit of applied area by PT in the agrarian economy of the municipalities within Brazilian Amazon Biome in 1995, 2006 and 2017: in USD. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017. Current values in BRL were restated for 2019 by the IGP-FGV and divided by the exchange rate of 12.31.2019 to get USD values.

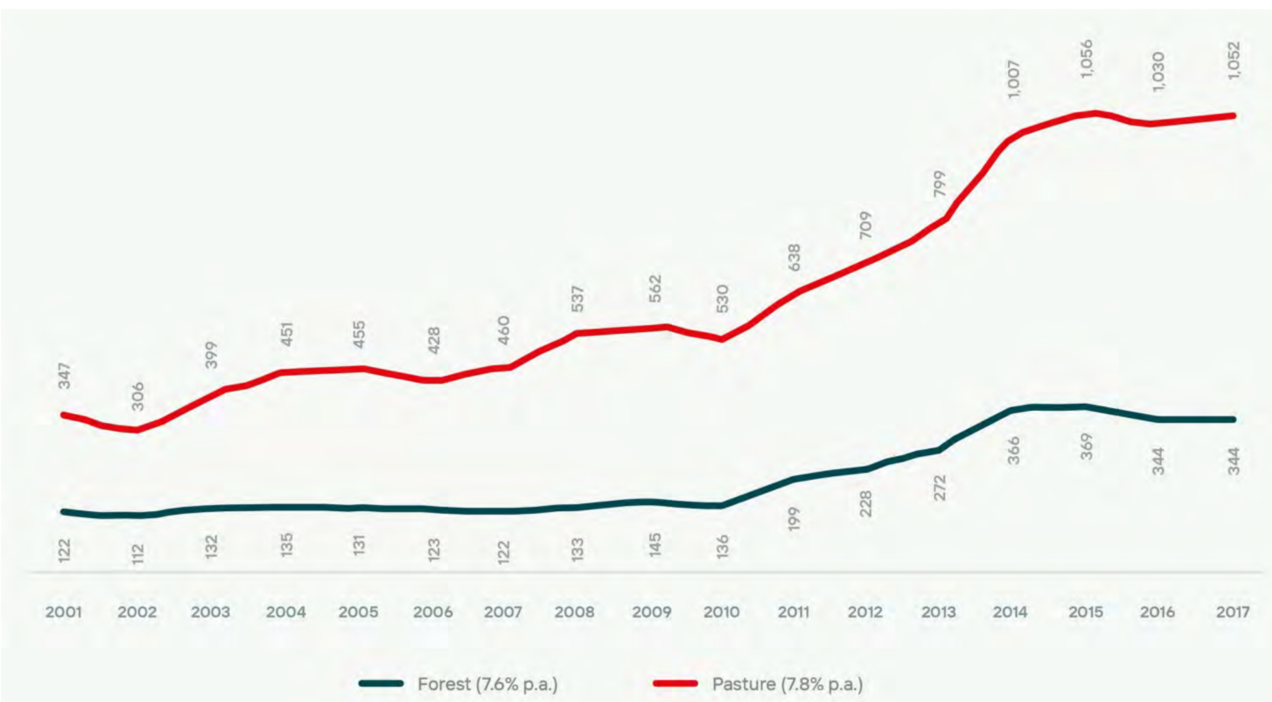

Figure 15.3a Evolution of land prices in the Amazon - 2001 to 2017 (Prices in USD). Source: FNP, Agriannual several years (IEG FNP | Agribusiness Intelligence). Current values in BRL were restated for 2019 by the IGP-FGV and divided by the exchange rate of 12.31.2019 to get USD values.

Figure 15.4a Ratio of used land to total owned land by PT in 1995, 2006 and 2017: in %. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017.

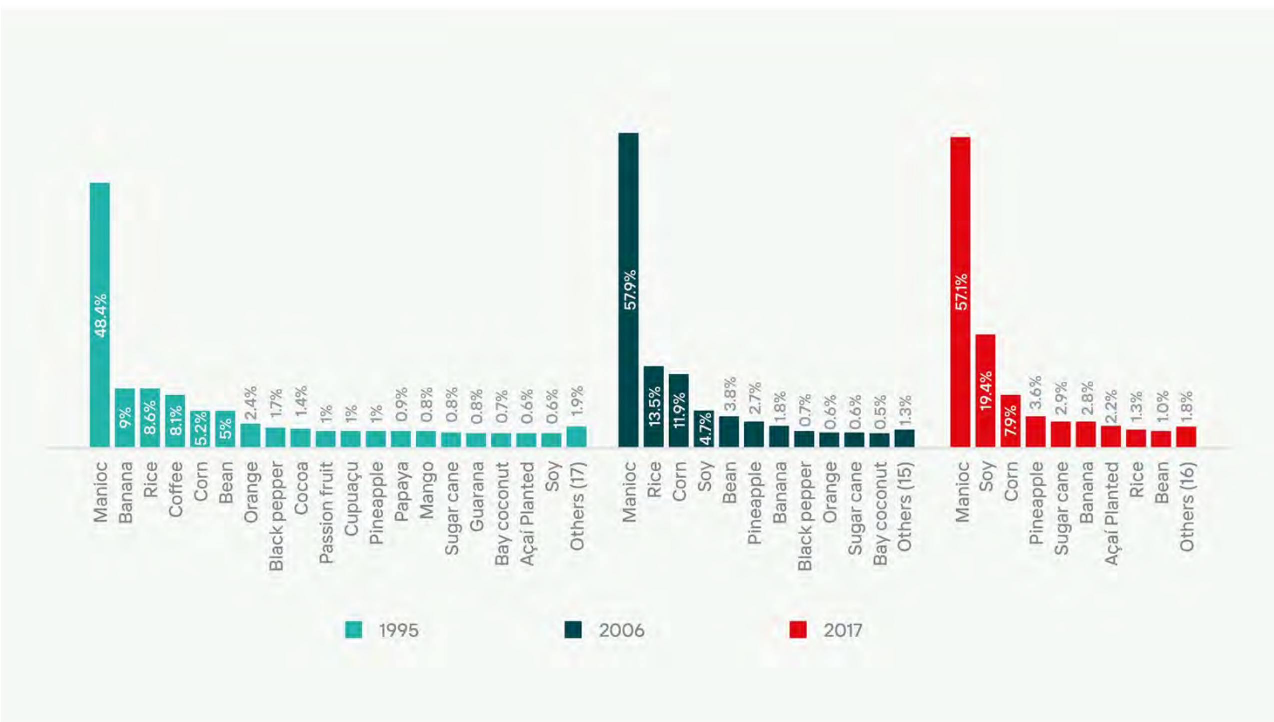

Figure 15.5a Evolution of PT-Family-based Agriculture production (% of GVP). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017.

Figure 15.6a Evolution of PT-Wage-based Agriculture production (% of GVP). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017.

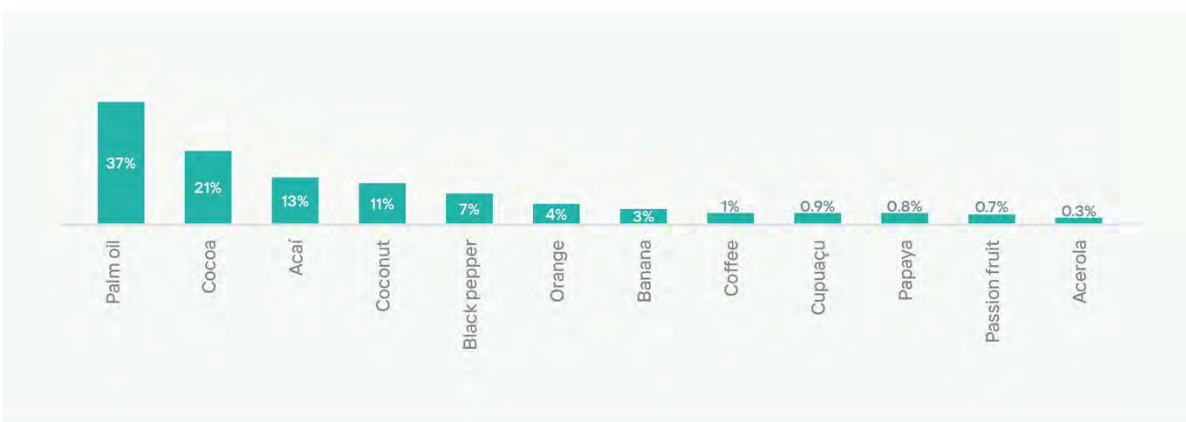

Figure 15.7a Order of importance of different permanent crops at PT-Wage-based Plantations. Source: IBGE, Agricultural Census 2017.

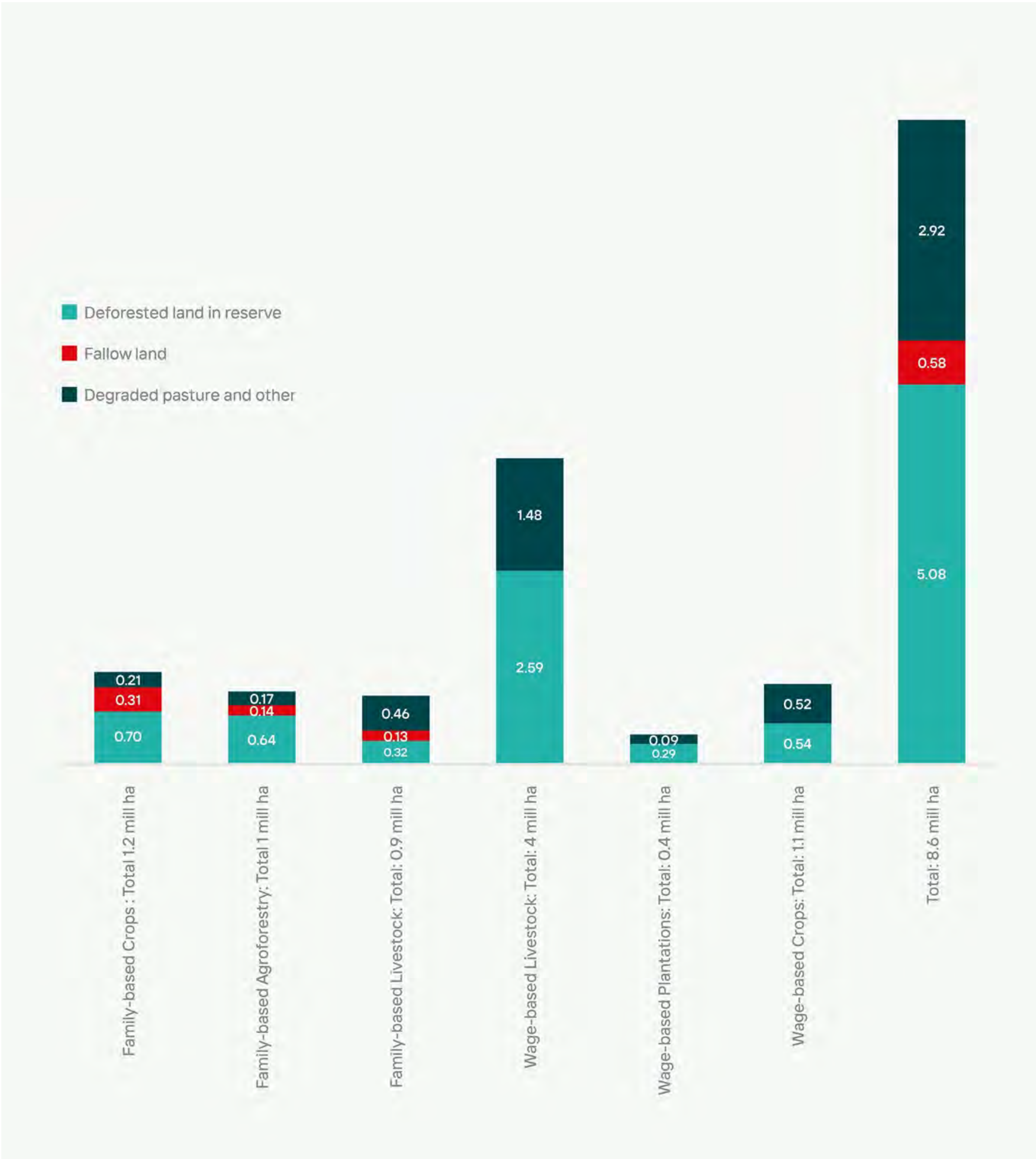

Figure 15.8a Lands with secondary vegetation in PTs: fallow land, deforested land in reserve and degraded land by PT in mill ha - 2017. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Costa 2016.

Table 15.1A Key variables of the agrarian sector by Productive Trajectories (PT), 1995, 2006 and 2017. Source: IBGE, Censo Agropecuário 1995, 2006 e 20017. Current values in BRL were restated for 2019 by the IGP-FGV.

	Family-based agriculture	Family-based agroforestry	Family-based livestock	Wage-based livestock	Wage-based plantations	Wage-based agriculture	Total
1995							
. Dairy cattle (BRL 1,000)	561,710	109,780	1,003,871	-		-	1,675,362
. Beef cattle (BRL 1,000)	459,316	81,498	509,311	3,032,217		979,522	5,061,865
. Small animals (BRL 1,000)	595,352	57,312	152,729	96,711		98,517	1,000,622
. Permanent cultures and forestry (BRL 1,000)	1,247,072	155,612	182,645	475,471		166,014	2,226,813
. Annual crops and vegetables (BRL 1,000)	3,189,688	583,663	708,084	1,336,611		3,057,473	8,875,518
. Timber extraction (BRL 1,000)	202,581	352,475	55,976	171,527		373,832	1,156,390
. Non-timber extraction (BRL 1,000)	148,180	443,832	38,994	28,065		20,653	679,723
Gross Value of Production (GVP) (BRL 1,000)	6,403,898	1,784,171	2,651,610	5,140,602		4,696,012	20,676,293
Production Costs (BRL 1,000)	1,665,024	381,528	560,625	2,990,419		3,073,907	8,671,504
Net Income (BRL 1,000)	4,738,874	1,402,643	2,090,985	2,150,182		1,622,105	12,004,790
Family workforce (Man/Year)	1,038,688	376,380	386,541	73,408		32,740	1,907,756
Net income by family worker (BRL 1,000)	4,562	3,727	5,409				
2006							
. Dairy cattle (BRL 1,000)	41,447	71,704	869,435	329,427	42,921	24,296	1,379,231
. Beef cattle (BRL 1,000)	175,638	263,941	1,708,231	6,223,744	564,486	709,894	9,645,933
. Small animals (BRL 1,000)	79,005	104,129	406,514	160,862	413,274	398,871	1,562,654
. Permanent cultures and forestry (BRL 1,000)	138,889	952,900	769,424	226,421	482,890	38,783	2,609,307
. Annual crops and vegetables (BRL 1,000)	2,826,327	1,662,753	1,530,223	1,468,098	213,891	11,137,391	18,838,683
. Timber extraction (BRL 1,000)	86,539	214,476	14,103	20,574	16,543	436	352,672
. Non-timber extraction (BRL 1,000)	47,873	646,262	44,107	18,613	54,949	2,134	813,938
. Other (BRL 1,000)	136,674	125,678	238,511	193,054	59,373	17,107	770,397
Gross Value of Production (GVP) (BRL 1,000)	3,532,390	4,041,843	5,580,549	8,640,793	1,848,328	12,328,911	35,972,815
Production Costs (BRL 1,000)	492,406	604,558	2,228,207	7,171,241	1,160,447	12,737,960	24,394,819
Net Income (BRL 1,000)	3,039,984	3,437,285	3,352,342	1,469,552	687,881	-409,049	11,577,996
Family workforce (Man/Year)	247,839	415,395	596,593	99,043	42,375	18,638	1,419,882
Net income by family worker (BRL 1,000)	12,266	8,275	5,619				
Credit (BRL 1,000)	132,121	154,180	638,872	864,314	226,368	2,940,086	4,955,941
2017							
. Dairy cattle (BRL 1,000)	255,073	322,799	1,482,096	432,675	25,208	71,841	2,589,692
. Beef cattle (BRL 1,000)	836,086	852,264	3,994,923	12,568,519	574,120	4,714,785	23,540,698
. Small animals (BRL 1,000)	151,455	267,418	403,673	939,152	366,003	1,944,365	4,072,065
. Permanent cultures and forestry (BRL 1,000)	206,055	861,195	641,039	198,455	666,954	199,739	2,773,437
. Annual crops and vegetables (BRL 1,000)	2,395,535	1,115,688	752,617	14,767,285	163,158	24,846,193	44,040,476
. Timber extraction (BRL 1,000)	55,547	4,164	810	70,631	1,696	11,813	144,661
. Non-timber extraction (BRL 1,000)	176,968	725,786	51,642	72,640	112,612	15,271	1,154,921
. Other (BRL 1,000)	444,659	255,783	157,468	1,056,395	176,530	863,347	2,954,183
Gross Value of Production (GVP) (BRL 1,000)	4,521,378	4,405,097	7,484,269	30,105,752	2,086,281	32,667,355	81,270,132
Production Costs (BRL 1,000)	1,517,396	1,308,509	2,905,299	15,235,613	1,935,703	18,264,487	41,167,006
Net Income (BRL 1,000)	3,003,983	3,096,589	4,578,969	14,870,139	150,579	14,402,868	40,103,127
Family workforce (Man/Year)	368,044	372,982	377,669	160,605	37,917	45,891	1,363,108
Net income by family worker (BRL 1,000)	8,162	8,302	12,124				
Cattle Herd (Head)	2,556,723	2,885,369	12,257,778	25,381,569	1,261,688	7,624,153	51,967,280
Establishments with technical assistance (U)	13,826	15,381	19,953	15,121	2,552	7,120	73,953
Credit (BRL 1,000)	381,293	387,181	1,861,172	8,592,448	286,084	9,300,500	20,808,678

Table 15.2B Shifts in Resources Among PTs, 1995 to 2006. Sources: IBGE, Censo Agropecuária 1995, 2006 e 2017.

Productive Productive Trajectories in 1995[1]	Productive Trajectories in 2006						
	Family-based Agriculture	Family-based Agroferestry	Family-based Livestock	Wage-based Livestock	Wage-based Plantations	Wage-based Crops	Total
			Number of Establishment				
Family-based Agriculture	76.709	71.418	112.778				260.905
Family-based Agroferestry	30.700	93.529	50.307				174.536
Family-based Livestock	2.752	14.858	88.359				105.969
Wage-based Livestock				33.128	10.963	2.402	46.493
Wage-based Plantations							-
Wage-based Crops				16.928	9.466	5.706	32.100
Total in 2006	110.161	179.805	251.444	50.056	20.429	8.108	620.003
Total in 1995	337.328	125.160	128.806	31.916		13.518	636.728
A1. Output/Input1995-2006	-76.423	49.376	-22.837	14.577	-	18.582	-16.725
			Owned Land				
Family-based Agriculture	1.899.647	1.965.371	4.885.993				8.751.011
Family-based Agroferestry	1.221.676	2.038.089	2.522.317				5.782.082
Family-based Livestock	202.937	720.193	5.008.967				5.932.097
Wage-based Livestock				29.559.020	4.760.842	2.425.397	36.745.259
Wage-based Plantations							-
Wage-based Crops				15.994.728	3.041.896	9.392.199	28.428.823
Total in 2006	3.324.260	4.723.653	12.417.277	45.553.748	7.802.738	11.817.596	85.639.272
Total in 1995	9.328.999	2.681.381	6.305.316	45.512.245		22.234.571	86.062.512
B1.Output/Input1995-2006	-577.988	3.100.701	-373.219	-8.766.986	-	6.194.252	-423.241
			Used Land				
Family-based Agriculture	989.942	1.053.982	3.010.549	-	-	-	5.054.472
Family-based Agroferestry	715.128	1.264.991	1.640.660	-	-	-	3.620.779
Family-based Livestock	101.463	475.814	3.419.155	-	-	-	3.996.432
Wage-based Livestock	-	-	-	17.522.566	2.318.352	1.439.745	21.280.663
Wage-based Plantations	-	-	-	-	-	-	-
Wage-based Crops	-	-	-	8.792.158	1.641.412	5.191.736	15.625.305
Total in 2006	1.806.534	2.794.786	8.070.363	26.314.723	3.959.764	6.631.481	49.577.652
Total in 1995	3.994.032	1.010.636	3.454.891	18.932.626		9.612.089	37.004.274
C1.Output/Input 1995-2006	246.517	2.312.298	232.646	1.152.548	-	5.078.685	9.022.694
			Workers				
Family-based Agriculture	185.934	176.401	275.509				637.843
Family-based Agroferestry	69.019	224.057	127.933				421.008
Family-based Livestock	7.921	33.120	216.084				257.124
Wage-based Livestock				167.493	39.247	17.777	224.517
Wage-based Plantations							-
Wage-based Crops				83.588	31.750	32.183	147.521
Total in 2006	262.873	433.577	619.525	251.081	70.997	49.959	1.688.013
Total in 1995	1.179.601	402.468	433.550	195.743		86.816	2.298.177
D1.Output/Input1995-2006	-541.758	18.541	-176.425	28.774	-	60.705	-610.165

Table 15.2C Shifts in Resources Among PTs 2006 to 2017. Sources: IBGE, Censo Agropecuário 1995, 2006 e 20017.

Productive Trajectories in 2006	**Productive Trajectories in 2017**						
	Family-based Agriculture	**Family-based Agroferestry**	**Family-based Livestock**	**Wage-based Livestock**	**Wage-based Plant-ations**	**Wage-based Crops**	**Total**
Number of Establishment							
Family-based Agriculture	**58,737**	19,686	20,478				98,901
Family-based Agroferestry	**63,652**	120,452	17,830				201,934
Family-based Livestock	**56,369**	46,203	160,496				263,068
Wage-based Livestock				56,312	4,205	11,369	71,886
Wage-based Plantations				12,362	12,151	4,721	29,234
Wage-based Crops				6,361		4,924	11,285
Total in 2017[3]	**178,758**	186,341	198,804	75,035	16,356	21,014	676,308
Total in 2006[4]	**110,161**	182,671	257,122	50,354	20,429	8,108	628,845
A2.Output/Input 2006-2017[2]	**-11,260**	19,263	5,946	21,532	8,805	3,177	47,463
Owned Land							
Family-based Agriculture	**1,345,416**	855,908	775,777				2,977,101
Family-based Agroferestry	**1,737,640**	3,178,188	789,207				5,705,035
Family-based Livestock	**2,360,995**	2,339,976	10,082,631				14,783,602
Wage-based Livestock				38,320,000	1,380,387	12,488,372	52,188,759
Wage-based Plantations				5,262,008	2,401,016	1,242,953	8,905,977
Wage-based Crops				5,600,370		8,687,250	14,287,620
Total in 2017[3]	**5,444,051**	6,374,072	11,647,615	49,182,378	3,781,403	22,418,575	98,848,094
Total in 2006[44]	**3,324,260**	4,745,295	12,634,788	45,650,989	7,802,738	11,817,596	85,975,666
B2.Output/Input 2006-2017[2]	**-347,159**	959,740	2,148,814	6,537,770	1,103,239	2,470,024	12,872,428
Used Land							
Family-based Agriculture	**694,879**	325,945	468,944				1,489,768
Family-based Agroferestry	**902,669**	1,306,313	568,665				2,777,647
Family-based Livestock	**1,358,786**	1,392,813	7,527,743				10,279,342
Wage-based Livestock				22,623,879	683,138	7,234,174	30,541,190
Wage-based Plantations				2,730,326	1,013,622	658,062	4,402,010
Wage-based Crops				3,107,664	-	5,196,324	8,303,988
Total in 2017[3]	**2,956,334**	3,025,071	8,565,352	28,461,868	1,696,760	13,088,560	57,793,945
Total in 2006[4]	**1,806,534**	2,794,786	8,070,363	26,314,723	3,959,764	6,631,481	49,577,652
C2.Output/Input 2006-2017[2]	**-316,766**	-17,139	2,208,979	4,226,467	442,246	1,672,507	8,216,294
Workers							
Family-based Agriculture	**126,356**	42,733	50,176				219,265
Family-based Agroferestry	**140,057**	263,997	38,660				442,714
Family-based Livestock	**126,155**	97,247	320,513				543,915
Wage-based Livestock				238,452	22,320	53,194	313,966
Wage-based Plantations				47,546	43,848	16,377	107,771
Wage-based Crops				24,473		32,767	57,240
Total in 2017[3]	**392,568**	403,978	409,348	310,470	66,168	102,338	1,684,870
Total in 2006[4]	**262,873**	439,493	634,235	252,016	70,997	49,959	1,709,574
D2.Output/Input 2006-2017[2]	**-43,608**	3,221	-90,320	61,949	36,774	7,280	-24,704
Total Output/Input 1995-2017							
Establischment (A1+A2)	**-87,683**	68,639	-16,891	36,109	8,805	21,759	30,738
Owned land (B1+B2)	**-925,147**	4,060,441	1,775,595	-2,229,216	1,103,239	8,664,276	12,449,188
Used Land (C1+C2)	**-70,249**	2,295,159	2,441,625	5,379,014	442,246	6,751,192	17,238,987
Workers (D1+D2)	**-585,366**	21,761	-266,746	90,723	36,774	67,985	-634,868

Notes: (1) For each year t there are two sets of data, one with elements that describe the rural peasant economy (Bct), and the other with elements that describe the wage-based rural economic (Bpt). In each of the data sets, each row describes a place and each place is associated in that year with only one PT, e.g., PT1t of the Bpt. If we add to each row the information about the PT that was in force in that place in year t-1, e.g., such as PT2t-1, then all the information in that row refers to the PT1t in year t and the PT2t-1 in year t-1. If it refers to a resource, such as land (L), the value reported (Lt) refers to the current domain of the PT1t and the past domain of the PT2t-1 over this resource: Lt came from PT2t-1 and is found with PT1t. Aggregating Lt in a matrix (like those that make up Table Annex 15.2a) whose rows are PTt-1's and columns are PTt's, leads to a special reading of the distribution of Lt by current PTt's in t, still considering the Pt-1's that originally (in year t-1) controlled resource L. In each cell, a value such as Lt(1,1), for example, means that Lt came from the PT1 in year t-1 and currently is under the domain of the same PT1 in year t; if Lt(2,3), it means that it came from the PT2 in year t-1 and is found under the domain of the PT3 in year t, and so on. (2) Each line of this matrix offers information on the exits of the resource from the PT in question. Considering that the exit flows, or use, in year t are made in relation to the stock of resources in year t-1, there is a final "balance" that is: Lt-1(PT1) – Lt(1,1) – Lt(1,2) – ... – Lt(1,n) = Lt(1,x) (1)This "balance," if negative, means that between the two moments the PT1 used more than the resource received from year t-1 and, therefore, had to acquire L outside of the systems described by Bpt (therefore, acquired from peasant PTs, or from the land market, or through direct appropriation of public lands) in the amount of Lt(1,n). If is positive, on the other hand, an amount Lt(1,n) was transferred by the PT1 outside the system (to peasant PTs, or to the urban system). These terms permit the reproduction of the practice of the process in the following relationship:
Lt-1(PT1) – Lt(1,2) – ... – Lt(1,n) – Lt(1,x) = Lt(1,1) (2) Literally: from the stock of lands of the PT1 proceeding from t-1 parcels of L were transferred to the other PTs of Bpt and to other systems if Lt(1,x) is positive; if negative, Lt(1,x) was added to form the initial stock of L in t, equivalent to Lt(1,1). In Table Annex 13.1a and in the graphs based on it Lt(1,x) has the sign it acquired in the relationship (2). (3) To the initial stock in t, parcels are added from the L resource transferred by the other PTs of the system to the PT1 to form the final stock in year t. Thus: Lt(1,1) + Lt(2,1) + ... + Lt(n,1) = Lt(PT1) (3) 4 From Table Annex 15.2a.

Amazon Assessment Report 2021

Chapter 16

The state of conservation policies, protected areas, and Indigenous territories, from the past to the present


Vista aérea da Terra Indígena Yanomami (Foto: Bruno Kelly/Amazônia Real)

Graphical Abstract

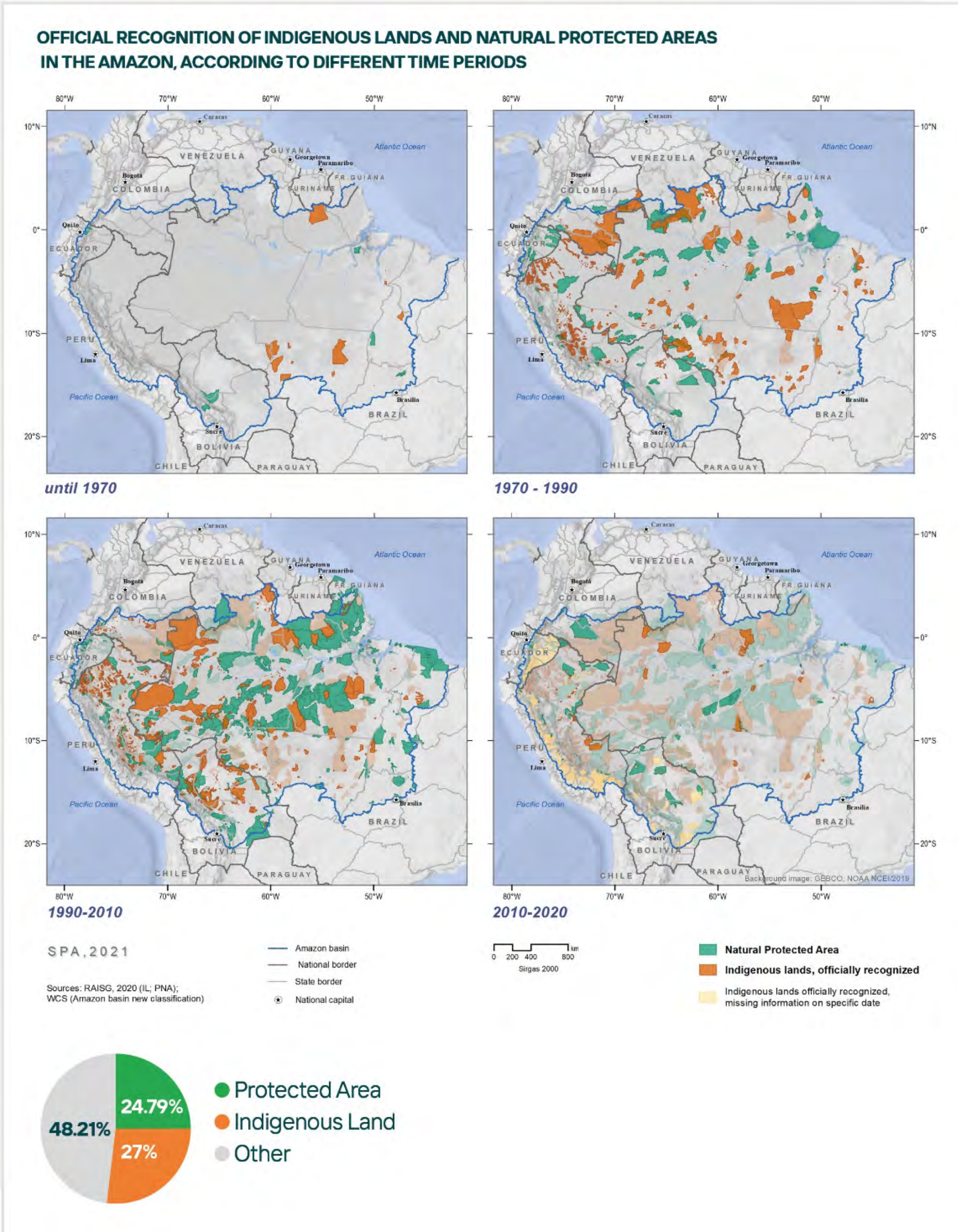

Figure 16.A Graphical Abstract

Past and Current State of Conservation Policies, Protected Areas, and Indigenous Territories

Carmen Josse[a], Silvia de Melo Futada[b], Martin von Hildebrand[c], María Moreno de los Ríos[d], María A. (Tina) Oliveira-Miranda[e], Edel N. de Moraes Tenório[f], Ermeto Tuesta[g]

Key Messages

- Including Indigenous territories, almost 50% of the Amazon Basin is under some type of recognized or legal protection framework, showing the great potential of the Amazon to conserve and manage vital ecological connectivity.
- Rates of deforestation are on the rise across the region, putting Indigenous territories (ITs) and protected areas (PAs) under renewed pressure.
- The commitment of countries to protect biodiversity through area-based strategies (previously Aichi Target 11) covering 30% of marine and terrestrial areas of the Earth by 2030 is not enough for the Amazon. Even with existing protected areas (PAs) covering close to 50% of the area, the business-as-usual scenario raises the risk that the Amazon will reach a tipping point. Indigenous territories (ITs), and the people that live in them, have made a significant contribution to maintaining forests, and serve as buffers to emissions from forest loss compared with regions outside their borders. This presents an opportunity to emphasize the contribution made by Indigenous territories (ITs) to the protection of biodiversity and to consolidate a vision of safeguarding macro-regional connectivity in the Amazon.

Abstract

This chapter focuses on recent historical processes (since the 1960s) of two types of management units that are cornerstones of Amazonian conservation: protected areas (PAs) and Indigenous territories (ITs). This historical account is presented from the perspective of the development and institutionalization of the National Systems of Protected Areas or Conservation Units. The recognition of Indigenous territories (ITs) in Amazonian countries, as well as the titling or regularization of these territories, are analyzed here in relation to periods of implementation of state policies that have determined occupation of the Amazon, land-use changes, and demographic composition in these areas. Both in the case of protected areas (PAs) and Indigenous territories (ITs), a summary of the current coverage of different types of protected area (PAs) categories and of recognized and unrecognized Indigenous territories (ITs) is provided.

This chapter also sheds light on other management frameworks that have been developed to explicitly include the presence of traditional Indigenous and non-Indigenous communities, recognizing their right to the sustainable use of forest resources in their settlement. The role of ecological connectivity as a conservation objective is also discussed, and examples of landscape-scale conservation initiatives at the watershed level are provided. Throughout this period, policies for the creation of management categories

[a] Fundación EcoCiencia, San Ignacio E12-143 y Humboldt Edf. Carmen Lucía, Quito 170517, Ecuador, carmenjosse@ecociencia.org
[b] Instituto Socioambiental, Av. Higienópolis, 901, São Paulo, Brazil
[c] Gaia Amazonas, Calle 70A #11-30, Bogotá, Colombia
[d] IUCN, Edificio Murano Plaza, 12th floor, 170515 Quito, Ecuador
[e] Wataniba, Calle Principal de la Urb. Monseñor Segundo García, Casa N° 6, Edo. Amazonas, Venezuela
[f] Memorial Chico Mendes, Rua Teófilo Said, Quadra G n° 05, Conjunto Shangrilla II, Parque Dez. Manaus AM 69054-693, Brazil
[g] Instituto del Bien Común, Jr. Mayta Cápac N° 1329, Jesús María, Lima, Perú

have presented advances and setbacks; however, mounting pressure on Amazon resources, such as unsustainable extraction and more policies favoring conventional development have put at serious risk what Amazonian countries have achieved in more than half a century of conservation policies. In particular, in the last five years, after a decade of declining deforestation, there has been an overall surge in deforestation in Amazonian forests, including inside protected areas (PAs) and Indigenous territories (ITs). This brings back, and more forcefully, the need for a discussion about more effective, innovative views on protected area systems and other effective area-based conservation measures, and the political stakes of the region's governments to honor their conservation commitments.

Keywords: *Indigenous territories, protected areas, conservation*

16.1 Recent history of Indigenous territories and the designation of protected areas in the Amazon

The socio-environmental dynamic corresponding to the historical period covered in this chapter highlights a common starting point among all the countries that share the Amazon basin. During the first half of the 20th century, or later in some countries, the National Security Doctrine (Buitrago 2002) was the paradigm from which state policies were designed and implemented to guarantee sovereignty in a space that was still disputed between Amazon countries, but also between transnational companies and between the latter and local populations. Therefore, campaigns such as the "Living Frontiers" in the Ecuadorian Amazon or the great "Westward March" in the Brazilian Amazon were promoted, which led to the colonization of "wastelands" and the expansion of the extractive economy in the Amazon (RAISG 2016). This logic of the occupation of wastelands, or uncultivated lands, was followed by institutional frameworks associated with agrarian development, colonization, and deforestation, with the market—formal, but also illegal—for land and tropical timber (RAISG 2015). Therefore, the contemporary process of forest loss was only one of the major impacts of the accelerated process of land-use change in the 20th century; the other was the displacement of Amazon peoples from their ancestrally occupied land. An analysis of the development ideologies of the historical period considered in this chapter and the policy framings stemming from them for the Amazon Is discussed in Chapter 13.

With the Agrarian Reform of 1953 in Bolivia and a few years later, in Colombia, Ecuador, and Peru, the colonized land in the region was distributed to settlers. These circumstances gave rise to schemes of dispossession and trafficking of lands inhabited by Indigenous peoples and other traditional groups, which enabled the concentration of land in parts of the Amazon (RAISG 2016).

Although Peru's 1920 Constitution recognized the legal existence of "Indigenous communities," their legal status, their autonomous makeup, and communal ownership of their lands, these rights did not apply to the Amazon Indigenous peoples until 1974, when the first Law of Native Communities of the Peruvian Amazon was enacted (Decree Law 20653, Law of Native Communities and Pro-motion of the Regions of La Selva and Ceja de Selva, Peru). In 1937, the Ecuadorian government was obliged through the first Communes Law to "protect [these] historical communities," recognizing them as beneficiaries of rural lands by the competent authority. However, this was not the case for the Indigenous populations of the rainforests on the Pacific coast and the Amazon because they did not fit into the farmers' economy scheme, where land is a factor of production, and because of the high level of ignorance and stigmatization of their culture. Later, traditional occupation and community lands were the subjects of legislation, and between 1964 and 1994 communal lands were titled in Ecuador over an area of approximately 40,000 km^2. The Agrarian Development Law (1994) recognized the exercise of collective land ownership and access to land titling. In subsequent years, through different codifications of this law, forms of access to collective land of ancestral possession were established, and in 2004, Article 49 of the Legalization Law stated that "the State will protect the lands that are destined to the development of the *Montubio*, Indigenous and Afro-Ecuadorian populations and will legalize them through free adjudication to the communities or ethnic groups that have been in their ancestral possession, under the condition that their own traditions, cultural life and social organization are respected." With the recognition of ethnic groups as beneficiaries, in Ecuador, the spectrum of land tenure was opened beyond the scope of the community, making room for the legalization of a territory claimed by a nationality (Ley de Tierras Baldías y Colonización, Codificación de 2004).

Beginning in 1966, Colombia promoted the creation of Indigenous reserves as a form of provisional collective tenure, and by 1977 these reserves began to be legally recognized as *resguardos*. At the end of the 1980s, territorial rights over 200,000 km² in the Colombian Amazon were recognized. The State adopted the legal regime of "Indigenous Reserves" for recognized territories of collective property of the communities, which have the character of being inalienable, imprescriptible, and unseizable (defined in Article 63, 329 of the 1991 Political Constitution); are a legal and socio-political instance of special character, formed by one or more Indigenous communities, which with a collective property title enjoy the guarantees of private property, own their territory and are governed for the management of this territory and their life by their autonomous organizations, protected by the Indigenous jurisdiction and their own normative system. Along with this, the Constitution recognized these Indigenous managed territories as part of the political-administrative structure of the nation.

In Brazil, in the context of the "Westward March'', the pattern for Indigenous land recognition was to distribute small parcels of land to small communities, which was the beginning of a standard of land tenure that became common in the years since then, but not guided strictly by the law, but by different situations of contact with Indigenous peoples and degrees of acculturation. This pattern tried to facilitate a process much desired by the State of incorporation of Indigenous people in agricultural production. Starting in the 1960s, the Indian Protection Service (SPI acronym in Portuguese) played an important role as an Indigenous "heritage manager", in which context the term Indigenous Land appeared, which would later become part of the Indian Statute in 1973. In 1967, the National Indian Foundation (FUNAI, acronym in Portuguese) was created to fulfill the role of the SPI in the management of Indigenous issues (land, work, and other resources). The creation of FUNAI was framed in the plans of the military government (1964–1984) for development, expansion of the agricultural frontier, and occupation and integration of the Amazon (RAISG 2016).

The Brazilian Federal Constitution of 1988 defines Indigenous Lands as "those inhabited by them on a permanent basis, those used for their productive activities, those indispensable to the preservation of the environmental resources necessary for their well-being, and those necessary for their physical and cultural reproduction, according to their uses, customs, and traditions." They belong to the Union, the Indians (BRASIL, 1988) have permanent possession and exclusive use of the riches of the soil, rivers, and lakes on the lands, and the State is obliged to promote the recognition of these lands.

The first period of incipient recognition of the Amazon Indigenous peoples and their right to land amid the national colonization of the regions was followed by processes of social organization. At the start of the 1980s in Ecuador, an Amazon confederation, currently CONFENIAE (Confederación de Nacionalidades Indígenas de la Amazonía Ecuatoriana), was consolidated; the same as in Peru with the subsidiaries of regional representative bodies such as AIDESEP (Asociación Interétnica de Desarrollo de la Selva Peruana) and others; in Bolivia the CIDOB (Confederación de Pueblos Indígenas del Oriente Boliviano); in Colombia the regional organization OPIAC (Organización Nacional de los Pueblos Indígenas de la Amazonía Colombiana). In Brazil, the regional organization COIAB (Coordenação das Organizações Indígenas da Amazônia Brasileira) was born in 1989 after the 1988 Constitution favored "political representation by delegation" within the Indigenous movement, thus improving dialogue with public institutions, especially to deal with territorial demands (RAISG 2016).

In addition to the demand for the right to land and the reaffirmation of Indigenous cultural identities, an international milestone in the recognition of Indigenous people's rights was the ILO Convention No. 169 in 1989, named Indigenous and Tribal Peoples Convention, ratified by the Amazon States over time.

Towards the beginning of the second half of the 20th century, the institutionalization of areas set aside for the protection of nature was also developing in the countries of the region. It was after the 1940 Pan-American Convention for the Protection of Fauna, Flora and Natural Scenic Beauties (Washington Convention) that several countries advanced with their ratification, towards the creation of the first protected areas. This first effort focused on the protection of transition zones, as in the case of the La Macarena Reserve in Colombia, created in 1948 to protect the significant biological diversity of Andean, Amazon, and Guiana Shield origin. In 1959, the first unit with a strict protection category was created in the Brazilian Amazon (Araguaia National Park), and then in 1960, the first System of National Natural Parks was institutionalized in Colombia. In 1961, Peru established the first protected area in the Peruvian Amazon, Cutervo National Park; Venezuela created the first forest reserve in the Venezuelan Amazon (Imataca); Brazil established new forest reserves in the Brazilian Amazon; and Bolivia created its first Amazon protected area, Isiboro Sécure National Park, in 1965. This was possible soon after in Ecuador, when in 1970, two conservation units were created in the Amazon, both in the Andean–Amazon foothills (RAISG 2016 and Supplemental Information annex).

The designation of protected areas (PAs) in the early twentieth century did not follow a standard, and each nation used its own approach to management. In 1962, during the First World Conference on National Parks in Seattle, the IUCN's newly formed Commission on National Parks and Protected Areas (CNPPA), now the World Commission on Protected Areas (WCPA), presented a paper on nomenclature for the categorization of protected areas (PAs). The Second World Parks Conference in 1972 called on IUCN to define types of protected areas and develop suitable standards and nomenclature for such areas, which was the background to the CNPPA decision to develop and periodically update over time a categories system for protected areas (PAs). This system eventually secured its endorsement by the Convention on Biological Diversity at the 7th Conference of the Parties to the CBD in Kuala Lumpur in February 2004 (Dudley 2008). This endorsement, as well as new norms of conduct entailing commitments from the countries, such as the 1992 Convention on Biological Diversity (CBD), triggered the development of new mechanisms and policy instruments (decrees, regulations, laws, codes or strategies and national programs), now better articulated to a centralized institution responsible for protecting a cultural and natural legacy during developmental processes in the Amazon biome of the countries that occupy the basin. These are the antecedents of the institutionalization of the current national systems of conservation units (SNUC in Brazil) or of protected natural areas (INPARQUES, SNAP, SINANPE or SINAP) in the Andean–Amazon countries.

16.1.1 Protected Natural Areas: Extent of the coverage and categories of protection

In the Amazon basin demarcated for this study, there are currently 571 protected areas (PAs) (Map 1) (RAISG 2020), some with a certain level of overlap between them, which are grouped depending on the administrative type, that is, which entities manage them (national, departmental, municipal, or private), or by the level of environmental protection or conservation they pursue. In this sense, the protected area where the protection objective is key, the permitted use is called indirect. This type of use permitted would be the equivalent of IUCN categories I, II, and III. Protected areas (PAs) of indirect use include most national parks, natural monuments, nature reserves, among others. In addition, there are protected areas (PAs) for direct use, where the extraction of natural resources is allowed, in principle, under a strategy of sustainable use of the resource. A third type is protected areas (PAs) with indirect/direct use, where internal zoning is what defines what type of territorial management each zone has. This grouping of management categories by type of use is the one used by the RAISG (Amazon Network of Georeferenced Socio-environmental Information), whose database updated through 2020 was used to obtain the figures presented here. The distribution for each country of the Amazon basin, in terms of quantity and surface area, is presented in Table 16.1, calculating the net protected area, without overlap. Guyana, although part of the basin, does not have protection figures in that area.

The protected area in the basin represents 25% of its surface, of which 59.6% is administered at the national level and the remainder at the departmental or state level (Table 16.2). The municipal level and private reserves were not considered due to limitations in access to this information and due to the small area that they represent. By country, the protected proportion varies between 21% and 51%; Peru has the lowest proportion of protection of its national Amazon basin and French Guiana has the highest. On the other hand, 42.2% of the protected surface is under the categories of indirect use, 57.6% is in categories of direct use and the remaining 0.2% in other categories.

The protected areas (PAs) for direct use are made up of a set of 342 units, in five of the seven countries represented in the Amazon basin. Brazil is home to 66% of these areas, grouped into 10 categories, Bolivia 21%, distributed in 27 categories, Peru 11% in six categories and the remaining 2% are held by Colombia and French Guiana. The name or category does not always reflect the type of management that is conferred on it. For example, in the case of Bolivia and French Guiana, there are areas of direct use that are National Parks and Natural Parks, which are considered areas of preservation and indirect use in most of the countries of the basin. To know the actual objective of the PNA in these cases, it is necessary to review their creation objectives and management plans. Furthermore, in Bolivia, protected areas (PAs) recognized by the Constitution can be autonomous Indigenous territorial entities at the same time, and they are not seen as mutually exclusive but even complementary (as is the case in Colombia).

The declaration of protected areas (PAs) in the basin since 1940, when the first was decreed, reached a maximum in terms of number in the period 2000–2009, a trend observed at the national level in Brazil, Bolivia, and French Guiana. In the case of Peru, the periods 2000–2009 and 2010–2019 are equally relevant, due in part to the growth of the protected areas (PAs) of Peru's largest Amazonian department, Loreto, during the period 1999–2018 (Pitman et al. 2021). The exceptions are Colombia and Ecuador, with the most areas created between 2010 and 2019. In the case of Venezuela, the protected areas (PAs) were established prior to 1999.

The growth in the number of protected areas (PAs) can be seen for the basin and for Brazil, reflected in the continued increase in surface area of protected area up to 2009 (Figure 1). However, the correlation does not hold for Bolivia, which, together with Peru and Colombia, had the greatest increase in protected area in the decade 2010–2019 (Figure 16.1). The regional trend over time has been towards an increase in the protected surface area, with the exception of French Guiana and Venezuela, which remained stationary for the last two periods (200-2009 and 2010-2019) and Ecuador with little variation.

In terms of the size of area designated as protected area, most countries have set aside significant extensions well before the 1990s, enacting decrees and laws at various levels to allow the designation,

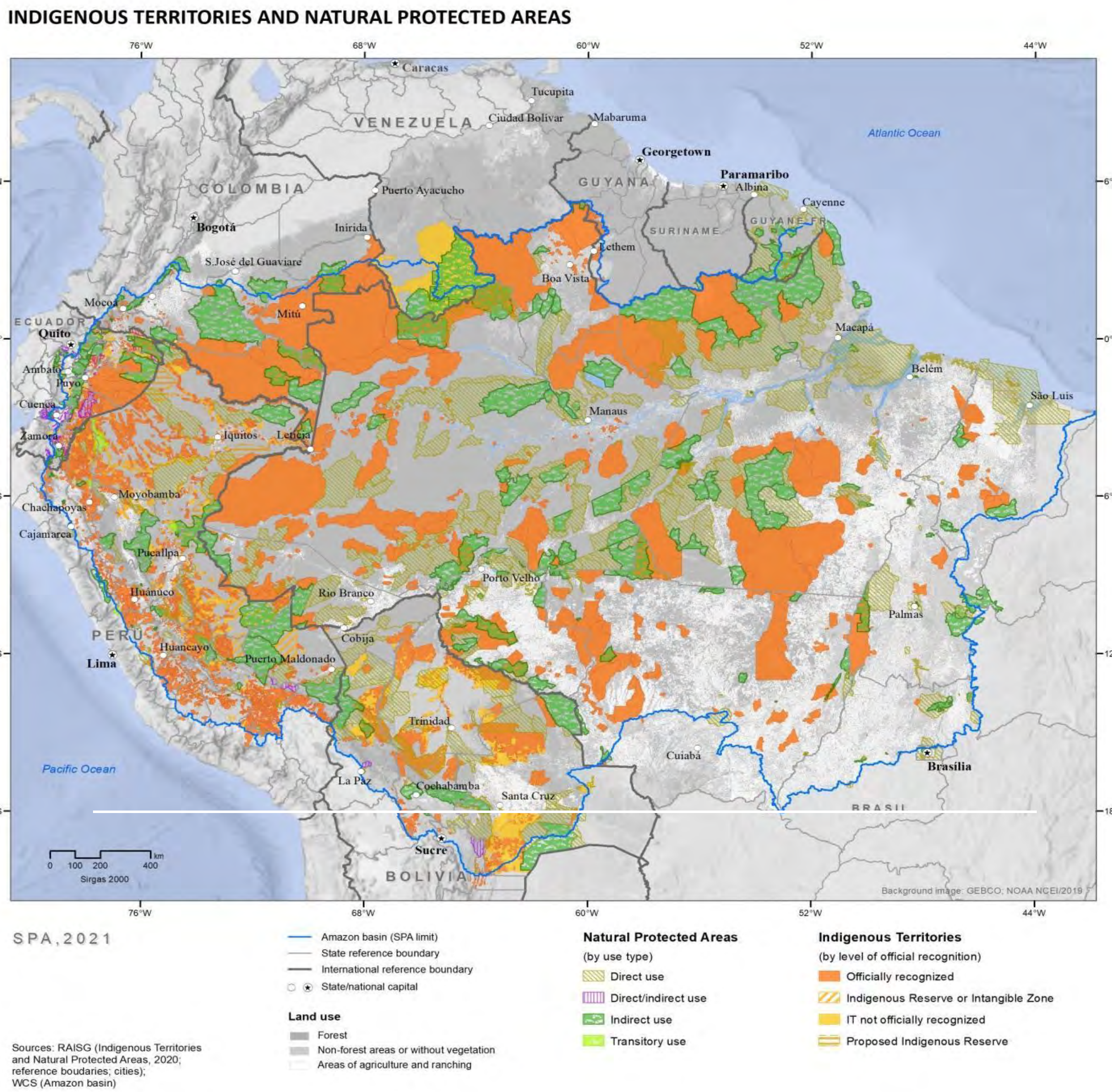

Figure16.1 Historical dynamics of the surface area covered by ANPs in the Amazon basin

Table 16.1 Coverage of Protected Natural Areas in the Amazon Basin

Territorial Unit	Number of Protected Natural Areas	Protected Surface Area without overlap (km^2)[1]	Distribution of total protected area in the Amazon basin (%)	Percentage of the Amazon basin area in each country set aside as protected area
Bolivia	81	216,322	11.9	30.3
Brazil	340	1,226,241	67.4	24.3
Colombia	39	89,091	4.9	26.0
Ecuador	26	35,487	2.6	26.8
French Guiana	5	12,685	0.7	50.7
Peru	66	203,916	11.2	21.1
Venezuela	6	23,838	1.3	46.0
Amazon Basin	563	1,819,368	100.0	24.9

Table 16.2 Protected Areas in the Amazon basin by administrative level and type of management. Percentages reflect the area in each category type relative to the area occupied by the Amazon Basin in each country. The last column (Amazon Basin) provides the percentages for the whole Amazon Basin.

	Percentage %							
ANP	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Peru	Venezuela	Amazon Basin
National total	14.1	13.2	25.7	26.3	51.5	17.8	50.7	15.1
Indirect use	6.8	6.6	25.5	26.3	41.0	10.7	50.7	8.8
Indirect/direct use	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Direct Use	6.8	6.6	0.2	0.0	10.5	6.5	0.0	6.1
Departmental total	16.7	11.8	0.3	0.5	0.0	3.2	0.0	10.2
Indirect Use	0.0	2.6	0.3	0.5	0.0	0.0	0.0	1.8
Direct Use	16.7	9.2	0.0	0.0	0.0	3.2	0.0	8.4
Total	30.7	25.0	26.0	26.8	51.5	20.9	50.7	25.3

administration, and regulation of protected land. Many of the areas were delimited overlapping Indigenous territories, which were not recognized at the time. Another important period of protected area designation and, more importantly, of institutionalization and, therefore, enhanced planning and resourcing of national systems of protected areas (PAs), is clearly associated with the Earth Summit of 1992, which, aside from achieving international commitments from countries of the Basin, favored the political treatment of conservation as an issue of collective interest. Moreover, future national constitutions included the States' obligation to promote the conservation of biological diversity and guarantee for its citizens safe environmental conditions and access to natural resources. Another trigger for protected area designation and enhanced management was the large amounts of international funding for conservation programs specific to the Amazon, for example, the ARPA program in Brazil that started in 2002.

Regarding the administrative competence, we find that the growth of the protected areas (PAs) in departmental areas was greater in the last 20 years than that of the national areas (142% and 101%, respectively), although the national ones represent 60% of the protected surface area in the Basin. This situation needs to be considered to ensure human and financial resources are in place to guarantee the conservation and sustainable use objectives that they were created for.

On the other hand, even though the growth in protected area can be considered an achievement in terms of protection of the Amazon ecosystems, there is a concern associated with the type of use of these protected areas (PAs), as 57.4% is for direct use, that is, they do not have conservation as their primary objective (IUCN categories I-III). In parallel with the designation of new protected area, there has also been a process of downgrading, downsizing and degazettement (See Box 16.1).

The direct use area category corresponds to the smallest overall surface area (40.6%), but this category experienced the highest percentage growth in surface area in the period 2000–2019 (79.8% versus 63.8%) (Table 16.3). In the case of the departmental protected areas (PAs), 82.2% are for direct use. The greater proportional increase in the surface areas for direct use can account for a permissiveness that jeopardizes the conservation objectives within the areas and the connectivity between protected areas (PAs) designated for stricter conservation purposes, as their category is of direct use which does not guaranty effective conservation. The countries in which the protected areas (PAs) for direct use represent a greater area of their total protected area are represented by Brazil and Bolivia. In Brazil, the surface areas for direct use represent 63.1% of the total protected areas (PAs); in Bolivia, it represents 76.4%.

16.1.1.1 An assessment of the degree of effective protection

Evaluating the effectiveness of protected area management is a key element in progress towards the CBD Strategic Plan and its Aichi Targets, especially Target 11, which addresses the contribution of a protected area system that is managed effectively and equitably (Hockings *et al.* 2015). The management effectiveness evaluation refers to: i) design aspects, both of individual sites as well as of protected area systems; ii) adequacy and appropriateness of management systems and processes; and, iii) delivery of protected area objectives (Hockings *et al.* 2006).

In 2008, as part of the regional efforts for the implementation of the Programme of Work on Protected Areas of the Convention on Biological Diversity (PoWPA CBD), the Latin American Technical Cooperation Network on National Parks, other Protected Areas, Wild Flora and Fauna (REDPARQUES, acronym in Spanish) with the support of the CBD Secretariat, WWF, IUCN, the Organization of the Amazon Cooperation Treaty (ACTO), and the Andean Community of Nations joined to launch the program Vision for the Conservation of the Biological and Cultural Diversity of the Amazon Biome based on Ecosystems (Amazon Conservation Vision). Its mission is to: contribute to the administration and effective management of the national systems of protected areas (PAs); contribute to the maintenance of goods and services, integrity, functionality, and resilience of the Amazon biome against effects of natural and anthropogenic pressures in the context of climate change; and to benefit economies, communities, and biodiversity. The Amazon Conservation Vision has a 2010–2020 Action Plan, structured around the PoWPA elements to comply with the CBD Aichi Targets, and a Strategic Plan for the 2018–2022 period.

In recent years, REDPARQUES has made an outstanding effort to evaluate, at the biome level, the management effectiveness of its protected areas (PAs) with a focus on two objectives contemplated in the PoWPA: objective 1.4, related to improving the planning and management of site-based protected areas (PAs) , and objective 4.2 related to the evaluation and improvement of the effectiveness of protected area management. The results show that in each of these objectives, significant progress was made in creating strategies to strengthen the national systems of protected areas (PAs), facilitating their management and governance, "a factor that has allowed the States to comply with the commitments of the CBD'" (REDPARQUES 2016), even when important gaps have been identified for protection beyond the formally established protected areas (PAs), that is, against representativeness, territories conserved by Indigenous peoples and local communities, and efficiently are observed in light of the highest international standards, as is the case of the IUCN Green List of Protected and Conserved Areas "whose nomination implies the most thorough analysis of world-class management effectiveness standards" (REDPARQUES 2016). Peru achieved two certified Amazon protected areas (PAs) in 2018, the Cordillera Azul National Park and the ECA Amarakaeri. In 2020, seventeen protected areas (PAs) from the Amazon biome in Bolivia, Colombia, Ecuador, and Peru started the certification process for the Green List standard (UICN 2020).

Tools have been developed and applied to analyze the effectiveness of the management of protected areas (PAs) of transboundary territories, such as the Trinational Program for Conservation and Sustainable Development of the Corridor of Protected Areas in Putumayo (Colombia, Peru and Ecuador), 3 mosaics (ecological corridors) in Brazil, the binational corridor Vilcabamba-Amboró (Peru and Bolivia), among others.

In terms of management effectiveness, the Amazon Conservation Vision showed the need to jointly interpret the variables of the national tools from a regional perspective to identify reference indicators that contain elements pertinent to the Amazon countries, to analyze how protected areas (PAs) contribute to the conservation of the biome from a regional perspective (Navarrete 2018)~~.~~ This need was addressed in the protocol for the measurement of management effectiveness of the Amazon biome, where the priorities identified: governance, climate change, evaluation of socio-environmental impacts, management programs, and compliance with the conservation objectives of the protocol, were considered for the components of the IUCN Green List Standard (IUCN et al. 2019).

This protocol, made up of 26 indicators, was applied in 62 Amazon protected areas of Bolivia, Brazil (Acre State), Colombia, Ecuador, and Peru. The main results for the indicators considered a priority are presented in Table 16.4 (REDPARQUES 2019). Based on these results, it is evident that up-to-date management programs (in place) is a theme that presents the least progress at the scale of the Amazon biome, followed by those of climate change and impact assessment. Those with the highest levels of effectiveness at the level of the Amazon biome are related to achievement of the conservation goals and governance.

As a result of the application of the protocol, the following recommendations for success in the management of protected areas (PAs) in the Amazon biome stand out (REDPARQUES 20190):

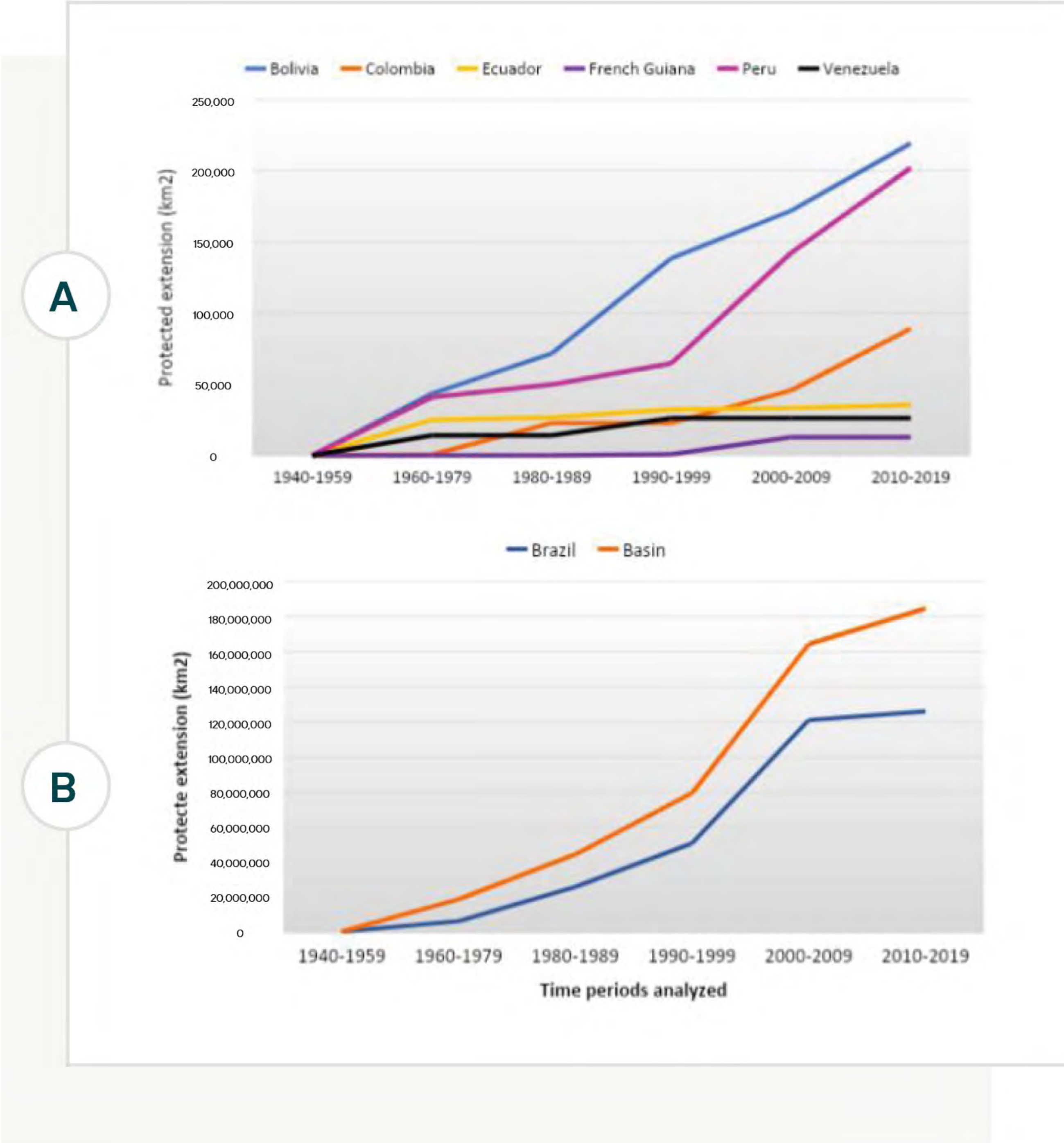

Figure 16.2 Historical dynamics of the surface* (A) area covered by ANPs in the Amazonian countries and (B) area covered by ANPs in Brazil and the Amazon

Box 16.1 Protected areas downgrading, downsizing, and degazettement (PADDD)

In the previous text, changes in the protected areas' limits, size, or category have been briefly mentioned. Studies that have analyzed PADDD, the processes by which protected areas (PAs) have changed in boundaries, reducing their spatial extent, diminished in their protection category, or eliminated over time, have found that historically the world has lost hundreds of thousands of square kilometers of protected land through this process. Here, we review some literature about this process and its effects in more detail for some Amazon countries.

A paper from 2014 (Mascia *et al.* 2014) alerted about this issue around the world. Despite agreements of the Parties to the Convention on Biological Diversity (CBD) to increase the global extent of protected areas (PAs) to 17% of national lands, PADDD has been occurring for years and has grown over time, impacting the achievement of the CBD land protection goal in some countries. Of the three, downsizing is the most common event and appears to be linked to industrial agriculture expansion, local land claims or resettlements, among other multiple causes, whereas mining and infrastructure are the most common causes for the downgrading of protected areas (PAs) (Mascia *et al*. 2014).

Although PADDD could be used as an option for better conservation planning, prioritized allocation of resources (Fuller *et al.* 2010; Kareiva 2010), tradeoffs between competing policy objectives (Bass *et al.* 2010), or the fair recognition of land rights (Dowie 2009), the analysis showed that a majority of PADDD events are a consequence of industrial-scale activities and local pressures (Mascia *et al.* 2014), and far from conservation objectives.

Looking more specifically into the Amazon countries, a study examining PADDD events in Brazil since 1900 (Pack *et al.* 2016) found that 70% of the analyzed PADDD events have occurred since 2005. Forty-eight events affected 88,341 km^2 of protected lands in the Brazilian Amazon. Ten active proposals related to PADDD would alter an additional 65,715 km^2 of conservation units in the Brazilian Amazon, with 42% of this area in strictly protected areas (PAs) and the remaining 58% in sustainable-use protected areas (PAs) .

Again, this study shows that among the enacted PADDD events, area downsizing is the most common and has had the most impact on Amazon protected areas (PAs), as compared with other biomes, with many of the altered sites considered biologically irreplaceable based on their representativeness and vulnerability (Pack *et al.* 2016). PADDD became more prevalent in Brazil since the early 2000s and is linked to hydropower development in 39% of the cases. Within the Brazilian legal Amazon, PADDD has resulted in the removal of 72,136 km^2 of land protected in conservation units, both federal and departmental. Several of the studies cited in Pack *et al.* (2016), Araújo *et al.* (2012), Bernard *et al.* (2014), Ferreira *et al.* (2014) highlight the need for a clear legal process for PADDD. As opposed to the creation of protected areas (PAs), which has well-defined technical and legal steps, the proposal or enactment of PADDD lacks a clear national policy and legally it can proceed without technical studies, solely based on a specific, ad-hoc law (e.g., a decree or provisional measure issued by an authority), all of which impedes transparency of the process. In most cases the process does not include clear geographical documentation about the area to be altered, making it difficult to track the event. In 2018, the Supreme Federal Court of Brazil considered the use of a Provisional Measure to change the category, reduce, or extinguish conservation units to be unconstitutional. The Provisional Measure is an exceptional legislative instrument in the Brazilian legal framework that is based on the relevance and urgency of the

Box 16.1 Protected areas downgrading, downsizing, and degazettement (PADDD) (cont.)

issue in question, has the force of law, determines validity and is edited by the President, and must be approved by the Legislature to become law. Although the decision does not guarantee reversibility to the provisional measures already applied, the judgment of the Direct Action of Unconstitutionality[a] establishes the unconstitutionality of future attempts to use this figure to void the environmental safeguards.

In Ecuador PADDD events, as analyzed by López-Acevedo (2015), have been mostly characterized by the reconfiguration of limits with the aim to exclude extractive areas from protected areas (PAs). As a result, the extent of the affected protected areas (PAs) ended up being larger, though not necessarily a better fit for conservation. There have also been elimination of protected forests to allow for mining concessions. According to the Environmental Code in force, "if necessary and considering the results of such technical evaluations, the National Environmental Authority may re-delimit them [the protected areas] or change their category under technical considerations, as appropriate." This leaves rather open the legal procedure for any PADDD event, especially in terms of the discretionary decision by the environmental authority.

In Peru, any modification of a national-level protected area can only be enacted through a law issued by the national congress (RAISG 2016). As of 2016, two events have occurred in the Peruvian Amazon-protected areas (PAs). One resulted in the subdivision of an existing reserve (transitory category) in three types of protected land, but downsizing the initial extent of the reserve. The area eliminated was concessioned to mining companies (Decreto Supremo No. 023-2007-AG).

For Colombia and Venezuela, there are no reports of PADDD events in their protected areas (PAs).

- Strengthen shared management agreements (established and signed) between the administration of protected area (PAs) and local communities/traditional authorities that favor the implementation of conflict resolution mechanisms.
- Strengthen the perception of protected area (PAs) as a source of benefits for local communities and direct users and strengthen the concerted mechanisms for the distribution of benefits.

- Implement sustainable and productive economic alternatives within the protected areas (PAs) and in their area of influence, improving the quality of life of local people.
- Generate information applicable to management, which enables validation on the state of biodiversity conservation and the cultural value of protected areas (PAs).
- Improve institutional capacities for the management and handling of protected areas (PAs), considering the implications in terms of governance.
- Implement land use planning strategies that focus the management of the protected areas (PAs) on their integration with the regional context, favoring connectivity, biological corridors, and conservation at the landscape scale; and,

  Visualize protected areas (PAs) as strategies for adaptation and conservation in the face of climate change and promote the generation of inclusion mechanisms at the regional level to strengthen management around climate change and its impacts.

Table 16.3 Growth by periods in the area protected (%) in the Amazon Basin considering the administrative level and type of use (protection category).

	Time period		
	1980-1999	2000-2020	Total
National	19.7	39.8	59.6
Indirect use	12.6	22.3	34.9
Indirect/direct use	0.03	0.14	0.2
Direct use	7.1	17.1	24.2
Departmental	11.8	28.6	40.4
Indirect use	0.4	6.8	7.2
Direct use	11.4	21.8	33.3
Total	31.5	68.5	100.0

Table 16.4 Level of progress in the management effectiveness at the scale of the Amazon biome based on thematic priority (in percentage, from the sample of 62 evaluated PA). Created from the data reported in REDPARQUES - IAPA Project (2019).

Themes	Progress Level (%)				
	High Level	Medium Progress	Low Progress	Limited Progress	n/a
Governance	52	32	8	5	3
Climate Change	37	6	0	0	57
Assessment of socio-environmental impacts	45	48	2	5	0
Management programs (management strategies)	26	55	13	2	4
Achievement of the conservation goals of PA	89	3	2	0	6

This set of recommendations that emerged from a biome-specific analysis indicates that what is most lacking in the Amazon is the implementation of an integrated conservation vision, where protected areas (PAs) together with other effective area-based conservation measures (OECMs) are planned with well-defined goals for biodiversity and ecosystem services conservation, co-managed with the local communities, and involve private stakeholders and other sub-national and local forms of government. Information to design effective site networks exists for the Amazon and elsewhere (Prüssmann *et al.* 2017; RAISG 2020; Maxwell *et al.* 2020). The constituent parts for this kind of conservation network are abundant in the Amazon given the extent of protected areas (PAs) and Indigenous territories (ITs) coverage, intact forests, and other private and community-based conservation and sustainable use areas. However, there are significant challenges, particularly those related with protected area resourcing and biodiversity protection effectiveness tracking (Maxwell *et al.* 2020). Based on the significant correlation between protected area resources (budget and staffing) and positive changes in vertebrate abundance (Geldmann et al. 2018 in Coad *et al.* 2019), an analysis comparing protected areas (PAs) of four biogeographical realms of the world (excluding North America, Western Europe and Australia), in terms of adequacy of resources, found that protected areas (PAs) of ecoregions in the Neotropics had the lowest scores (Coad *et al.* 2019). When geographic ranges of thousands of vertebrate species were overlapped with the scored protected areas (PAs), results show that only a very low percentage of the species are adequately protected: using simple protected area coverage metrics to measure progress toward Target 11 of Convention on Biological Diversity, under the assumption that all protected areas (PAs) are effective, is likely to overestimate effectively protected area coverage by approximately 400% and vertebrate species representation by up to 700% (Coad *et al.* 2019). For the Amazon region, Prüssmann *et al.* (2017) show that there is a reduced number and extension of protected areas (PAs) with strict conservation categories (IUCN categories Ia and Ib). In some countries in the Amazon region, these categories are even non-existent. On the other hand, Category VI, which allows sustainable use of natural resources, is the category most implemented within the region, as also indicated above in Section 1.1. Aggravating the situation, the current economic downturn in the region's nations, combined with low political priority given to environmental conservation issues, could widen the financing gap of all protected areas (PAs) in the Amazon. The magnitude of threats that currently affect protected areas (PAs) is discussed in Section 1.3 of this chapter.

16.1.2 Indigenous Territories

16.1.2.1 Indigenous territories governance as a conservation example

Ensuring the integrity of the ecosystem in the Amazon is a global priority in the environmental crisis we are experiencing today. For this, it is essential to understand the close link between ecological dynamics and the knowledge and territorial management systems of Indigenous peoples who have inhabited the region for thousands of years, ensuring the conservation of vast territories. This section begins with the definition of the concept of Indigenous territory, which will enable a better understanding and contextualization of its content.

Article 13 of Convention 169 of the International Labor Organization, which is a guiding force in these matters since the countries of the region ratified the Convention, highlights that territory means "the entire habitat of the regions that the peoples in question occupy or use in any other way." In Brazil's Federal Constitution (1988), the lands traditionally occupied by Indigenous people are those "they permanently inhabit, those used for their productive activities, those essential for the preservation of the environmental resources necessary for their well-being and for their physical and cultural reproduction, according to their uses, customs, and traditions." Colombian legislation (Decree 2,166 of 1995. Law 160 of 1994) specifies that Indigenous territories are "areas owned regularly and permanently by an Indigenous peoples group and those that, although not controlled that way, constitute the traditional scope of their social, economic, and cultural activities."

Indigenous peoples' groups have traditionally and immemorially occupied a territory they consider their own. According to this cultural worldview, this original Indigenous territory was predestined to each group by the creators and bequeathed to each group by their direct ancestors. From this perspective, Indigenous territory refers to the ancestral territorial jurisdiction of each ethnic group. Roughly speaking, the peoples that identify themselves as part of these jurisdictions recognize them as territorial spaces culturally defined by their knowledge systems expressed in their historical origin. In turn, the continuous ancestral territories that constitute this macro-Indigenous territory show complementarity in ecological and geographical aspects (ACIMA - Asociación de Capitanes Indígenas del Mirití Amazonas 2018). Most of these systems of traditional thought share "cultural principles" that are related to what the non-Indigenous world has defined as conservation models, since they result in the protection of biodiversity and ecosystems.

According to Fundación Gaia Amazonas (2020a), based on studies in a region of 1.3 million km^2 in the northwest Amazon, connecting areas belonging to two hydrographic basins of the Amazon: basins of the upper Negro–Vaupés River and lower

Table 16.5 Indigenous territories (ITs) in the Amazon Basin

Territorial Unit	Number of ITs	Surface area (km²)	Distribution of ITs area of the Basin (%)	% of the Amazon Basin recognized as IT
Bolivia	148	189.037	9.6	26.5
Brazil	382	1.153.843	58.6	22.8
Colombia	162	185.852	9.4	54.3
Ecuador	643	73.957	3.8	55.9
French Guiana	4	3.271	0.2	13.1
Peru	5.060	328.183	16.7	34.0
Venezuela	17	29.259	1.5	56.5
Amazon Basin	6.443	1.968.594	100.0	27.0

Caquetá–Japurá, in Colombia and Brazil, the description of the ancestors' journey for the settlement in the areas that these peoples currently occupy is described in the origin stories, which provide precise details that explain the relationship that exists between the territory's geography and traditional knowledge, and daily life practices and rituals of each group. This thinking and management framework constitutes a conservation model that includes deep and detailed geographical knowledge, ancestral population models of the territory, management of sacred sites systems, food systems, and ecological calendars, among other aspects, as the current basis of the governance of Indigenous territories that explains the complex and complete vision of the territory they share (see also Chapter 10). Maintaining the balance of this original ordering implies new generations assuming commitments and responsibilities related to learning management knowledge and respect for the regulatory regimes established in the laws of origins. The latter is one of the main challenges for the conservation of the Amazon, given the share of land under Indigenous management, the growth of its population, lack of income sources, and the increasing tensions within the context of cultural globalization (Chapter 13), accelerated by social media and mobile communications more broadly. Furthermore, the lack of governmental attention paid to these sparsely populated territories exacerbates the risk from increased pressures due to an escalation of illegal activities (e.g., mining, logging, land trafficking, illicit crops) within these territories (processes well explained in Chapter 13, section 3.3).

16.1.2.2 Recognized Indigenous territories: Extent of coverage and state of recognition

There are currently 375 or more Indigenous peoples (Walker *et al.* 2020) in the Amazon, depending on the sources and the geographic limit that is used (RAISG 2020), with a total population estimated at approximately 2 million. If all the other social groups that live there are counted, both in the urban municipal capitals as well as in farmer, black, and *quilombo* settlements, the Amazon is inhabited by more than 40 million people.

In the Amazon Basin demarcated for this study, 6,443 Indigenous Territories (IT) are identified (Map 1) (RAISG 2020), which cover approximately 27% of the region (Map 1, Table 16.5). The country with the highest number of titles of Indigenous Territories is Peru, followed by Ecuador, which, when considering the area, indicates that many are areas with small surface. The average area of Brazil, Venezuela, Bolivia, Colombia, and French Guiana range in decreasing order between 3,021 and 818 km². At the other extreme, Peru, Ecuador, and Guyana account for average areas ranging from 65 to 192 km2.

This is indicative of different policies; in the former, Indigenous territories (ITs) are considered as a large territorial unit, i.e., the macro territories described in the previous section, and in the other case, a reduction is generated, associated with the existing procedures and requirements for their recognition (Peru's case is further explained in Section 1.2.4 of this Chapter).

Four types of classes were identified in the basin regarding the legal recognition of the territories (Table 16.6), of which 89% of the surface area in Indigenous territories (ITs) is officially recognized, 6.5% does not have legal protection, and the remaining 4% covers Indigenous Reserves (proposed or existing) and Intangible Zones. Indigenous Reserves and Intangible Zones (depending on the country) are territories for the protection of Indigenous Peoples in Voluntary Isolation or Indigenous Peoples in Isolation and Initial Contact (PIAV and PIACI, acronyms in Spanish).

At the national level, countries such as Brazil, Colombia, and French Guiana stand out, where all the Indigenous territories are officially recognized. Although in the case of Brazil, this is not quite the case because many of the Indigenous territories (ITs) are in an unfinished process of recognition. Since 1988 in Brazil, the executive power has had the responsibility to complete the demarcation of the Indigenous territory within five years, but this has not occurred timely. Currently, in addition to the demands that have not even had their legal recognition process initiated, there are 114 Indigenous territories (ITs) being reconsidered because, among other things, of the lack of match between the territory identified before 1996 and the actual extent of the claimed ancestral land (Fany Ricardo, *personal communication, Aug2020)*. In contrast, Venezuela only has territories that are not yet considered to be legally recognized.

From a regional historical perspective, before 1970, less than 6% of the total surface area of the Amazon had some type of recognition, mostly concentrated in the Indigenous lands of Brazil (RAISG 2016). In the following two decades, additional areas were recognized in Brazil, Peru, Colombia, and Ecuador under different forms according to existing national regulations. Since the 1990s, extensive surface areas of Indigenous territories (ITs) were recognized in Bolivia, Ecuador, and Peru in response to claims for territorial rights based on the demands of the Indigenous movement— and supporting organizations—at the juncture of 500 years of resistance in 1992 (RAISG 2016). Details of the recent historical context in which the process of recognition and formalization of Indigenous territories in the Amazon countries occurred are discussed in the Supplementary Information Annex and Chapter 10.

Table 16.6 Recognized Indigenous Territories in the Amazon Basin

Country	Officially recognized Indigenous Territory (km²)	Indigenous Territory without official recognition (km²)	Indigenous Reserve or Intangible Zone (km²)	Proposed Indigenous Reserve (km²)
Bolivia	123.208	65.828		
Brazil	1.153.843			
Colombia	185.852			
Ecuador	51.804	10.222	11.931	
Guyana	5.192			
French Guiana	3.271			
Perú	233.510	23.557	29.129	41.988
Venezuela	0	29.223		
Amazon Basin	1.756.716	128.830	41.060	41.988

16.1.2.3 Existing policies for Indigenous Peoples in voluntary isolation (PIAV and PIACI, acronyms in Spanish)

In the region, Brazil is the country with the greatest number of records of the presence of isolated Indigenous peoples, from groups formed by hundreds of people to those reduced to a few survivors (Opas *et al.* 2018). In the Brazilian Amazon, 120 records have been identified, located in 55 Indigenous lands and 24 conservation units, of which 28 have been confirmed. Although not consistent with official Indigenous policy, there are still eight areas with no protection mechanism (Ricardo and Gongora 2019). With the 1987 shift towards the autonomy of Indigenous peoples, FUNAI played an important role as a regional reference in relation to PIAV policies. It was established as official policy in Brazil that “the verification of the existence of isolated Indigenous people does not necessarily determine the obligation to contact them” (Portaria No. 1900 / FUNAI of July 1987). In this way, reversing the logic of the contact agents of previous times, it takes advantage of the information accumulated over decades to identify, demarcate, monitor, and protect the territory of peoples without physical contact with those populations (Torres *et al.* 2021).

In 2018, in the Peruvian Amazon, the Ministry of Culture reported the existence of approximately 7,000 people belonging to 18 Indigenous peoples in a situation of isolation and initial contact (PIACI). Between the 1990s and 2005, five Territorial Reserves were created in Peru in perpetuity, and studies were prepared that proposed the creation of a few others. However, it was not until the 2000s that specific regulations were developed to guarantee the protection of PIACI. Law 28736, approved in May 2006, established that if there is evidence of the presence of PIACI in an area, Indigenous reserves will be created. Article 2 of the regulation defines these areas as “Lands delimited by the Peruvian State, of temporary intangibility, in favor of [the PIACI] [...], and as long as they maintain such situation, to protect their rights, their habitat and the conditions that ensure their existence and integrity as peoples”. The emphasis on transience indicates that Reserves are only recognized temporarily or under conditional circumstances. Also, although Article 5 of the law grants intangibility to these areas, Article 6 establishes a series of exceptions to this condition. These provisions are expanded in the regulation of the law, approved in 2007 and modified in 2016 (DS 008-2016-MC), which adds the use of natural resources within the Reserves when the State "... deems it of public necessity". This modification puts the survival of these peoples at risk because there is no clarity regarding the criteria in which a public need is established. Currently, there are three Indigenous Reserves (adjusted from the former Territorial Reserves), two Territorial Reserves, and proposals for the creation of six Indigenous Reserves in the Peruvian Amazon (https://bdpi.cultura.gob.pe/piaci).

As in Brazil, although currently to a different degree, the advance of territorial recognition and the effective work of protection systems in Peru are facing opposing interests from the governments themselves in promoting investment and large infrastructure in the Amazon. Likewise, the protection system for these reserves does not manage to effectively confront activities such as illegal timber extraction and drug trafficking, which are proven to be present in the territories of these peoples, which is a common scenario throughout the Amazon basin (Vaz 2019).

In 1979, Ministerial Agreement MA322 designated the Yasuní National Park (PNY) in Ecuador. During the following years, reports of random encounters and violent or fatal attacks made evident both the presence of uncontacted groups near PNY, and the need to delimitation of an area large enough to ensures their protection. In 1999, Executive Decree ED552 established the Tagaeri Taromenane Intangible Zone (ZITT) in the Eastern portion of the PNY, and banned “...in perpetuity, all kinds of extractive activities” within this area. However, little or nothing was done to effectively protect these groups: the map of oil concessions underwent only small variations, and the farming frontier, tourism, deforestation and illegal logging, the incursions of explorers, religious missions, and adventurers all augmented the threats and pressures to these territories and worsened pre-existing conflicts with the newly contacted Waorani people. Accordingly, in 2006, the OAS' ICHR (Organization of American States' Interamerican Commission for Human Rights) requested the Ecuadorian government "to adopt effective measures to protect the life and integrity of the people living in voluntary isolation, the Tagaeri-Taromenane", within the ZITT. With ED21872 in 2007, the ZITT limits were created (resulting in an area of 758,051 ha), with a buffer zone of 10 km around it, and a plan of Precautionary Measures for the protection of uncontacted groups was designed and implemented through a national policy. In 2008, the national Constitution (article 57) declared the ancestral and irreducible possession of their territories; however, in 2013, the National Congress approved a resolution declaring oil exploitation within blocks 31 and 43 of national interest; these blocks partially overlap with the northeastern areas of the ZITT. In 2018, a national consultation process approved an increase of at least 50,000 ha in the ZITTs area, which granted a total area of 818,501ha to the ZITT, but also altered and abolished various articles from the ED21872 of 2007, allowing hydrocarbon perforation and exploitation platforms within the buffer zone.

16.1.2.4 Risks to recognized Indigenous territories and other conservation policies due to recent policy changes: Cases from Brazil and Peru

Brazil

Contrary to constitutional rights achieved over many years of struggle by Indigenous and traditional peoples and civil society movements, the current government of Brazil (2019 until present) seeks to eliminate the social, cultural, and material reproduction of Indigenous, *quilombola*, and traditional peoples, including violation of their territorial rights. These rights were unjustly announced as an obstacle for agribusiness and development (Escobar 2018; Ferrante and Fearnside 2019; Araújo 2020; Andrade *et al.* 2021; Vale *et al.* 2021) (see also Chapter 30) given that small-scale agriculture is responsible for most of Brazil's food production, rural employment, and agricultural income (Paulino 2014). The conflict is not about production but comes from the eagerness of access to land under Indigenous tenure to put in action a paradigm shift in public policies. This new paradigm aims to reestablish the ideological, political, and economic project of the period prior to the re-democratization—Federal Constitution of 1988— (see Chapters 13 and 14), in favor not only of agribusiness interests but also of the exploration of the subsoil of Indigenous lands, to weaken their territorial rights while simulating the transformation of Indigenous peoples into some sort of business partners.

In 2019, a drastic proposal for a ministerial structure was presented, and although some points were later revised, the initial proposal subordinated the recognition of Indigenous and *quilombola* territories to the Ministry of Agriculture. In fact, most of the proposals under the actual government are connected to the agribusiness caucus, a historical opponent of the democratization of access to land in Brazil, as widely evidenced (Torres *et al.* 2017; Opas *et al.* 2018; Oliveira 2021; Urzedo and Chatterjee 2021). According to Rajão *et al.* (2020), a small but very destructive portion of the sector poses a threat to the economic prospects of Brazil's agribusiness, in addition to causing regional and global environmental consequences. The proposal for a ministerial structure also tried to eliminate competences over the national natural heritage, whether forests or water resources, and the climate agenda, from the Ministry of Environment, subordinating them to other ministries, in addition to prohibiting the participation of civil society in various councils and collegiate guiding public policies (Brazilian Law Nº 9759/2019). The second restructuring of the Ministry of the Environment during the current government (2019–2022), which took place in 2020, created a specific unit for the theme of concessions, something exceptional in the history of the ministerial structure. In July 2020, an action by the Federal Public Prosecutor's Office (AÇÃO CIVIL DE IMPROBIDADE ADMINISTRATIVA 8ª Vara de Justiça federal 1037665-52.2020.4.01.3400), requested immediate removal of the secretary for the environment due to administrative improbity, pointing to responsibility for the regulatory disorder through legal and infra-legal changes, the dismantling of transparency, and social participation bodies in resource allocation and inspection processes. The Federal Public Prosecutor's Office considered the secretary to be directly responsible for the dismantling of the country's environmental protection system, which caused an increase in deforestation, fires, illegal mining, and land grabbing.

In 2020, further reorganizations assigned the fight against environmental crimes in the Amazon to the Brazilian army, a role previously played successfully by IBAMA and ICMBio. These bodies were responsible for the conception and operationalization of a system of integral inspection that led to the historical reduction of deforestation between 2004 and 2009, and the demobilization of the logistics of the criminal network involved. Since 2014, public investments in environmental issues have declined, and protected areas (PAs) have been directly affected by this trend: the coordinated audit in Amazon conservation units carried out by the Federal Audit Court pointed out that only 4% of federal and state conservation units in the Legal Amazon had a high degree of implementation, indicating that insufficient financial resources were one of the main causes of this situation. Nevertheless, according to historical analysis of the mandatory and discretionary budget for the Ministry of the Environment and related entities, the expenditure forecast for 2021 was the lowest in two decades, with a 27.4% drop in the federal budget for environmental inspection and fighting forest fires in comparison with what was authorized in 2020, and 34.5% compared with 2019.

Also, in recent years, the perception of impunity has led to increased illegal activities such as deforestation and gold mining. These activities drive violence in the countryside, which grew 23% from 2018 to 2019, adding up to more than 1,800 conflicts, a record since 1985 (Comissão Pastoral da Terra, 2020). In the last six years, Brazil was among the most lethal countries for environmental activists (Global Witness, 2019). In 2019, the highest deforestation rate in the last ten years was recorded in the Legal Amazon and preliminary data already indicate that in 2020 (INPE, 2021) the situation is likely to worsen. Illegal mining has also intensified throughout the Amazon: in mid-2020, in the Yanomami IT alone, an estimated 20,000 invaders were estimated, who, in the context of the COVID-19 pandemic, would have the potential to contaminate nearly 40% of the Yanomami, whom they lived close to in the illegal mining areas, a situation denounced by Indigenous organizations in the National Human Rights Council of the ICHR (Interamerican Commission of Huma Rights. Resolution 35/2020. MC No. 563-20).

Peru

As of 1978, the New Law of Native Communities grants ownership to native communities only of those areas that prove to be suitable for agriculture in their demarcated territory, while lands suitable for forestry and protection remain under the ownership of the State; however, they are ceded in perpetuity to the communities. These actions take place within the framework of the Forestry and Wildlife Law, enacted in 1975, one year after the previous Law of Native Communities. The Forestry Law, in order to conserve tropical forests, states in its article 1 that "Forest resources and wildlife are in the public domain and there are no acquired rights over them", which implies that land titling of and with forestry aptitude cannot be granted, reserving the said lands for the State. From the perspective of Indigenous organizations, this constituted a direct violation of the rights of Indigenous peoples: first, the economy of these peoples in the Amazon largely depends on the extensive use of the forest, and second, practically all the lands of the great plain of the Peruvian Amazon are of "forestry aptitude" and are therefore excluded from being granted in private property to the Indigenous peoples. Likewise, the territorial rights of Indigenous peoples are only specific to the lands, not granting any rights over forests, bodies of water, and subsoil, which continue to be the property of the nation. The processes of recognition and titling of communal lands have been institutionalized since 1975 with the Law of Native Communities. In the first decade of its observance, only small communal areas were titled; since the mid-1980s, communities have succeeded in titling larger spaces (up to 500 km^2) owing to pressure from Indigenous organizations and supporting organizations, which now amount to a substantial fraction of the region (see Section 2.2.2 of this Chapter). However, the titling processes have continued to be slow for several reasons, including successive regulatory adjustments that have legal loopholes or excessively complicate the titling processes. This has generated numerous socio-environmental conflicts motivated by the overlapping of various rights, mostly extractive concessions and easements on the communities' territories.

16.1.3 Conflicting policies and threats to protected areas and Indigenous territories

In all the Amazon countries, the transfer of ownership in favor of individual or communal owners can be reversed if a priority interest for the nation is alleged. In fact, the most common conflict that occurs in recognized territories is due to the overlapping of concessions for extractive industries or infrastructure, which impacts the rights of the owners in various ways (see Chapter 16). According to Convention 169 of the International Labor Organization and the United Nations Declaration on the Rights of Indigenous Peoples, the Indigenous peoples are entitled to be consulted by States through culturally appropriate procedures, through a process called Free, Prior and Informed Consent (FPIC) on all laws, projects, strategies, or other works that affect their territories and their lives. As an international legal framework, both Convention 169 and the UN Declaration affirm that the objective of consulting Indigenous Peoples is to obtain their agreement or consent. The consulted Indigenous peoples should have the possibility to modify the initial plan, and the States have two important duties. 1. The duty of accommodation: it is the duty to adjust or even cancel plans or projects based on the results of the consultation process. When it does not comply with this duty of accommodation, the State must provide objective and reasonable justifications for not having done so. 2. The duty to approve reasoned decisions: although not all consultation processes seek consent, this does not reduce them to a simple formality. States should take into consideration the concerns, demands, and proposals of the impacted Indigenous peoples and consider them in the final design of the plan or project.

The reality is that due to the absence of clear regulations at the national level, in most cases, the consultation process is reduced to a mere notification or informing of the decisions already taken, or it is carried out by dividing Indigenous organizations (government or corporate agents that commonly create divisions within Indigenous organizations and promote the fraction that is allied to the extractive industry). News about this type of conflict is frequently found in the public media in the region.

In the *Amazonia Under Pressure Atlas* (RAISG 2020), the pressures exerted on Indigenous territories (ITs) and protected natural areas owing to the advances of extractive activities and infrastructure development (i.e., energy and roads) are systematically analyzed. The analysis shows that in the case of protected natural areas, 51% of their extent is under some type of pressure, the majority with moderate or low rates. The panorama is similar in Indigenous territories, 48% of which experience pressure, with a third of Indigenous lands having more than half of their area with high and very high rates of pressure.

These regional data present differences by country, and although the *Atlas* (RAISG 2020) indicates Ecuador as the most dramatic case owing to the prevalence of moderate, high, and very high-pressure rates in its Indigenous territories and protected natural areas, there are conflicts in the Indigenous territories (ITs) and protected areas (PAs) of all Amazon nations.

The expansion of the agricultural frontier is one of the drivers of change towards protected areas. The

Atlas (RAISG 2020) indicates that between 2001 and 2018, the increase in new areas of agricultural use within the protected natural areas was more than 220%, transforming 53,269 km^2 inside protected areas (PAs), 74% of which had forest cover in 2000. Sixty-four percent of this conversion took place in departmental protected area of direct use, a category that represents 33% of the total protected extent in the region. Although protected area of direct use can allow the sustainable use of resources, the question here is forest conversion and land-use change. Considering that across the basin, the growth of departmental protected area was greater in the last 20 years than that of the national protected area (142% and 101%, respectively) (Section 2.1. this Chapter), both this trend and the conversion inside should be a matter of concern. The increase in deforestation has also occurred on Indigenous territories (ITs) of which 42,860 km^2 have been converted into new areas of agricultural use, of which 71% were forests in 2000. Despite fluctuations over this period (2000–2018), the figures of annual deforestation in ITs varied between 1,000 and 1,700 km^2 until 2016, but in 2017 and 2018, they exceed all the preceding annual values including the 2004 peak, with values of 2,500 km^2 and 2,600 km^2, respectively (MAPBIOMAS 2020).

Many of these transformations begin illegally with the invasion or land grabbing by external agents, who then try to regulate the property. This situation highlights the need for greater control over land use, the urgent need for rural cadasters, the improvement of production practices to increase productivity and avoid encroachment, and, foremost, adequate management of areas designated for protection or sustainable management.

16.2 Comparative patterns of forest conversion and degradation within protected areas and Indigenous territories and lands outside

Unlike protected areas (PAs), the main objective of which is biodiversity conservation, the aim of establishing Indigenous territories is to safeguard the rights of Indigenous peoples to their lands and livelihoods for social, cultural, and equity reasons (Maretti *et al.* 2014). However, there is sufficient evidence in the scientific literature to corroborate that the Indigenous peoples of the Amazon play a measurable and significant role in maintaining forests, thus reducing forest carbon emissions and mitigating climate change (Ricketts *et al.* 2010). Several studies have shown that Indigenous territories in the Amazon act as buffers for external pressures associated with the expansion of the agricultural frontier, reducing deforestation (Oliveira *et al.* 2007; Soares-Filho *et al.* 2010; Schwartzman *et al.* 2013; Stevens *et al.* 2014; Jusys 2018) and the occurrence of fires (Nepstad *et al.* 2006) compared with the areas outside its limits. Between 2000 and 2018, 87% of the total deforested area was located outside Indigenous territories (ITs)and protected areas (PAs) and 13% within their limits (MAPBIOMAS 2020), even though the protected areas (PAs) and the Indigenous territories (ITs) together cover more than half of the region's forests (Walker *et al.* 2020). Blackman and Veit (2018) combined regression analysis and cross-sectional correspondence to estimate avoided deforestation and carbon emissions attributable to Indigenous management. The authors found that Indigenous peoples' land-use practices reduced deforestation and associated carbon emissions.

In RAISG's Atlas (2020), the analysis of deforestation from 2000 to 2018 indicates that as of 2015 there has been a clear upward deforestation trend in the Amazon, after reaching its lowest point in 2010. Although 87% of the deforestation that occurred in the period took place outside of protected areas (PAs) and Indigenous territories (ITs), 8% and 5%, respectively, occurred in these areas, and the data indicate that 2017 and 2018 were the worst years. Regarding the status of recognition of Indigenous territories, previous RAISG analyses (2016) found that deforestation in Indigenous territories without legal recognition increased more than 50% between the 2000–2005 period and the 2010–2015 period. Other publications have analyzed the effectiveness to reduce deforestation between those territories that are legally recognized and those that are not and have concluded that the legal and full recognition of their collective rights is a significant cause for the decrease in deforestation rates within Indigenous territories (ITs) (Blackman *et al.* 2017; Baragwanath and Bayi 2020).

Analysis that focused on carbon gains and losses in the Amazon during the 2003–2016 period (Walker *et al.* 2020), using an update of the data originally published by Baccini *et al.* (2017) and disaggregating the losses into those attributable to the conversion of forests (deforestation) and those due to anthropogenic degradation and natural disturbances, had similar findings. Land outside Indigenous territories (ITs) and protected areas (PAs) (i.e. "Other Land") accounted for approximately 70% of the total carbon losses and almost 90% of the net change, in less than half of the total land area. In contrast, Indigenous territories (ITs) and protected natural areas, which accounted for more than half of the total land area, accounted for only 10% of the net change and 86% of losses on those lands were offset by gains through forest growth. Therefore, there was a nine-fold difference in net carbon loss outside Indigenous territories and protected natural areas (−1,160 MtC) compared with inside (−130 MtC). The authors suggest that the continued regeneration of forests in Indigenous territories has allowed these lands to offset emissions from degradation and disturbance (Walker *et al.* 2020).

16.3 Complementary Conservation Strategies

16.3.1 Conservation including people

16.3.1.1 Communal lands in the National System of Conservation Units of Brazil

To the 12 categories of protected areas (PAs) recognized by Brazil's SNUC, and which correspond to the IUCN classification, can be added other specific categories created at the state level that are not included in Section 1.1. The domain and concession of the land, the possibility and intensity of use of resources, and the degree of conversion of the environment are important guiding axes of the system and vary between these additional categories. Among them, the Extractive Reserve (Resex, acronym in Portuguese), an innovation that arose from the struggle of the organized rubber tappers' movement assisted by partners to deal with the unfair land concentration in Brazil, deserves special mention.

In the context of opposition to the exploitation of family work in the rubber plantations of Acre, the appropriation of public lands, and the clearing of native forests, in 1985, the 1st National Meeting of Rubber Tappers was held in Brasília, the first articulation of greater visibility at the national scene. This is when the National Council of Rubber Tappers was created, of which Chico Mendes became president in 1988, extending alliance circles, spanning the Green Party, Brazilian and foreign non-governmental organizations, and the Union of Indigenous Nations, led by Aílton Krenak, with whom Chico Mendes launched the "Alliance of the Peoples of the Forest" (Almeida 2004). The political and intellectual boldness of the unions and associations stands out, which, based on the systematic reconcentration of land in areas of agrarian reform, proposed an innovative model that rejected individual property titles, affirming the collective right to land and the traditional extractivist occupation rights (Allegretti 2008), an innovation that proved capable to guarantee the local governance of resources, implementing an adaptive governance model of complex systems and a robust institutional arrangement (Dietz *et al.* 2003).

At the same time, but in a different territory, the concept of the Sustainable Development Reserve (RDS acronym in Portuguese) arose from the mobilization on the ecological demands from riverside communities to ban commercial fishing from their territories, which intensified unequal competition, leading to the exhaustion of resources and affecting the local way of life (Lima and Peralta 2017). Its own terminology reflects the historical context of its creation: a post-Rio Summit-92 context, where an attempt to combine conservation and development predominated. Located in the state of Amazonas, RDS Mamirauá was the first of its category in Brazil (Lima and Peralta 2017). Meetings between nuclei of social movements with different trajectories and livelihoods weaved the possibility of articulation at the national level, spreading the idea of these communal reserves throughout Brazil.

Currently, in Brazil, there are Extractive Reserves in 19 states and the RDS in eight, especially in the Amazon and along the coast, contributing to guarantee the collective rights of populations with diverse organizations and ways of life, such as rubber tappers, fishermen and artisanal fishermen, shellfish gatherers, and Brazil-nut and *babaçu* gatherers, among others. Currently, there are 77 Resex and 26 RDS in the Brazilian Amazon, representing approximately 3% and 2.3% of this territory, respectively. According to the Ministry of the Environment (2015), there were 199 proposals for the creation of new federal protected areas (PAs), of which 97 were Extractive Reserves and 14 were Sustainable Development Reserves all over the country and 72 were proposed for the Amazon (Data requested by the Instituto Socioambiental to the Brazilian Ministry of Environment through protocol 026800008392015 56).

16.3.2 Ecological and sociocultural connectivity policies in the region

16.3.2.1 Connectivity as an object of conservation

Ecological connectivity refers to the uninterrupted movement of species and the flow of natural processes that sustain life on Earth (Taylor *et al.* 1993), a condition without which ecosystems cannot function adequately. Therefore, without it, biodiversity and other essential elements for life are put at risk.

Since the 1970s, the way in which isolated areas of the forest lose their functionality and how their biological diversity deteriorates has been proven, with serious consequences for ecosystems, their functioning, their regulatory capacity, and therefore environmental services (Tollefson 2013). Furthermore, connectivity decreases the rate of extinction, enabling species transit, seed dispersal, gene flow, and colonization of suitable sites (Noss 1992). Along with this, it facilitates seasonal and daily migrations between a variety of habitats, contributes to the preservation of biodiversity and ecosystems, the protection of water resources, balancing of the climate, and the recovery of the landscape (Beier and Noss 1998)- all of which are key conditions to enable adaptation in a climate change context.

Although a significant percentage of protected areas (PAs) are not connected, those that are connected may be connected by nearby or contiguous protected areas (PAs), or by unprotected areas. The loss of biodiversity within protected areas (PAs) continues to be high due to the possible lack of connectivity with other protected areas, limiting or impeding the interaction with other populations and natural habitats (Saura *et al.* 2017).

Therefore, it is widely recognized that increasing connectivity in protected area systems is the most urgent and challenging task for conservation strategies and programs. Numerous studies that have analyzed the representativeness and connectivity of protected area systems at a global level have found that although 15% of the land is under some form of protection corresponding to categories I to IV of the IUCN, only 7.5–9.3% of the land has well-connected protected area systems (Castillo *et al.* 2020). To address the global challenge of managing well-connected protected area systems, it is important to re-evaluate the different categories of protected areas (PAs) and the very concept of national protected areas systems, since the range of possible management (Saura *et al.* 2017). For this reason, there is a need to speak of ecological networks for conservation, understood as "a system of habitats (protected areas, other effective conservation measures, and other intact natural areas) connected by ecological corridors, which is established, restored (if necessary) and maintained to conserve biological diversity in systems that have been fragmented" (International Union for Conservation of Nature 2020).

In addition to public lands and protected areas (PAs), measures involving private properties also play an important role in landscape connectivity, as is the case in Brazil, notwithstanding substant-

Box 16.2 Ecological and sociocultural connectivity corridors initiatives and protection figures co-ordination initiatives

In the Amazon region, various initiatives, policies and programs that seek to guarantee the ecosystem connectivity of landscapes at different scales (national, regional, cross-border) by way of different approaches and societal sectors of society, as well as the coordination of different protection figures and management for conservation and sustainable development, are being implemented (Map 2). These proposals seek to promote the conservation of the ecological and sociocultural connectivity of the Amazon by providing solutions and bringing innovative aspects to conservation management in the Amazon, to respond to the challenges posed by the fragmentation of ecosystems and uncoordinated environmental management. Some of these initiatives are presented below.

Mosaico da Amazônia Oriental (Brazil) - implementation of a participatory and integrated management for the coordination of conservation and sustainable development units

The creation of the Eastern Amazonia Mosaic in Brazil has its origin in a project presented and approved by the National Environment Fund - FNMA (Edital No. 01/2005) in 2006, which is part of the Law and decree instituted by the SNUC in which the mosaics of protected areas are recognized as instruments of integrated management. The Eastern Amazonia Mosaic includes 6 Conservation Units and 3 Indigenous Lands for a total of 12,397,347 ha. In the context of this project, various public institutions of the State of Amapá, civil society organizations, and representatives of the agro-extractivist and Indigenous communities of western Amapá and northern Pará have participated in the effort to develop a proposal to integrate the management of the Conservation Units and other protected areas (PAs) in the region, through a participatory and inclusive management council, in order to implement integrated management that contributes to social, cultural, political, and ecological connectivity between conservation units. (Instituto de Pesquisa e Formação Indigena – Iepé 2017).

Precedents for an Andean-Amazon connectivity regulation. Sangay-Podocarpus connectivity corridor in Ecuador

Since 2014, the Ecuadorean Decentralized Autonomous Governments (GAD, acronym in Spanish) of Azuay, Loja, Zamora Chinchipe, and Morona Santiago, in collaborative work with non-governmental organizations and local populations, have been consolidating a connectivity corridor as a complementary conservation strategy to connect the Sangay National Park, Natural Heritage of Humanity, and the Podocarpus National Park, a core area of the Podocarpus Biosphere Reserve. As a result of this work, the Sangay-Podocarpus Connectivity Corridor (CCSP) was declared as the first corridor in Ecuador in May 2020 by the Ministry of the Environment through a ministerial agreement that also provides the guidelines for the establishment, design, and management of connectivity corridors in the country. This allowed Sangay-Podocarpus to become the first of its kind under the existing environmental regulations (Nature and Culture Ecuador 2020). The CCSP covers an area of 567,067 hectares and is located on the eastern slope of the Andes. The CCSP is an example of how connectivity corridors contribute to guarantee species migration, genetic flow between populations, biodiversity conservation and resilience in degraded ecosystems, enabling species adaptation to climate change. Additionally, the CCSP helps to maintain the ecological connectivity of the Amazon with the Andean region, which presents high degrees of fragmentation, and sets a precedent for the management of regulations for ecosystem connectivity in the countries of the Amazon region.

Box 16.2 Ecological and sociocultural connectivity corridors initiatives and protection figures coordination initiatives (cont.)

Basin approach connectivity. Putumayo Biological and Cultural Corridor Cross-Border Initiative

This is an initiative to bring together the various actors of the four countries that make up the Putumayo basin (Brazil, Colombia, Ecuador, and Peru), integrate the management of protected areas (PAs) and Indigenous territories (ITs), strengthen cultural connections, and ensure a coordinated response to threats to the watershed, which is home to one of the last great intact forests in the world, with more than 75% of the watershed within Indigenous territories, conservation areas, or areas proposed for conservation. Currently, there is a proposal to create three conservation areas in Peru: Medio Putumayo-Algodon, Ere-Campuya-Algodon, and Bajo Putumayo. The corridor has an area of 12 million ha, of which 39% are made up of Indigenous territories (ITs) and 19% are conservation areas. The initiative works on the creation of an advisory council with representatives of national and local governments, Indigenous peoples, local communities, and civil society organizations of the four countries to ensure integrated management of the basin and protect its ecological integrity going forward (Field Museum of Natural History *et al*. 2020).

Initiative for Ecological and Socio-Cultural Connectivity Andes-Amazon-Atlantic

Civil society organizations in the Amazon, regional Indigenous organizations, and governments have been promoting the connectivity of the Amazon with the bioregions of the Andes and the Atlantic coast and strategies to strengthen the ecological and sociocultural connectivity between protection figures. That includes Indigenous territories and areas for sustainable development in the northern part of the Amazon River, which covers approximately 200 million hectares in eight countries and is 67% legally protected. Based on the identification of strategic corridors for connectivity, this initiative seeks to motivate decision makers from the Amazon countries and other actors to implement, through their legal frameworks, existing initiatives and instruments for conservation management and development based on the sustainable use of the forest, participatory programs for the recovery of fragmented ecosystems, the coordination of management between protected areas and the strengthening of the governance of collective territories in order to ensure the connectivity of the Amazon with the Andes and the Atlantic. Based on actions aimed at guaranteeing future socio-cultural and ecological connectivity, the initiative seeks to help the Amazon continue to fulfill its role as a regulatory system for the global climate and as a support system for life on earth. (Fundación Gaia Amazonas 2020b)

tial changes that have weakened Brazil's Forest Code in 2012. In Brazilian Amazonia, 80% of each property in forest areas and 35% in savannah areas are protected under this law, unless the municipality already has over 50% of its area occupied by conservation units or Indigenous lands (Brazilian Forest Code, Law nº 12,651/2012).

16.3.2.2 Recognition of the contribution of Indigenous territories to connectivity

The discussion regarding area-based goals has been a central element in the framework for the formulation of the new global biodiversity goals, since it has been suggested that many of the countries may be overestimating their areas under protection and management by reporting the percentage of the territory under some form of, not necessarily effective, protection (Coad *et al.* 2019; Castillo *et al.* 2020). In this context, it is important to value not only areas under existing IUCN cate-

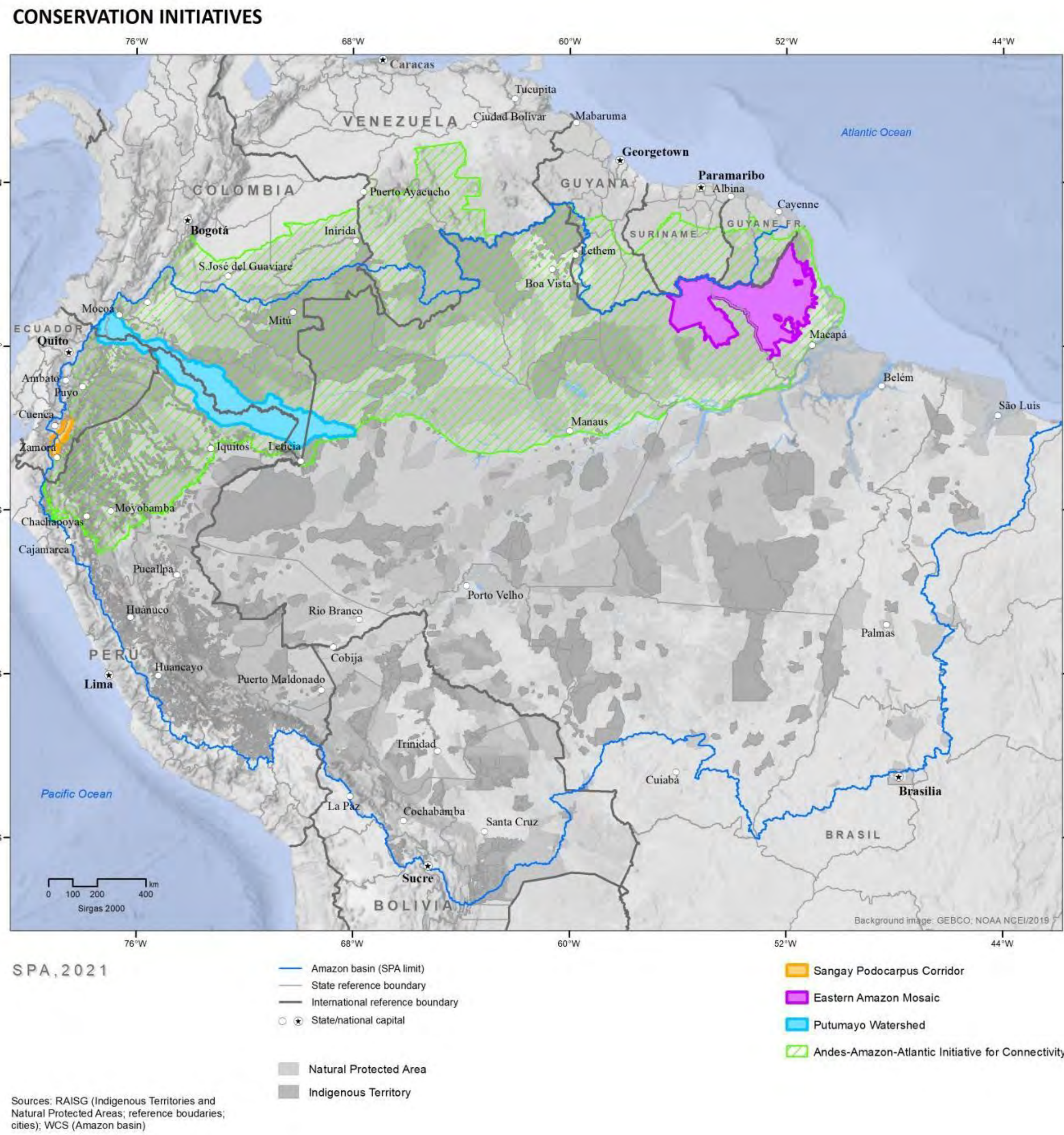

Figure 16.3 Conservation Initiatives across the Amazon Basin

gories that allow the sustainable use of natural resources but also other effective area-based conservation measures, understood as territories that provide effective conservation through various governance and management regimes even though conservation may not be its primary management objective (International Union for Conservation of Nature 2019).

The negotiations of the new post-2020 Framework of the Convention on Biological Diversity, as well as the IPBES Global Report published in 2019, constitute global frameworks that privilege the importance of connectivity as well as the role of Indigenous peoples in the protection of biodiversity.

To date, negotiations (OEWG1 and OEWG2) of the post-2020 CBD Framework have raised key elements for full recognition of the contribution of Indigenous territories to the protection of biodiversity. Evidence of this is collected in Goals 1 and 2, which address area-based goals, reiterating the importance of talking about a) a system of protected areas (PAs) instead of protected areas (PAs) as isolated units to promote a vision of ecosystem connectivity, b) including cultural diversity as well as biological diversity, c) including other effective area-based measures, d) strengthening the importance of effective management (Zero Draft CBD, 2020). These elements reflect the interest in considering both quantitative and qualitative aspects to determine how to constitute ecologically representative and well-connected systems of protected areas (PAs).

16.3.2.3 Connectivity in the Amazon

The widespread interest in raising the commitment of countries with respect to the protection of biodiversity through area-based strategies (previously Aichi Target 11) to 30% in marine and terrestrial areas of the Earth by 2030 presents an opportunity to position the contribution made by Indigenous territories to the protection of biodiversity and to consolidate a vision of safeguarding macro-regional connectivity in the Amazon. The articulation between protected areas (PAs) and Indigenous territories (ITs) constitutes a strategy within the framework of which sustainable-use landscapes, conservation corridors, co*mmun*ity-based conservation areas, and the recognition of other effective conservation measures can be established.

The Amazon has the necessary elements to consolidate connectivity through the coordination of a diversity of management categories related to conservation and sustainable use such as protected areas (PAs), Indigenous territories (ITs) and forest reserves, extractivist reserves, and complementary strategies such as connectivity corridors, among others. In fact, if Indigenous territories are included, 50% of the basin is under some type of recognized or legal protection framework (RAISG 2020 and this Chapter), acknowledging that the Amazon is among the world's biomes that have a high connectivity index (Saura *et al.* 2017). The sum of the efforts that each Amazon country has made independently and because of the adoption and ratification of a series of binational and international agreements constitutes the basis for maintaining connectivity and guaranteeing the functions of the Amazon ecosystems, which are key to the regulation of global climate and protection of biodiversity. However, the continuous transformation of natural landscapes in key areas such as the Andean–Amazon foothills not only affects current connectivity indices, but also compromises the future of the system of protected areas (PAs) as a network (Castillo *et al.* 2020).

International frameworks (post-2020 CBD Framework) have emphasized the importance of building comprehensive conservation plans for large ecoregions or sets of adjacent ecoregions, which are crucial to formulating global goals (Woodley *et al.* 2019). For this reason, today, more than ever, the continuous work that has been carried out in the region by civil society organizations and governments is relevant. This work has resulted in the formulation, design, and implementation of a series of conservation projects and initiatives, policies, and models to ensure the integrity of this region.

Because of the close relationship between Indigenous peoples' ancient system for land management and the comparatively good state of forests in Indigenous territories (ITs), key actors in the region have raised the need to broaden the perspective of connectivity according to this context, towards ecological and socio-cultural connectivity (Box 16.2). This concept is defined by the connections that maintain ecological flows and the representation of the local habitat network necessary for maintaining landscape permeability, biodiversity, the water cycle, climate balance, and the system's resilience as a whole.

16.4 Conclusions

The eight countries of the Basin have traversed a long and fruitful path in recognizing the importance of protecting the biological diversity and associated ecological processes and services of their Amazon regions. After more than 60 years of conservation policies, 25% of the Amazon area is under some category of protection, with percentages ranging from 21% to 51% depending on the country. Many of them are classified as megadiverse countries at a global level because of their Amazon territory. Even with some differences, societies and governments have progressed in the development of policies for the declaration, administration, management, planning, and financing of systems of protected natural areas.

When analyzing the recent historical contexts that have generated the most prolific periods in the declaration of conservation units, we see that many of them are linked, as perhaps is natural in history, to the influence of international political currents and the actions of actors and groups convinced, in this case, of the need to protect biodiversity, its inherent processes and the services it generates for humanity. This has exerted pressure for governments in the region to enact laws and regulatory frameworks favorable to conservation and sustainable development. We must not forget that this region was simultaneously the last frontier in the process of occupation of national territories and that in the conception of the dominant culture, it was considered an empty space to be occupied for the extraction of renewable and non-renewable resources and the expansion of productive activities and colonization spaces.

However, the Amazon is not only forests and exuberant biodiversity but is occupied, and has been for centuries, by a myriad of peoples who have lived there and sustained themselves from the area in practically symbiotic ways, developing ways of using space and the resources by effectively taking advantage of all that diversity. This is the other reality that the Amazon countries and their dominant and mestizo societies have had to face and resolve with respect to this territory. It is in this context that the legal framework for the recognition of the rights of Indigenous peoples is also evolving, including the right to their territories. This process has been more difficult and rugged, but there has also been progress, although 27% of the Amazon territory formally recognized for Indigenous peoples is far from the extent of ancestral occupation that they claim. Besides the local, organized struggle of these peoples that has made the achievements in terms of rights of possession of their communal lands possible, there are advances in international legal frameworks regarding Indigenous rights, which facilitate formal spaces for demands and pressure in the face of injustices committed or to gain participation in decisions that directly affect their rights. The former is numerous, as the recognition of their rights to land is not complete nor includes ownership of subsoil resources, and this has been one of the major causes of conflicts. Furthermore, the use of resources by others has generally left behind the worst part: pollution, transculturation, and very little of the wealth generated for the nation, even in the form of health, sanitation, education, and the development of capacities to function in an ever-changing reality. Despite all this, the recent information that can be derived thanks to the maintenance of better records of the area and of what happens in the protected areas (PAs) and Indigenous territories (ITs) clearly shows evidence that the Indigenous territories (ITs) have worked as well as protected areas (PAs) to stop the advance of deforestation in the Amazon. In the face of the imminent threats of climate change, the protection provided by Indigenous peoples to the forests in their territories is an invaluable service to humanity and not currently recognized the way it should be.

In a world that is increasingly connected in every way, where in addition to the production of commodities and raw materials, the growing illegal activities also play a disruptive role in the Amazon, it is not enough to recognize Indigenous territories or the extension of declared protected lands. The changes can be risky and precipitous; therefore, new, transparent, participatory, proactive, and creative forms of management and law enforcement based on knowledge, are necessary. This will lead to the safeguarding of key services at national and global scales such as water and food security and climate resilience, while ensuring the protection of biodiversity and enhancing benefits for Indigenous communities.

16.5 Recommendations

The Amazon is one of the biomes with the largest proportion of protected area in the form of protected areas (PAs) of different categories, other effective area-based conservation measures, and undesignated intact natural areas. However, the evaluation of the effectiveness of conservation measures indicates that what is mostly lacking in the Amazon is the implementation of an integral conservation vision in which protected areas (PAs), together with other effective area-based conservation measures (OECMs), are seen as ecological networks for conservation and planned with well-defined goals for the conservation biodiversity and ecosystem services, co-managed with the local communities, and involving private stakeholders and other sub-national and local forms of government. Implementing this vision requires increased funding.

More concrete actions are needed to protect ITs, such as full recognition of the territories and the strengthening of territorial governance as one of the most important strategies to maintain forests and mitigate the impacts of COVID-19 in the Indigenous territories of the Amazon. More balanced and direct funding, and capacity building, for Indigenous peoples' organizations and communities is essential to provide the necessary resources and thus continue to conserve these important forests.

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Chapter 17

Globalization, extractivism, and social exclusion: Threats and opportunities to Amazon governance in Brazil

Desmatamento em áreas protegidas, Beruri, Amazonas, 2010 (Foto: Alberto César Araújo/Amazônia Real)

INDEX

Graphical Abstract

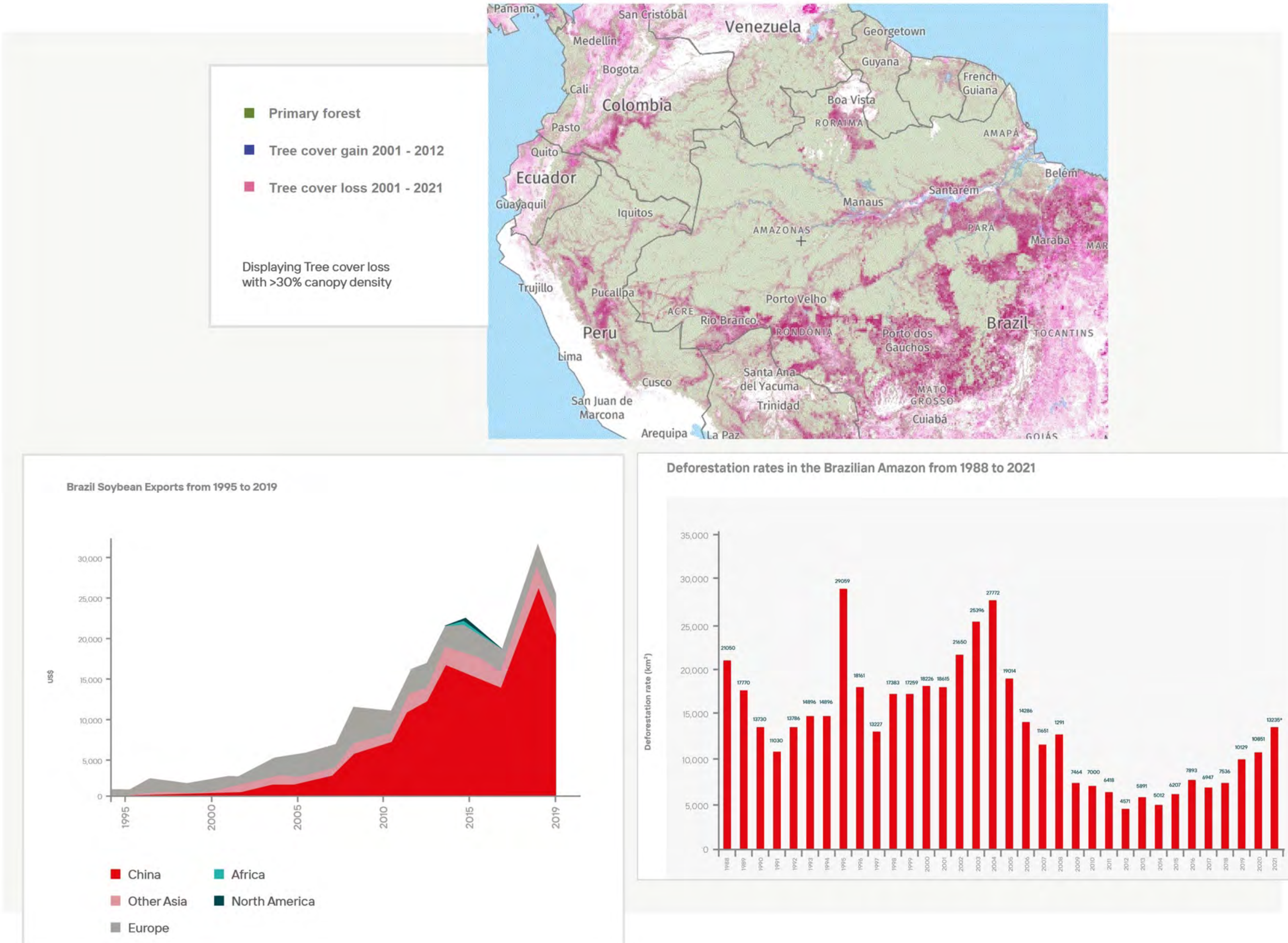

Figure 17A. Graphical Abstract

Globalization, Extractivism and Social Exclusion: Threats and Opportunities to Amazon Governance in Brazil

Carlos Larrea[*a], *María R. Murmis*[b], *Tasso Azevedo*[c], *Felipe Nunes*[d], *Raoni Rajão*[e], *João Paulo Ribeiro Capobianco*[f], *César Rodriguez Garavito*[g], *Britaldo Soares-Filho*[e], *Richard van der Hoff*[e]

Key Messages

- Globalization and widespread changes in consumption have drastically altered the type and scale of human intervention in the Amazon, generating social and environmental impacts of unprecedented magnitude and gravity. Together with countries from the Global North, China is an increasingly dominant actor in this process.
- Brazil provided a strong example of how deforestation control, implemented through strategic state policy involving the commitment and coordinated involvement of multiple government areas, can contribute to significantly reducing deforestation.
- Deforestation reduction and forest conservation policies are vulnerable to changing governments and political priorities.
- Initiatives to reverse deforestation must involve the participation of all stakeholders (different levels of government, multiple sectors of the economy, civil society actors, Indigenous peoples and local communities (IPLCs), international organizations, etc.), including the cross-cutting perspectives of gender and youth.

Abstract

From the 1970s onwards, the Amazon experienced the deepest social and environmental transformation in its history. In the context of changing global political hegemony and deep regional integration into the world economy, the majority of countries that make up the Amazon region have become a commodity and energy provider for both domestic and international markets, while being afflicted by detrimental social and environmental effects in the process of uneven regional development.

Large investments by international corporations, often in association with local partners, have led to a dramatic expansion of cattle ranching, soy cultivation, large-scale mining, mega-infrastructure projects, oil and gas extraction, illegal gold mining, and drug trafficking. These activities are associated with deforestation, environmental degradation, and biodiversity loss, reshaping the region. The living conditions of local peoples have barely improved, while social conflict and violence have become widespread, particularly affecting Indigenous peoples.

In a new multipolar international order, China has led globalization, becoming the most significant commodity importer, a large credit provider, and a partner of oil, mining, and infrastructure investments in most countries. A rapid expansion of agricultural and extractive activities, mostly for export but also for domestic markets, driven by urbanization and increases in income, have led to serious deforestation and

[a] Andean University Simon Bolivar, Toledo N2280, Quito, Ecuador, clarrea_2000@yahoo.com
[b] Andean University Simon Bolivar, Toledo N2280, Quito, Ecuador
[c] Mapbiomas, Brasília, Brazil
[d] Centro da Inteligência Territorial (CIT), Rua Araguari, 358, Legal Space, Bairro Barro Preto, Belo Horizonte, Brazil
[e] Universidade Federal de Minas Gerais (UFMG), Av. Pres. Antônio Carlos, 6627 - Pampulha, Belo Horizonte, Brazil
[f] Instituto Democracia e Sustentabilidade (IDS), Travessa Dona Paula, 01, Higienópolis, São Paulo, Brazil
[g] Center for Human Rights and Global Justice, 40 Washington Square S, New York NY 10012, USA

environmental degradation. The extractive development model has generally prevailed, despite the globalization of conservation efforts.

The Brazilian experience between 2005 and 2012 was the only exception to the unchecked developmentalist model, during which environmental degradation was successfully reduced and an 84% decline in deforestation was achieved. This experience reveals the conditions required to make such results possible: an integrated, multisectoral, and consistent set of policies with efficient monitoring, effective law enforcement, conservation incentives, expansion of protected areas (PAs) and Indigenous territories (ITs), and strong international support. It portrays a different picture to that associated with the mainstream, short-term extractive model and has the potential to be replicated either at a pan-Amazon or national level. Despite recent setbacks, the Brazilian case constitutes a lesson on what is possible and a stepping-stone for improvement so that such policies can last over time, transcending changes in political preferences and administrations.

The prevailing extractivist commodity-oriented model of unequal development poses a serious risk to the integrity of the rainforest and local, regional, and global sustainability. Sustainable pathways in the Amazon require a shift towards new practices that are no longer associated with conventional economic thinking. A sustainable Amazon implies substituting the current system with a new and equitable development strategy that maintains the provision of environmental benefits from a standing rainforest and flowing rivers, while respecting the integrity of Indigenous cultures, promoting the participation of local populations in decision making, considering gender issues, and improving the living conditions of Amazonian peoples in general.

Keywords: Conservation policies, deforestation, extractive development model, law enforcement

17.1 Introduction

At first glance, the fires that raged in the Amazon in mid-2019 and mid-2020 (NASA Earth Observatory 2021) may have seemed like random events. For a concerned viewer helplessly watching the images streamed live on social media around the world, fires may appear as the quintessential "natural" disaster: an uncontrollable cascading event spark-ed and fueled by forces of nature that recur every season.

However, when seen from a natural and social sciences perspective, fires and other extreme events affecting the Amazon are anything but random. As Chapters 19–21 show, the natural sciences offer robust evidence about the role of environmental deterioration—stemming from economic drivers such as mining, oil extraction, soybean cultivation, cattle ranching, and large energy and infrastructure projects—on patterns that compromise the stability and survival of the Amazon, including the disruption of the water cycle, increasing temperatures and hydrometeorological extreme events, and biodiversity loss (see also Chapters 22–24; 27-29).

This chapter and the next examine these and other drivers and processes from the viewpoint of the social sciences. A wealth of studies in political economy, sociology, economics, anthropology, and other fields have documented the social determinants and impacts of environmental deterioration in the Amazon. Importantly, they have shown that those socioeconomic forces operate not only at the local and national levels, but also at the transnational scale.

This chapter examines the drivers of deforestation in the region and explores the conditions necessary for its successful reduction—although, as history would confirm, the latter proved to be vulnerable to changing political environments. The exploration of such conditions is done through an in-depth analysis of the only experience in the region leading to a significant decrease in deforestation, the case of Brazil between 2005 to 2012, and the factors influencing its subsequent dismantling. Brazil's strategy during those years reveals a different and contrasting picture to that of the predominant extractive model. It is indicative of what can be done, improved, and replicated, by individual countries or, better yet, at a pan-Amazon scale, with genuine local and international commitment and multilateral support.

The chapter presents a long-term view of the urgent challenges in the Amazon brought about by global and regional transformations, along with opportunities revealed by a concrete, large-scale experience within the region, showing the possibility of and suggesting the way to finding effective solutions, as seen from a broader socioeconomic perspective.

17.1.1 The Political Economy of the Amazon: An Overview

Two epochal processes have marked the political economy of the Amazon over the last three decades. The first one is the global commodity boom at the turn of the twenty-first century and the entrenchment of a development model in Latin America that relied on the production of commodities for export—from fossil fuels to metals to beef and soybeans (see also Chapters 14 and 15). Driven by increasing demand from China and continued demand from Europe and North America, the Amazon became the new frontier for extractive economies embraced by governments throughout the subcontinent as oil, minerals, and other goods reached record prices in what has been called a "super-cycle" that took off in the early 1990s and ebbed in the mid-2010s (Erten and Ocampo 2012; The Economist 2013; Erdem and Ünalmış 2016; Ocampo 2017). The impact on Latin American economies, which had been highly dependent on commodity production, was considerable. For instance, mineral extraction in the region increased by 400% in the 1990s, reaching unprecedented growth in countries such as Peru (where it went up by 2,000%) (Bebbington 2011).

As one of the last mineral and agricultural frontiers, the Amazon has experienced drastic social and ecological pressures from the re-commodification of Latin American economies, both directly and indirectly (Verburg *et al*. 2014). Directly, the Amazon has been affected by a flurry of new extractive projects, both legal and illegal; governments have opened or slated large swaths of the Peruvian and Ecuadorian Amazon for oil exploitation, legal and illegal logging and gold mining have proliferated across the region, and land clearing for cattle ranching has been a major source of deforestation in Brazil, Colombia, and more recently Bolivia, as have monocultures such as soybean production in countries across the region (Charity *et al*. 2016). The Amazon has also experienced heavy pressure from rapid transformations to its ecosystems and societies, which are indirectly associated with the extractive boom. Increased demand for energy and transportation for mining and other extractive economies is one of the drivers behind new infrastructure projects, including large hydroelectric dams such as Belo Monte in Brazil (Ioris 2021) and major waterway and road construction projects, largely associated with the China-backed Initiative for Regional Infrastructure Integration in South America (IIRSA) (Van Dijck 2013), all of which have further fragmented Amazonian ecosystems.

From a societal perspective, the extractive boom has had a significant impact on local communities and economies. Rapid population influx, disorderly urbanization, weak governance, and a long history of violence have made for a volatile mix that has turned the region into an active hub of socio-environmental conflict (EJAtlas 2021). The growth of extractive economies relies on the continuous expansion of areas for resource extraction, which has amounted to a model of "accumulation by dispossession" (Harvey 2003) that creates immense pressure on Amazonian IPLCs (Dagicour 2020).

The second process with regional and global implications that has impacted social life in the Amazon runs in the opposite direction. Just as economic globalization (including the model of production of commodities for export) expanded over the last three decades, growing awareness about climate change, environmental deterioration, and existential threats to IPLCs' lives have spurred a countermovement. Led by Indigenous peoples in alliance with segments of governments, civil society, and the private sector, a series of actions—from legislation to protests, from litigation to consumer boycotts—have exerted countervailing pressure to implement existing legislation protecting the Amazon, enforce IPLCs' rights as recognized by national constitutions and international law, and set limits to the aforementioned social and ecological impacts (Garavito and Diaz 2020). The Sarayacu case in Ecuador is a successful example of a local oil conflict that achieved international significance when the Interamerican Human Rights Court ruled accepting Indigenous demands in 2012 (Rodríguez-Garavito 2020), showing how socioenvironmental movements are often strengthened by a strategic integration of local, national, and international actions. This countermovement has received different names in different countries, such as socio-environmentalism in Brazil and the aspiration to "Buen Vivir" in Ecuadorian constitutional law and Bolivian legislation and has been accompanied by broad social mobilization (Estupiñán Achury *et al*. 2019). The notion of "good living" (*Buen Vivir* or *Sumak Kausay*), inspired by the cosmovision of Indigenous cultures and other contributions from critical and green perspectives, emphasizes community values, participation, interculturality, and harmony with nature as alternative social principles (Larrea 2015; Larrea *et al*. 2017; Chassagne 2019; Kothari *et al*. 2019).

Similar to the commodities boom, the political economy of this countermovement is global in nature. Starting with the International Labour Organization's Convention 169 (1989) and continuing with the United Nations Declaration on Indigenous Peoples' Rights (2007), the rise of the contemporary Indigenous peoples' movement has translated into a new global legal framework with direct impact on Latin America in general, and the Amazon in particular. Indeed, 14 out of the 23 states that have ratified ILO 169 are Latin American (ILO 2021), and many of them have incorporated Indigenous peoples' right to free, prior, and informed consultation and consent (FPIC) about extractive activities in their lands into their national constitutions (see Chapters 16 and 31). The language and the rules of FPIC figure prominently in legislation, litigation, social movement campaigns, and public debates on the Amazon, as Indigenous peoples and their allies increasingly demand that governments and corporations interested in extractive projects in the Amazon respect Indigenous peoples' right to have a voice in decision making and veto such projects when they endanger their physical or cultural survival (Rodríguez-Garavito 2011).

Advances in climate change science, policy, and public debates have provided an additional impetus for this countermovement. The adoption of the 2015 Paris Agreement by Amazonian countries, youth mobilization for climate action, and increased evidence of massive human rights impacts attributed to climate change have gradually converged with the aforementioned political and legal mobilization by Indigenous peoples (EJAtlas 2021), as shown by the 2019 summit of representatives from those movements in the Brazilian Amazon and its resulting declaration[h]. Given the central role of the Amazon in any scientific and regulatory efforts that aim to avoid the most catastrophic climate change scenarios (Salles and Esteves 2019), this convergence is likely to be a key source of bottom-up pressure for the protection of people and ecosystems in the region.

The opposition between globalized extractive forces and environmentalist and human rights networks with international support has led to

[h] See "Declaration of Civil Society Organizations on the Crisis of Deforestation and Burning in the Brazilian Amazon," available at https://www.inesc.org.br/wp-content/uploads/2019/12/Declaration-CSOs_deforestation_Amazon_ENG-Final.pdf

complex struggles in different countries, resulting in varied outcomes. However, the former has generally prevailed, and many public policies have promoted an extractivist-development approach that merely included certain environmental checks and balances but did not substantially change the prevailing model (Baletti 2014).

This chapter, as well as the broader social science literature on the present and future of the Amazon, bears out the actors, mechanisms, volatile interactions, and impact of the two aforementioned processes. In turn, country studies help exemplify the form that these prevailing processes took in different countries (see Chapter 18).

17.2 Effects of Global and Domestic Economic Changes on the Amazon (1970–2020)

Human presence has influenced the Amazon for at least 12,000 years (see Chapter 8). However, the changes brought about by modern globalization, and a set of transformations from the 1970s onwards have been unprecedented in both speed and magnitude of their social and environmental effects. In a context of changing global political hegemony—described below—and deep expansion of regional integration into the global economy, the Amazon is becoming a commodity and energy provider for both domestic and international markets and is being affected by detrimental social and environmental effects caused by uneven regional de-

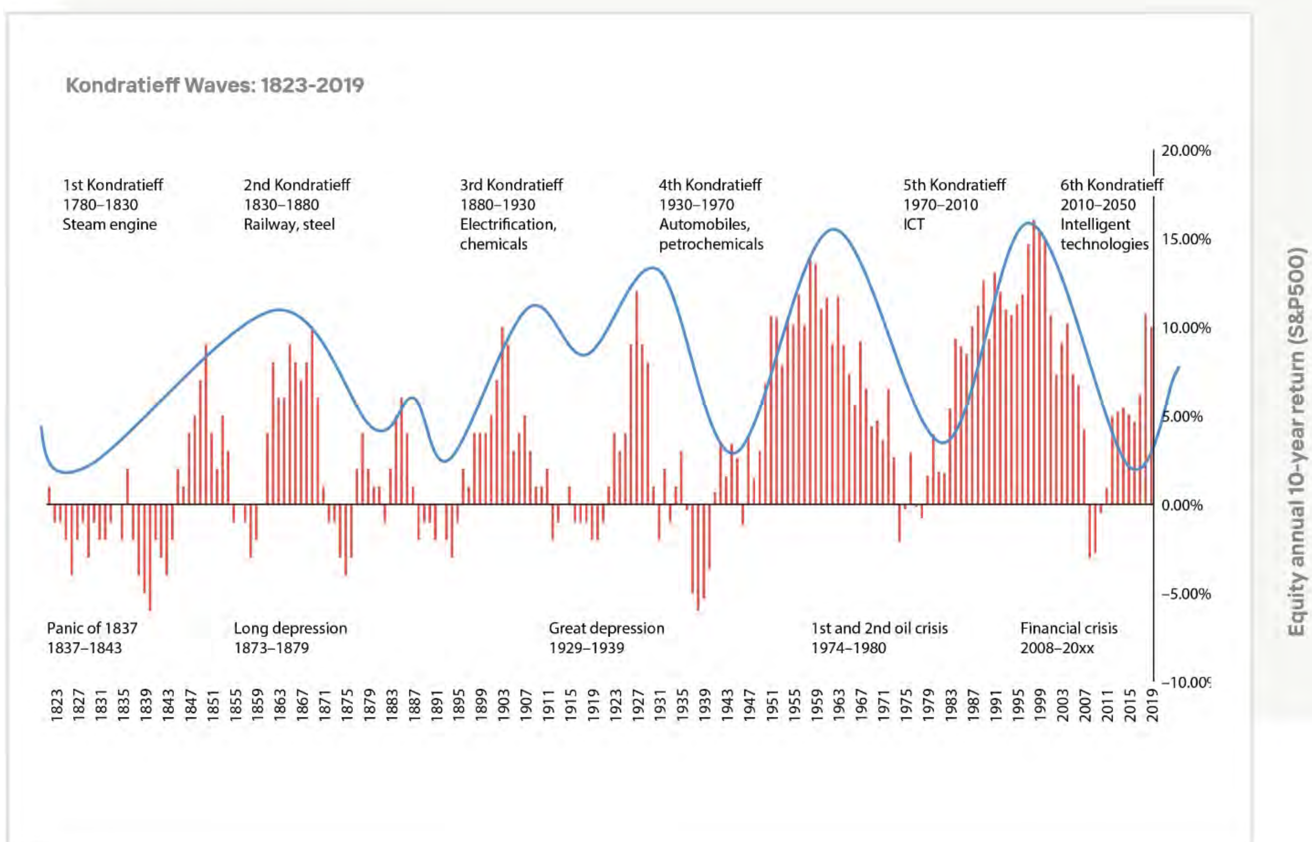

Figure 17.1 The Ages of Globalization. Columbia University Press. Source: adapted from Sachs, J. D. (2020).

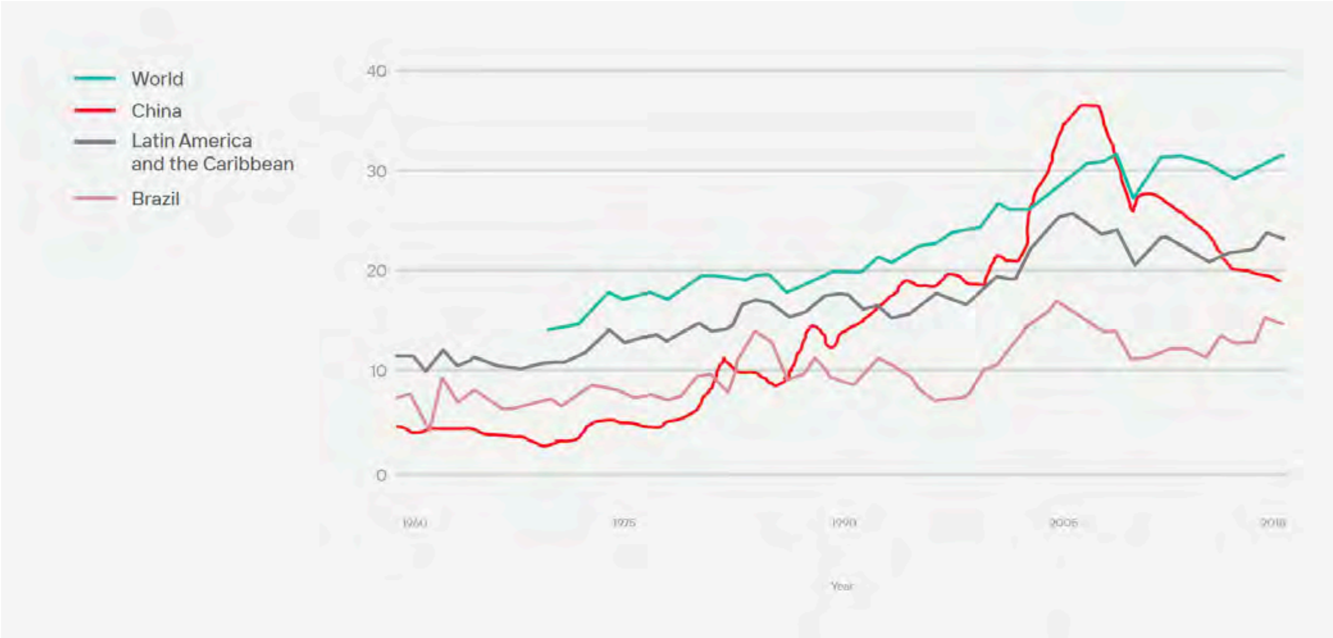

Figure 17.2 Exports/GDP (%). Source: World Bank. World Development Indicators, 2020. https://databank.worldbank.org/source/world-development-indicators.

velopment processes (Harvey 2019). Human intervention, which generated positive effects on biodiversity before the Iberian conquest (Chapter 8), is currently the main threat to rainforest integrity.

The expansion of the world economy, rather than being a continuous linear process, evolves in the form of long-term cycles (Figure 17.1). In the late 1970s, the Fordism model (Harvey 1989) of accumulation became exhausted and a new global development paradigm, based on neoliberal concepts, emerged (Cox 1987; Harvey 1989, 2005).

Latin America shifted from import-substituting industrialization towards an export-oriented and market-friendly model (Thorp and others 1998, see Chapter 14). Exports, led by commodities, grew faster than gross domestic product (GDP), (Figure 17.2). Regional commodity exports expanded, and the Amazon progressively became a significant provider of raw materials, such as oil (Peru, Ecuador, Colombia), gas (Bolivia, Peru), iron ore, soybeans, and beef (Brazil), gold (Peru, Venezuela, Suriname), timber, and hydroelectric power. A complex process of infrastructure expansion, migration,[i] and urbanization occured without substantially improving living conditions. The model accelerated deforestation, degradation, and biodiversity loss. This process has taken different forms over time, according to dominant products and local social and environmental conditions.

Sachs (2020) differentiated two recent long-term cycles in the global economy using Kondratieff waves (Figure 17.1). The first one, between 1970 and 2010, was mostly driven by information and communication technologies, whereas the current cycle is based on intelligent technologies and robotics (Sachs 2020). Each global economic wave, sparked by technological innovation, generates its own way of reshaping the world order and the role of different regions. As the Chinese economy expanded until the 2008 crisis, Latin America took advantage of soaring commodity prices and became a raw material provider, with strong effects

[i] In addition to internal migrations from densely populated region to the Amazon, current human mobility includes massive international flows (e.g., from Venezuela to other Amazon countries), circular and temporary migration (Chapter 14).

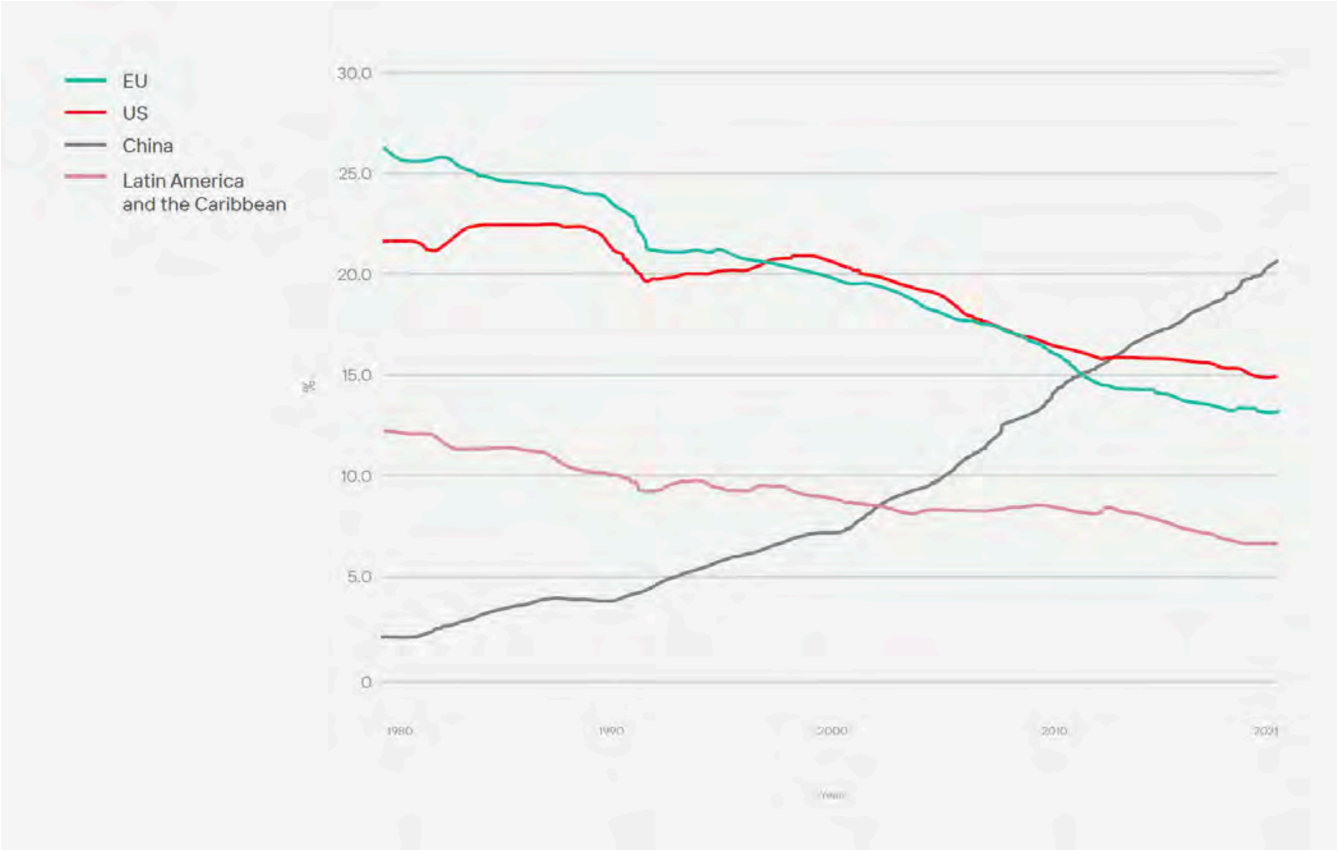

Figure 17.3 Shares of World GDP, Selected Regions and Countries: 1980 – 2020. Source: IMF 2020. World Economic Output, April 2020. https://www.imf.org/external/pubs/ft/weo/2020/01/weodata/download.aspx.

on the Amazon. After 2014, China adopted a different model, reducing its growth, shifting towards the expansion of its internal market, and fostering certain environmental protection measures. The decline in commodity prices affected Latin America and the Amazon (Ocampo 2017).

From a political economy perspective, a significant change was the transition from the bipolar world of the Cold War, and the strong influence of the United States (US) on Latin America, to the current multipolar scenario dominated by the emergence of China, and a complex equilibrium between the dominant powers of the US, the European Union (EU), and China (Sachs 2020; Ray 2021). China's share of global GDP increased from a marginal 2.3% in 1980 to 20% in 2020, surpassing the US in 2013 to become the largest economy on the planet (Figure 17.3).

China became the largest importer of several commodities extracted from the Amazon. In 2018, Brazil was the leading world exporter of soybeans (56% share)—cultivated in the Cerrado and the Amazon—and China the largest importer (57% share) (OEC 2021). Shares for iron ore are lower but significant (Figures 17.4 and 17.5), and beef exports from Brazil to China increased from almost zero early in the century to approximately 46% in 2019 (Meat & Livestock Australia 2020). In 2018, Brazil became the world's largest beef exporter, led by growing Chinese demand. Other important destinations were the Middle East and North Africa, Singapore, Russia, and the EU. Ecuador began exporting oil from the Amazon in 1972, and oil has been the single largest export and backbone of Ecuador's economy ever since. Colombia's main export also became Amazonian oil recently (OEC 2021).

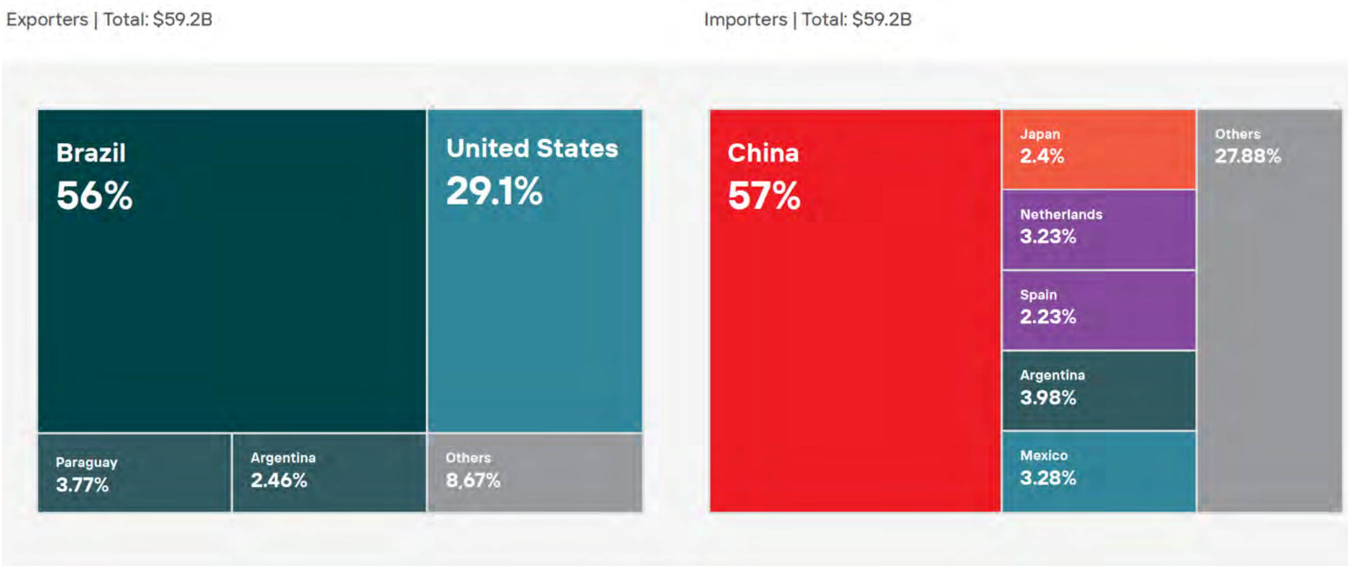

Figure 17.4 Exporters and Importers of Soybeans. Source: OEC, 2020. https://oec.world/en/profile/hs92/21201

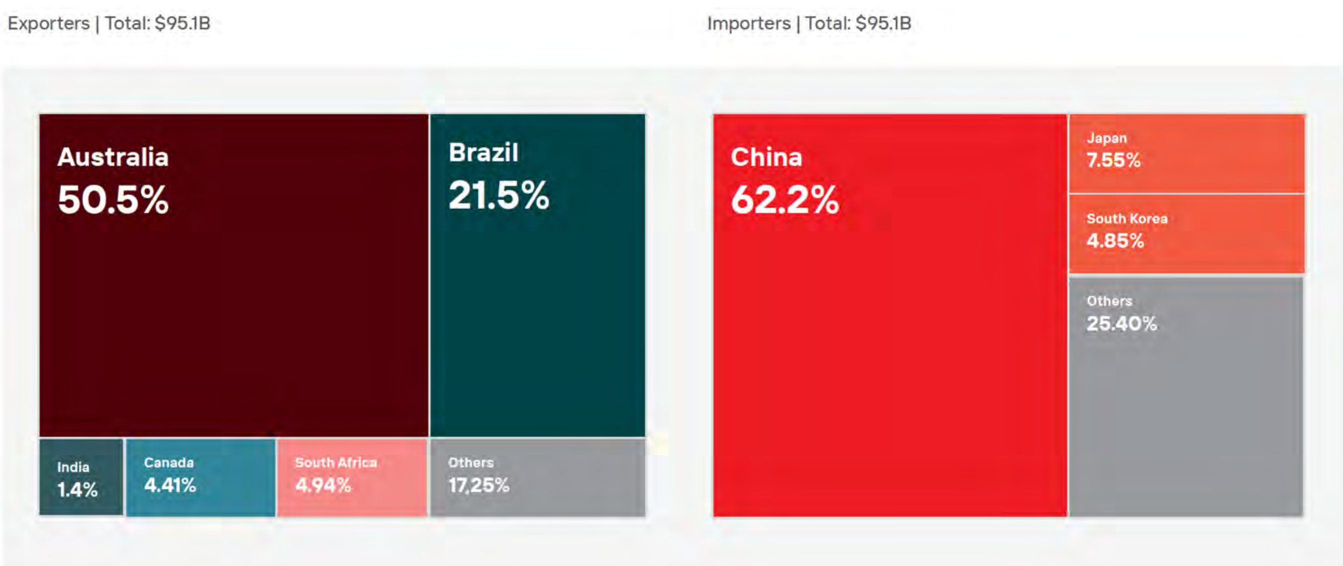

Figure 17.5 Exporters and Importers of Iron Ore. Source: OEC, 2020. https://oec.world/en/profile/hs92/52601 .

As China became one of the largest trade partners in Latin America, regional exports were concentrated in a small group of commodities, with several coming from the Amazon. In Brazil and Peru, China became the top export destination and outpaced the US. In 2018, soybeans were the main export product of Brazil, and iron ore was the third; Colombia and Ecuador share a similar pattern of increasing participation of China as a trade partner in a small number of commodities, predominantly from the Amazon (Table 1). In Ecuador, Chinese companies (Sinopec and Petrochina) recently became the most significant foreign partners in the oil industry. These cases reflect China's fundamental interest in securing access to commodities. In return, China contributes needed infrastructure and investments to the host countries.

Table 17.1 Export structure in several Amazon countries in 2019

Country	Main products			Main Partners	
	Order	Name	Share (% total)	Name	Share
Brazil	First	**Soybeans** *	11.4	China	27.6
	Second	Crude oil	10.6	US	13.2
	Third	**Iron ore** *	10.0	Argentina	4.3
Colombia	First	**Crude oil** *	32.2	US	30.7
	Second	Coal	15.9	China	11.3
	Third	Coffee	5.9	Panama	5.8
Ecuador	First	**Crude oil** *	34.3	US	29.5
	Second	Bananas	15.0	China	12.5
	Third	Crustaceans	17.0	Chile	6.6
Suriname	First	**Gold** *	78.4	Switzerland	38.5

(*) Products from the Amazon.
Source: The Observatory of Economic Complexity (OEC) 2020. https://oec.world/.

China was not only a commodity importer, but it also financed large infrastructure projects in the Amazon (such as the Coca-Codo Sinclair dam in Ecuador and the Belo Monte–Rio de Janeiro Second Transmission Line in Brazil), and invested in oil, mining, agribusiness, energy, finance, and communications (Ray 2021). It became one of the region's main financial partners. In 2020, cumulative Chinese loans reached US $62.2 billion in Venezuela, US $28.9 billion in Brazil, and US $18.4 billion in Ecuador (The Inter-American Dialogue 2020). Chinese involvement in the Amazon is not only the result of increasing demand, but has also been guided by the long-term geopolitical strategy of an emerging world power (Ray 2021). Canadian companies also played a significant role in large-scale mining investment in the Amazon (Deonandan and Dougherty 2016). Financing and financial institutions have a significant role in leveraging and profiting from activities that drive deforestation and the associated infrastructure that enables them. A mix of international incentives and local drivers are frequently the main immediate forces of environmental deterioration, as illustrated by the promotion of IIRSA by Brazilian companies and the expansion of oil extraction by Ecuadorian state companies with Chinese support (European Commission 2010).

Since the early 1990s, Latin American exports have become more dependent on primary products, reversing a long trend towards diversification with the expansion of manufactures (Figure 17.6). As a result, the Economic Complexity Index of Exports declined in Amazonian countries between 1995 and 2019.[j] Brazil, Bolivia, Peru, and Venezuela present a negative and statistically significant trend, whereas in Ecuador and Colombia the decline is not significant (Figure 17.7). The Latin American profile in international trade was reshaped, with a new role as commodity provider to China.

Commodity-export expansion depends on international prices, which have been very unstable during the past decades (International Monetary Fund 2020a), with two ascending periods (the 1970s and the 2004–2014 decade) and two depressed phases (from early 1980 to the turn of the century and after 2014) (Figure 17.8). During periods of low prices, extractive activities do not necessarily decline.

[j] The Index of Economic Complexity of a country is an indicator of the economic diversification and technological sophistication of its exports (Hidalgo and Hausmann 2009).

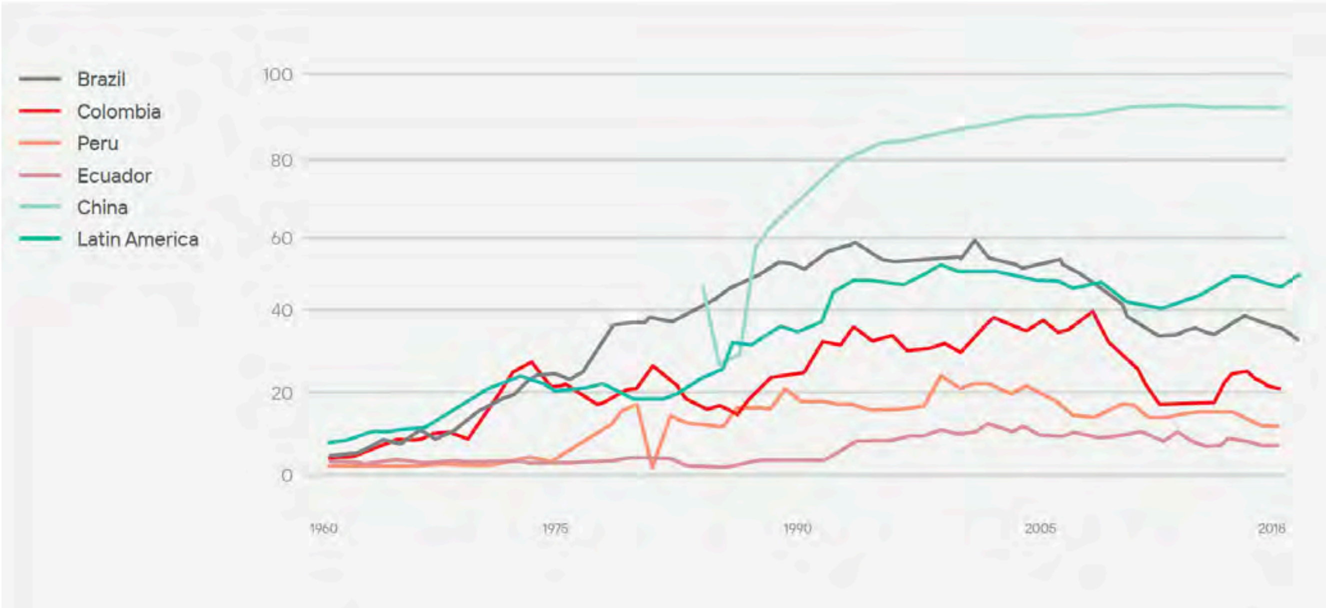

Figure 17.6 Manufactures share in Exports (%). Source: World Bank, World Development Indicators, 2020. https://databank.worldbank.org/source/world-development-indicators

Figure 17.7 Economic complexity Indices: 1995-2019. Source: OED 2021. https://oec.world/

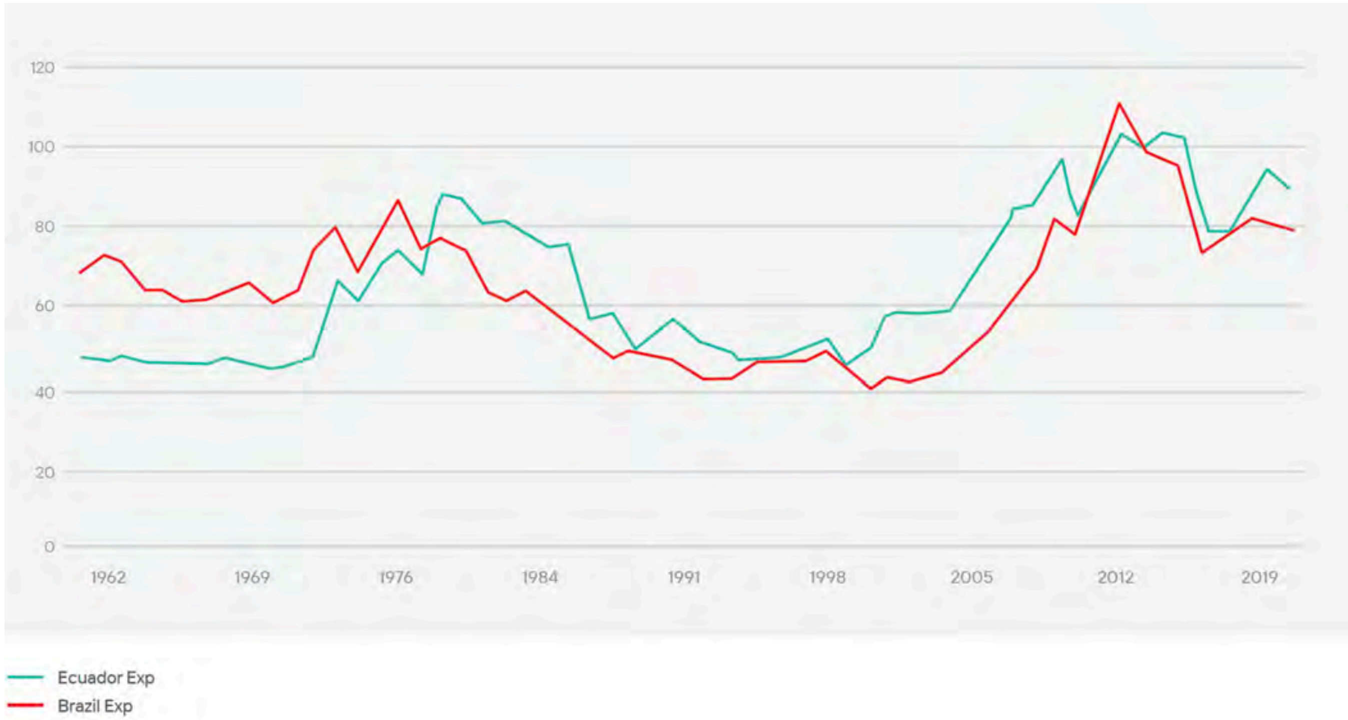

Figure 17.8 Commodity Export Price Indices for Brazil and Ecuador: 1962-2019. Source: IMF 2000. IMF Primary Commodity Prices.

Conversely, in a context of scarcity and fiscal crisis, countries may opt to expand extraction to overcome short-term problems, having been "locked into" path dependence resulting from previous investment and the interwoven social, political, and technical conditions associated with them (Braun 1973). In the context of heavy debt burden and economic crisis, expansion of extractive activities, such as oil in Ecuador, is a way to alleviate short-term economic pressures. In addition, interconnections in global commodity markets may lead domestic policies to have cross-product and cross-country effects, which can result in changes in land use. For example, the 2006 US corn subsidies for ethanol production resulted in higher soy prices, stimulating deforestation in the Amazon (Laurance 2007). Biofuel production, being highly influenced by government policy and subsidies, by feedstock cost (soybeans, sugarcane, corn, palm-oil), and by oil prices (IEA 2019), has long been a subject of concern, given the possible effects of policy and price changes on deforestation (Laurance 2007; (Ferrante and Fearnside 2020).

Illegal activities linked to international markets also played a key role in extractive outcomes, as in the case of coca production and drug trafficking, mostly in Colombia and Peru. An important part of coca cultivation comes from the Amazon, and drug trafficking activities can be important shapers of the social and physical landscape. Drug trafficking provides large amounts of (laundered) money to purchase land for monocultures and cattle ranching, particularly in Colombia. Illegal activities can be stimulated by lawful international markets, such as cases of illegal timber extraction and gold mining, occurring in all Amazon countries (Reyes-Hernandez 2010).

Commodity-driven deforestation has become the main driver of forest loss both globally and in Latin America, accounting for about 64% in the region (Curtis *et al.* 2018). Pressure comes not only from international forces but also from domestic market expansion. For example, in Brazil, cattle ranching is responsible for more than three-quarters of deforestation, with internal demand four times larger than exports (Skidmore *et al*, 2020; Ermgassen *et al*, 2020). The existence of a beef production and commercialization value chain and sector driven by domestic demand, and the availability of land in the vast Cerrado and Amazon biomes, provided a platform from which export-oriented beef production was able to take off, by taking advantage of opportunities emerging from international markets. In turn, soy and beef dynamics are closely interconnected, as beef production makes way for more profitable soy for export and moves deeper into the Amazon, resulting in more deforestation (see Chapter 15). As intensive soy cultivation in the Cerrado expands, extensive cattle ranching is displaced to the Amazon. Soybean production is also a direct driver of deforestation, albeit second to the beef industry (Da Silva and Guerreiro 2017). Development and infrastructure policies, different capabilities and time horizons of actors involved in deforestation driving activities, expectations about changing markets, and relative prices and costs are leading to land speculation and relay-type land use, where the activity that originated the clearing is soon replaced by another. This process sometimes obscures the true motivation behind the visible cause of deforestation (Gao *et al*. 2011, Margulis 2003).

International agricultural drivers are not only on the demand side. Supply has become increasingly concentrated in large-scale multinational actors. A technological package spearheaded by global chemical and trading companies and based on GMO seeds, agrochemicals, no-till cultivation, and new machinery emerged alongside modes of organization in which landowners are replaced by production firms and operating capital is often provided by seed and agrochemical companies or trading firms (Bianchi and Szpak 2017). These predominantly consist of international companies such as Monsanto and Bayer Cropscience (merged in 2016), Syngenta, Dow - DuPont - Pioneer (since 2016 Corteva Agriscience), Nidera, Cargill, Bunge, Dreyfus, AGD, ADM, Noble, Toepfer, among others (Bianchi and Szpak 2017). Therefore, the current export-oriented model introduces strong international interests as direct determinants of land-use change and property size. In line with China's policy of securing access to agricultural commodities, Chinese companies have acquired some of the leading firms in the market: Syngenta, Noble Agri, and Nidera.

The complex alliance between international and domestic actors has created strong political pressure for the expansion of extractive use of the Amazon (European Commission 2010). The case of Brazil has become the paragon of how the combination of international market conditions and domestic policies can have long-lasting and substantial impacts on the environment. Brazil's growth became increasingly linked to exports as the country responded to opportunities arising from international markets (Müller 2020). At the origin of these opportunities is a secular and global process of rising income and increasing demand for food, improved income distribution, and urbanization in emerging economies led by China (Boanada 2020; Fearnside 2015; European Commission 2010; WWF 2018). Brazil has succeeded in taking advantage of this process and has positioned itself as a leading world supplier of commodities and a major emerging economy, driving large-scale land-use change that has generated dramatic socioenvironmental impacts. Therefore, the fate of the Amazon is tied to the demands and functioning of international markets.

According to Sachs (2020), current globalization has aggravated not only global environmental problems but also social inequality. Deep ecological impacts and uneven social and economic development are crystalized in the Amazon. This is reflected in a recently published poverty map of Brazilian municipalities, which shows the Amazon and the Northeast regions as the most deprived in the country (Ottoni *et al*. 2017). The situation is similar in other Amazon countries (World Inequality Database 2021), including Ecuador (Larrea *et al*. 2013).

In addition to social and ethnic inequality, exclusion has a gender dimension. Women generally have lower access to education and suffer labor discrimination and violence. Oil and mining activities usually involve gender-related inequalities. Formal employment in oil and mining camps is almost exclusively for men, with a marked underrepresentation of women in the workforce, the burgeoning of induced prostitution, and gender-based violence. Women are more likely to experience involuntary resettlement, socioeconomic displacement, pollution, environmental degradation, loss of access to water and land, and generally increased vulnerability and food insecurity, often being or becoming primary caretakers within their families (Addison and Roe 2018). Taking an example from Ecuador, women in the rural Amazon have, on average, fewer years of schooling, higher illiteracy rates, and lower labor income compared with men (UASB 2021). Women are also more vulnerable to the effects of floods and other climatic disasters.

The COVID-19 pandemic has evidenced the region's fragility in the face of globalization. As COVID-19 disproportionally hit the Amazon, it also demonstrated the aggravated effects of globalization on social inequality. By October 2021, Brazil was the second most affected country in the world in terms of absolute number of deaths, with 600,000 (Worldometer 2020). Subnational data in Brazil and Ecuador evidenced that the Amazon region had higher infection rates than national averages. In Brazil, Manaus, with a population of over two million inhabitants, was one of the most devastated cities in the world, and the mortality rate per million inhabitants was well above the Brazilian average in all Amazonian states except Tocantins, Pará, and Acre[k] (Worldometer 2020; Conass 2020; FVS 2020; Ministerio de Salud Pública 2020; Turkewitz and Andreoni 2020). The rapid spread of COVID-19 among dispersed communities in the Amazon was a result of a weak prevention network and the complex dynamics of circular migration, multi-sited households, and strong rural–urban interaction and dependence, as presented in Chapters 14 and 34. It also showed the inadequacy of basic health services in the region and the low priority given to social services and infrastructure.

The COVID-19 pandemic also brought to the fore the impacts of deforestation and biodiversity loss on the emergence and spread of infectious diseases, underscoring the importance of the conservation of nature for pandemic prevention and the relationship between pandemic prevention and economic well-being (IPBES 2020). Therefore, the processes driving deforestation and forest degradation can also be considered drivers of disease crossover from wildlife to humans, and of pandemics (see Chapter 21). Habitat loss and fragmentation caused by new land uses — mining, oil and gas, modern agriculture, livestock, wildlife trade, infrastructure development, and urbanization (Tollefson 2020; Dobson 2020; The Guardian 2020; UNEP 2020) — increase the probability of contact between humans and wildlife and are "a major launch-pad for novel human viruses" (Dobson 2020; Kondouri *et al*. 2021).

In summary, since the 1982 Mexican debt crisis, Latin America has shifted from an inward-oriented, import-substituting industrialization model towards a market-friendly strategy of export promotion. Soaring commodity prices during the 2004–2014 period, and Chinese economic expansion have helped redefine the main role of the region as a commodity provider, pushing a neo-extractivist development strategy based on a small group of products (Burchardt/Dietz 2014; Svampa 2019). The Amazon was deeply affected by a dramatic expansion of oil, gas, and mineral extraction, as well as soybean cultivation, large-scale cattle ranching, and drug trafficking, coupled with energy and infrastructure projects, such as hydroelectric dams. The neo-extractivist development model deepened social exclusion and severe environmental deterioration in the Amazon (see Chapters 14 and 15).

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[k] On December 26, 2020, Manaus had a mortality rate of 15.1 per million inhabitants, the Brazilian Amazon had 9.6, and the Brazilian average was 9.1. In Ecuador, the confirmed cases in the Amazon region were 150 per million inhabitants, while the national average was 119. In January 2021, Manaus was hit by a new wave of COVID-19, sparked by a new variant of the virus.

Stricto sensu, extractive activities are only the exploitation of non-renewable resources or the overexploitation of renewable ones. Extensive cattle ranching, with low land productivity and often declining yields, may lead to a non-reversible reduction of soil fertility. Capital-intensive soybean cultivation may also lead to long-term soil deterioration. Soybean and beef production, although not necessarily extractive activities, imply a deterioration of natural endowment. In the broad sense of the term, the neo-extractivist development strategy refers to a development model, adopted by most Latin American countries from the 1980s onwards, that is dependent on commodity export expansion, frequently under dominant market-friendly strategies. Although the "pink tide" of nationalistic governments in several Latin American countries in the early twenty-first century promoted a stronger state role in development policies, partially departing from market-friendly strategies, this change did not reduce the strong dependence on commodities (Svampa 2019).

In contrast, some positive contributions to conservation have come from the international arena. With force since the 1980s, there have been progressively louder and more influential voices expressing concern about conservation. They have prompted local initiatives and global events, such as the United Nations Conference on Environment and Development (UNCED), also known as the 1992 Rio Earth Summit, which aimed to "reconcile worldwide economic development with protection of the environment". It resulted in the Convention of Biological Diversity (CBD) and the United Nations Framework Convention on Climate Change (UNFCCC), and paved the way to subsequent accords such as the Sustainable Development Goals (SDGs, see also Chapter 26) and the Paris Agreement. Stronger government policies started to appear, and environmental and social safeguards began to be introduced by multilateral agencies, financial institutions, and the private sector. Conservation financing increased and consumers, local and global social movements, and environmental activism was empowered (IEA 2021; Teske 2021). Positive examples described in this chapter emerged from these transformations or were supported by them.

Although extractivism prevailed over conservation, and the net result has been the advance of deforestation, ecosystem degradation, and pollution in the region, the expansion of protected areas and recognized Indigenous territories, which currently cover approximately 50% of the Amazon Basin (Chapter 16), was a significant achievement and demonstrated the strength of balancing regulatory policies. Social resistance to unsustainable extractivism and several successful experiences leading to economic diversification coupled with biodiversity conservation can also be mentioned (see Part III).

The most significant (albeit later reversed) experience in countering the prevailing extractivist model has been Brazil's success in reducing deforestation rates by 84% between 2005 and 2012. Brazilian policy under the Workers Party (Partido dos Trabalhadores, or PT, in Portuguese) government was also an important departure from the market-friendly paradigm, which minimizes the state's role in development. Public policies played a leading role in deforestation reduction.

The Brazilian model resulted from a combination of smart national policies, private sector involvement, foreign sector support, and domestic and international pressures. The experience may also provide elements for its possible replication at a Pan-Amazon scale in the future.

The current reversal of environmental policies in Brazil, particularly during the present federal administration, shows the power of the prevailing extractive paradigm. The next section of this chapter analyzes both the implementation and reversal of Brazil's counter-hegemonic policy, focused on the design and implementation of specific public policies.

17.3 Rise and Fall of Conservation Policies: Combating Deforestation in the Brazilian Amazon in the 2000s

Despite the importance of the socio-environmental heritage of the Amazon (see Chapters 8 and 10), its contribution to climate processes and stability at the local, national, and global levels (see Chapters 5–7; 22-24), and its enormous potential for economic development (see Chapter 30), deforestation has already compromised a significant portion of the Basin (see Chapter 19), and land uses other than forest have not generated perennial socioeconomic benefits with regional importance (Almeida 1996; Becker 2000; Andersen 2002). The most recent official data on deforestation increase in the Brazilian Legal Amazon[1], verified from August 1, 2020, to July 31, 2021, estimates an area of 13,235,00 km² (INPE 2020) (Figure 17.9), increasing the accumulated total deforestation to 806,862.735 km² (INPE 2021b). As a result, 19.1% of the original forest has been converted to other uses, an area greater than the sum of the territories of Germany, Italy, and Greece. This loss occurred in just two decades, since the first survey carried out based on LANDSAT images, from 1976 to 1978, showed only 1.8% of forest cover loss (Tardin *et al.* 1980). This is a direct result of regional development programs and projects, which stimulate regional occupation and advance an economy primarily based on agricultural production (Hecht and Cockburn 1988).

From the Getúlio Vargas government in the 1950s until today, and especially during 2019 when deforestation accelerated, the only period in which there was a consistent reduction in deforestation in the Brazilian Amazon was between 2004 and 2012, when rates declined from 27,722 km²/year to 4,571 km²/year (Figure 17.9). The groundwork for this monumental achievement was laid in the 1980s and 1990s through the increasing political influence of counter-hegemonic environmental movements, embodied for example in the 'ecological action caucus' in the National Congress (Viola 1988, 2004). Early victories included the 1998 environmental crimes law (Law 9.605/98) and the National System of Conservation Units (SNUC) created in 2000, but advances in environmental policymaking mainly took off in the 2000s, a period marked by the implementation of the Plan for the Prevention and Control of Deforestation in the Amazon (PPCDAm), determined by the Federal Decree of July 3, 2003. This section details how this plan (and environmental politics, in general) fostered synergetic impacts on deforestation dynamics in the Brazilian Amazon.

17.3.1 Integrating Public Policies to Combat Deforestation

The early 2000s were marked by the strong impact of data showing increasing deforestation in the Brazilian Amazon, proving control initiatives adopted by previous governments ineffective. To face this problem, the Ministry of the Environment (Ministério do Meio Ambiente, or MMA) proposed a reorganization of the Federal Government's activities in the region to the Presidential administration elected in 2002, with the fundamental objective of overcoming disconnected actions, considered the main reason for the advance of social inequality and environmental degradation, with deforestation being its most visible feature. The goal was to establish a new economic development model for the Amazon, capable of promoting economic growth, meeting the demands of the local population, and breaking with previous models through the structured incorporation of sustainability (MMA 2007).

The MMA, as recorded by Capobianco (2017), operated on three integrated and complementary fronts: a sustainable development program for the

[1] The Brazilian Legal Amazon comprises the Brazilian states of Acre, Pará, Amazonas, Roraima, Rondônia, Amapá and Mato Grosso, as well as the northern regions of Tocantins and Goiás and the western regions of Maranhão (law nº 12.651/2012, art. 3-I). The microregion was created by Law to better plan the social and economic development of the Amazon, forming a surface of approximately 5,020,000 km², larger than the area of the Amazon Biome, which has 4,196,943 km².

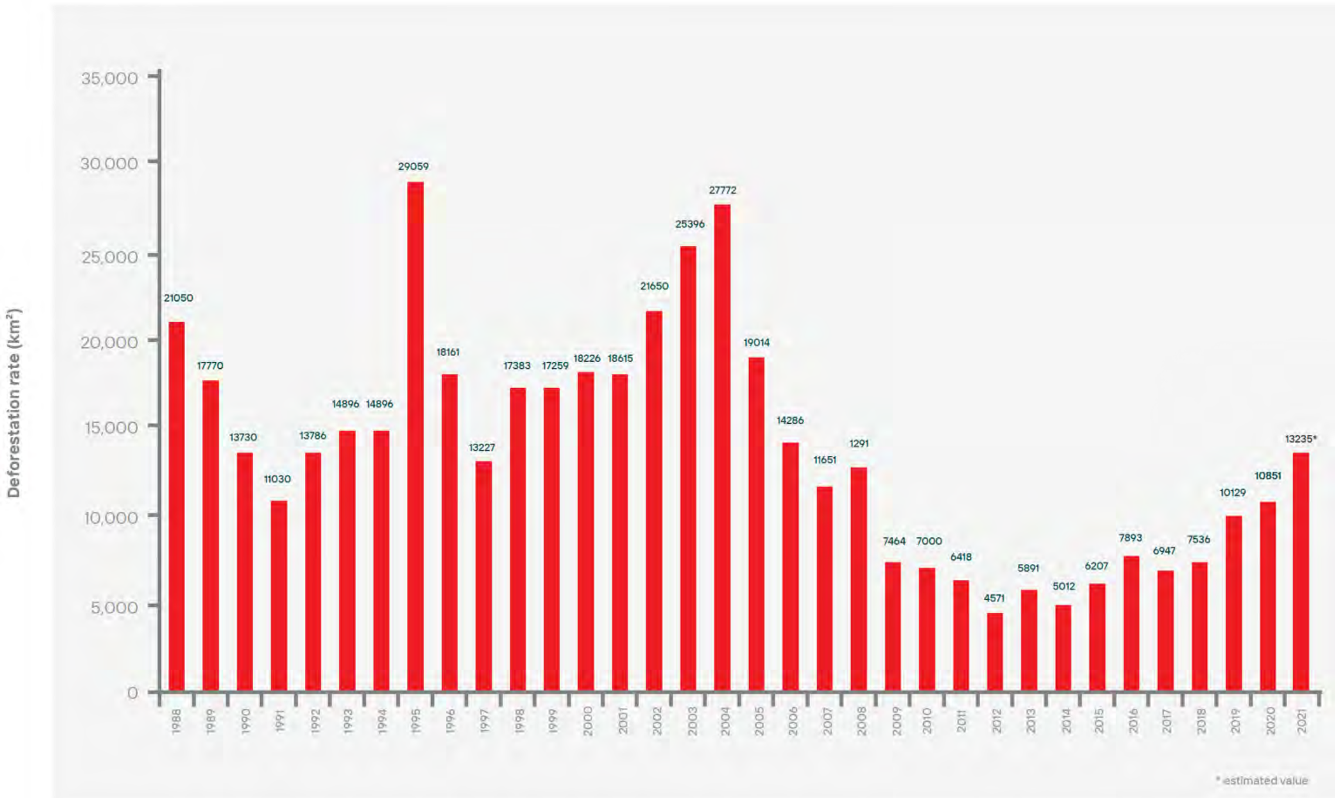

Figure 17.9 Annual evolution of deforestation rates in the Legal Amazon (km2). Source: PRODES/INPE 2021.

macro-region that committed Federal and State funds to Brazil's Sustainable Amazon Program (Programa Amazônia Sustentável or PAS); an action plan for immediate interventions to reverse deforestation rates (PPCDAm); and a local development plan for those regions most threatened by the expanding deforestation frontier, built on multi-actor, multi-sector, and multi-level governance strategies (e.g., Plano BR-163 Sustentável). These initiatives were presented and discussed as early as 2003. The first two (PAS and PPCDAm) were approved and started in the same year, whereas the latter was formally launched in 2004. All three had the strong and broad involvement of different ministries and related agencies instead of being solely in the hands of MMA.

Strategies for action on these three fronts were based on five premises considered essential for the success of the initiatives: (1) to convert the sustainability issue in the Amazon into a government matter by leaving the sectorial sphere of the MMA and obtaining the direct endorsement of the Presidency of the Republic for its articulation; (2) to guarantee political solidity and internal summoning power in the government apparatus; (3) to make actions intersectoral, committing all the ministries and related bodies of the Federal Government that, directly or indirectly, were related to the problem or had capacities and/or institutional expertise to solve it; (4) to establish a permanent evaluation system for implemented policies, generating high-quality and credible periodic feedback; and (5) to consolidate an external support community for the definition, implementation, and pressure for continuity (MMA 2008a).

Part of the strategy adopted in the period consisted of strengthening environmental governance capacity. One action was to significantly increase the number of public servants in federal environmental agencies, including the Brazilian Institute of

Environment and Renewable Natural Resources (IBAMA), through public tender. In addition, the Chico Mendes Institute for Biodiversity Conservation (ICMBio) was established in 2007 to manage protected areas (PAs). That same year, MMA's organizational structure was updated, creating *inter-alia* the Climate Change Secretariat and the Directorate for Climate Control Deforestation in the Amazon (MMA 2008b).

17.3.2 PPCDAm

PPCDAm is emblematic of the synergetic and intersectoral approach to environmental governance in Brazil. In June 2003, preparations for the PPCDAm mobilized an unprecedented 54 members from 12 ministries to define strategies and priorities for public policy formulation in the Amazon (Capobianco 2017). The structuring of the Plan was led by the Civil House of the Presidency, responsible for summoning the technical and political staff of the public agencies involved and for demanding that the necessary subsidies to support the work were provided; and by MMA teams, responsible for systematizing proposals and contributions received and the overall structuring of the Plan.

In addition, PPCDAm sought to foster policy synergies by focusing on three axes: (i) land and territorial planning; (ii) environmental monitoring and control; and (iii) fostering sustainable and productive activities. This plan propelled institutional ownership of the deforestation issue in two specific ways. The first was the establishment of a detailed plan of 149 activities, each with explicitly assigned institutional responsibilities, an execution period, and objective indicators for implementation evaluation. The second was linking the necessary resources for the development of the plan (USD 394 million in total) to budgets already approved in the Pluriannual Plans (PPA) of the participating ministries. This guaranteed the financial conditions for the immediate start of the actions without depending on complex negotiations to obtain additional resources from the Federal Budget (MMA 2008).

PPCDAm's three axes made significant contributions to environmental governance in complementary ways. One of the cornerstones of the monitoring and control axis was the development of a Deforestation Detection System in Real Time (DETER) by the Brazilian Institute for Space Research (INPE) in 2004. DETER represented a technological innovation for monitoring deforestation in the Amazon at very short intervals (weekly to monthly), and became a powerful and efficient surveillance tool (Rajão *et al.* 2017; Trancoso 2021; Kalamandeen 2018; Börner *et al.* 2015). Conceived as an open Internet platform, DETER allowed the press and society to follow the evolution of deforestation, stimulating permanent public debate on the results of control policies.

DETER is one of the best examples of how technology can reduce costs in obtaining vital information to guide actions to control deforestation and plan public policies in a region of continental proportions such as the Amazon. With images produced by the MODIS sensor of the Terra satellite and the WFI sensor of the Sino-Brazilian satellite CBERS, which had a spatial resolution of 250 m, DETER enabled the constant monitoring of areas under pressure at negligible costs. It also reduced the likelihood of corruption within IBAMA and other inspection bodies by providing auditable information.

Another innovation was the involvement of the Federal Police in criminal investigations and in operations carried out by IBAMA and state environmental police, following a strategic plan that considered technical criteria and territorial priorities. As a result, approximately 1,500 clandestine timber companies were closed, and more than 1 million cubic meters of wood were confiscated. Organizations promoting illegal logging were also dismantled, leading to the imprisonment of 659 people, including federal and state government officials.

Within the land and territorial planning axis, the creation of PAs was central to combating deforestation, particularly in the early phases (West and Fearnside 2021). Between 2004 and 2009, 40 PAs were created in the Amazon, totaling 26 million hectares. In six years, the PPCDAm expanded the territorial extension of these areas by more than 76% compared with everything that had been created since the establishment of the Caxiuanã National Forest in 1961 (the first UC of the region).

Early Amazonian PAs (established prior to 2003) were mostly located in remote regions, far from agricultural expansion areas, with some exceptions in the federal states of Rondônia and Acre. However, since 2003, PAs have been actively integrated into the regional land tenure strategy. More specifically, the designation of protected areas, both as PAs and as ITs, strongly discourages land grabbing, as it makes land titles more difficult to obtain, and therefore land speculation more difficult, reducing the likelihood of deforestation. As a result, new PAs were primarily located in areas with strong anthropic pressure (IPEA 2011). Together with the demarcation of approximately 10 million hectares of ITs, many of which are recognized and approved under the PPCDAm, PAs have become a 'green barrier' against deforestation, protecting extensive areas that were still highly conserved but showed an intense increase in deforestation rates in southern Pará, northern Mato Grosso, and southern Amazonas. According to Soares-Filho *et al.* (2010), the creation of PAs was responsible for 37% of the reduction in deforestation between 2004 and 2006.

In addition to the establishment of PAs, the fight against land grabbing was intensified by canceling approximately 66,000 claims for land titles that had no proven legal origin in the registers of the National Institute of Colonization and Agrarian Reform (INCRA), and profoundly modifying the mechanisms and procedures for tenure registration (MMA 2007).

Although the third axis, sustainable productive activities, was less prominent during the first phase (2004–2008) (West and Fearnside 2021), it contained the proposal, approval, and regulation of the public forest management system by Law 11.482/06 in 2006 and the regulation of wood circulation control by CONAMA (National Council on Environment) Resolution 379/06. PPCDAm's three axes became the template for distributing financial resources from the Amazon Fund, which received (and later disbursed) over US $1.2 billion between 2008 and 2017 from international (Norway and Germany) and domestic (Petrobrás) sources (Correa *et al.* 2019).

The strengthening of environmental governance reached far beyond the PPCDAm, which complemented its actions and strengthened its impact. Punishment for illicit deforestation activities was increased in 2008 via decree 6.321/07, which established, among other measures, concentrated and priority action in municipalities that together were responsible for 50% of deforestation in the Amazon, with mandatory re-registration of land and limitation of new authorizations for forest removal above 5 ha, while decree 6.514/08 tightened law enforcement. Illegality also received economic disincentives through the conditional obtainment of rural credit (Assunção *et al.* 2020) from the Brazilian Central Bank (resolution 3.545/08), adoption of the soy moratorium in 2006 (Heilmayr *et al.* 2020; see also Chapter 15), and preparations for a beef moratorium in 2012 (Gibbs *et al.* 2016). Amazonian federal states also increased their creation of PAs, even surpassing the area of those created by the federal government, while the state of Pará initiated the creation of its Green Municipality Program (PMV) (Soares-Filho and Rajão 2018; Assunção and Rocha 2019; Cisneros *et al.* 2015).

17.3.3 Policy Impacts on Deforestation Dynamics

There is extensive literature that provides a rigorous assessment of key PPCDAm policy efforts, offering insights on direct policy impacts, externalities, and mechanisms, which are crucial for strengthening Amazon conservation (e.g., the causal evidence of the effectiveness of monitoring and law enforcement efforts, the conditioning of rural credit, and the definition of priority municipalities for action). A summary of this literature and links to individual studies is available on the "Evidence-Based Forest Protection Platform" (CPI 2021).

PPCDAm obtained significant results in the first 10 years of its implementation. The main indicator of success was the consistent decline of deforestation rates in the Amazon, from 27,423 km² in 2004 — the second highest in PRODES[m] (Amazon Deforestation Monitoring System, by INPE) records — to 4,571 km² in 2012 — the lowest ever recorded (Figure 16.1). This period was marked by an unprecedented increase in initiatives implemented by the Federal Government aimed at halting deforestation. During this period, seven federal laws, three provisional measures, six CONAMA resolutions, 156 decrees, and 16 normative acts of government agencies were approved. There were also 29 major surveillance operations involving the Federal Police. In total, there were 232 initiatives, of which 134 were directly aimed at controlling and combating deforestation, over nine years. This is significantly higher than the 77 actions undertaken over a 13-year period from 1990 to 2002 (Capobianco 2017). Furthermore, during the early stages of the PPCDAm the emphasis was on the strict enforcement of socio-environmental legislation, which increased local actors' perception of the risks associated with illegal and predatory deforestation. This stimulated initiatives by state and municipal governments, as well as by society in general, which contributed to the program's success. In a way, it represents a tangible legacy of the increasing political power of environmental movements in the 1990s.

It is important to highlight that this unprecedented reduction in deforestation occurred in a period of high valuation of the two main commodities, soy and beef, produced in the Amazon (see section 17.1). Until 2005 there was a clear correlation between the growth of these two economic activities and deforestation (Capobianco 2017). As of 2007, a gradual decoupling between these variables began and, despite the return of growth in soy production and an increase in cattle herding in response to rising commodity prices, Brazil saw a decline in deforestation rates.

According to Koch *et al.* (2019), the greater risk of criminal sanctions for illegal deforestation makes illegal land expansion more expensive and less profitable, and induces farmers in a growing agricultural market to reinvest in capital instead of land, leading to increased land productivity per hectare. When analyzing data on livestock production in the state of Mato Grosso, Macedo *et al.* (2012) identified that large-scale deforestation for pasture declined more than 70% from 2005 to 2006. According to these authors, the growing risks and costs of expanding pastures through illegal land occupation, combined with the implementation of techniques to intensify production, turn into a movement to replace extensive grazing (less than one head of cattle per hectare) with animal confinement, a practice that grew 286% between 2005 and 2008.

This demonstrates that the constant and consistent deforestation reduction in the Legal Amazon in the 2000s was not directly related to the advancement of the main commodities of the region. Concurrently, the economic conjuncture on national and international agricultural markets was favorable to reduce pressure to open new areas at the beginning of the first phase of the program (2004 to 2006). Brazil's experience in combating deforestation in the 2000s shows that it is possible, through coordinated actions, strong commitment from the bodies that formulate and implement public policies, and in partnership with society, to establish a governance process capable of promo-

[m] PRODES is the first monitoring tool (currently one of several) designed to calculate annual deforestation rates in the Brazilian Amazon. The Amazon Deforestation Monitoring System, created in 1989 by Inpe, measures the annual clear cut in polygons larger than 6.25 hectares in the Brazilian Amazon. These measurements are carried out in periods with good observation conditions in the Amazon region, which generally take place from July to September, when 90% of the region can be seen due to reduced cloud cover. The analysis period comprises the beginning of August to the end of July of the following year. As it is more detailed than other systems and depends on weather conditions for capturing images, its analysis is carried out only once a year. Its first estimate is released until December of the current year and the consolidated data are made available at the end of the first semester of the following year. For a broader discussion, see Rajão *et al.* (2017) and Richards *et al.* (2017).

ting a fast and significant decrease in deforestation rates in the Amazon.

17.4 The Fall of Brazil's Forest Conservation Policies

The systematic construction of environmental governance in Brazil, as described in the previous section, did not last long. With the turn of the decade, hegemonic movements that advanced the neoliberal development agenda in Brazil, premised on soybean and beef production, regained control of the environmental agenda. At the same time, counter-hegemonic movements represented by professionalized and politicized environmental organizations were losing traction (e.g., Sauer and França 2012). This shift in political dynamics is symbolized by steadily rising deforestation rates, from 4,571 km^2/year in 2012 to approximately 11,000 km^2/year in 2020. This section presents the key factors that explain what has been notoriously called a 'systematic dismantling' of Brazil's forest conservation policies (Abessa *et al.* 2019).

17.4.1 Weakening Environmental Law Enforcement in Brazil

The changing tides of environmental politics in Brazil started with revisions to the Forest Code proposed by the rural caucus. According to Sauer and França (2012), the reorganization of rural Brazil and the rural caucus started in the late 2000s as a response to tightening law enforcement and increasingly difficult access to rural credit. Although the original bill proposing revisions since 1999 did not pass through congress during most of the 2000s, its legislative process was accelerated in 2009 with the establishment of a special commission. The outcome of this protracted debate was the approval of a new legislative text on the protection of native vegetation by the Brazilian Congress in 2012 (Law 12.651/12) that substantially changed — mostly negatively — the previous Forest Code (Law 4.771/65). The revised Forest Code had two major detrimental effects: most significantly, it granted amnesty to past deforesters, exempting them from recovering the 58% vegetation of all illegally deforested areas prior to 2008 (Soares-Filho *et al.* 2014). This severely changed the perceived risks of illegality, mostly because it denoted a reward rather than a punishment, thereby disadvantaging law-abiding landowners.

The second negative effect relates to the Rural Environmental Registry System (CAR), a national, obligatory, and fully-transparent self-registration system for rural landowners, which could have significantly strengthened law enforcement institutions (e.g., IBAMA) to remotely monitor and punish illegal deforesters (Soares-Filho *et al.* 2014). The CAR registration process was a success, with the number of properties growing from less than 1 million in 2014 to approximately 6.3 million nationwide (1 million in the Legal Amazon) by September 2021 (SICAR 2021), mostly because landowners need to register to have access to bank loans and notary transactions. Nevertheless, information available in the system has not been used for law enforcement, as initially anticipated. Except for a few hundred fines issued through operation "Controle Remoto" by IBAMA between 2016 and 2020, most law enforcement still occurs through local field inspections rather than through the CAR dataset combined, with the official PRODES deforestation monitoring system. This contributes to a high level of perceived impunity for illegal deforestation within properties registered in CAR. For instance, Rajão *et al.* (2020) observed that only 23% of the properties with evidence of illegal deforestation in the state of Mato Grosso had been embargoed between 2009 and 2018. The waning effect of CAR as a deterrent to illegal deforestation was also observed in the state-level initiatives that preceded the national registry. In 2008–2009, the properties registered in CAR deforested less than the properties outside the registry, whereas by 2012 landowners inside and outside the registry had similar behavior (Azevedo *et al.* 2017).

The negative effects of the Forest Code reflected a broader trend of substantially weakening environmental law enforcement in Brazil and, in particular, concerns about the institutional capacity of IBAMA and ICMBio, the two federal agencies responsible for enforcing the environmental legislation on private and public lands, respectively. The number of staff has declined since 2010 in the two institutions owing to the lack of replacement of retirees. The total number of IBAMA staff dedicated to law enforcement plummeted from 1,311 people in 2010 to 591 in 2020 (Borges 2020). Under the federal administration that started in January 2019, the MMA has also systematically replaced experienced managers from IBAMA and ICMBio with military police officers from São Paulo with little knowledge of the federal environmental agenda. Moreover, this administration has controversially discouraged field inspectors from destroying equipment used in illegal deforestation operations as an administrative punishment, an effective environmental sanction permitted by law and highly recommended for remote regions. The decreased capacity of these environmental law enforcement institutions is reflected in the falling number of fines issued in 2019 and 2020 to a historical low (Muniz *et al.* 2020; Lopes and Chiavari 2021).

The weak conservation status of protected areas in the Amazon is another challenge. Since the 2010 presidential election, the creation of new PAs has nearly ground to a halt, and following the impeachment of the president in May 2016, the new federal administration actively tried to dismantle existing protected areas in exchange for political support. Some of these attempts were thwarted, but others, such as in the case of the National Forest of Jamanxin, succeeded and were approved in congress. With the new federal administration starting in January 2019, suspension of PAs' designation became an explicit federal policy. Furthermore, both the President and the Minister of the Environment threatened to review the sizes of 59 PAs and to pass new legislation that would allow highways and hydroelectric dams to be developed in protected areas (Borges 2019). Consequently, deforestation inside protected areas has risen from 640 km^2 in 2017 to more than 1,100 km^2 in 2020, as land grabbers expect to benefit from future downgrading, downsizing, and degazettement of those areas. Combined threats to environmental law enforcement — lenient conservation requirements on private lands (Sauer and França 2012), CAR ineffectiveness (Azevedo *et al.* 2017), diminishing institutional capacity (Lopes and Chiavari 2021), and weakened protected areas (Borges 2019) — send a strong signal to deforesters that theirs is a favorable legislative and political climate for increasing deforestation.

17.4.2 Pro-deforestation Discourse from Political and Business Leaders

Although concrete law enforcement actions and territorial restrictions play a key role in reducing deforestation, the rhetoric of political and business leaders constitutes a powerful factor in shaping potential deforesters' perception of risk. Brazilian presidents and ministers of the environment, between 2003 and 2010, used strong language against deforestation, but the reverse is true in the years that followed. Environmental politics became less potent during the term of the administration elected in 2010. Following the impeachment of the president in 2016, the executive branch became even more exposed to the ruralist lobby and pro-deforestation interests, with the federal administration issuing several decrees that weakened the status of PAs and provided amnesty to land grabbers, as described above. Although some attempts to dismantle environmental policies were reverted, such as the relaxation of environmental licensing rules and the end of the Reserva Nacional de Cobre e Associados (RENCA, a large mining reserve), there was a strong signal that the political context was now becoming more lenient to illegal deforestation, resulting in increasing deforestation rates between 2015 and 2018, despite a rise in the number of environmental fines and the continuation of the PPCDAm (West and Fearnside 2021).

Although pro-deforestation clamor from rural political leaders has become increasingly louder since 2012, it has accelerated substantially since 2019. During the 2018 presidential campaign, commitments to halt the creation of PAs and to hamper IBAMA's "industry of fines" were made, and often landowners were portrayed as victims of biased environmental legislation. The administration that started in 2019 favored environmental deregulation and mild inspection of the sector. The effectiveness of law enforcement was questioned, and threats were made to reduce the autonomy of field inspectors. The current administration also proposed to decommission PAs, threatened to punish IBAMA personnel in charge of environmental sanctions (Brandford 2019; Watts 2019a), and senior administration officials challenged the veracity of deforestation and fire occurrence reports from the Brazilian Institute of Space Research. They also accused NGOs of setting fires in the Amazon, without evidence (Watts 2019b; Maisonnave 2019).

Politicians from the rural caucus were not alone in overtly supporting a pro-deforestation discourse in recent years. A video from an official cabinet meeting was released in which senior officials suggested taking advantage of the COVID-19 pandemic to "pass the herd", hinting at the approval of an array of bills to reduce bureaucratic processes supporting environmental legislation (Vale *et al.* 2021). Changes introduced by the current administration include reductions in the protection of wetlands and the further reduction of civil society participation in policy fora. In response to outrage from civil society, the scientific community, and some politicians, several business associations in Brazil acquired full-page ads in *Estado de São Paulo*, one of the country's main newspapers, to advertise their support for measures adopted by the current administration. Other business associations went even further by recommending further ways to relax environmental requirements. For instance, APROSOJA (Mato Grosso Soybean Producers Association) is calling for an end to the soy moratorium in the Amazon under the pretext of free trade principles (Samora 2019), whereas UNICA (the Brazilian Sugarcane Industry Association) has drastically changed its position on ban on growing sugarcane in the Amazon. In 2018, when a senator proposed to lift the ban, UNICA strongly defended it, particularly as 98% of its sugarcane is grown outside of the Amazon. They also emphasized the importance of reducing the risk of deforestation to promote exports of sugar and ethanol to the EU. However, under a new administration, UNICA changed its position and successfully helped terminate the ban (Follador 2019; Girardi 2019).

Counter-movements have not been silent. Some agribusiness associations; NGOs; and researchers from the Brazilian Coalition on Climate, Forests, and Agriculture have played an important role contesting the pro-deforestation narrative. At the end of 2019, the Coalition carried out a campaign ("Be Legal with the Amazon") promoting legal, sustainable agricultural practices in the Amazon, calling for a halt to land grabbing and further weakening of the Forest Code. In reaction, SRB, UNICA, and Abiove (the Brazilian Association of Vegetable Oil Industries) left the Coalition. As of March 2020, ABAG (the Brazilian Agribusiness Association), IBA (the Brazilian Tree Industry Association), and ABIEC (the Brazilian Beef Exporters Association) were the only major associations still participating in the Coalition, indicating the limited ability of sustainability-oriented agribusinesses to influence the growing pro-deforestation discourse.

17.4.3. Lost Opportunities Owing to Deforestation

The pro-deforestation discourse and actions carried out by the current administration in Brazil, endorsed by the rural lobbies and some agribusiness associations, undermine opportunities towards a sustainable development agenda. This has cost Brazil its global reputation and halted Amazon Fund financing from Norway and Germany, owing both to disappointing deforestation reduction results (van der Hoff *et al.* 2018) and the dismantling of environmental institutions. International investment funds concerned about the direct or indirect support of activities that further degrade our planet have already warned Brazil about its detrimental policies, threatening to divest in the country. The European Union is already developing mechanisms to halt the import of products linked to deforestation, including soy and beef, as well as programs to phase out their agricultural dependence on Brazil in the long run, which may increase the chances that the Mercosur trade agreement is not ratified by the EU. China may soon follow suit (Wachholz and Dutra 2021). In not fulfilling its commitment to curb deforestation, Brazil and its agricultural sector may suffer severe consequences and miss opportunities in new environmental markets (e.g., PES, green bonds, regulated in Law 14.119/21).

17.5. Conclusions

Dominant elites in South America have predominantly perceived the Amazon as an empty space with almost unlimited raw materials to be exploited, ignoring IPLCs and the crucial services provided by the Amazon. Before the 1970s, the Amazon was affected by a series of booms in the extractive sector, searching for rubber, gold, minerals, quinine, and other commodities, leaving behind deep disruptions. The expansion of the extractive sector during the past five decades has been unprecedented by its magnitude, widespread diffusion, and adverse social and environmental effects.

During the mid-1970s, Latin America began a shift from an inward-oriented and state-led model of import-substituting industrialization towards an internationally open and market-friendly development strategy of export promotion, following neoliberal principles. This transformation was part of the emergence of a new global model of a world economy based on a paradigm of flexible accumulation (Harvey 1989). Latin America became progressively integrated into the international economy, mostly as a commodity provider, in a new multipolar world with the increasing relevance of China. As a result, the Amazon experienced an accelerated expansion of the extractive sectors and agri-business, mostly soybean cultivation, cattle ranching, iron and other metal mining, and oil and gas, coupled with the building of large infrastructure and energy projects. Between 1990 and 2011, Brazilian soybean, iron ore, and beef exports increased more than 18 times, with a cumulative annual growth rate of 15% (CEPAL 2020). The expansion of oil and gas exploration was particularly relevant in Colombia, Ecuador, and Peru. Illegal drugs played a significant role in Colombia and Peru, often coupled with violence and land grabbing. Domestic markets also contributed to expanding demand, particularly in the case of beef. China is not only the main commodity importer from the Amazon region but is also a credit provider and a direct investor in extractive and infrastructure projects. Different transnational corporations in agribusiness, mining, and oil participate in the expansion of the extractive sector, often in alliance with national public and private companies.

This process has taken different forms depending on the distribution of natural endowments and mineral reserves, national policies, foreign investment, and social conflicts. Shifting commodity prices have defined periods of accelerated expansion, stabilization, or even decline in extractive activities.

The current prominence of agricultural commodity interests fails to see broader opportunities for economic development, as embodied in green finance, sustainability trends in the financial sector, international trade requirements, and related geopolitics. It also fails to perceive standing forests as the bedrock for developing conventional commodities such as soy and beef, since these depend on steady rainfall patterns and pollination services. They also need to satisfy an increasingly conscious market in terms of sustainability.

Conservation policies have also become globalized, receiving significant support from international institutions and even governments in developed societies. They have achieved important results, such as the expansion of PAs and ITs, which currently cover approximately 50% of the Amazon Basin (Chapter 16), and an 84% reduction in deforestation rates in Brazil during the 2005–2012 period. The expansion of protected areas and Indigenous territories has been a rather continuous trend in almost all Amazon countries since the 1960s, intensified during the last two decades, and has been a cornerstone for conservation in the Amazon.

Although PAs and ITs have significantly lower deforestation rates relative to other areas, the Amazon in general still suffers from high levels of deforestation and degradation.

The successful — albeit currently reversed — conservation policy implemented in Brazil from 2005 to 2012 is the most important national departure from state policies that promote, and to some extent regulate, extractive development in the region (section 17.3). It serves as evidence that deforestation and forest degradation can be controlled and reduced when the political will exists. Its success is the result of conservation being placed as a high political priority at the national level, with the participation of government, local authorities, business, and civil society, and strategic international cooperation. Its significance lies in the potential replicability of the experience at a Pan-Amazonian level or through coordinated national strategies, and in its role as a basis for stronger institutional arrangements and long-lasting results.

Brazil achieved important outcomes in curbing deforestation and expanding protected areas and Indigenous lands. However, sustainable economic diversification and improvement in living conditions while respecting environmental limits are still limited in the whole Amazon region. Achieving a sustainable Amazon implies substituting the limited commodity-dependent economy through economic diversification, increasing productive linkages, expanding biodiversity-based services, and improving the living conditions of Amazonian peoples. Sustainable pathways for the Amazon will be further analyzed in Part III of this Report.

The conservation paradigm has not been strong enough to control or detain the main adverse environmental and social impacts of the extractive development model. As a result, unsustainable extractivism remains the leading paradigm guiding public policies and private investment. The Brazilian case highlights complex politics linked to the 'epochal processes' of hegemonic and counter-hegemonic movements. On the one hand, the challenges posed by environmentalism to the extractive development hegemony provoked strong reactions in the latter's advocates, reversing many of the advances made in the 2000s (section 17.4). On the other hand, the subjugation of environmental policies by these hegemonic processes jeopardizes its resilience to changes in the natural environment (e.g., Lovejoy and Nobre 2017) or broader geopolitical and economic preferences (section 17.4). A middle ground needs to be found.

Despite important environmental achievements, policies and private strategies in the Amazon remain linked to a dominant extractive paradigm. Although the region was deeply transformed by a sustained expansion of commodity production both for international markets and domestic demand, and a rapid process of migration and urbanization reshaped the region's demographic profile, the transformation failed to bring about sustained and equitable improvement in living conditions. Instead, social exclusion, poverty, and lack of political participation of Indigenous peoples and other marginalized groups prevail. Moreover, deforestation, degradation, and biodiversity loss are close to a tipping point, which could unleash a self-sustained process of permanent degradation, jeopardizing not only rainforest integrity but also critical climate services to South America and the world (Lovejoy and Nobre 2017). Social inequality and unsustainable activities are critical failures of the current extractive development strategy in the Amazon, which leads the region to an unequal development process, as rents and profits are frequently appropriated and reinvested elsewhere, and labor remuneration remains at subsistence levels.

The current development model has not only failed to generate a sustainable, participatory, and equitable improvement in human capabilities, but also lacks solid theoretical basis. There is strong criticism that neoclassical economic theory cannot be applied to current development problems. Conventional economic theory does not have an adequate framework to explain interactions between the economy and the environment, nor market distortions generated by monopolies and transnational corporations (Lefeber 1991; Stiglitz 1998, 2002, 2013; Stiglitz *et al.* 2008).

A new, sustainable, and equitable development strategy is necessary for the Amazon, to maintain the provision of environmental benefits from rainforests, the integrity of Indigenous cultures, and improve living conditions for most of the population. Such a strategy should also maintain cultural diversity, provide decent employment, eliminate poverty, and reduce social inequality.

Building new paradigmatic strategies may also need a departure from conventional economic thinking towards more comprehensive and integrated approaches, such as the emerging framework of ecological economics (Brown and Timmerman 2015; Common and Stagl 2005; Martínez Alier and Roca 2000; Daly 2010).

17.6 Recommendations

1. Globalization and widespread changes in consumption have drastically altered the type and scale of human intervention in the Amazon, generating social and environmental impacts of unprecedented magnitude and gravity. Together with countries from the Global North, China is an increasingly dominant actor in this process. Environmental and social sustainability must be embedded and mainstreamed into global and local political decision-making and business incentives. Non-Amazonian countries, particularly developed countries and China, are important actors in mounting an effective response and must be part of the solution.

2. Brazil provides a strong example of how deforestation control, implemented through strategic state policy involving the commitment and coordinated involvement of multiple government actors, can contribute to significantly reducing deforestation. The involvement should not be exclusively restricted to environmental authorities and should include genuine international commitment and support. Brazil's experience can be replicated in other Amazonian countries, adapted to local conditions and realities. Country by country strategies may be complemented by trans-Amazonian coordinated policies within the framework of the Leticia Pact.

3. Deforestation reduction and forest conservation policies are vulnerable to changing governments and political priorities. Institutional agreements that transcend changing political cycles must be implemented to ensure continuity of policies for forest conservation, as the international climate-change strategy suggests.

4. Initiatives to reverse deforestation must involve the participation of all stakeholders (different levels of government, multiple sectors of the economy, civil society actors, Indigenous peoples and local communities (IPLCs), and international organizations), and including cross-cutting voices of gender and youth. IPLCs' participation is essential for sustainable forest and river management, and must include a socio-environmental perspective, where sustainable, healthy livelihoods and conservation are coupled.

17.7 References

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Amazon Assessment Report 2021

Chapter 18

Globalization, extractivism, and social exclusion: Country-specific manifestations

Imagem aérea de gado e plantação de soja em área desmatada, 2020 (Foto: Bruno Kelly/Amazônia Real)

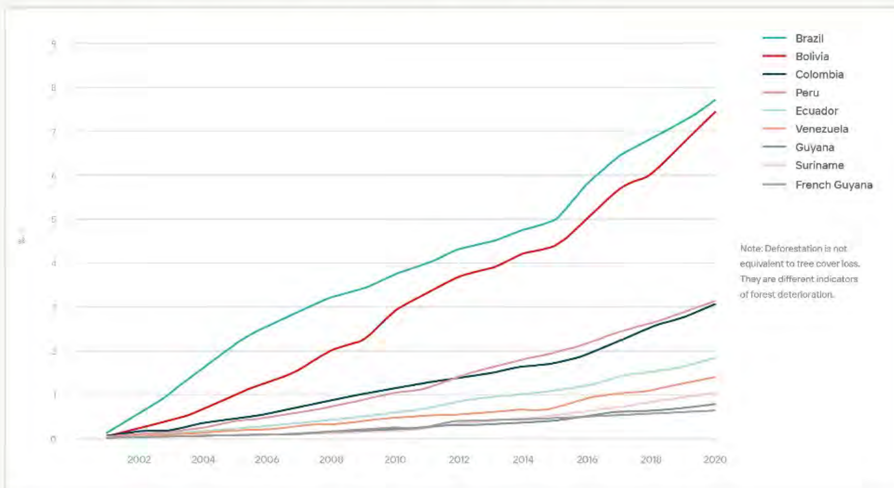
INDEX

Graphical Abstract

Primary Forest Loss by Countries (2001-2020)

Although forest deterioration differs among countries and territories, in all cases there is a recent increasing trend.

Cumulative Tree Cover Loss in Amazon Countries: 2001-2020 (% 2000 Area)



Amazon conservation threats and policies by country

Country or Territory	Cumulative tree cover loss in primary forests 2001-2020 (% area 2000)	Level	% Protected areas 2020	% Indigenous territories 2020	Main degradation drivers	Public policies
Brazil	7.77	High	24.3	22.8	Cattle ranching, soybean, iron mining, infrastructure	Extractivism compensated with Protected Areas and Indigenous Territories (PAIT), reducing deforestation (2005-2012).
Bolivia	7.49	High	30.0	26.5	Cattle ranching, Large Scale Agriculture	Extractivism with conservation rhetoric and PAIT.
Peru	3.16	Medium	21.1	34.0	Cattle ranching, oil, shifting agriculture, illegal drugs	Extractivism with PAIT.
Colombia	3.08	Medium	26.0	54.3	Cattle ranching, oil, illegal drugs, illegal gold mining	Extractivism with conservation rhetoric and PAIT.
Ecuador	1.86	Medium-low	26.8	55.9	Oil, shifting agriculture, cattle ranching	Extractivism with conservation rhetoric and PAIT.
Venezuela	1.41	Low	46.0	56.5	Illegal gold mining	Weak state presence, mining promotion.
Suriname	1.05	Low	-	-	Gold mining	Mix of intervention and conservation, weak state presence.
Guyana	0.79	Low	-	-	Gold mining	Mix of intervention and conservation, weak state presence.
French Guyana	0.65	Low	50.7	13.1	Gold mining	Mix of intervention and conservation.
Total	**5.45**		**24.9**	**27.0**		

Figure 18A. Graphical Abstract

Globalization, Extractivism, and Social Exclusion: Country-Specific Manifestations

Carlos Larrea[*a], María R. Murmis[b*], Stefan Peters[c], Andrés Escobar[c], Daniel Larrea-Alcázar[d], Luz Marina Mantilla[e], Eduardo Pichilingue[f], Emiliano Terán-Mantovani[g], Michiel van den Bergh[h]*

Key Messages

- Local manifestations of deforestation and degradation are particular to national and local contexts as a function of their natural, historical, social, political, and economic conditions.
- Two antagonistic ideas have predominated as models for the region, "extractivism" and "conservation". The current Amazonian development model is not sustainable, and the transition to an alternative path is necessary. A new model must achieve forest conservation and meet the self-determined welfare objectives of Indigenous peoples and local communities (IPLCs), redefining economic activities, rules, incentives, and business models, while being regionally coordinated and sustainable in the long term.
- The Amazon is characterized by severe social inequality, particularly unequal land distribution; when coupled with land tenure irregularity, this hinders sustainable development. The disproportionate impact of COVID-19 on the most vulnerable populations, in particular Indigenous peoples, is a clear example.
- The transition to a low-emission and sustainable development path must include effective policies to reduce inequalities and involve the just distribution of land and regularization of tenure, considering, where necessary, different cultural notions of property. This should be coupled with social policies that help maintain ties to the land and enhance the ability to obtain good standards of living.

Abstract

This chapter presents country-specific descriptions of human intervention in the Amazon. In general, a rapid expansion of agricultural and extractive activities, mostly for export but also for domestic markets, and to a lesser degree small scale agriculture, have led to extensive deforestation and environmental degradation without improving the living conditions of the population. Government policies and the extent of State ascendancy in the area also seem to be a powerful determinant of the nature and scale of the process. Despite the common underlying international and domestic economic and political forces in the Amazon, each country has its own particularities. In the case of Colombia, the process was shaped by the guerilla presence and deteriorated after the Peace Treaty, which does not mention "deforestation" and perpetuates Colombia's extractivist model. Ecuador's case is representative of the link between fossil fuel extraction, environmental deterioration, and social exclusion. The case of Peru shows an Amazon perceived as a territory awaiting to be "conquered, occupied, and exploited", subjected to an unwavering extractive and market-orientated drive. In Bolivia, contradictions between conservation and state-led development policies and business activities, which have transformed it into the second-highest deforestation hotspot

[a] Andean University Simon Bolivar, Toledo N2280, Quito, Ecuador, clarrea_2000@yahoo.com
[b] Andean University Simon Bolivar, Toledo N2280, Quito, Ecuador, mariamurmis@gmail.com
[c] Justus-Liebig-Universität Giessen, Instituto CAPAZ
[d] Asociación Boliviana para la Investigación y Conservación de Ecosistemas Andino-Amazónicos (ACEAA-Conservación Amazónica), Calle Flores Quintela, Ed. Nro. 7, Oficina 1B, La Paz, Bolivia.
[e] Institute of Amazonian Research – SINCHI, Avenida Vásquez Cobo Entre Calles 15 Y 16, Leticia, Colombia
[f] Pachamama Alliance, Perú. Universidad San Francisco de Quito, Ecuador.
[g] Universitat Autònoma de Barcelona (Spain) and member of the Observatory of Political Ecology of Venezuela. Spain.
[h] WWF, Suriname.

after Brazil, are presented. The Venezuelan Amazon is subject to rampant violence and illegal activity driven by the political geography of gold in mixed configurations of governance, with blurred boundaries between legality and illegality and prevailing negligence concerning conservation. The Guianas share low deforestation levels and lower environmental pressures, but the recent expansion of gold mining poses a serious threat. The Brazilian case presented in the previous Chapter is referenced here when comparing countries' experiences. Conservation experiences are also included. In all cases, unsustainable extractivist models have outpaced conservation policies; however, these experiences can prove useful in the design of effective conservation policies, reduction of greenhouse gas emissions, and improvements in living conditions of Indigenous peoples and local communities.

Keywords: Globalization, extractivism, deforestation, conservation policies, development policies.

18.1 Introduction

Human intervention in the Amazon has accelerated since the 1970s, threatening the rainforest, its environmental benefits, and the integrity and survival of its diverse Indigenous peoples and local communities (IPLCs). The rapid expansion of agricultural and extractive activities, geared mostly towards export but also to supply domestic markets, has driven significant deforestation and environmental degradation without improving the living conditions of the population. Extensive cattle ranching, soy cultivation, oil, gas, mining, illegal gold extraction, and drug trafficking, coupled with roads and mega infrastructure projects, such as hydroelectric dams, has contributed to an unequal and unsustainable development process (Chapters 14 and 17; WWF 2016).

Although the underlying international and domestic economic and political forces generating these processes are common to all Amazonian countries and territories, there are country-specific manifestations, transformations, and conservation policies (Box 18.1). This chapter explores the specific traits of country cases and the underlying causes, which serve to understand the complex and changing character of current human intervention in the Amazon.

The analysis in this chapter includes two comprehensive national cases in the Andean Amazon (Colombia and Ecuador), and succinct studies of cases in Bolivia, Peru, Venezuela, Guyana, Suriname, and French Guiana. The Brazilian case was explored in-depth in the previous chapter. The first case is the Colombian experience after the peace agreement with the Fuerzas Armadas Revolucionarias de Colombia (FARC) guerrilla group, which resulted in increased deforestation. The second case is Ecuador's oil-driven intervention in the Amazon, illustrating the link between fossil fuel extraction, environmental deterioration, and social exclusion. To complement the mosaic of experiences, other cases are briefly analyzed: Peru, a country with an unwavering extractive and market-orientated profile; Bolivia, a pioneer in environmental legislation but subject to critical contradictions between conservation and state-led development policies and business activities; Venezuela, where the Amazon is subjected to rampant illegal activity and mixed configurations of governance driven by the political geography of gold and limited ascendancy by formal state structures; and finally, the Guianas (here inclusive of Guyana, Suriname, and French Guiana), a subregion where deforestation rates are the lowest in the Amazon, but where environmental threats are rising rapidly.

National experiences differ, not only by their specific drivers of environmental degradation, but also by magnitude (Costa 2020). Taking primary forest tree cover loss between 2001 and 2020 (World Resources Institute 2021) as an indicator, forest deterioration is led by Brazil, with a 7.8% loss. Containing 58% of the Amazon rainforest area in 2000, Brazil accounted for 77% of primary forest tree cover loss across all Amazonian countries (Figures 18.1, 18.2, 18.3; Table 18.1).

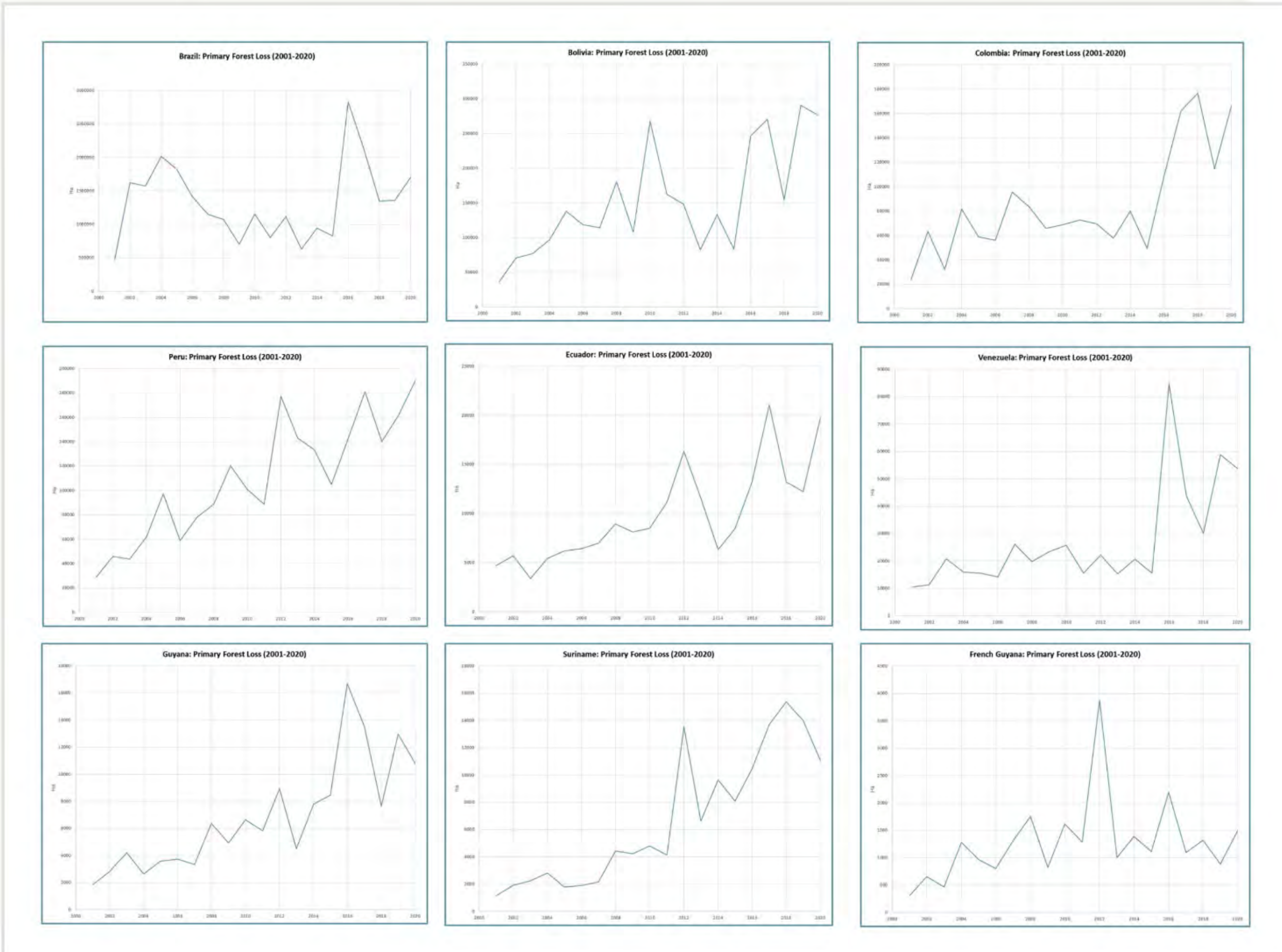


Figure 18.1 Primary Cover Loss by Countries (2001-2020). Tree cover loss is not equivalent to deforestation. Source: World Resources Institute (2021).

Between 1985 and 2019, the bulk (89%) of deforested land in Brazil's Amazon was transformed into pastures, and 9% for soy cultivation (RAISG 2021). Pasture area increased more than three times in the period, except during the 2005–2012 interval, when deforestation declined (Chapter 17). Soy cultivation began in 2000 and increased 20 times, with an average growth rate of 17% per year. Extensive cattle ranching and soy cultivation have been the leading direct factors in Brazilian deforestation (Chapter 17), but in both cases the growth declined or stopped when deforestation was controlled, and resumed with lower intensity when the policies launched in 2003 and 2004 to control deforestation and establish a sustainable development model in the Brazilian Amazon (PAS, PPCDAm and among others Plano BR-163 Sustentável) were reversed, as covered in detail in Chapter 17 (Figure 18.4). Brazil also has most of the Amazon's large-scale mining operations, particularly for iron ore. Large infrastructure projects — roads (Initiative for the Integration of the Regional Infrastructure of South America, or IIRSA) and hydroelectric dams — are significant drivers of environmental degradation (RAISG 2020).

Degradation has also been intense in Bolivia (Figure 18.3). Despite its environmentalist rhetoric, the Bolivian government actively promoted land clearing for large-scale cattle ranching and agriculture,

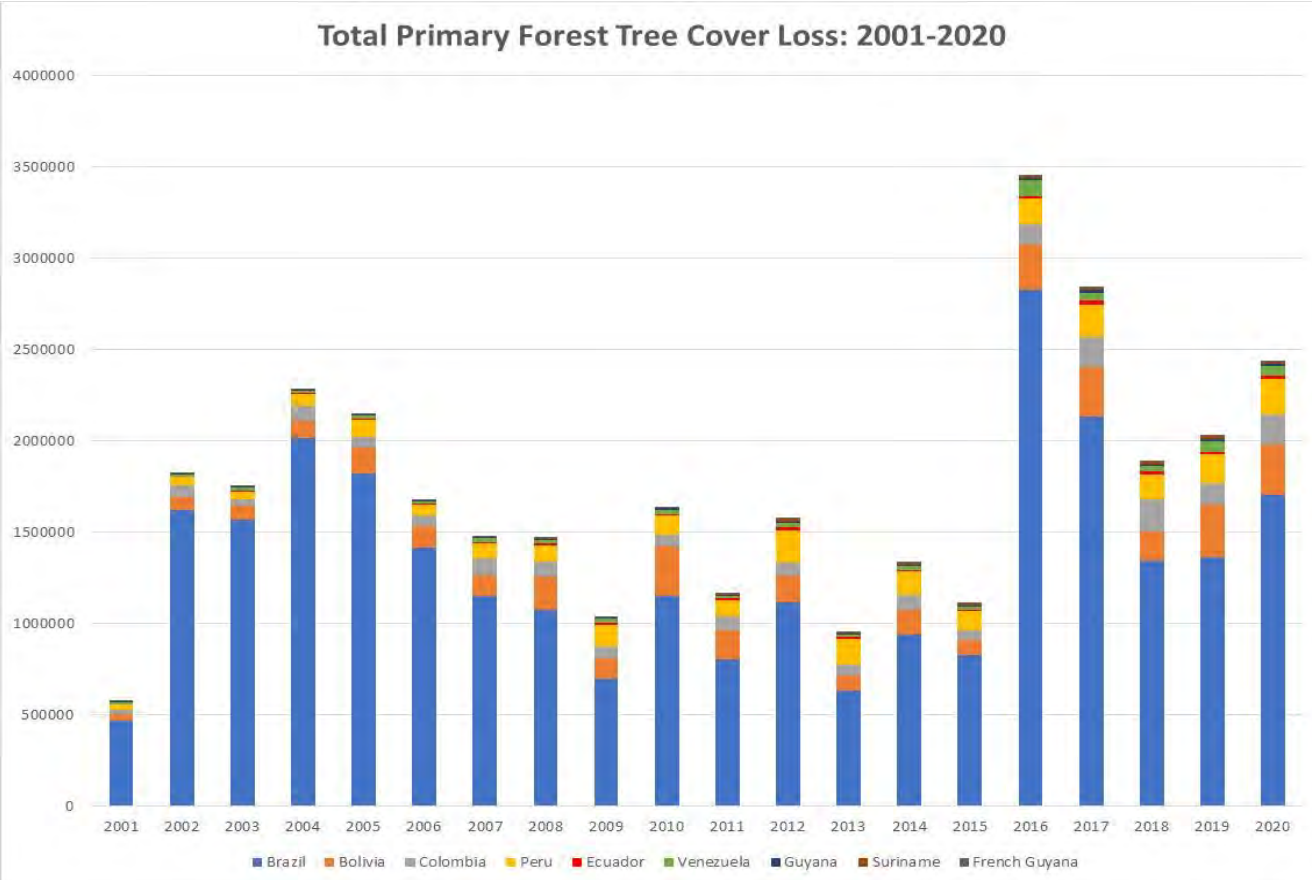


Figure 8.2 Source: World Resources Institute (2021).

extractive activities, and infrastructure, particularly roads and dams, all within and outside national parks. As a result, tree cover loss was also extensive in Bolivia (7.5%), which closely follows Brazil's case. Peru, Colombia, and Ecuador have lower primary forest losses (3.2%, 3.1%, and 1.9%, respectively).

Commercial agriculture has had an important role in the higher forest-loss countries, Brazil and Bolivia. In most cases, oil extraction has played a significant role as an environmental deterioration driver (Figure 18.5). Crude oil is currently the main export product of Ecuador and Colombia, whereas in Peru the Camisea megaproject provides natural gas for export (OEC 2021). Oil and gas extraction in the Andean Amazon has also led to severe environmental impacts in protected areas (PAs), such as Yasuni National Park in Ecuador, regarded as the most biodiverse place in the western hemisphere (Bass et al. 2010; Larrea 2017).

Ecuador's case study not only includes the detrimental environmental impact of oil extraction, but also the lack of social distribution of revenue in the region. The Amazon is still the poorest region in the country, and oil extraction areas are more socially deprived than non-oil subregions. In Ecuador's Amazon, deforestation is mostly conducted by poor migrant peasants, with large-scale livestock and plantations less frequent. The analysis finds that peasant families do not perceive lasting benefits from deforestation, as land productivity is low and declines over time (Larrea 2017; Wunder 2000).

Mining megaprojects are concentrated in Brazil and have recently expanded to Ecuador, whereas illegal gold mining causes heavy environmental

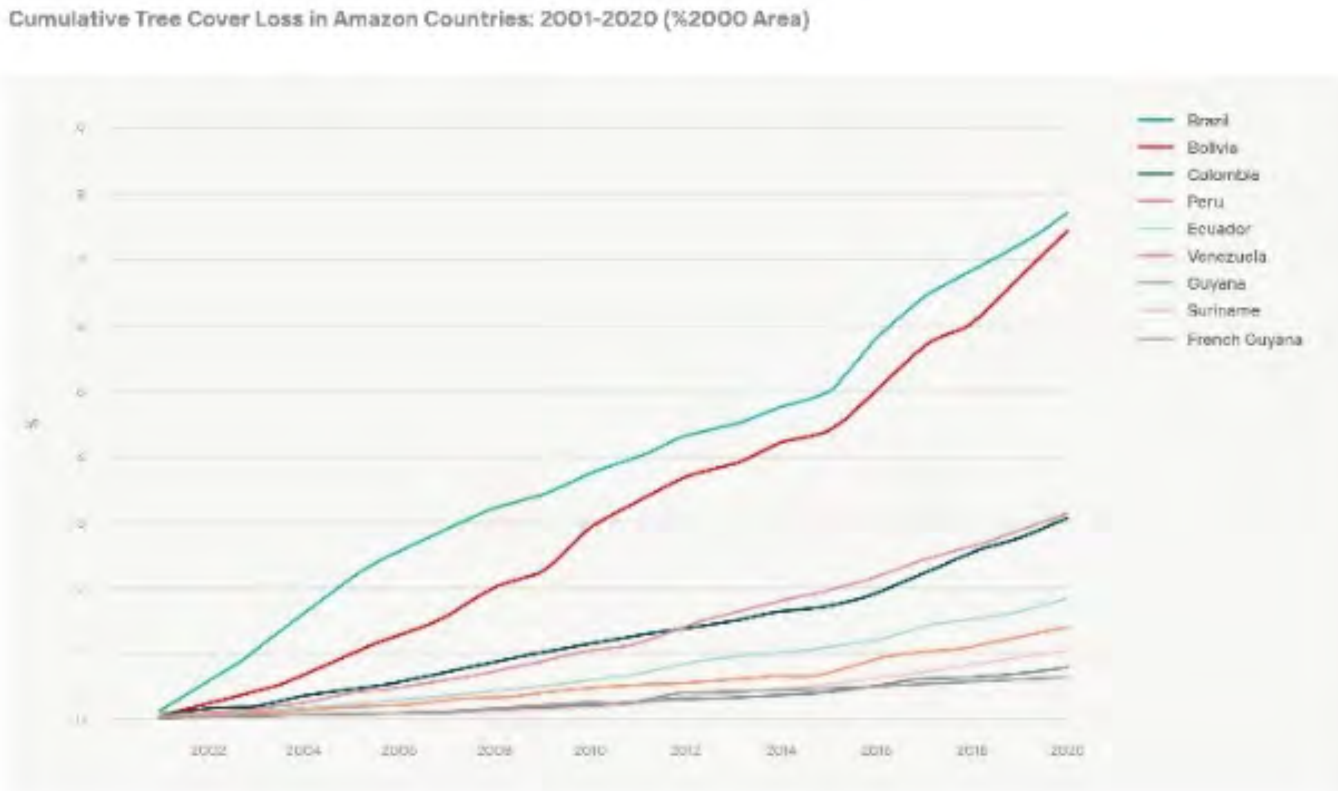


Figure 18.3 Tree cover loss is not equivalent to deforestation. Source: World Resources Institute (2021).

impact in all Amazonian countries. According to recent estimates, illegal gold extraction accounts for 28% of gold mined in Peru, 30% in Bolivia, 77% in Ecuador, 80% in Colombia, and 80–90% in Venezuela (Figure 18.6). It is estimated that the value of illegal gold exports is comparable to that of cocaine exports (GI-TOC 2016). Gold is the main export product in Suriname.

In the recent Colombian experience, increasing deforestation was registered in the Amazon region after the 2016 peace agreement. An extractive model predominates, with cattle ranching, oil expansion, and land grabbing prevailing. The study is also illustrative of the effects of illicit extractive activities, often linked with chronic violence, which are also present in Peru and Venezuela, and manifest in most other countries.

A third group of countries and territories with low forest loss are Venezuela (1.4%), Suriname (1.1%), Guyana (0.79%), and French Guiana (0.65%). Land-use change from forest to agriculture has been low in all of them, but forest loss is on the rise, principally driven by gold extraction, but also by unsustainable forestry and fishing practices, and poaching, with an incipient potential offshore oil and gas boom in Guyana and Suriname.

In Venezuela, where abundant oil reserves located outside the Amazon did not stimulate economic diversification, extractive pressures on the rainforest were weaker and deforestation remained low. During the so called “Big Crisis” (2013 to today), the government promoted mining in the Amazon Orinoco Arc. Although large-scale mining remained weak, expansion of illegal mining of gold, coltan, and other minerals took place, often linked to organized crime. As a result, environmental deterioration and social conflict increased, with particularly dire consequences for Indigenous peoples.

This chapter shows the varying configurations seen in the individual cases while the presence of

Pasture and Soy Cultivation Area in Brazilian Amazon 1985-2019 (Semilog scale)

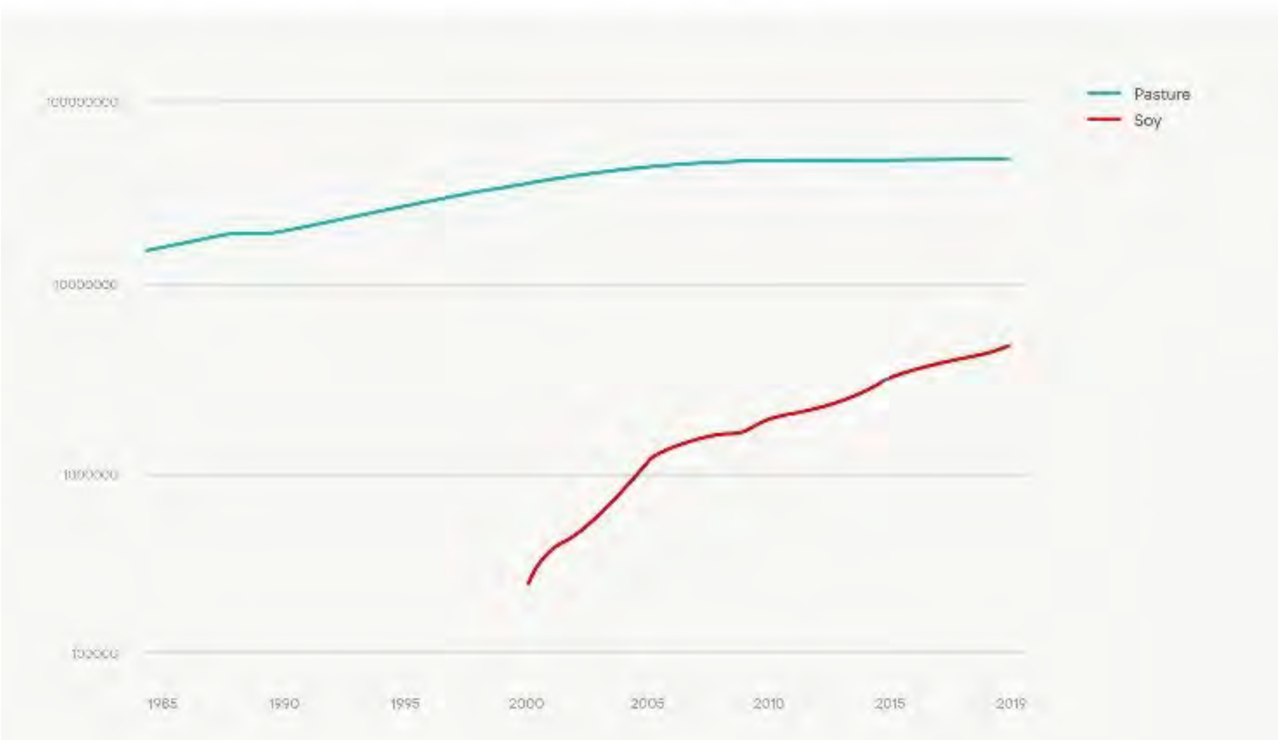


Figure 18.4 Pasture and Soy Cultivation Area in Brazilian Amazon. Source: RAISIG 2021.

underlying and cross-cutting common forces permeates the region. These common forces may involve shared internal factors, such as institutional weakness, or external influences, such as demand for commodities, but together their compounded effect is seen country by country and regionally in a degraded, plundered, and unsustainable Amazon.

18.2 Amazon Deforestation in Post-Conflict Colombia

Approximately 43% of Colombia is in the Amazon (Figure 18.7), making Colombia one of the five megadiverse countries in the world. In 2018, the Colombian Supreme Court of Justice declared the Colombian Amazon Subject of Right and disposed that the Colombian government must create a concrete mechanism to protect the Amazon (Bustamante et al. 2020; Sentence 4260-2018 of the Colombian Supreme Court of Justice).

However, in the twenty-first century, 5.7% of Colombia's forested areas (4.4 million ha) have been cleared (Global Forest Watch 2020). This is roughly equivalent to the area of Denmark. The main deforestation areas are within five Colombian departments: Caquetá, Meta, Guaviare, Antioquia, and Putumayo (Figures 18.8 and 18.9). Except for Antioquia, all departments are in the Amazon/Orinoquía region. Similar to other countries of the region, deforestation in Colombia has various facets: a) severe socio-cultural and socio-economic transformations that threaten the traditional lifestyles of Indigenous communities; b) massive biodiversity loss; and c) disastrous impacts on the global climate (IDEAM et al 2017).

Deforestation has significantly accelerated after the historic signing of the peace treaty between the Colombian government and the FARC-EP guerrilla group in 2016. This is no surprise, as international empirical evidence indicates that post-conflict scenarios often accelerate deforestation (Murillo-Sandoval et al. 2020). In the Colombian case, defor-

Table.18.1 Tree Cover Loss in Primary Forests. Source: World Resources Institute 2021. Tree cover loss is not equivalent to deforestation.

	Tree Cover Loss in Primary Forests (ha)									
Year	Brazil	Bolivia	Colombia	Peru	Ecuador	Venezuela	Guyana	Suriname	French Guyana	Total
2001	465543	36530	24082	28699	4701	10438	1835	1145	313	573285
2002	1621765	70601	63302	46059	5693	11323	2825	1932	655	1824155
2003	1570576	77167	32050	43733	3379	20775	4216	2243	465	1754604
2004	2016477	96611	81695	62035	5436	15924	2630	2814	1283	2284906
2005	1824425	137831	58906	97399	6205	15565	3579	1808	965	2146683
2006	1415580	118804	56051	58813	6438	14244	3744	1893	804	1676371
2007	1149563	114376	95539	77992	6995	26116	3346	2158	1313	1477398
2008	1075146	180575	83619	88797	8953	19859	6377	4431	1757	1469512
2009	700169	108163	65824	120186	8112	23435	4929	4227	820	1035865
2010	1153025	267751	68739	100970	8491	25809	6656	4797	1620	1637857
2011	803049	162625	72601	88886	11175	15590	5831	4125	1279	1165161
2012	1116088	148294	69587	177236	16354	22125	8942	13540	3872	1576038
2013	632094	82290	57713	142870	11590	15349	4512	6628	1001	954046
2014	940905	133268	80036	133107	6330	20609	7790	9659	1386	1333088
2015	828870	83299	49643	104864	8472	15546	8463	8080	1116	1108352
2016	2830977	246088	108566	142720	13198	84705	16689	10457	2195	3455595
2017	2134649	270346	161945	181090	21085	43759	13505	13718	1097	2841194
2018	1347133	154489	176977	140185	13220	30169	7628	15367	1318	1886485
2019	1361094	290499	115090	161590	12231	58827	12964	14013	883	2027194
2020	1704092	276883	166485	190199	19747	53702	10763	11076	1498	2434446
Total Loss	**24987130**	**2779604**	**1521963**	**1997230**	**178060**	**490167**	**126460**	**123033**	**24142**	**32227789**
% Area 2000	7.77	7.49	3.08	3.16	1.86	1.41	0.79	1.05	0.65	5.86
Area 2000	343383394	40833752	54836889	69170714	10652183	38666663	17297899	12775509	3923496	591540498
% By country	58.0	6.9	9.3	11.7	1.8	6.5	2.9	2.2	0.7	100.0
Loss % Area 2000	77.0	8.8	4.9	6.3	0.6	1.6	0.4	0.4	0.1	100.0

Figure 18.5 Oil and gas consessions in the Amazon. Source: RAISG, 2021.

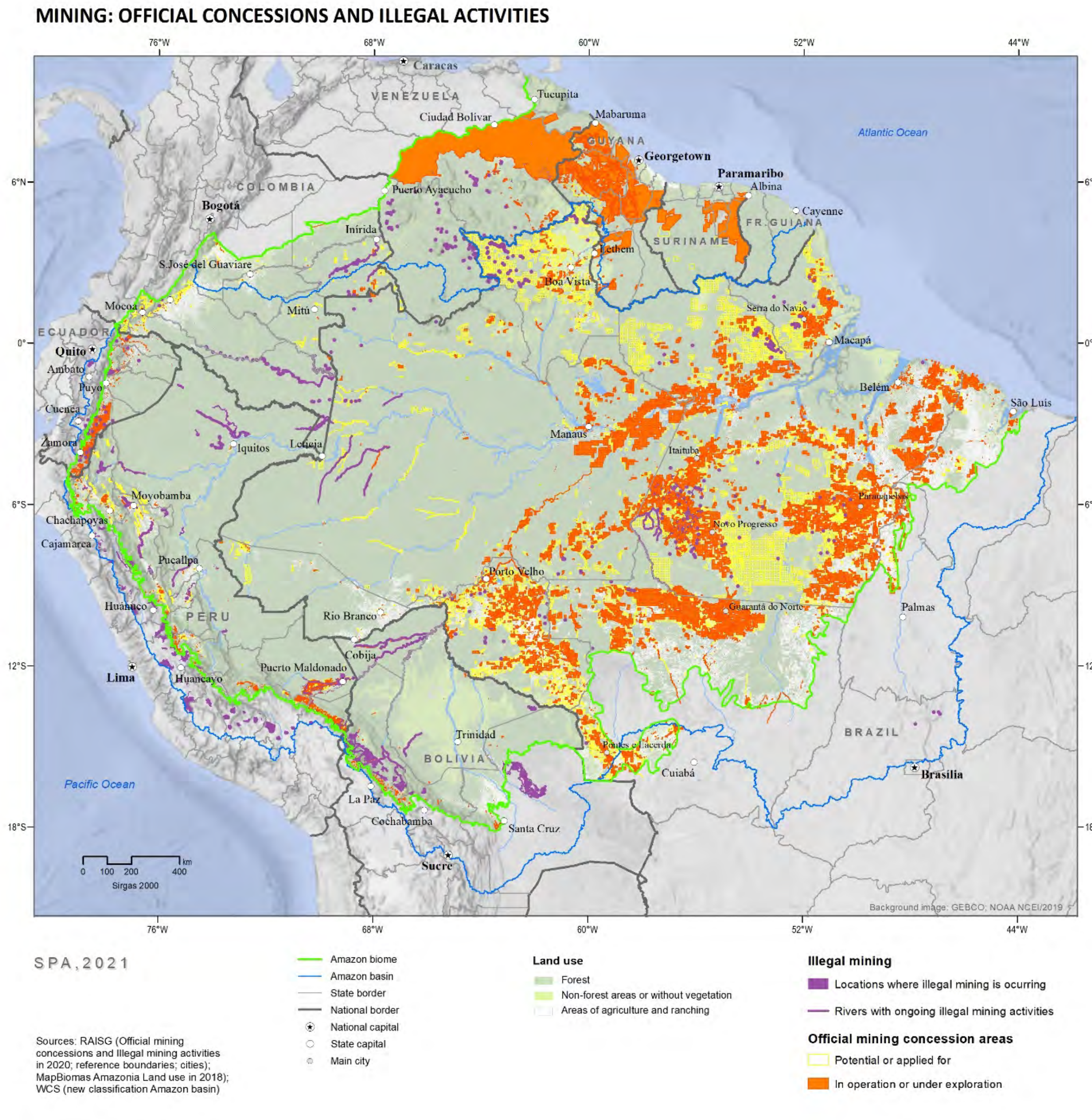


Figure 18.6 Official mining concessions and illegal activities. Source: RAISG, 2021.

Figure 18.7 Colombian Amazon is distributed in the departments of Amazonas, Caquetá, Guainía, Guaviare, Putumayo, and Vaupés as well as parts of Meta and Vichada, and small parts of Cauca and Nariño. Source: Colombian

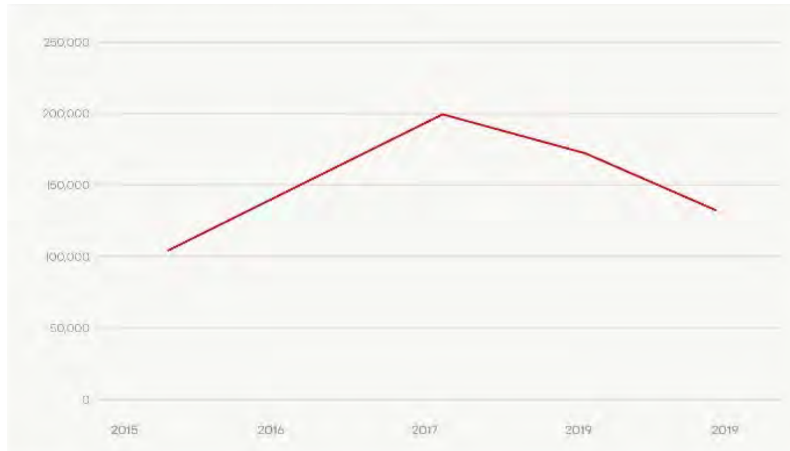


Figure 18.9 Top 10 Departments Deforestation in Hectares. Source. Own construction based on IDEAM (Colombian Institute of Environmental Analysis) deforestation reports between 2015 and 2019.

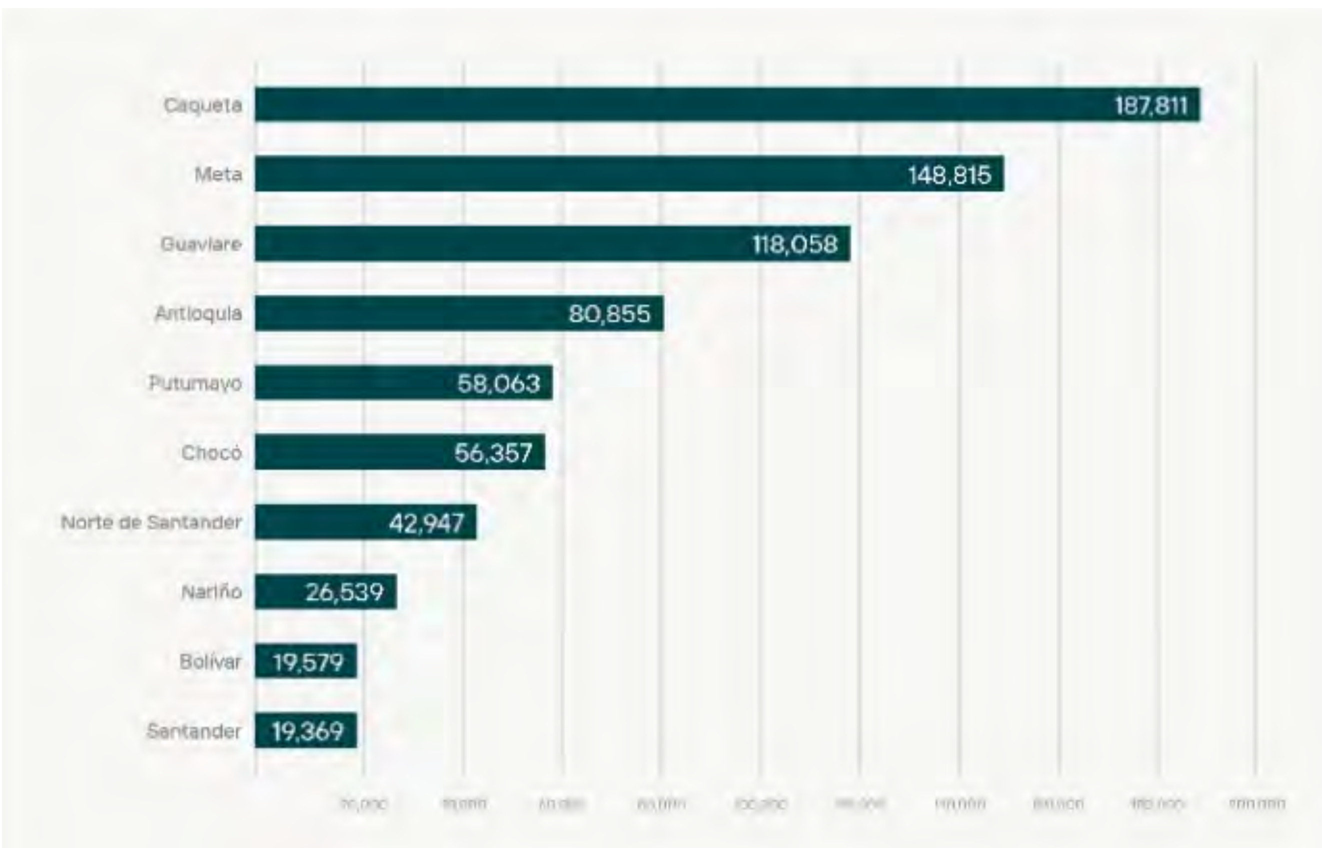


Figure 18.8 Accumulated deforestation top ten Departments in Colombia: 2015–2019. Source: Colombian Institute of Environmental Analysis- IDEAM,2020.

estation was not appropriately addressed during the peace negotiations, with the term "deforestation" not being mentioned in the final agreement. Instead, the document includes objectives to modernize the Colombian countryside, which would arguably trigger deforestation. However, the main challenge for forest protection is linked to the Colombian extractivist development model. The former federal administration (2010–2018) presented the extractivist development model as the backbone for financing the peace process (Ulloa and Coronado 2016), a vision also shared by the current administration (2018–2022) (DNP 2018: 695). However, the current administration introduced major political changes, slowing down the implementation of the peace agreement (Instituto Kroc 2021). The focus on the extraction and the "export of nature" (Coronil 1997) has far-reaching negative economic and social outcomes and implies harsh negative social-ecological consequences (Gudynas 2015).

The Colombian Amazon was a stronghold of the FARC-EP guerrilla group (Van Dexter and Visseren-Hamakers 2019; Krause 2020), which slowed deforestation through "gunpoint conservation" (Álvarez 2003: 57). The FARC conserved the forest as a natural barrier for their own protection against incursion, while the presence of armed groups curbed development projects and related forest clearing (Rodríguez-Garavito and Baquero 2020; Murillo-Sandoval et al. 2020). To avoid misunderstandings, the internal conflict in Colombia had multiple negative effects on the environment, such as oil spills and environmental damage owing to direct impact from battles, including in the Amazon region (Nuñez-Avellaneda et al. 2014; Pereira et al. 2021). The staged self-image of the FARC guerrillas as armed environmentalists is more myth than reality. However, although conflict did not prevent deforestation (Negret 2019), the strong guerrilla presence in the Amazon region indeed slowed down deforestation (Mendoza 2020).

The signing of the peace agreement was a game-changer. It reduced armed violence and represented a pre-condition for a better future for Colombia. Unfortunately, the environment is a victim of the fragile Colombian peace process, owing to accelerated development and modernization projects. Official figures (Reardon 2018) show how deforestation rates in Colombia have soared since 2016 (Figures 18.1 and 18.9). This is especially true for large parts of the Amazon region, in which "unintended peace-induced deforestation rates" (Prem et al. 2020: 7p.) dramatically increased during the peace process (Álvarez, 2003; Krause 2020; Graser et al. 2020). This also applies to PAs and Indigenous territories (ITs), where parallel markets for land are reported (Armenteras et al. 2019; Clerici et al. 2020; Murillo-Sandoval et al. 2020; Tobón Ramírez et al. 2021). This process is highly linked to the expansion of the extractive frontier in the Colombian Amazon (mining, hydrocarbons, and agrarian extractivism, including illicit crops), processes of land grabbing, and a deep-rooted socio-cultural preference for land ownership by elites as a symbol of status and political power (Richani 2012).

18.2.1 Drivers of Deforestation and Extractivist Development Projects in the Colombian Amazon

Deforestation in the Amazon region does not follow a shared logic. Instead, the diversity of the region corresponds to the heterogeneity of the dynamics of deforestation and thus requires locally or regionally adapted protection strategies. The main drivers for deforestation include: i) cattle ranching; ii) land grabbing; iii) extractivism; iv) illicit drug cultivation; v) infrastructure development; and vi) the expansion of the agricultural frontier by smallholders (see Chapters 19 and 20). However, the various drivers of deforestation should not be considered as equivalently relevant for deforestation, nor should they be analyzed in isolation, but rather in their interdependence (Hoffmann, García Márquez and Krueger 2018).

Extensive cattle ranching is by far the most important driver of deforestation in Colombia in terms of area (Prem et al. 2020). In Colombia, the cattle ranching model combines the historical continuity of an extremely unequal distribution of land with rentier logic that links land ownership with political power and social status. Extensive cattle ranching is supported institutionally by the fact that this form of land use is an easy and inexpensive way to demonstrate the productive use of land and is therefore undertaxed. However, cattle ranching should not be analyzed in isolation, as it is strongly linked to land grabbing.

Land is a major investment opportunity both for legal and illegal money. This leads to increased land concentration and deforestation, as clearing the land is seen as a productive improvement and backs legal land claims (Armenteras 2019; see also Chapter 14). In the context of the peace process, one objective is formalizing land titles throughout the country. Although this is an important advance for ensuring smallholders' rights, it might also support land grabbing and land concentration processes by giving legal certainty to investors. Moreover, cattle ranching is often closely linked to the illegal drug economy. Clearing forest for coca production is often followed by livestock farming, and land transactions are a preferred form of laundering drug money (Richani 2012; van Dexter and Visseren-Hamakers 2019; Vélez Escobar 2020).

The Colombian development model is based on extractivism (for a discussion of the term see e.g., Burchardt and Dietz 2014; Gudynas 2015; Svampa 2019; Peters 2021). This was decisively accelerated during the liberalization of the Colombian economy at the end of the 20th century. Extractivism in Colombia led to an increase in the share of primary goods in total value of exports between 2000 (67.5%) and 2018 (79.3%) (Peters 2021). Compared to other Latin American countries, Colombia has a rather diversified extraction structure, including oil production, mining, and monocultural agrarian extractivism. The expansion of the extractivist frontier has particularly strong impacts in the Amazon, including deforestation owing to mining projects and the start of new oil extraction projects, deforestation due to lumbering precious woods (International Crisis Group 2021a: 21) for export, and the expansion of extractivist monocultures with a focus on palm oil, also leading to new conflicts on land use with local communities (Marín Burgos and Clancy 2017; Pereira et al. 2021).

Coca cultivation is also an important driver of deforestation, especially in remote areas (Dávalos, Sánchez and Armentreras 2016; Mendoza 2020). Approximately 47% of coca cultivation in Colombia takes place beyond the agricultural frontier, mostly on small plots of land in adjacent areas, including Indigenous territories and Afro-Colombian communities. Coca production in Colombia has risen sharply in recent years and is increasingly found in the Amazon regions of Putumayo, but also in Caquetá, Guaviare, Meta, and Vichada (UNODC 2021: 26). Coca production implies severe negative consequences for forests and biodiversity (Rincón-Ruiz and Kallis 2013). However, impacts vary widely at the local level and data on cultivation on a municipality basis should be taken into consideration (Table 18.2).

Additionally, the activity implies further environmental degradation through the production of pasta base and the gradual expansion of the agricultural border. In the past, these were controlled by aerial spraying with glyphosate as part of the Plan Colombia, with worrying environmental consequences (Dávalos et al. 2021). The Plan Colombia was jointly agreed between the Colombian and US governments in 1999. It focused on improving security conditions in the Colombian countryside by fighting illegal armed groups and reducing production and trafficking of illicit drugs. Plan Colombia was financed by the USA and fostered their strategic position in the region. The current Colombian administration (2018–2022) considers the fight against coca to be the most important instrument to curb deforestation and blamed consumers for their responsibility for deforestation in the Amazon. Currently, there is a renewed increase in the number of voices calling for a return to aerial spraying, although there is abundant evidence of its detrimental socio-economic and socio-ecological consequences (Vélez and Erasso 2020; Pereira et al. 2021). Recent data suggest that coca cultivation decreased in 2019. However, this is not necessarily good news for forests. Instead, the current

Table.18.2 Coca Cultivation in selected Amazon municipalities: 2013-2019 (ha). List of Amazon municipalities that have at least in one year exceeded 1,000 hectares of coca cultivation.

Municipality (Department)	2013	2014	2015	2016	2017	2018	2019
Cartagena de Chairá (Caquetá)	703	1,050	949	1,188	1,369	1,007	416
Milan (Caquetá)	359	530	696	1,040	1,135	1,226	461
MontaNita (Caquetá)	816	1,335	1,504	1,744	2,492	2,990	823
San José de Fragua (Caquetá)	488	611	1,084	1,031	1,415	1,593	1,410
Solano (Caquetá)	933	1,269	1,285	1,577	764	825	447
Piamonte (Cauca)	461	602	1,167	1,459	1,780	1,997	1,905
El Retorno (Guaviare)	1,314	1,600	1,615	2,192	1,406	1,545	1,195
Miraflores (Guaviare)	1,780	1,922	1,852	2,297	1,699	1,378	1,022
San José de Guaviare (Guaviare)	1,232	1,522	1,501	1,807	1,401	1,175	758
Puerto Rico (Meta)	1,101	1,616	1,620	1,593	1,773	1,082	617
Vistahermosa (Meta)	806	1,337	1,353	1,451	1,473	857	488
Orito (Putumayo)	784	1,639	2,190	2,988	3,970	3,949	3,073
Puerto Asís (Putumayo)	2,150	4,437	6,052	7,453	9,665	7,658	6,810
Puerto Caicedo (Putumayo)	682	1,046	1,481	1,782	2,998	2,905	2,617
Puerto Guzmán (Putumayo)	624	915	1,299	1,585	2,030	2,014	1,750
Puerto Leguízamo (Putumayo)	1,077	1,276	1,805	1,992	1,404	1,104	1,652
San Miguel (Putumayo)	659	1,094	2,338	3,128	3,554	3,329	3,752
Valle del Guamuez (Putumayo)	1,093	2,050	3,660	4,886	4,132	3,363	3,540
Villagarzón (Putumayo)	545	1,041	1,131	1,231	1,760	2,015	1,703

Source: https://www.minjusticia.gov.co/programas-co/ODC/Paginas/SIDCO-departamento-municipio.aspx

activities of manual eradication seem to push cultivation further into remote areas, leading to further clearings (Rincón-Ruiz and Kallis 2013). Simultaneously, global demand for cocaine grows, arguably strengthening the illegal drug economy (UNODC 2021).

In the context of the peace process, various infrastructure projects are planned in the Amazon. These include rural development measures, as explicitly provided for in the first section of the peace treaty, envisaging the construction of rural infrastructure as a means of improving market access for peasants. However, this is not the main driver of deforestation. More worrisome are large road projects that have both a direct impact on deforestation and are used to open the region for development and extraction projects, supporting further deforestation processes. In this respect, infrastructure projects included in the Amazon Hub of the IIRSA are under criticism (Uribe 2019). In addition, there is increasing economic interest in hydroelectric power generation in the Amazon region, especially at the Caquetá and Putumayo rivers (La Liga contra el Silencio 2019).

Expansion of the agricultural frontier is also driven by smallholders and peasants, historically owing to the extremely unequal distribution of land and associated lack of access to land for small farmers or landless people (Sanabria 2019). Another factor is the massive displacement of the rural population during the armed conflict and widespread rural poverty. In this vein, expansion of the agricultural frontier has been a political constant for attending to the agrarian question while preserving the historical privileges of the land-owning elites. However, it is important to highlight that at the same time, large amounts of land were given to a few arguably powerful individuals (CNMH 2017).

In practice, in the Colombian Amazon, land was often cleared by peasants and then appropriated by large landowners, preferentially using land for extensive cattle ranching. Population growth — especially in the context of unequal land distribution — generates further pressure on forests (Lara 2021). These trends (poverty, unequal land distribution, land grabbing, violence) continue in the Amazon today. Hein et al. (2020) similarly suggest that as an effect of the peace process and the “departure of the FARC from the territory”, other actors have taken advantage of the power vacuum to access land through different means (Prem et al. 2020).

The large number of drivers of deforestation is by no means owing to academic reticence or the exacerbation of complex interrelationships. Importantly, and as described above, not all drivers are equally important. Moreover, regional and local differences are crucial. Although the Amazon is often homogenized in international debates, there is a great deal of variation on the ground. As a result, deforestation drivers also differ. When we talk about the Colombian Amazon, we need to distinguish among different regional processes. In the South of Colombia, especially in Putumayo, the extractivist development model revolves around mining, oil, and coca, whereas in Caquetá, in addition to coca and oil, there is extensive pasture farming, and in the Amazon municipalities of Meta, the agro-export model has been extended to include large palm oil monocultures. In Vichada and Vaupés, there is extensive pasture farming, above all else. These different models are complemented by large infrastructure projects, in particular hydroelectric power plants and roads, which are intended to accelerate development processes and thus increase deforestation (Interview with Estefanía Ciro, 2020/09/26).

18.2.2 Confronting Deforestation: Little Advances and Structural Voids

Past Colombian governments have lauded their own efforts to address deforestation and climate change. The previous administration stated that "environmental massacres" would no longer be allowed (El Espectador 2012). This commitment led to important international cooperation agreements. One example is Vision Amazonía, a project introduced in 2015 that relies on important financial support from Norway, Germany, and the United Kingdom (Krause 2020). The current administration also made climate protection and the fight against deforestation a political priority (El Espectador 2020). Although the deforestation rate declined in 2019, data for 2020 show it has skyrocketed again, and in general terms, figures remain well-above pre-2016 levels (Figure 18.1). Moreover, deforestation also takes place in thepro-

BOX 18.1 Successful Conservation Experiences. Conservation Agreements in the Department of Guaviare (Colombian Amazon). A Strategy from Science and Public Policy to Defeat Deforestation.

Colombian public policy included fighting deforestation as a significant goal. Recently, because of the environmental and social crisis caused by forest fires, and under the leadership of the Colombian government, the Leticia Pact for the Amazon was signed. This pact commits the signatory countries to issues such as protection, conservation, research, and joint management of this region, regarded as vital for the planet's climate balance.

In the department of Guaviare, Colombia, a conservation project based on non-deforestation agreements with peasants has been successfully applied. The framework was an agro-environmental approach developed by the SINCHI Institute, an NGO linked to public policies, which also considers the singularities of the Colombian Amazon. Science and technology have been used to implement agroforestry arrangements that include Non-Timber Forest Products (NTFP), technical assistance and technology transfer, and technological tools to follow up and monitor the agreements, which by 2020 benefited the inhabitants of the department and contributed to achieving the country's goals on reducing deforestation. The agro-environmental approach integrates food security and rural poverty reduction with climate change mitigation and adaptation. It has a systemic scope with multiple objectives based on the economic, social, and environmental dimensions of sustainability. This approach also recognizes the vulnerabilities and particularities of the various landscapes that make up the Colombian Amazon. In addition, in Colombia's Amazon, the agro-environmental approach has been oriented towards an alternative model of territory intervention based on reducing deforestation and conserving forests through activities that ensure the organization of communities, improving their incomes with com-

BOX 18.1 *continued*

petitive market insertion, the establishment of agreements between actors aiming at reducing deforestation, and promoting sustainability.

Between 2017 and 2019, agreements signed with peasants in the department of Guaviare reached 1,046 families on 32,446 ha. In this way, a conservation index of 85% was achieved (Mos-CAL 2019). Seventy-five percent of the peasants chose to pursue the enrichment of stubble and degraded forests as part of their commitment to be implemented within the framework of the property planning, conservation, and restoration agreements.

Conclusions and Recommendations

- Research institutions play an important role in positioning priority issues on the country's political agenda.
- Actors responsible for public policy must engage in dialogue and find opportunities arising from the potentialities of territories.
- Conservation agreements and the agro-environmental approach have shown the effectiveness of science and technology for solving real problems with stakeholder participation.
- Amazonian countries must take concerted action to advance conservation of the region, with participatory approaches. The Leticia Pact provides an opportunity for this type of action.

Eco-harvest: Challenges and opportunities in the Bolivian Amazon

In Bolivia, the 2009 Constitution approved delimiting the Amazon into 23 municipalities (the "Constitutional Amazon"). This political-administrative delimitation includes in its limits all Amazon forests with Brazil nut trees (*Bertholletia excelsa*) in Bolivia, or approx. 84,000 km^2 (Larrea-Alcázar et al. 2018). The Constitution also refers to the elaboration and promulgation of a law to promote integrated development in the region, including tourism, ecotourism, or regional enterprises, and establishes a penalty for the felling of Brazil nut and rubber or "syringa" (*Hevea brasiliensis*) trees. Both non-timber species form part of the recent past and the history of the Bolivian Amazon.

The eco-harvest of Brazil nuts represents the main economic driver of the region (Guariguata et al. 2017). However, its contribution to the national GDP is low (approximately 2%, INEC 2019). The exploitation of Brazil nuts has limited conversion of the forest to livestock landscapes. High prices and demand for Brazil nuts in the international market supports an economic incentive to preserve standing forests. Furthermore, deforestation requires increased investment. Most of the land tenure or ownership in the Constitutional Amazon belongs to Indigenous territories and other rural communities, which represent the base of the Brazil nut production chain and other emerging resources in the process of consolidation (e.g., açai and other palm trees such as *Mauritia flexuosa* and *Euterpe precatoria*, *paiche* meat and leather [*Arapaima gigas*]). Currently, inter-institutional articulation efforts are underway to strengthen the use of Amazonian fruits in the region as a basis and input for planning in the area (PICFA 2020).

The Law of the Rights of Mother Earth (2010) and the Framework Law of Mother Earth and Integral Development to Live Well (2012) establish the foundation for and principles to promote integrated development of the country in harmony and balance with nature ("Mother Earth"). However, they do not relate or allude to the Constitutional Amazon. Subsequent laws on road construction, oil and gas exploration, and expansion of the agricultural frontier seem to contradict the principles proposed by both laws (Romero-Muñoz et al. 2019). Additionally, a resolution to solve the spillover of informal gold mining on the Madre de Dios River, currently the main threat to the Constitutional Amazon, is still pending; this requires clear policies and decisions.

tected conservation zones of National Natural Parks, an especially worrisome trend (Tobón Ramírez et al. 2021; MAAP 2020).

The government's emphasis on the protection of the Amazon Forest as part of its commitment to curb climate change is contradictory to its extractive development strategy. Instead, efforts to protect forests seem to be concentrated on the fight against illicit activities and especially coca production (Montaño, 2017; Vélez 2021; WWF 2021). The production of illicit drugs is one driver of deforestation, as previously discussed, but it is not the main one. Moreover, the relation between coca and deforestation is indirect through fueling cattle ranching, armed conflicts, and displacements, or the deforestation effects of measures to fight coca (Vélez and Erasso 2020; Dávalos et al. 2021). Given the variety of factors behind the alarming levels of deforestation in the Amazon, this focuses on combating illegal drugs seems arbitrary and, in some cases, counterproductive (Rincón-Ruiz and Kallis 2013; Dávalos 2016; Vélez and Erasso 2020). This is evident considering the current strategy against deforestation increasingly focuses on promoting the state's presence in the Amazon through militarization (including assigning tasks of forest protection to the military in the Plan Artemisa; Interviews with researchers and activists working on the Colombian Amazon in El Tiempo 06-12-2020). In fact, the Amazon is currently the setting of violent conflicts over territorial control between the military and different non-state armed groups (WWF 2021). In this context, the fight against coca legitimizes the militarization of environmental protection and, at the same time, combines it with counterinsurgency measures. The Plan Artemisa follows an approach that Wacquant (2009) called, although in a different context, "punishing the poor". In fact, Plan Artemisa prefers to present success by capturing poor peasants linked to deforestation instead of attacking structural problems; further, it practically excludes local participation. Keeping in mind the worrying human rights problems of the Colombian security forces and continuous tensions between military forces and peasants in remote Colombian areas, this has counterproductive effects. Moreover, the militarization of environmental protection increases the spiral of violence in remote areas and even worsens the already dangerous situation for environmental activists and civil society organizations (Gutiérrez Sanin 2021; Jones 2021; Oritz-Ayala 2021; WWF 2021). According to Global Witness, Colombia is the most dangerous place for environmental activists, who face criminalization, threats, violent attacks, and assassinations, with Indigenous groups being especially vulnerable (Global Witness 2020 2021). Furthermore, military approaches by no means solve the problem of expanding illegal drug cultivation, but rather shift it to more remote areas, thus contributing, albeit unintentionally, to the further expansion of the agrarian frontier. According to Prem et al. (2020), proximity to military presence increases deforestation in Colombia.

Colombia's strategy to combat deforestation by focusing on curbing coca production leaves several gaps, especially the lack of viable measures for alternative income generation for producers (Dávalos and Dávalos 2020; International Crisis Group 2021). Although the peace treaty rightly gives priority to rural development and the solution of the drug problem, progress in implementing the planned measures is very slow (Instituto Kroc 2020). However, in the absence of sustainable reforms for producers, the issue of illicit drugs will not be resolved.

Although the government highlights illegal activities as deforestation drivers, expansion of the extractivist development model is not addressed in the strategy to curb deforestation. In other words, land grabbing partly linked to the drug economy, extensive cattle ranching, and in general terms the extractivist development model, are excluded from measures to curb deforestation, and are even promoted by the government. The priority to reduce deforestation is very much welcomed; however, the focus on political interventions needs major changes to ensure that the environmental concerns of the official discourse will also achieve the results the Amazon's forests and the world's climate urgently need.

18.2.3 Structural Reforms Needed: Alternatives to Deforestation in the Colombian Amazon

Deforestation in the Colombian Amazon has multiple causes and cannot be reduced to simple formulas. Instead, a regionally or locally adapted strategy is needed to curb deforestation in the short term. In view of the enormous challenges, in the medium and long term, a selective reduction of pressure on the forest areas in the Colombian Amazon will not be enough to conserve forests and biodiversity and slow down climate change. It is necessary to think outside the box and include far-reaching transformations of the status quo.

The solution in Colombia is a shift away from extractivist development models and the construction of viable alternatives to unsustainable extractivism. Colombia is currently trapped in an "extractive imperative" (Arsel et al. 2016), which requires a continuous expansion of the extractive frontier and represents a continuous driver of deforestation. Therefore, economic diversification is key for social development and environmental protection (Peters 2019). Second, the country needs to reduce extreme inequalities in land tenure. The land question in Colombia has been a contested topic that also affects the Amazon. It was considered as one of the main triggers of the armed conflict (Fajardo 2014; Galindo and Pereira 2020), and some tension around land tenure in the Amazon is currently considered as an element that could lead to new, conflictive situations among the inhabitants. Therefore, reducing land inequalities continues to be a pressing and simultaneously conflictive topic. Policy options exist, especially regarding the reduction of the incentives for low-productive, land-consuming, and therefore environmentally damaging extensive cattle ranching. A key instrument would be an increase in land taxes. Third, alternative ways to tackle the problem of illicit drugs are needed. This should include a reorientation of international drug policy and increased political efforts towards decriminalizing the drug economy. At the national and local level, strategies that offer a decent life for peasants are of particular importance (Dávalos and Dávalos 2020). This includes opportunities for the commercialization of legal small-scale farming products, the creation of decent jobs, and the reduction of social inequalities. This also requires the development of infrastructure and transport routes in the Amazon that may lead to small-scale deforestation. Therefore, it is not a question of a radical reversal or even utopian considerations to totally stop deforestation in the short run. Instead, intelligent planning is needed to implement projects that promote sustainable development strategies, providing alternatives to nature exploitation and addressing the problem of land ownership inequalities and the need for socio-economic improvement of impoverished peasants. Such initiatives will need to encourage a new approach that allows inhabitants to cohabit the territory, contribute to radically decreasing deforestation, carry out activities that give them access to good living conditions, and recognize their organizational forms and participatory mechanisms, including social movements and local organizations.

18.3 Social and Environmental Impacts of Oil Extraction in Ecuador's Amazon

This section analyses the economic, social, and environmental effects of oil extraction in Ecuador since 1967. Although the country has a small share (1.6%) of the Amazon rainforest, Ecuador's Amazon, with other Andean countries, holds some of the highest biodiversity per square kilometer in the region, particularly in the upper Napo Basin and Yasuni National Park (Bass et al. 2010; RAISG 2015). It shares with the other Andean Amazon countries (Colombia, Peru, and Bolivia) specific climatic conditions, deforestation drivers, and impacts of extractive activities. Given the high significance of oil on its development performance, Ecuador lends itself as a representative case study on the impacts of oil extraction in the Amazon.

18.3.1. Oil and Development in Ecuador

In 1967, large oil reserves were discovered in the northern Amazon, and since 1972 Ecuador has been an oil exporter, turning this product into the backbone of the economy. Five decades later, oil has contributed little to equitable and sustainable development, despite bringing about significant economic, social, and institutional transformations. Economic growth has remained evasive and unstable (Figure 18.11), with an average annual growth rate of 1.55% in income per capita between 1972 and 2019, lower than that the 2.07% of the pre-oil period (1950–1972; See a periodization of the 1950–2019 interval in Appendix Table 18.1B and Figure 18.11.). Despite important social achievements during the oil boom (1972–1982) and between 2006 and 2014, the social, ethnic, and regional disparities that have historically affected the country remained pervasive, with 30% of the population living below the poverty line and underemployment affecting 40% of the labor force in 2017 (Ayala and Larrea 2018). Social inequality barely declined, evidenced by the Gini coefficient remaining at 0.52 in 2015 (ECLAC 2015; Vallejo et al. 2015; Larrea, 2017). The COVID-19 crisis sparked an increase in poverty to 40% and underemployment to 48% (UASB 2020).

Oil extraction in Ecuador occurs in a formerly undisturbed region in the Amazon Basin, leading to severe socio-environmental effects, particularly deforestation, loss of biodiversity, pollution, and human health hazards (Herbert 2010; Amazon Defense Coalition 2012; Becerra et al. 2018). Between 2004 and 2014, a new development strategy was applied, strengthening state intervention in the economy, and promoting more inclusive social policies, in an international context of high oil and commodity prices. The whole strategy collapsed since the price of oil plummeted in 2014. Neo-extractivist strategies failed to diversify the economy, and under a heavy debt burden and limited oil reserves, the county is currently affected by a deep economic, social, and political crisis (Larrea 2019).

18.3.2 Threats to Conservation: Extractive Policies in the Amazon

Since the Spanish conquest, external forces, mostly articulated towards resource extraction (gold, rubber, and recently oil) have led to adverse impacts on ecosystems and Indigenous peoples in the Amazon. Among those cycles, the oil period has had the longest and deepest impacts. Colonial or national policies, fostered by international interests, have seen the Amazon as an unlimited source of raw materials and an almost empty space to be exploited, ignoring both Indigenous peoples and biodiversity. During extractive phases before oil expansion, the Amazon suffered from plundering, without any concern for the exhaustion of natural resources (Taylor 1994). In the oil period, although the resource-extraction vision prevailed, conservation concerns resulted in the creation of protected areas, partial recognition of Indigenous territories, recognition of the rights of nature, the inclusion of the “good living” concept in the 2008 constitution, and minor additional conservation policies that have failed to significantly reduce deforestation (Larrea 2015, Larrea and Bravo 2009). The environment ministry was created in 1996.

Protected areas now cover 20% of Ecuador’s territory. The most important in the Amazon are Yasuni National Park and the Cuyabeno Reserve, both established in 1979. Oil extraction has been allowed in both reserves since the 1980s and the budget for PAs is low; therefore, the degree of protection is weak (Larrea 2017). Indigenous territories cover a large proportion of the Ecuadorian Amazon, approximately 3 million ha, with approximately 70% of them legally recognized in the form of collective property rights. Nevertheless, the legal competencies of ITs are weak, and several oil and mining concessions have been granted on Indigenous lands without properly consulting Indigenous peoples, as established by ILO (International Labour Organization) and recognized by Ecuador (Interview with Dr. Mario Melo, lawyer expert in Indigenous rights, Quito, August 22, 2020).

Since 1964, when the state signed a large oil concession in the Amazon to Texaco, public policies consistently promoted the expansion of oil extraction, as well as large-scale mining. The main issue in oil policies has been the debate between nationalistic policies aimed at increasing state participation in oil revenues versus transnational companies and strategies to attract foreign investment with incentives. The former prevailed in periods of high oil prices and strong state negotiating capacity, whereas the latter was mostly evident in periods of low oil prices and economic crises. Little attention has been paid to public policies aimed at reducing the environmental impacts of extractive activities or introducing low-impact technologies, such as roadless oil exploitation (Larrea 1993, Larrea 2017). The only significant exception was the Yasuni-ITT Initiative, that stands for the oil fields Ishpingo, Tambococha and Tipu-tini, aimed to keep a large oil reserve in the Yasuni National Park indefinitely unexploited in exchange for an international fund for conservation and investment in renewable energy (Box 18.2) (Larrea 2017).

Transnational participation in oil extraction in Ecuador has changed over time. Between 1972 and 1993, the dominant company was Texaco (acquired by Chevron). Later, the participation of Occidental and other companies such as Repsol was significant, but the share of state companies increased particularly after 2007. During the last decade, the participation of Chinese companies (Sinopec and Petrochina) has become significant. In addition to extractivism, public policies fostered colonization in the Amazon during the 1960s and 1970s, to reduce demographic and political pressures on the coast and highlands, and as a strategy to build “living frontiers” in areas close to the Peruvian border.

18.3.3 Oil Expansion and its Regional Effects in the Amazon

Although the Amazonian provinces account for 47% of Ecuador’s national territory, the region remained historically isolated from the rest of the country until oil discoveries in 1967. After the Spanish conquest, only two short periods of resource extraction deeply disrupted the region’s Indigenous cultures; gold mining in the sixteenth century and rubber extraction in the late nineteenth to early twentieth centuries (Taylor 1994). The Amazon held only 1.7% of the nation’s population in 1962.

Oil extraction stirred a rapid internal migration to the region, causing expansion of the agricultural frontier, deforestation, and severe environmental impacts. Between 1962 and 2010, the population of the Ecuadorian Amazon expanded more than ten times, reaching 739,814 (Appendix Table 18.2B). Unlike in Brazil, Colombia, and Peru, urbanization in the Ecuadorian Amazon has been moderate. Only 33% of the population lived in cities with more than 5,000 inhabitants in 2010, and the largest city, Lago Agrio, had only 48,500 inhabitants. Despite significant migration, Indigenous peoples still represent 33% of the population and 10 different Indigenous languages are spoken (INEC 2010).

The expansion of extractive activities, oil and recently large-scale copper and gold mining, has been the most important indirect driver of deforestation and degradation in Ecuador since 1967 (Gold mining in the Amazon started in the sixteenth century but stopped soon partially due to indigenous resistance). In 2018, cumulative deforestation accounted for 16.2% of original Amazon forests in Ecuador (Sierra 2020) (Figure 18.10). Unlike in Brazil, deforestation in Ecuador is mostly undertaken by small-scale farmers moving into the region along roads constructed by oil and mining interests (Wunder 2000; Becerra et al. 2018; Larrea 2017). Large cattle farms or plantations are less frequent.

Agriculture is the main employment source, despite the often-low aptitude of Amazonian soils for cultivation. Deforestation does not provide lasting social benefits to the peasants. As land yields decline, they must move to deforest another plot of land, approximately every 15 years. Agriculture in the Amazon is extensive, inefficient, and has low capital investment, with land productivity reaching only 31% of the national average and labor productivity only 35%. Pastures represent 73% of cultivated land (Table 18.3).

Although oil extraction contributes 65% of Ecuador’s Amazonian GDP, its contribution to employment is extremely low at 0.9%. In contrast, agriculture accounts for only 4% of GDP but provides 54%

BOX 18.2 The Yasuni-ITT Initiative

The Yasuni-ITT Initiative, presented in 2007 and canceled in 2013, was the first and remains the only international proposal to keep a large oil reserve in a developing country unexploited to preserve a biodiversity hotspot in exchange for sustainable social development assistance. Despite its cancellation, it provides ideas and tools for keeping fossil fuel reserves underground in the Amazon and other rainforests. At least two-thirds of global fossil-fuel reserves must remain unexploited to fulfill Paris Agreement goals; therefore, oil and gas reserves in the Amazon should remain unexploited to prevent the high environmental impact of exploitation, conserve biodiversity, and avoid CO_2 emissions.

The Yasuni-ITT Initiative was launched in 2007 by Ecuador's president to maintain unexploited oil in the ITT fields of Yasuni National Park, one of the most biologically diverse hotspots in the western hemisphere. Ecuador committed to refrain from extracting the 846 million barrels of petroleum and requested the cooperation of the international community in the form of half of the income that would have been generated from extracting the oil. A capital fund was created, administered by the United Nations Development Programme (UNDP), with the participation of the Ecuadorian government and civil society, and international contributors. The Fund's capital would be invested in renewable energy projects throughout the country and in local sustainable development and forest recovery projects. In addition to mitigation, its purpose was to overcome Ecuador's dependence on fossil fuels and help the country transition to sustainable development, placing social and environmental values first and exploring ways other than oil to benefit economically from the Amazon. The strategy also aimed to reduce vulnerability to climate change. In addition, it involved respecting local communities and, particularly, allowing the Tagaeri and Taromenane peoples to remain in voluntary isolation.

The Initiative received unanimous support from the German parliament, the active participation of the United Nations, and economic contributions from Spain, Italy, Chile, and Peru, among other countries (Larrea 2015). According to members of the 2008 steering committee, the international support was adequate for maintaining the project, but the main reason for its cancellation was the lack of political support from the Ecuadorian president, who publicly discouraged donations, removed several of the managers, and persistently threatened to extract oil from the ITT fields.

Although the initiative did not prosper at the time, the idea should not be abandoned, considering the limits of the carbon budget and the universal endorsement of the Paris Agreement. If two-thirds of global fossil fuels are to be kept underground (Meinshausen et al. 2009; McGlade and Ekins 2015), reserves underlying areas of high conservation value must be among them.

In addition, it is time to take advantage of instruments that are embraced by the Paris Agreement, which calls for ambitious action and cooperation between developed and developing countries (Art. 6.1, 9.1). It also encourages actions to conserve and enhance greenhouse gases' sinks and reservoirs, including forests (5.1), and engage in adaptation (7.1). Launched in 2007, the Initiative is consistent with the precepts of the 2015 Paris Agreement. Additionally, it was designed to promote equitable access to sustainable development, food security, human rights (including the rights of Indigenous peoples), the integrity of ecosystems, and sustainable lifestyles, consistent with the principles held forth in the Paris Agreement. The Initiative could be transformed into an international cooperation instrument involving several megadiverse countries as beneficiaries, scaling up sustainability benefits and emissions reductions while having a more stable institutional structure.

Although the Yasuni-ITT Initiative had many strengths, it also had weaknesses; these must be addressed in any proposal to establish a similar initiative. As the first of its kind it was unlikely to be perfect, similar to Brazil's successful and subsequently abandoned policy to reduce deforestation. Neither policy should be discarded; instead, they are a powerful foundation upon which to build a sustainable and just low emissions future.

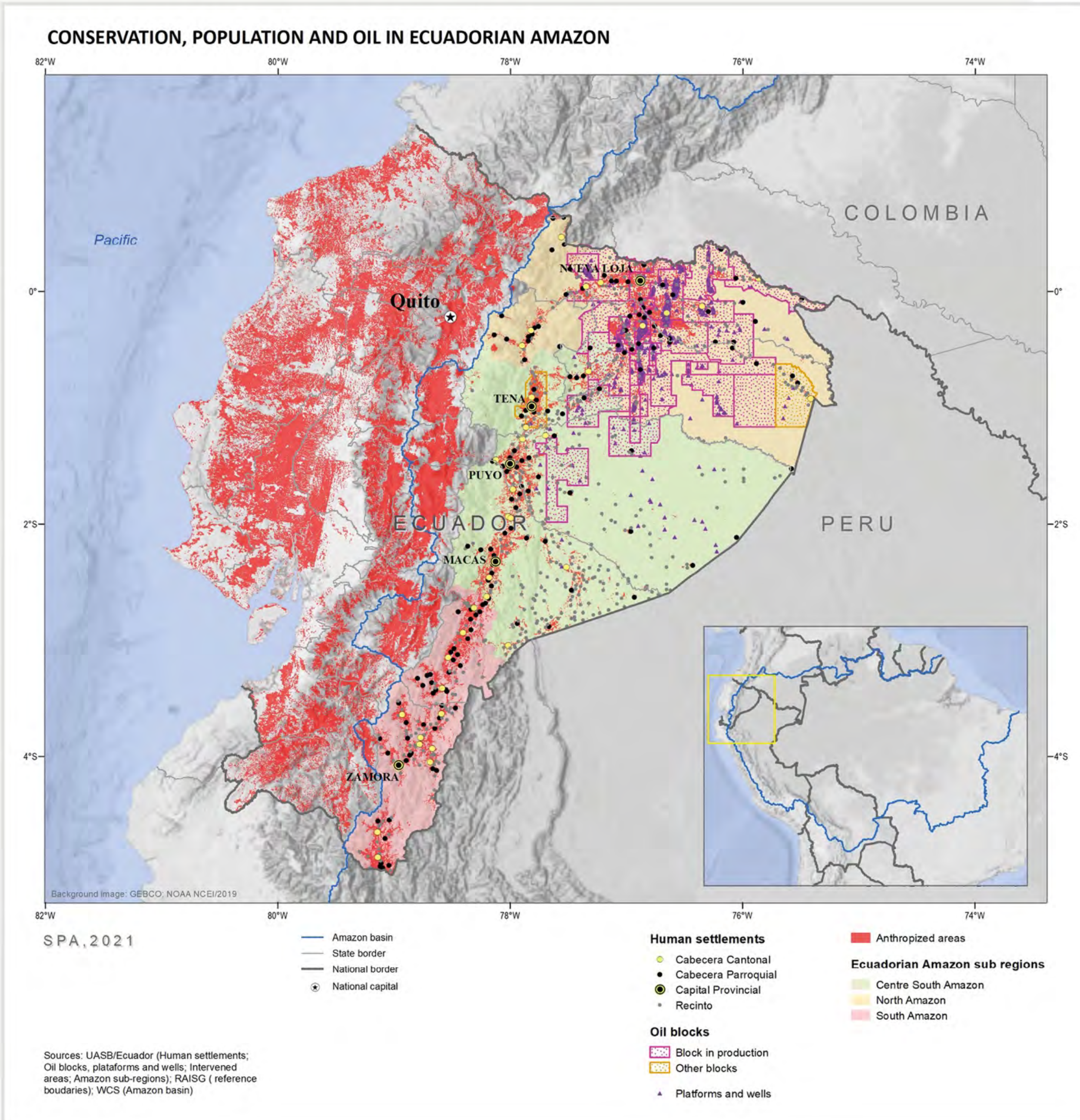


Figure 18.10 Conservation, Population, and Oil in the Ecuadorian Amazon. Source: Unidad de Información Socio Ambiental, UASB.

Table 18.3 Output, Labor and Land Use of Ecuadorian Agriculture by Region, 2018–2019.

				Productivity		
Region	Employment	Area	Output	Land	Labor	Labor per ha
	(Workers)	(ha)	(Thousand $)	($/ha)	($/worker)	(Workers/ha)
Coast	983949	2,884,000	6418415	2,226	6,523	0.34
Highlands	1069015	1,621,496	2842171	1,753	2,659	0.66
Amazon	234723	605,052	353811	585	1,507	0.39
Total	2287687	5,110,548	9614396	1,881.28	4,202.67	0.45

Source: Banco Central del Ecuador 2019, INEC 2019a, INEC 2019b.

Figure 18.11 Per capita GDP in Ecuador, 1950 - 2019. Source: Author estimates based on PENN World Table, 10.0.

of employment. Public and social services are significant employment sources, and tourism has importance in particular areas, accounting for 4.2% of regional employment (INEC 2019; BCE 2018). The Amazon region remains the poorest in the country, both in urban and rural areas, with oil revenues benefitting mostly urban highlands, including Quito. The gap between the rural Amazon and the national average did not decline, according to the censuses of 1990, 2001 and 2010.

18.3.4 Social development in the Ecuadorian Amazon

From the mid-1960s onwards, oil has been the most significant indirect driver of environmental deterioration in Ecuador, and deforestation has taken place mostly by the expansion of agricultural frontier from immigrant peasants. In this section the social effects of oil on living conditions are explored, mostly by comparing social indicators, at the local level, between oil extraction areas and the remaining zones in the Amazon. Additionally, a statistical analysis on local effects of deforestation on the social conditions is presented.

To capture local basic needs satisfaction, a social development index (SDI) was elaborated, combining 19 indicators from the population censuses of 1990, 2001, and 2010, using principal component analysis. Six indicators deal with education, two with health, three with gender and employment, and eight with housing (Larrea 2017; Larrea et al. 2013). The Appendix for this chapter contains the complete list of indicators and the methodology of SDI. The selected social indicators and the SDI are directly relevant for the following Sustainable Development Goals (SDGs, see chapter 26): 1 (no poverty), 3 (health), 4 (education), 5 (gender equality), 6 (clean water), and 7 (energy). There are strong indirect links with SDG 2 (zero hunger), 8 (decent work), and 10 (reduced inequalities). To explore the social and regional distribution of oil revenues in Ecuador, the SDI was broken down by region and area of residence for 1990, 2001, and 2010 (Table 18.4).

To refine the analysis, the Amazon was divided into an oil extracting sub-region and the remaining part (Appendix Table 18.3B). The results illustrated that within the Amazon, oil extracting zones are consistently more affected by social deprivations than the corresponding non-oil zones, both in urban and rural areas. Lower differences in the number of average schooling years, a representative education indicator, were evident because of the high proportion of immigrants in the population (Appendix Table 18.2B).

Immigrants usually have higher than average levels of education in their original regions (Larrea 1993). In contrast, worse human health conditions are evident in oil extracting zones in the Amazon, compared with the remaining areas of the region. As shown in Table 8.4, the results for 1990 and 2001 were similar and inequalities remained consistent during the 20-year period.

These results indicate that the Amazon barely benefited from the regional distribution of oil revenues. Although the SDI improved in the Amazon between 1990 and 2010, the gap with the remaining regions persisted or increased (Appendix Table 18.6B). Not only did the region consistently remain the most socially deprived in Ecuador, but the oil

Table 18.4 Social Development Index in Ecuador by region and Area, 1990–2010

Region and Area	1990	2001	2010
Rural Highlands	42.1	49.0	59.0
Urban Highlands	67.3	72.1	78.4
Rural Coast	42.4	47.7	55.3
Urban Coast	59.6	63.1	69.6
Rural Amazon	41.0	45.8	54.3
Urban Amazon	54.1	60.5	68.3
Rural Galápagos	62.1	65.9	69.6
Urban Galápagos	65.5	66.8	74.6
Total	55.2	60.4	68.1

Growth rates were estimated from a kinked regression, controlled from first order autocorrelation, using Prais-Winsten and Cochrane-Orcutt models. Source: Author estimates based on PENN World Table, 10.0.

Table 18.5 Social Development Index by Subregion and Area: 1990-2010.

Subregion	Zone	1990	2001	2010
Urban Amazon	Oil extracting	47.6	55.3	64.1
	Non-oil extracting	58.3	64.8	72.5
Amazonia Rural	Oil extracting	40.4	44.9	53.0
	Intervened, Non-oil extracting	41.9	47.0	55.8
	Non intervened	31.1	35.6	42.3
Rural Highlands		42.1	49.0	59.0
Urban Highlands		67.3	72.1	78.4
Rural Coast		42.4	47.7	55.3
Urban Coast		59.6	63.1	69.6
Galápagos Islands		63.6	66.4	73.4
Total Nacional	Total	55.2	60.4	68.1

Sources: UASB-UISA, based on: INEC, Censos de Población y Vivienda, 1990, 2001, 2010.

extracting subregion also had lower social benefits than the non-oil part of the Amazon, both in urban and rural areas. The analysis suggests that oil extraction may have a detrimental net effect on local social development. However, the data in the tables does not demonstrate this relationship, given that social improvement is the result of multiple additional factors, such as differential soil fertility among zones, access to markets, opportunities for economic diversification, and the development of non-agricultural employment. To test the net effect of local oil activity on social development, including the available information on other factors that potentially influence social development, a spatially autoregressive multiple regression model was elaborated (Appendix, Methodological Notes). The model took the SDI as the dependent variable, and its independent variables included oil extraction proximity, soil fertility, access to markets, proportion of deforested area, a dummy variable for rural sectors, and three employment indicators (proportion of agriculture, wage earners, and tourism in the labor force). The model results and detailed main findings are presented in the Appendix, Methodology and Table 18.4B.

The model strongly suggests that; after controlling for observed factors influencing living conditions, such as soil fertility, access to markets, proportion of deforested land, and employment structure and diversification; the proximity or local presence of oil extraction has a net detrimental effect on basic needs satisfaction, statistically significant at the 1% level. The result is consistent with the negative effect of oil extraction on SDI presented in Table 18.5.

As oil extraction is highly capital intensive, its local contribution to employment is low, and usually concentrated on male skilled labor coming from outside the Amazon. Oil extraction only has an important, local, unskilled labor component during the brief construction phase. However, oil may have an important fiscal link with social development because of local investment of oil revenues in schools, health facilities, housing, credit, technical assistance, or other services and infrastructure. Social investment may come from the national government, local governments, or oil companies. On the other hand, the many detrimental effects include pollution, disincentives to tourism, social conflict, prostitution, and corruption. The negative coefficient suggests that in Ecuador, detrimental effects overcome social benefits from oil. The environmental impact of oil in Ecuador's Amazon has been evaluated as severe, particularly during the Texaco period (1967–1993), as mining waste was systematically dumped into the environment without treatment. Afterwards, the frequency of oil spills remained high, averaging approximately one a week (Herbert 2010; Amazon Defense Coalition 2012; Durango et al. 2018). In April 2021, a large oil spill severely affected several communities in the northern Amazon.

Deforestation has a strong impact on biodiversity and is the most important source of CO_2 emissions (36%) in Ecuador (WRI 2020). Deforestation rates in Ecuador remain high due to the lack of effective control and may be increasing (Figure 18.1). Although there is no agreement on deforestation figures, according to FAO, Ecuador had a 0.6% yearly deforestation rate between 1990 and 2015 (FAO 2015).

To explore the social effects of deforestation on local living conditions, the regression model included the proportion of intervened areas in quadratic form (Appendix, Table 18.4B). Broadly speaking, the contribution of deforestation to peasants' local living conditions is low and takes a parabolic shape with decreasing returns. Local living conditions mostly improve at the initial stages of deforestation and later tend to disappear, so that the function reaches a stable level with no further gains when deforestation is higher than 65%, with a small decline after 80% of deforestation (Figure 18.12). According to the model, the total improvement of the SDI between 0% and 100% of deforestation is 7 points (from 30 to 37), and there is no improvement at all from 65% to 100% of deforestation. This weak and decreasing association between deforestation and living conditions may be owing to low and decreasing land productivity in most Amazonian soils. During the first years of deforestation, soil fertility remains relatively high and family income may improve by selling wood. Later, decreasing land productivity reduces agricultural revenue, as described above. These findings are broadly consistent with research on the Brazilian Amazon (Rodrigues 2009).

Oil has been the main indirect driver of environmental degradation in the Ecuadorian Amazon since 1967, leading to a cumulative forest loss of 13%, the second largest among Amazon countries after Brazil (see Chapter 19). Nevertheless, remaining oil reserves are limited, and the country may become a net oil importer in approximately a decade or less, potentially leading to a deep crisis (Espinoza et al. 2019; Larrea 2021). In this context, the Ecuadorian Amazon will probably soon face a transition towards a post-extractivist society, and a participatory process to promote a sustainable and equitable path should become a social and environmental priority.

18.3.5 Conclusions and recommendations of the Section

The Amazon remains the most socially deprived region in Ecuador, both in urban and rural areas. Among the most critical conditions are lack of appropriate health services and high levels of child mortality, while differences in education are less severe. A spatially autoregressive multiple regression model was built to explore the local effects of oil extraction, local deforestation, soil fertility, access to markets, and employment structure on social development. The model found local oil extraction had a negative and statistically significant effect of on social development, after controlling for all remaining variables.

The findings strongly suggest that in the Ecuadorian Amazon, the detrimental effects of environmental degradation, pollution, loss of biodiversity, and social conflict overcome the potential local benefits brought about by employment and local investment of oil revenues. The lack of a positive relationship between oil extraction and social improvement extends, at the microregional level, the conclusions of several national studies on the weak link between oil extraction and development in Ecuador. From an international perspective, the oil curse theory points out the detrimental economic, social, and environmental effects of oil export specialization on developing countries.

In Ecuador, oil expansion has been an important indirect driver of deforestation in the Amazon. The regression model suggests that deforestation has a small and short-lived contribution to improving living conditions of the local population. Some social gains are observed only in the initial phases of deforestation, but as local deforestation increases above 65% of the land, social benefits disappear. Unfortunately, the analysis shows that not only is the net local direct contribution of oil extraction to social development minimal or even negative, but also that the local improvement brought about from deforestation-based agriculture and cattle raising is modest and short-lived. Including the detrimental effects of deforestation on climate change and loss of biodiversity, the whole balance

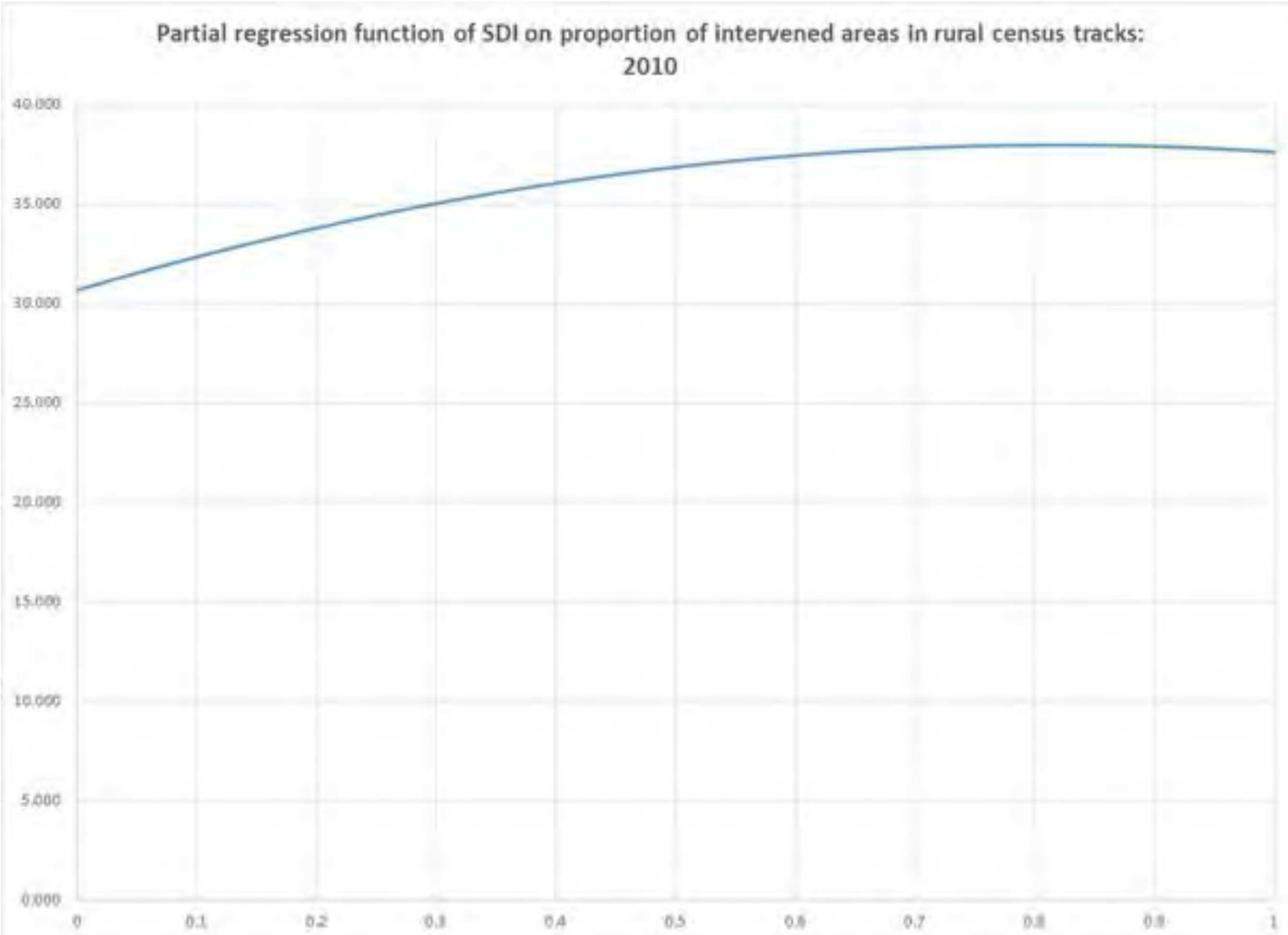


Figure 18.12 Partial regression function of DI on proportion of intervened areas in rural census tracks, 2010. Note: 1,509 rural census tracks were included in the model. Source: Appendix Table 18.1B.

of benefits may become negative. Therefore, the Amazon region requires a deep structural process of social and economic transformation to find alternatives toward sustainable and distributive social development. The social distributive effects of diversification towards tourism are rewarding. Ecotourism is an example of a way of diversification able to improve living conditions, simultaneously preserving natural and cultural heritage.

As remaining oil reserves in Ecuador are low, estimated to last no more than 7.4 years at current extraction levels (BP 2021), and the detrimental effects of current agricultural practices may exceed social gains, a structural transformation towards sustainable and distributive development strategies is required. Fortunately, a low emission development path, based on activities such as ecotourism, agroforestry, and agroecology, seems feasible (Larrea 2017). Deforestation can be drastically reduced or eliminated, as the Brazilian experience between 2005 and 2012 demonstrates (see Chapter 17). Nevertheless, the required transformation in regional development strategies requires further research, and available information only suggests some hypothetical transformative ways.

18.4 Extraction Activities in the Peruvian Amazon

Peru is the country with the highest percentage of its territory covered by the Amazon Forest after the Guianas. However, owing to its distance from policy and decision-making centers and Peru's historically centralized form of government, the Amazon has been relegated to the category of a territory awaiting "conquest, occupation, and exploitation". Oil exploitation in the Peruvian Amazon began during the military governments of 1968–1975 and 1975–1980. It brought about massive environmental liabilities that have yet to be remediated. During the 1980s, the country returned to democracy and in 1981, Shell initiated its activities in the southern part of the Ucayali Basin in the Amazon. In 1982, oil companies were granted tax exemptions. During this period, Shell discovered the natural gas deposits of Camisea in the Cusco Amazon Region. This new resource became a priority for the next government (1985–1990), who signed an exploitation agreement with Shell.

Extractivist policies were further reinforced by the neoliberal model prevailing in the 1990s. During those years, a political narrative revolving around economic development based on extractivism penetrated and dominated, not only in the circles of economic and political power, but also in all social strata of the urban population. In this way, the dominant classes "succeed in naturalizing inequality and limiting the impact of socioenvironmental protest and discontent," which became much more frequent during this decade (Damonte 2014). The federal government adopted policies to stimulate mining exploitation in the Amazon, revising and withdrawing gold concessions from companies that were not using machinery and making them available to small scale or artisan miners, who were also given incentives for the purchase of equipment. These measures generated so-called "machinery fever" and enormous environmental impacts.

The extractivist logic continued during the following administrations. During the 2001–2006 administration, forest legislation was modified to grant a large number of timber concessions that eventually failed. Demands by Indigenous organizations for the creation of Reserva Territorial Napo-Tigre, where oil companies were operating, were stalled under corporate pressure. During the 2006–2011 administration, a confrontation with Indigenous peoples and peasant farmers began through a series of editorials in the newspaper *El Comercio de Lima*, known as "dog in the manger" articles. In these texts, the President expressed deep contempt for Indigenous peoples and peasants, a sentiment largely shared by a significant portion of non-Indigenous people in urban centers. He described them as perverse, limited intellectually and educationally, and susceptible to manipulation, and faulted Indigenous peoples for not cutting down forests. He lamented that these territories could not be granted in concession to large private companies, blamed pervasive problems such as unemployment on these "dogs in the manger", and was convinced that it was necessary to profit from public property and goods through privatization and land titling schemes.

A peak in confrontation was reached in 2009 in the context of the Free Trade Agreement with the United States (US), when the Peruvian President promoted several legislative decrees to harmonize Peruvian legislation with that of the US, arguing that unless these changes were made, the US would leave the Agreement. Three of these decrees affected Indigenous territories and facilitated extractivism; one modified the forest and wildlife law, another reduced to 50% plus one the quorum necessary to expropriate communal lands, and the third changed administrative procedures for communal lands in the highlands and forests to match those of the coast (Morel 2014). This triggered an uprising by Indigenous organizations, which was repelled; 33 people lost their lives in a brutal clash between police and Indigenous organizations, known as "Baguazo".

Hopes were high with the new administration of 2011, which represented a change with regards to extractivism. Initially, steps were taken that seemed to point to a radical shift. Government policy regarding extractivism aimed to establish greater tax-system justice and the Mining Royalty Law was enacted (Lanegra 2015). This Law changed the tax base for the calculation of royalties from value of sales to operating income, thus increasing royalty amounts for firms having higher operating margins (Lasa Aresti 2016). To reinforce this initial step, the long-awaited Public Consultation Law was also approved and became a regional milestone. However, this momentum did not last. The 2012 commodity crisis led to a turnabout in federal policies. Seeking to promote foreign investment, policy shifted towards making social and environmental regulation more lenient. Despite the instability of recent years, this tendency in policy has not changed.

Socioenvironmental conflict accompanies this tendency, with Indigenous peoples demanding access to justice and respect for their rights. In July 2020, after many years of campaigning, the Federation of the Achuar Nationality of Perú (FENAP) and the Autonomous Territorial Government of the Wampis Nation (GTANW) succeeded in reversing a concession to the oil company GeoPark, which had been operating on their land without an environmental or social license. At the same time, Indigenous peoples face significant risks. At a protest of PetroTal installations in Loreto on 8 August 2020, to demand that the federal government honor promises made in 2019 to install basic services and better health care in the context of the COVID-19 pandemic, three members of the Kumala community were killed and several people were seriously wounded on both sides.

The logic of "conquest, occupation, and exploitation" of the Peruvian Amazon remains dominant. Petroleum production in 2019 neared 53,000 barrels per day, and the target for 2023 is 100,000. It can be expected that the new administration will implement actions to achieve that goal, with the likely outcome new social conflicts, environmental consequences, and increased emissions.

18.5 Venezuela: Predatory Extractivism, Illegal Economies, and Hybrid Governance

The Amazon bioregion covers 453,915 km^2 of Venezuela, representing 49.5% of the national continental surface area (EcoCiencia 2016). It houses 12 PAs and 29 Indigenous nations, including three groups in voluntary isolation or initial contact. It also contains significant mining resources, such as gold, diamonds, bauxite, iron, and coltan (MPPEFCE 2021). The territory has suffered from increasing environmental impacts since the nineteenth century, gaining force with the post-war development model, essentially focused on iron, bauxite, and hydropower. The 1980s represented a turning point due to the rise in international gold prices, which not only made new mining projects more attractive, but also illegal mining. Additionally, the historical decline of conventional crude oil reserves, located outside the Amazon, drove government elites to focus on new areas of oil exploration, such as extra-heavy crude oil from the Orinoco Oil Belt (OOB), and to diversify extractivism to activities other than oil. In the 1990s, mining, forestry, and tourism projects, connective infrastructure, and the expansion of new oil ventures in the Orinoco delta were prioritized (Terán 2015).

Since 1999, the "Bolivarian Revolution" has represented a significant change in the political strategy of the country, but extractivism has remained a priority. Despite the 1999 Constitution's protection of environmental and Indigenous rights, the government emphasized extractivist development policies in the Amazon that the previous government had promoted but had not been able to consolidate (Terán 2015).

In the first decade of the 2000s, the Bolivarian process reached its hegemony and extractivism acquired new dimensions. In addition to setting a target of 6 million b/d of oil production by 2021 essentially from the OOB, the government advanced towards the expansion of big mining, with enormous consequences for the Amazon. This period saw new oil, timber, agro-industrial, infrastructure, and energy projects. The boom in primary product prices provided an extraordinary incentive, leading to a new "gold fever" that impacted the Amazon, not only with new licit mining projects, but also with a notorious expansion of illegal mining (Terán 2016).

Mining concessions and investments, regularization plans, agreements with Chinese companies, and the nationalization of gold culminated in the President's announcement of a mega-project in the Amazon called the "Orinoco Mining Arc" (OMA), from where gold, bauxite, coltan, and diamonds would be extracted. This took mining in Venezuela to a new scale and represented a fundamental step in the changes that extractivism would undergo in the years of "The Big Crisis" (2013–2021) (Terán 2016).

The Big Crisis was a national collapse of multi-dimensional character leading to the disintegration of all spheres of a nation and economy built around the oil industry during the previous 100 years. The dissolution of the petro-state — not of the State in itself — involved a complete prevalence of impunity, the resolution of public affairs and conflicts by means of force, and an extraordinary boom in corruption and in underground economies, expressed itself in the acceleration of natural resource extraction and destruction, where mining prevailed as a fundamental tool for expanding local and national power structures. The Venezuelan Amazon became the most attractive frontier to materialize these power networks (Terán 2016).

The described factors led to the emergence of a new governance structure attuned to processes of territorial conquest and appropriation of natural resources that have resulted in a general landscape of predatory extractivism. In 2016, the Venezuelan President established a “special economic zone” in the OMA, a scheme promoted principally by China, and one that cut labor and environmental regu-lations. The plan was a call for international investment and a means to organize rampant illegal mining activities in the region, but the extractive dynamics of the area soon proved to be profoundly determined by the control of mines and territories by armed actors of diverse types, including criminal gangs (“mining syndicates”), Colombian armed groups, and official security squads, mostly belonging to the military. The political geography of gold ruled; local power structures, commercial transboundary relations (mostly Colombia and Brazil), and operation essentially outside the sphere of legality, be it because the activities themselves are illegal or criminal, or because they violate human rights, the Constitution, environmental regulations, or Indigenous rights. Violence was and continues to be the primary resource for operation and control (Terán 2018).

The government responded by increasing military presence in the region and in the management of the companies. Their unlimited access to tools for the management of natural resources placed them openly and thoroughly in the extractivist business. The continuing prevalence of illicit economies and local power networks resulted in various hybrid governance structures that blur the boundaries between legal and illegal operations and exhibit no concern for conservation (Terán 2018).

The plight of the Venezuelan Amazon, traversed and pervaded by the logic of violent territorial enclave economies, has profound consequences for the natural ecosystem and local peoples. Even before the crisis, advances on the territory generated immense environmental impacts, including high levels of deforestation, mercury pollution, and degradation of water bodies and watersheds. It also displaced local economies, had significant impacts on local populations, and spurred conflict and systematic violations of human rights. This critical situation was aggravated by the deepening economic collapse, increasing levels of institutional decomposition and political corruption, international economic sanctions on the country, the need for appropriating gold by local and national power circles, as well as the dynamics of the Colombian armed conflict and the migration to mining areas by transboundary actors. The crisis exacerbated the deterioration of the social, ecological, and cultural impacts that were already in place (Terán 2018).

Despite these circumstances, Venezuela has a relatively low rate of deforestation compared with other countries in the region (Appendix Table 18.1B). The described situation of an exposed Amazon, open to forces with an attitude of conquest and globalization, still offers an opportunity for conservation, if only those forces could be kept at bay.

18.6 Bolivia: The Amazon’s Second Deforestation Hotspot

Bolivia has the second highest rate of primary-forest cover loss in the Amazon after Brazil, despite having one of the lowest human population densities in South America. The largest share of deforestation occurs in the lowland region, predominantly around the city of Santa Cruz de la Sierra and the Santa Cruz Department, the main agricultural center of the country.

Santa Cruz underwent an intense colonization process from the 1950s through to the 1990s. Between the mid-1980s and the early 1990s, deforestation accelerated due to the influx of agro-industrial corporations, farmers, and foreign producers who cleared large areas for agriculture. This process was facilitated by government policy and international development financing. World Bank financing aimed at promoting market-oriented production and economic growth. During the 2000s, the main drivers of deforestation were conversion of forest to pasture (with more than 50% of deforestation from 2000 to 2010); mechanized agriculture, mostly soybeans, largely by Brazilian and Argentinian producers (30%); and to a lesser extent small-scale agriculture (20%). Increased demand from the domestic market owing to growing urbanization, international investments, and greater integration of the agricultural economy with export markets' growing demand for soy and beef, increasingly became the major underlying causes of deforestation. Progressively, deforestation expansion radiated from Santa Cruz to the north and east, and eventually adopted a dispersed pattern, even reaching the northern border with Brazil (Kaimowitz et al. 1999).

In parallel to this process, Bolivia was a pioneer on many environmental issues. Beginning in the 1990s, faced with environmental and social problems, the government started adopting policies inspired by the Rio Summit ("Earth Summit") of 1992. However, it was not until the early 2000s that a new paradigm was introduced proposing non-market approaches to environmental policy and the principle of "Living Well", which was encoded in the country's Constitution of 2009 and proposed internationally. Bolivia became a pioneer of environmental legislation, passing the Law of the Rights of Mother Earth (2010) which recognized the rights of nature and the State's obligations to ensure these rights, and the Framework Law of Mother Earth and Integral Development for Living Well (2012), establishing the rights of Indigenous, rural, and Afro communities, within a development proposal for sustainable natural resource use (Romero-Muñoz et al. 2019).

However, despite this innovative legal framework and sustainable proposals, little progress was made in avoiding deforestation and forest degradation. In fact, these conservationist policies are in constant tension with agricultural promotion policies, and directly contradict plans to guarantee and increase food production and exports, widespread road and infrastructure improvement and expansion (after agriculture and pastures, the leading cause of forest degradation and deforestation), and allowing oil exploration in PAs. It is noteworthy that nearly half the expansion of the hydrocarbon frontier in the Amazon from 2008 to 2015 occurred in Bolivia (Romero-Muñoz et al. 2019).

Most PAs in the lowlands are directly or indirectly threatened by the rapid expansion of commodity frontiers. As a result, Bolivia has the second highest proportion of PAs under intense human pressure in all of South America. Agricultural expansion is causing massive biodiversity loss and eroding PA connectivity; 11 of the 22 PAs have overlapping oil and gas blocks covering at least 17% of the protected surface; at least nine Amazonian PAs are fragmented by roads and subjected to roadside deforestation; gold mining is rapidly expanding in the north, including inside PAs, causing water and soil pollution; nine hydroelectric projects, mainly for export to Brazil, are located inside or near PAs, and at least three dams are planned immediately upstream or downstream of seven ITs, inducing displacement (Romero-Muñoz et al. 2019).

Despite >40% of the national population identifying as Indigenous (the highest in Latin America), and constitutional guarantees of the right of Indigenous peoples to free, prior, and informed consent to infrastructure development and resource extraction in their territories, a 2015 Decree allows the government to decide the timing and procedure for consultation with national Indigenous organization rather than with affected communities, thus rendering the process ineffective and threatening conservation. Traditional knowledge and livelihoods are associated with forest conservation (Blackman et al. 2017, see also Chapter 10) and many Bolivian Indigenous communities retain their traditional culture and worldviews on which the Living Well principle enshrined in the Constitution is based (Romero-Muñoz et al. 2019).

The future of the Bolivian Amazon is contingent on the government honoring the Rights of Nature enacted in the law and the principles established in the national Constitution.

18.7 Conservation Opportunities and Threats in the Guianas

The three Guianas (Guyana, Suriname, and French Guiana) form a unique Amazonian region, as the two countries and French territory are almost entirely Amazonian, with 85-95% of their total land area covered by tropical rainforest (Butler, 2020). In fact, the Guianas are among the most forested countries on Earth and, given their low population density of approximately four persons per km^2 (Worldometers 2021), they are among the top five countries with renewable internal freshwater resources per capita in the world.

Deforestation rates in the Guianas are the lowest in the Amazon region. Suriname lost 1.05% of its primary forest tree cover between 2001 and 2019, and Guyana lost 0.79% in the same period (Global Forest Watch 2021). The Guianas provide a counterbalance to the Amazon Basin and tropical ecosystems where large-scale deforestation, forest fires, intensive human settlement, and industrial development for agriculture have threatened the existence of wildlife and local communities for decades. However, environmental threats are on the rise, especially due to irresponsible gold mining, unsustainable forestry and fishing practices, excessive poaching, and climate change.

Gold continues to be the main economic earner, not only for national economies, but also as the main livelihood of tens of thousands of families. It is also by far the largest driver of deforestation, and the mercury used by artisanal mining affects freshwater ecosystems, biodiversity, and human health. An estimated 40,000 artisanal, small- and medium-scale miners in the Guianas use mercury in the extraction of alluvial gold. This toxic substance has been widely found in the fish upon which local communities rely (Watson et al. 2020). In 2008, researchers discovered that people from the Indigenous Wayana village of Kawemhakan in Suriname, where artisanal gold mining takes place, had mercury levels significantly higher than the safe limits defined by the World Health Organization. Researchers determined a causality between high mercury levels in the people and their fish consumption, also their main source of livelihood (De Souza Hacon et al. 2020; Peplow and Augustine 2012).

While forest cover remains high and deforestation is still relatively low despite gold mining, large areas of the Guianas are allocated as forest concessions. This has resulted in substantial forest degradation mainly from intensive logging and has the potential to become a primary source of forest carbon emissions. In Guyana, 13.5% of the overall forest carbon emissions were attributed to forest degradation, of which 96.3% came from timber harvesting (Guyana Forestry Commission 2020). Furthermore, the construction of logging roads also increases access for gold mining, hunting, and poaching.

Excessive hunting, poaching, and capture of wildlife, together with habitat destruction, have caused significant declines in populations of fish, birds, mammals, amphibians, and reptiles. These include endangered and protected species, such as the iconic jaguar, parrots, and marine turtles, which are captured for illegal wildlife trade.

Climate change over the next few decades will increase pressure on natural habitats and the species that live within them (see Chapters 22–24). A WWF study (2018) reports the impacts of various global climate scenarios on the extinction of various species groups within the Amazon-Guianas Priority Region. Plants and amphibians are most vulnerable, reptiles have an intermediate position, and birds and mammals seem less vulnerable. Dispersal ability reduces vulnerability of species groups. Global warming is predicted to constitute an “escalator to extinction” for species that live on mountains, because species are generally moving to higher elevations as temperatures increase. Species that live only near mountaintops may then run out of room (Freeman et al. 2018).

Guyana and Suriname are on the eve of a massive oil and gas boom. Exploitation of offshore oil fields is predicted to generate billions of dollars for these countries, which have been struggling to strengthen their economies for decades. The region is currently at a crossroad; they can follow the traditional development path of most oil producing countries, in which development is largely based on income from natural resource exploitation at the cost of the environment and the well-being of the people, or choose a more sustainable, green development pathway, which includes building a new relationship between people and nature through a sustainable, post-COVID-19 economic recovery (see Chapters 25 and 26). The success of REDD+ (reduced emissions from deforestation and forest degradation, plus the sustainable management of forests, and the conservation and enhancement of forest carbon stocks) in Guyana, paradoxically funded by Norway's largely oil and gas proceeds, could serve as an example, including for the use of oil and gas revenues. Norway agreed to support Guyana to maintain low levels of deforestation, providing up to USD 250 million over a five-year period ending in 2015 to implement a low carbon development strategy (LCDS) and REDD+. The program has also supported regular monitoring, reporting, and verification (MRV) of forest area changes. The Guyana Forestry Commission (GFC) has developed a MRV system, now in its tenth year, which has allowed for comprehensive, consistent, transparent, and verifiable assessments and reporting of forest area change. Funding has also created incentives and changes in the legal framework, such as strengthening law enforcement in the forestry and mining sectors (Benn et al. 2020). Suriname and Guyana may also receive support from a proposed global mechanism to compensate small oil and gas rich nations for foregoing oil and gas development. That said, if oil and gas are to be exploited by Guyana and Suriname, it must be done under the best environmental and social practices, while oil and gas revenues are invested in a sustainable economic transition.

18.8 Conclusions

Since the 1970s, and particularly during the early twenty-first century, the Amazon experienced the largest expansion of human intervention in its history. Facing a new wave of globalization and the expansion of commodity exports from Latin America, several commodities extracted from the Amazon boomed, mostly soy, beef, iron ore (Brazil), oil and gas (Colombia, Ecuador, Peru), gold (Peru, Venezuela and the Guianas), and illegal drugs (Colombia, Peru, Bolivia). Moreover, large infrastructure projects (roads, hydroelectric dams) complemented the transformation, becoming far-reaching indirect drivers of deforestation and forest degradation. The neo-extractivist development model has not generated significant improvements in living conditions of the local population, including countless Indigenous communities who have suffered the greatest impacts to the environment upon which they depend (Chapter 19).

National manifestations of this process are heterogeneous and vary according to resource endowments, social and political conditions, and changes over time. Yet, there is evidence of the shared importance of domestic markets, influenced by urbanization and rising incomes in other areas of the country, international markets, and global forces, especially associated with commodities (beef, cattle, oil, and minerals), and of the role of government policy.

Interestingly, government policy is observed to be determinant, either by positive action or by absence. The latter case is demonstrated in Colombia and Venezuela. A relatively low deforestation in Venezuela is associated with an Amazon that has consistently eluded intervention of the State, first because the region was forgotten as generous oil revenues came from outside it; and subsequently because of the difficulty of successfully intervening in the territory due to the existing informal but consolidated power networks. In Colombia, a rise in deforestation was experienced after the Peace Agreement with the FARC, which until then had restricted the intervention of the State and the advance of government policy in the region. Conversely, state policy, by concrete action rather than by omission, has been an important determinant of the influx of activities that have affected the territory in all other cases. Likewise, the degree to which the adverse effect of these activities has been controlled is associated with political will and consistency of state policy, as well as with state capacity for law enforcement.

Except for Venezuela and the Guianas, agriculture and cattle ranching seem to be the most important deforestation drivers in terms of surface area. Countries differ regarding the importance of small versus large scale producers. This process may be influenced by natural conditions, government policy, and market access, among other factors, but it may also hide confounding factors associated with small-scale production, which collectively refer to a diverse universe with varying relationships to the market and with drastically different technological packages and environmental impacts (Murmis 1991). The cases presented here include small scale farmers, such as those who migrate to the Amazon from other regions and activities, and local small scale traditional farmers and harvesters. Another example comes from Peru, where small scale farmers supply domestic and international markets for cocoa and coffee (Ravikumar et al. 2016), shedding a different light on the drivers of deforestation and pointing to the importance of understanding the type and relation to market of the small-scale farming involved. However, the role of large-scale modernized agriculture and cattle ranching is clear; it radically accelerates deforestation and fragmentation where it is introduced (Brazil and Bolivia).

Infrastructure development, in particular road expansion, is an underlying indirect driver of massive changes in forest area by opening access to direct drivers, legal and illegal. Road construction and improvements have gone hand in hand with strong forest conversion, particularly in Bolivia and Brazil, where large scale agriculture is predominant. Road building plans are widespread in the region. It has been estimated that 75 projects are planned for the next five years in Bolivia, Brazil, Colombia, Ecuador, and Peru, extending 12,000 km and mostly lacking “rigorous impact assessments or even basic economic justification”; these could lead to 2.4 million hectares of deforestation in the following two decades (Vilela et al. 2020).

From the perspective of the intensity of the deforestation process, three main groups can be identified. Brazil and Bolivia share high tree forest loss, involving land-use change from forest to cattle ranching, intensive soy cultivation, oil and gas (Bolivia), mining (Brazil), and infrastructure development. A second group with medium includes three Andean countries (Colombia, Peru, and Ecuador). In all cases oil has been significant factor, while commercial farming is important in Peru, and peasant agriculture in Ecuador. The extent of illegal activities, such as coca cultivation (relevant mostly in Colombia and Peru), gold mining, logging, and drug trafficking, remains an open question, as they escape formal and comparable statistics. It is known that they cater to international markets, are deeply transnational, and may have a significant degree of integration (Castro Pereira and Viola 2021).

A third group, with relatively low tree cover loss, includes Venezuela, Suriname, Guyana, and French Guiana. In all cases, forest conversion to agriculture has been moderate, but the recent expansion of illegal mining and criminal activities, mostly in Venezuela, has created a well-defined increase in forest impacts.

It is interesting that the low degree of forest conversion in Venezuela has resulted from a lack of development policies in the region due to the absence of state presence in the area. Similarly, the lack of intervention of government policy in Colombia up to the signing of the peace agreement with the guerrillas kept deforestation relatively low. These facts and the developmentalist policies that have induced deforestation in other countries and periods, in contrast with the success of the Brazilian-government-led conservation policies between 2005 and 2012, point to the critical role of the state in the fate of the Amazon, be it by act or omission, and should be a major criterion in designing sustainable development paths for the future.

Overall, in all cases, the neo-extractivist model has been stronger than conservation policies, despite the fact that nearly half the region is covered by recognized PAs and ITs, as described in Chapter 16. The only national strategy with substantial effects in curbing deforestation was the Brazilian experience between 2005 and 2012, with an 84% reduction in deforestation rates (see Chapter 17). Although this policy has been dismantled and the outcome is currently reversed, the model's success sheds light on the path needed for its replication and enhancement for long term viability, embedded in a comprehensive new paradigm towards conserving biodiversity and forest ecosystems, and reducing emissions while improving the living conditions of local peoples and respecting Indigenous cultures.

These different cases show how the manifestations of deforestation and forest degradation are particular to national and local contexts. Therefore, local context must be a central factor in designing policies and programs. Given the variety of experiences, there are no one-size solutions applicable to all countries or even to the entire Amazon within the same country. Moreover, a sustainable path for the Amazon requires the participation of local voices, particularly those that were most impacted by the negative consequences of the current model and were the least involved in the decision making that led to the current situation. It is also imperative that the presence of common, underlying, and cross-cutting major and, in many cases, global forces permeating local experiences be addressed. This requires action at the scale and level at which these forces operate, but policy measures in response to these forces must also be customized and incorporated in the locally adapted strategies.

18.9 References

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18.10 Annex to Chapter 18

Table 18.1B Average annual growth rates on Ecuador GDP by periods (1950-2019)

Period	Growth rate
1950-1965	2.14
1966-1972	2.42
1973-1981	4.23
1982-1990	-3.31
1990-1999	-1.29
2000-2004	6.31
2005-2014	5.40
2015-2020	-1.99

Note: Growth rates were estimated from a kinked regression, controlled from first order autocorrelation, using Prais-Winsten and Cochrane-Orcutt models.
Source: Author estimates based on PENN World Table, 10.0

Table 18.2B Ecuador's Population by Region: 1950-2010

Region and area	**1950**	**1962**	**1974**	**1982**	**1990**	**2001**	**2010**
Quito	209932	354746	599828	866472	1201954	1621646	1979831
Remaining urban highlands	191111	325261	537834	785349	1079922	1520092	1960146
Rural highlands	1453909	1591338	2008903	2150018	2117137	2319000	2509378
Total highlands	1854952	2271345	3146565	3801839	4399013	5460738	6449355
Guayaquil	258966	510804	823219	1119344	1535393	2007892	2307587
Remaining urban Coast	133072	334231	703649	1161982	1678402	2266478	2987451
Rural Coast	910059	1290559	1670771	1707631	1653063	1854439	1974168
Total Coast	1302098	2135594	3197639	3988957	4866858	6128809	7269206
Urban Amazon	0	0	0	32763	59575	152696	241236
Rural Amazon	46471	74913	173469	224915	312958	395723	498578
Total Amazon	46471	74913	173469	257678	372533	548419	739814
Urban Galápagos	698	1165	2381	4493	8013	14142	18085
Rural Galápagos	648	1226	1656	1626	1772	4498	7039
Total Galápagos	1346	2391	4037	6119	9785	18640	25124
Total Urban	**793779**	**1526207**	**2666910**	**3970403**	**5563259**	**7582946**	**9494336**
Total Rural	**2411087**	**2958036**	**3854800**	**4084190**	**4084930**	**4573660**	**4989163**
Total National	**3204867**	**4484243**	**6521710**	**8054593**	**9648189**	**12156606**	**14483499**

Sources: INEC. Population censuses.

Table 18.3B Selected Social indicators in oil extracting and remaining Amazon regions, 2010

Subregion	Area	Years of Schooling	Child mortality proportion	Social Development Index
Amazon oil extracting region	Rural	6.7	0.057	48.7
	Urban	8.6	0.044	64.1
	Total	7.7	0.050	56.8
Amazon non-oil extracting region	Rural	7.1	0.047	50.8
	Urban	9.8	0.034	72.9
	Total	8.2	0.042	58.7
National Total	Rural	5.9	0.046	51.9
	Urban	9.5	0.032	73.1
	Total	8.7	0.035	68.1

Sources: UASB-UISA, based on: INEC, Censos de Población y Vivienda, 1990, 2001, 2010.

METHODOLOCAL NOTES FOR ECUADOR'S SECTION

The social development index (SDI). The Social Development Index was estimated from 19 indicators from the 1990, 2001, and 2010 Ecuadorian census databases, broken down by parishes in the rural area and municipalities in the urban area. Six indicators deal with education, 2 with health, 3 with gender differences in education and employment, and 8 with housing. Parishes are the smallest administrative division in Ecuador, and the country was divided into 1024 local circumscriptions. The SDI was estimated as the first component using principal components analysis, maximizing its statistical representativity, and explained 50.5% of the total variance of its 19 components.

Education indicators were: 1. Average years of schooling for the population older than 23 years (ESCOL). 2. Proportion of literacy in the population older than 14 years (ALFAB). 3. Net assistance rate for primary education (TPRIM). 4. Net assistance rate for secondary education (TSECUN). 5. Net assistance rate for higher education (TSUP). 6. Proportion of population older than 23 years with access to higher education (TACSUP).

Health indicators were: 7. Weighted health personnel for each 10,000 inhabitants (PERSAL). 8. Proportion of dead sons and daughters from mothers aged between 15 and 49 (PNINMUER).
Gender indicators were: 9. Difference between male and female literacy rates (DISEXAL). 10. Difference between male and female schooling (DISEXESCOL). 11. Female proportion in the economically active population (PFEMPEA).

Housing indicators were: 12. Proportion of dwellings with access to piped water inside the house (PAGUA). 13. Proportion of dwellings with sewerage (PALCAN). 14. Proportion of dwellings with garbage collection service (PBASURA). 15. Proportion of dwellings with electricity (PELEC). 16. Proportion of dwellings with adequate walls (PPARED). 17. Proportion of dwellings with adequate floor (PPISO). 18. Proportion of households with less than 3 persons per room. 19. Proportion of dwellings with toilets inside the house (PSSHH).

The SDI was rescaled to an interval between 0 and 100 points. Its formula is:

SDI = 0.904 * ESCOL24 + 0.707 * ALFAB15 + 0.604 * TPRIM + 0.859 * TSECUN + 0.822 * TSUP + 0.771 * TACSUP - 0.452 * DISEXAL + -0.299 * DISEXESCOL + 0.714 * PERSAL - 0.722 * PNINMUER+ 0.233 * PFEMPEA + 0.802 * PAGUA + 0.749 * PALCAN + 0.848 * PBASURA + 0.734 * PELECT + 0.693 * PPARED + 0.602 * PPISO + 0.716 * PPERCUA + 0.839 * PSSHH (Larrea et al 2013).

The initial analysis broke down the SDI by area of residence (urban and rural) and natural region (Coast, Highlands, Amazon, and Galapagos). The urban area includes all cities and towns with populations higher than 10,000 inhabitants. The Amazon region was further divided into an oil extractive sub-region and the remaining part. The oil extractive subregion was integrated by the parishes or municipalities containing oil blocks in production in 2017.

The spatially autoregressive multiple regression model. In the regression analysis, the SDI was used as a dependent variable, breaking down the 2010 Census by census tracks (sectors). Ecuador was divided into 40,640 census tracks in 2010. The model included 2,408 census tracks in the Amazon region with valid data (145 tracks were excluded because of missing values). The Amazon region was defined as including all the six regional provinces, which incorporate not only the dominant lowlands but also the foothills of the Andean mountains, where many Amazon headwaters originate.

As information is spatially defined, OLS regression models may have a bias due to spatial autocorrelation, because of influences among neighboring or closer tracks. To control for spatial autocorrelation, a spatially autoregressive model was used, with a dependent variable lag and an inverse distance matrix among tracks.

Independent variables in the regression model

Proximity to oil wells index. Defined as the sum of inverse distances between the centroid of each census track and the surrounding oil wells. The PRAS map (2013) was used to identify wells. A radius of 50 km from the centroid was used to identify surrounding oil wells. The variable was included for identifying the effects of local oil extraction on social conditions.

Soil fertility index. Defined as the percentage of area with at least medium soil fertility in each census track. The source is the map of soil agricultural aptitude from the MAGAP-SIGTIERRAS (2015) program of Ecuador´s Ministry of Agriculture, which identifies four categories of fertility: very low, low, medium, and high. The variable intends to evaluate the effects of local soil quality on living conditions.

Proportion of intervened areas. Defined as the proportion of artificially modified areas on the total area of each census track, excluding natural water bodies. Modified areas include cropland, pastures, artificial water bodies, human settlements, infrastructure, and no forested-covered areas. The source is the 2016 map of land use of the Ministry of Environment. This variable was included in the regression model in parabolic quadratic form. The variable intends to measure the effect of deforestation on local social conditions.

Travel time to the closest agricultural market. Defined as the number of hours required to travel from the centroid of each census track to the closest agricultural market. The variable is expected to evaluate the social contribution of market access.
Dummy rural. Dichotomous variable included to differentiate rural sectors from small towns, concentrated (blocked) settlements, and cities.

Additionally, 3 local employment indicators were included in the regression model to capture the potential effect of economic diversification and the expansion of capitalist relations in the labor force. Information was obtained from the 2010 population census.

Proportion of agriculture in economically active population (EAP). Included as an indicator of economic diversification from agriculture, the traditionally dominant sector.

Proportion of wage earners in EAP. Expected to capture the influence of capitalist social relations of production, as opposed to traditional family-based or independent ways of production, which prevail among peasants and small urban producers.

Proportion of hotels, lodging, restaurants, and food services in EAP. Expected to capture the extent of tourism in employment.

To differentiate between deforestation leading to expansion of agricultural frontier and deforestation leading to urban expansion, an interaction term (Dummy rural) * (Proportion of intervened areas) was also included.

The model results are presented in **Table 18.4B.** Their main findings can be summarized as follows:

1. All independent variables have regression coefficients significant at least at the 5% level, and most of them were significant at 1% level.

2. The regression coefficient of proximity to oil wells is negative and statistically significant at 1% level. The result is consistent with the negative effect of oil extraction on SDI presented in Appendix Table 7, and strongly suggests that, after controlling for other observable factors that influence social conditions, such as soil fertility, access to markets, proportion of deforested land, and employment structure and diversification, the proximity or local presence of oil extraction has a net detrimental effect on basic needs satisfaction.

3. The soil fertility index captures spatial differences in the land aptitude for agriculture and has the expected positive regression coefficient at 5% significance level. Travel time for markets captures transportation costs of agricultural products and has the expected negative and significant association with SDI. Dummy rural captures differences in living conditions between towns and the countryside, which are high in Ecuador. Its regression coefficient is negative and statistically significant. All the remaining variables refer to employment structure. As a high proportion of agriculture in the labor force implies low diversification, their expected effect on SDI is negative. The proportion of wage earners, an indicator of expansion of capitalist relations, has an expected positive influence. Finally, the proportion of logging and food services, as an indicator of tourism, has a strong positive coefficient with 1% significance, as expected. Its high value suggests an important socially distributive effect of tourism in Ecuador´s Amazon.

4. The proportion of deforested areas, presented in quadratic form, has an effect on SDI with decreasing returns and low initial gains, after controlling for the remaining variables, suggesting a weak and short-lived association between deforestation and local living conditions.

Results of the spatially autoregressive multiple regression model

Table 18.4B Spatially Autoregressive model on factors influencing local social development in Ecuador's Amazon, 2010

Dependent variable: Social Development Index (SDI)
Number of observations = 2408
Maximum likelihood estimates:
Wald chi2 (11) = 8894.03
Prob > chi2 <= 0.0001
Log likelihood = - 7016.191
Pseudo R2 = 0.7842

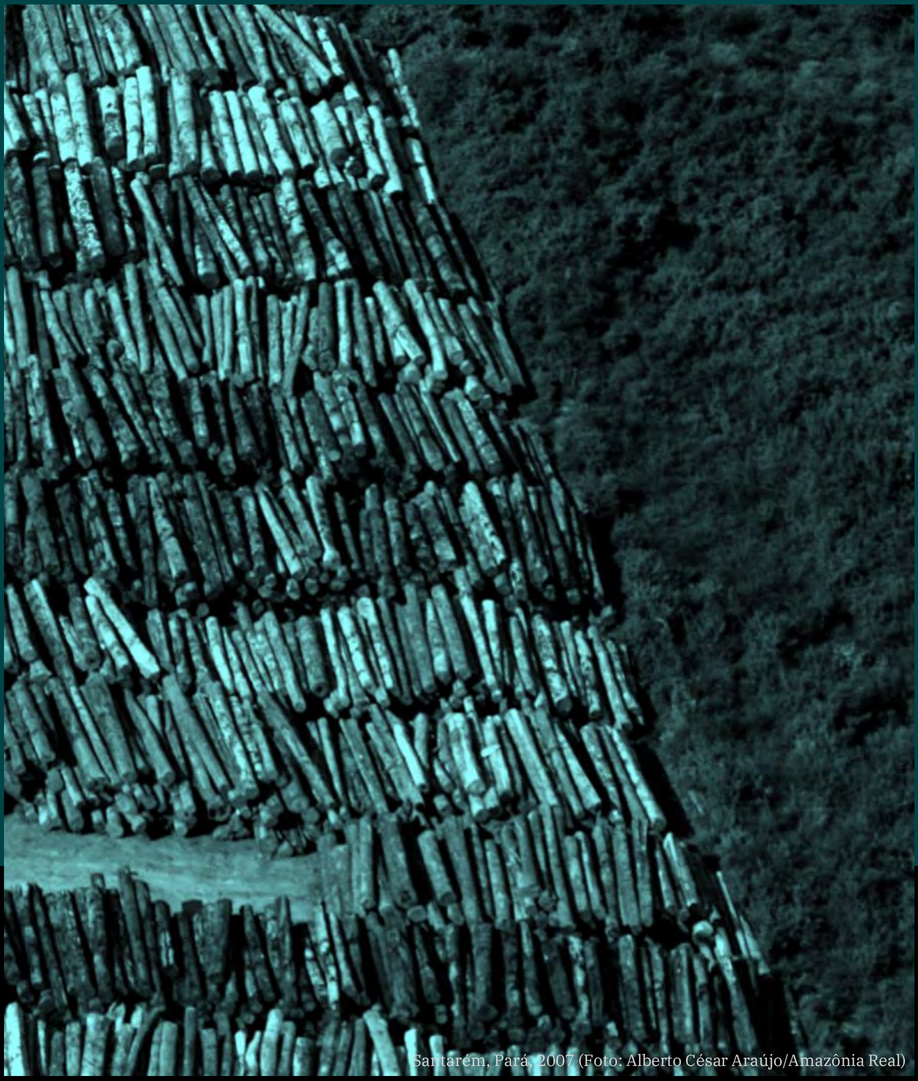
InDesSoc100	Coefficient	Std. Error	z	P>|z|	[95% Conf. Interval]	
InDesSoc100					Minimum	Maximum
Proximity to oil wells index	-0.261	0.026312	-9.93	<0.001	-0.313	-0.210
Soil fertility index	0.854	0.4222169	2.02	0.043	0.026	1.681
Prop. of intervened areas	20.506	2.231269	9.19	<0.001	16.133	24.880
Prop. of intervened areas²	-10.879	1.392222	-7.81	<0.001	-13.607	-8.150
Travel time to markets	-0.482	0.0688226	-7	<0.001	-0.616	-0.347
Prop. Agriculture in EAP	-5.042	0.6216075	-8.11	<0.001	-6.260	-3.823
Prop. wage earners in EAP	7.233	0.6529073	11.08	<0.001	5.953	8.512
Prop. logging in EAP	22.438	3.684288	6.09	<0.001	15.217	29.659
Dummy rural	-2.675	1.202942	-2.22	0.026	-5.033	-0.318
DRural*PropIntAreas	-2.666	1.328097	-2.01	0.045	-5.269	-0.063
Constant	35.197	1.363232	25.82	<0.001	32.525	37.869
Widist2 distance matrix						
InDesSoc100	0.077	0.009	9.05	<0.001	0.061	0.094
var(e.InDesSoc100)	19.876	0.573			18.784	21.031

Note: To control for spatial autocorrelation, a spatially autoregressive model was used, with a dependent variable lag and an inverse distance matrix among tracks. The model was run with Stata statistical software (version 15).

Amazon Assessment Report 2021

Chapter 19

Drivers and ecological impacts of deforestation and forest degradation



Santarém, Pará, 2007 (Foto: Alberto César Araújo/Amazônia Real)

INDEX

Graphical Abstract

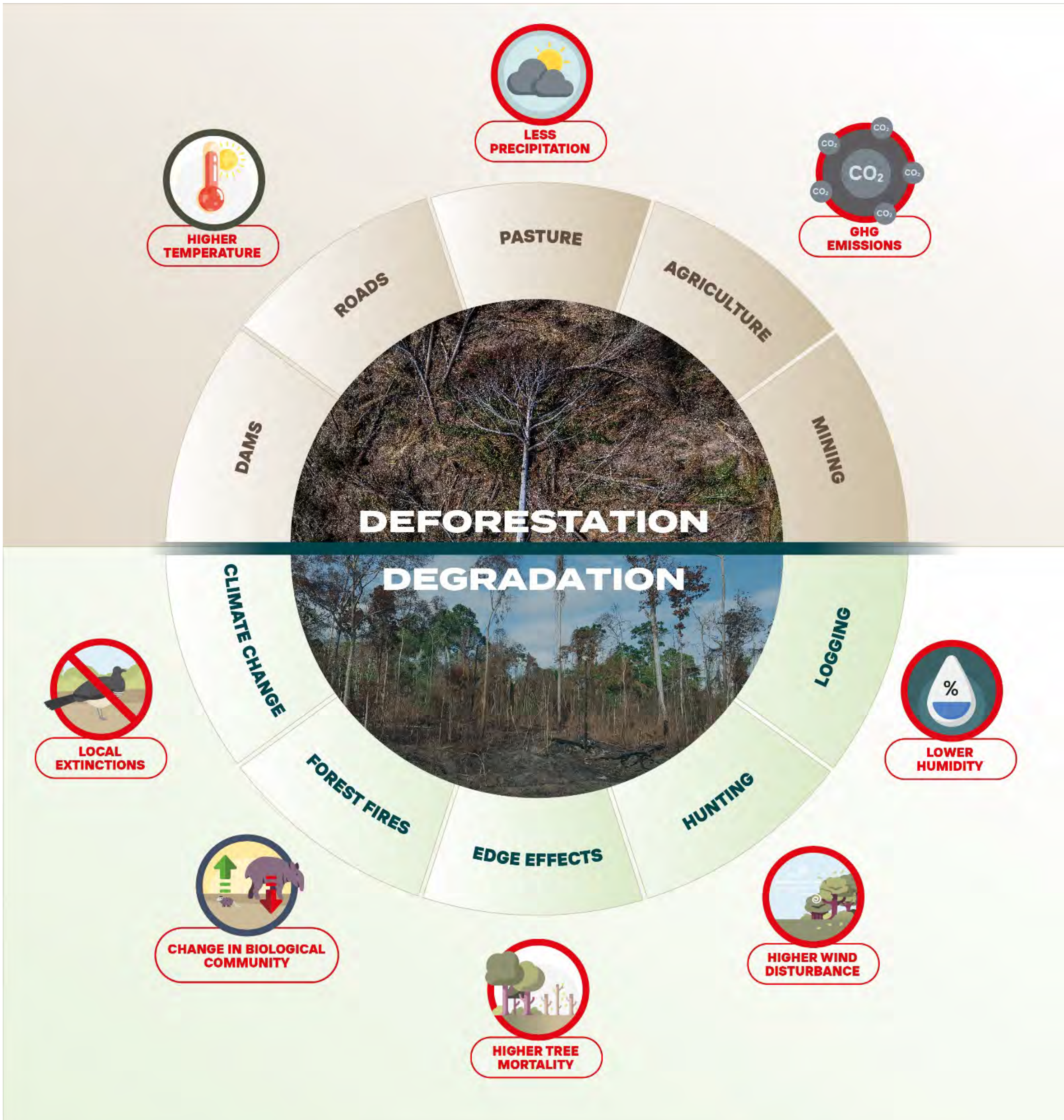


Figure 19.A Graphical Abstract

Drivers and Ecological Impacts of Deforestation and Forest Degradation

Erika Berenguer[a,b], Dolors Armenteras[c], Alexander C. Lees[d], Charlotte C. Smith[b], Philip Fearnside[e], Nathália Nascimento[f], Ane Alencar[g], Cláudio Almeida[h], Luiz Aragão[h], Jos Barlow[b], Bibiana Bilbao[i], Paulo Brando[g,j,k], Paulette Bynoe[l], Matt Finer[m], Bernardo M. Flores[n], Clinton N. Jenkins[o], Celso H. L. Silva Junior[h], Carlos Souza[p], Roosevelt García-Villacorta[q]

Key Messages

- By 2018, the Amazon lost approximately 870,000 km^2 of primary forests.
- There are at least 1,036,080 km^2 of degraded Amazonian forests.
- Agricultural expansion, mainly cattle ranching, is the greatest driver of deforestation in the Amazon.
- Deforestation leads to local, regional, and global impacts.
- Forest degradation encompasses significant changes in forest structure, microclimate, and biodiversity.
- Deforestation and forest degradation are responsible for enormous quantities of CO_2 emissions.

Abstract

Deforestation, the complete removal of an area's forest cover; and forest degradation, the significant loss of forest structure, functions, and processes; are the result of the interaction between various direct drivers, often operating in tandem. By 2018, the Amazon biome had lost approximately 870,000 km^2 of its original forest cover, mainly due to agricultural expansion (pasture and croplands). Other direct drivers of forest loss include the opening of new roads, construction of hydroelectric dams, exploitation of minerals and oil, and urbanization. Impacts of deforestation range from local to global, including local changes in landscape configuration, climate, and biodiversity; regional impacts on hydrological cycles; and global increase of greenhouse gas emissions. Of the remaining Amazonian forests, 17% are degraded, corresponding to approximately 1,036,080 km^2. Various anthropogenic drivers, including forest fires, edge effects, selective logging, hunting, and climate change can cause forest degradation. Degraded forests have significantly different structure, microclimate, and biodiversity as compared to undisturbed ones. These

[a] Environmental Change Institute, School of Geography and the Environment, University of Oxford, South Parks Road, OX1 3QY Oxford, UK, erika.berenguer@ouce.ox.ac.uk
[b] Lancaster Environment Centre, Lancaster University, LA1 4YQ, Lancaster, UK
[c] Ecología del Paisaje y Modelación de Ecosistemas ECOLMOD, Departamento de Biología, Facultad de Ciencias, Universidad Nacional de Colombia, Cra 45 #2685, Bogotá, Colombia, darmenterasp@unal.edu.co
[d] Manchester Metropolitan University, John Dalton Building, Manchester M1 5GD, UK
[e] Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA), Av. André Araújo 2936, Petrópolis, Manaus AM 69067-375, Brazil
[f] Universidade Federal do Espírito Santo - UFES, Instituto de Estudos Climáticos, Vitória, Espírito Santo, Brazil.
[g] Amazon Environmental Research Institute, SCLN 211, Brasília DF 70863-520, Brazil.
[h] Instituto Nacional de Pesquisas Espaciais, Avenida dos Astronautas 1758, Jd. Granja 12227-010 São José dos Campos SP, Brasil
[i] Universidad Simón Bolívar, Apartado 89000, Caracas 1080, Venezuela.
[j] Department of Earth System Science, University of California, Croul Hall, Irvine CA 92697-3100, USA.
[k] Woodwell Climate Research Center, 149 Woods Hole Road, Falmouth MA 02540, USA
[l] University of Guyana, Turkeyen Campus, Greater Georgetown, Guyana
[m] Amazon Conservation Association, 1012 14th Street NW, Suite 625, Washington, DC 20005, USA
[n] Federal University of Santa Catarina, Campus Universitário Reitor João David Ferreira Lima, s/n. Trindade 88040-900, Florianópolis, Brazil.
[o] Florida International University, Department of Earth and Environment & Kimberly Green Latin American and Caribbean Center, Miami, FL 33199, USA.
[p] Instituto do Homem e Meio Ambiente da Amazônia (IMAZON), Trav. Dom Romualdo de Seixas 1698, Edifício Zion Business 11th Floor, Bairro Umarizal 66055-200, Belém, PA, Brazil.
[q] Cornell University, E145 Corson Hall, Ithaca NY 14853, USA.

forests tend to have higher tree mortality, lower carbon stocks, more canopy gaps, higher temperatures, lower humidity, higher wind exposure, and exhibit compositional and functional shifts in both fauna and flora. Degraded forests can come to resemble their undisturbed counterparts, but this depends on the type, duration, intensity, and frequency of the disturbance event. In some cases, this may prohibit the return to a historic baseline. Avoiding further loss and degradation of Amazonian forests is crucial to ensure they continue to provide valuable and life-supporting ecosystem services.

Keywords: Deforestation, forest degradation, cattle ranching, agriculture, mining, wildfires, edge effects, selective logging, hunting, biodiversity loss, CO_2 *emissions*

19.1 Introduction

Across the Amazon, deforestation and forest degradation are the result of the interplay between various underlying and direct drivers acting at global, regional, and local scales (Armenteras *et al.* 2017; Barona *et al.* 2010; Clerici *et al.* 2020; Rudel *et al.* 2009). Underlying drivers are factors that affect human actions (IPBES 2019), such as lack of governance and variation in both the price of commodities and the price of land (Brandão *et al.* 2020; Garrett *et al.* 2013; Nepstad *et al.* 2014). Conversely, direct drivers represent the human actions that impact nature (IPBES 2019), including the expansion of pastures and croplands, opening of new roads, construction of hydroelectric dams, or exploitation of minerals and oil (Fearnside 2016; Ometto *et al.* 2011; Sonter *et al.* 2017). Drivers often act simultaneously, making it very difficult to quantify their individual impacts. For example, road construction and paving leads to the creation of new urban centers and the advance of the agricultural frontier (Fernández-Llamazares *et al.* 2018; Nascimento *et al.* 2021). Although each of these drivers (road building, urbanization, and agricultural expansion) will increase deforestation rates, it is very difficult to estimate their isolated impacts on ecosystems processes and functions.

The impacts of deforestation and forest degradation can be direct or indirect and have local, regional, or global consequences (Davidson *et al.* 2012; Magalhães *et al.* 2019; Spracklen and Garcia-Carreras 2015). The most obvious direct impact of deforestation is biodiversity loss –species-rich forested areas are converted to species-poor agricultural lands. However, there are more cryptic impacts resulting from deforestation and forest degradation, such as changes in local temperatures and regional precipitation regimes or increased global greenhouse gas emissions (Longo *et al.* 2020; Mollinari *et al.* 2019). These impacts can interact with others, amplifying their individual effects. For instance, changes in precipitation patterns can increase plant mortality, leading to more greenhouse gas emissions, which in turn contribute to further changes in climate (Esquivel-Muelbert *et al.* 2020; Nepstad *et al.* 2007).

Although both the direct drivers and the impacts of deforestation and forest degradation do not necessarily occur in isolation, we will discuss them separately in this chapter, trying to acknowledge the role of different drivers across the Amazon, as well as their varied impacts. We start by presenting a general discussion of deforestation, followed by a detailed presentation of its main drivers, namely agricultural expansion (including both pasture and croplands), infrastructure, and mining. Whenever possible, we also try to quantify the direct and indirect impacts of each individual driver. We then present a general framework of degradation of Amazonian forests, discussing in more detail its main drivers, including understory fires, edge effects, selective logging, and hunting. The quantifiable impacts of each of these drivers are discussed in their individual sections. Despite the tight links between underlying and direct drivers of deforestation and forest degradation, the former is not dealt within this chapter, but rather in Chapters 14 to 18. Finally, although the direct drivers of deforestation and forest degradation also impact aquatic ecosystems and human well-being, these are discussed elsewhere (Chapters 20 and 21, respectively).

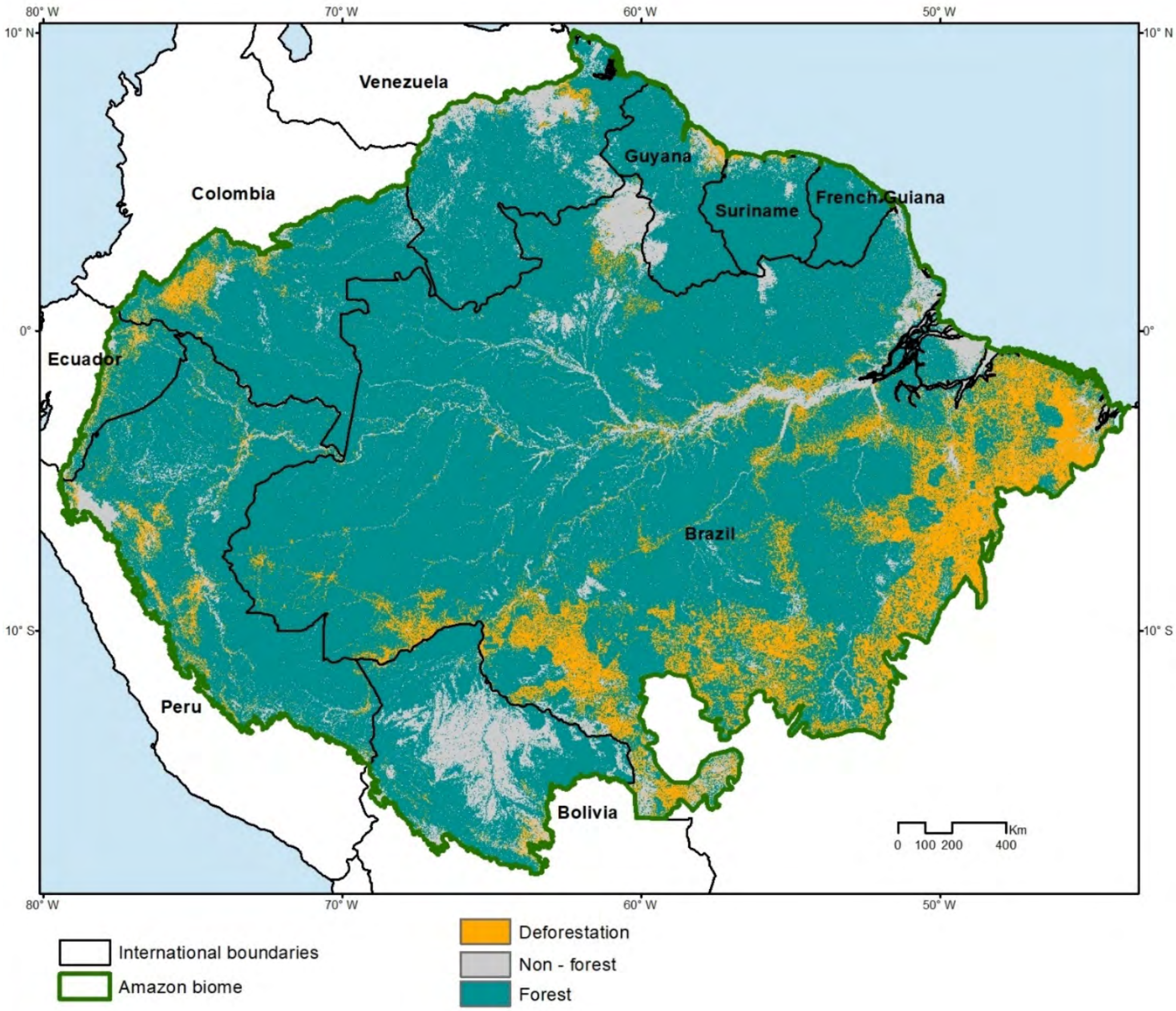


Figure 19.1 Current land occupied by either natural vegetation or pasture and agriculture across the Amazon biome. Cumulative deforestation data is shown until 2018 (MapBiomas 2020) and analyzed according to (Smith et al. 2021).

In this chapter, we focus only on the Amazon biome (Figure 19.1), therefore using a different geographical limit than those used in previous chapters; however, most maps will present both limits for the reader's reference.

19.2 Deforestation: An overview of direct drivers and impacts

Deforestation is defined as the complete removal of an area's forest cover (Putz and Redford 2010). In the Amazon, 867,675 km^2 had been deforested by 2018 (MapBiomas 2020), equivalent to 14% of its original forested area (Fig. 19.1). Most deforestation has been concentrated in Brazil, which lost approximately 741,759 km^2 of forests (MapBiomas 2020; Smith *et al.* 2021) – an area 15 times greater than that lost by Peru, the country with the second largest deforested area (Fig. 19.2a). In relative terms, the country that lost most of its Amazon

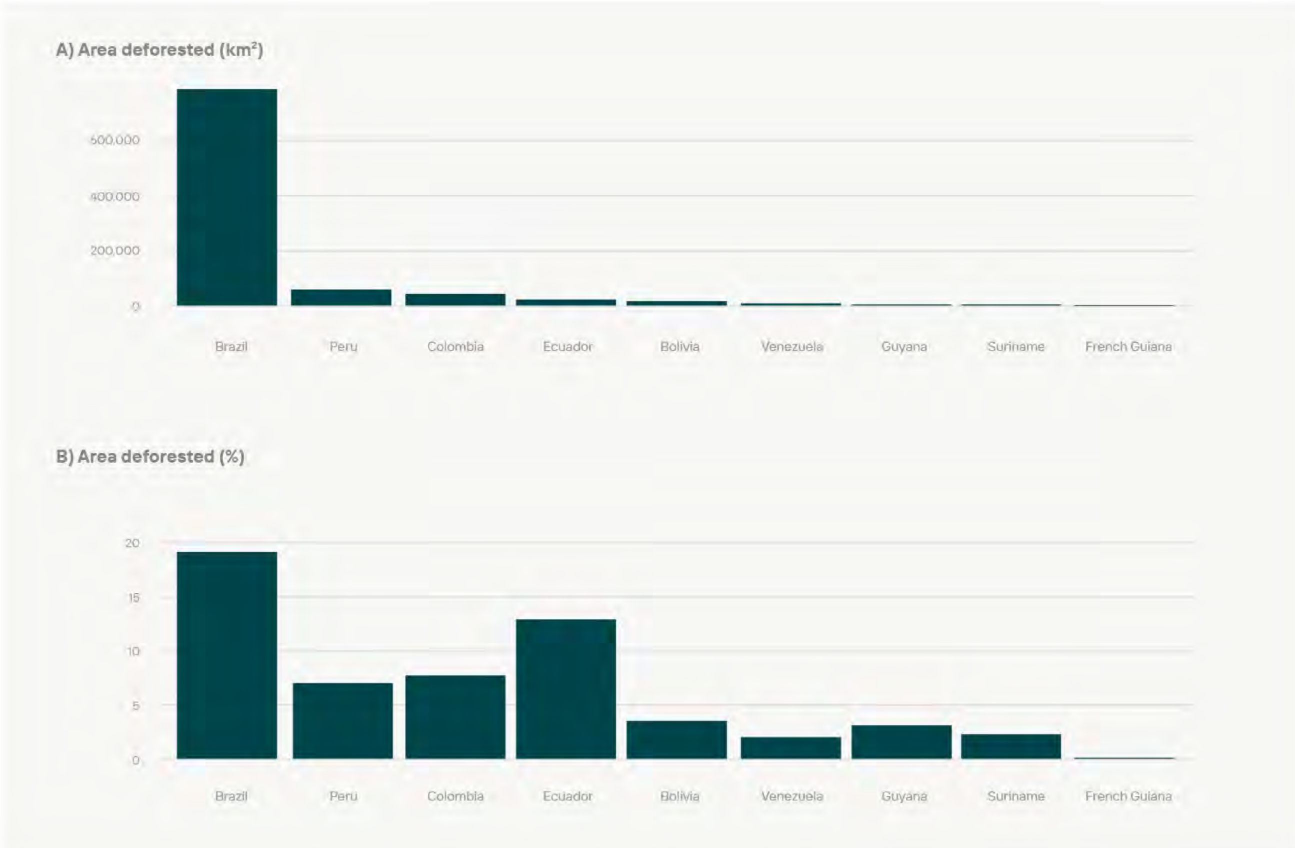


Figure 19.2 Country-level deforestation in the Amazon biome. A) Cumulative deforestation until 2018. B) Percentage of the biome deforested in each Amazonian country or territory. Data obtained from MapBiomas 2020 and analyzed according to Smith et al. 2021.

biome was Brazil (19%), followed by Ecuador (13%). To date, French Guiana, Suriname, and Venezuela have the greatest proportion of original vegetation cover, 99.85%, 97.92%, and 97.89%, respectively (Fig. 19.2b).

Deforestation varies not only across space, but also across time. Between 1991 and 2006, annual deforestation was consistently above 20,000 km^2, peaking in 2003 when 31,828 km^2 of forests were lost (MapBiomas 2020). From 2007 until 2018, annual deforestation in the region was much lower, ranging between 9,918 km^2 and 17,695 km^2 (Fig. 19.3). By 1990, only 5% of the forests in the basin had been lost. However, this figured reached 9% in 2000 and 12% in 2010 (MapBiomas 2020; Smith *et al.* 2021). See Annex I for a time series of forest loss in each Amazonian country.

Amazonian deforestation has been mainly driven by agricultural expansion (including both pastures and croplands), although other drivers also contribute, such as mining and infrastructure development, including urbanization and the building of roads, railways, waterways, and large-scale hydropower dams (Fig. 19.4).

These drivers often act in tandem, creating positive feedbacks. For instance, after the building of large roads crossing the Brazilian Amazon, there was an influx of migrants to the region, creating new cities and expanding existing ones. In rural

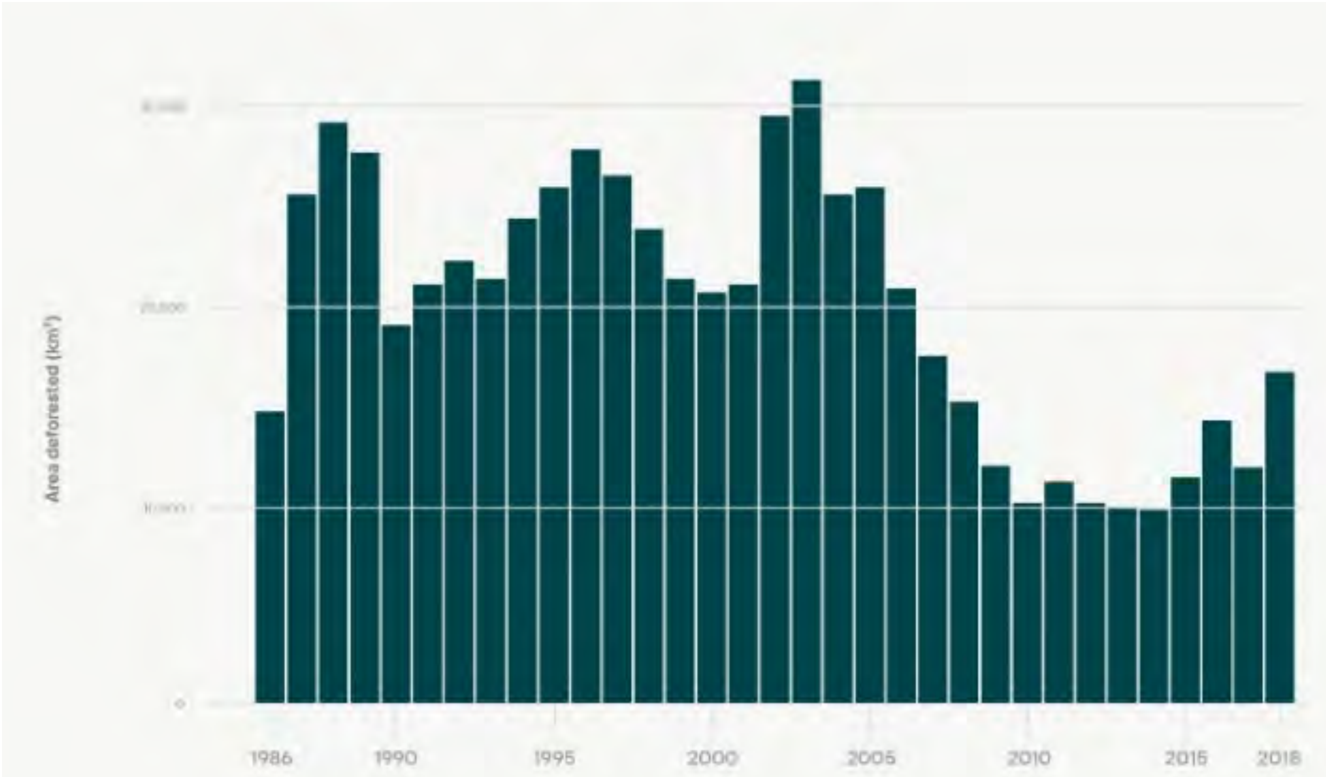


Figure 19.3 Annual deforestation across the Amazon biome. Deforestation data comprises the period of 1986 until 2018 (MapBiomas 2020).

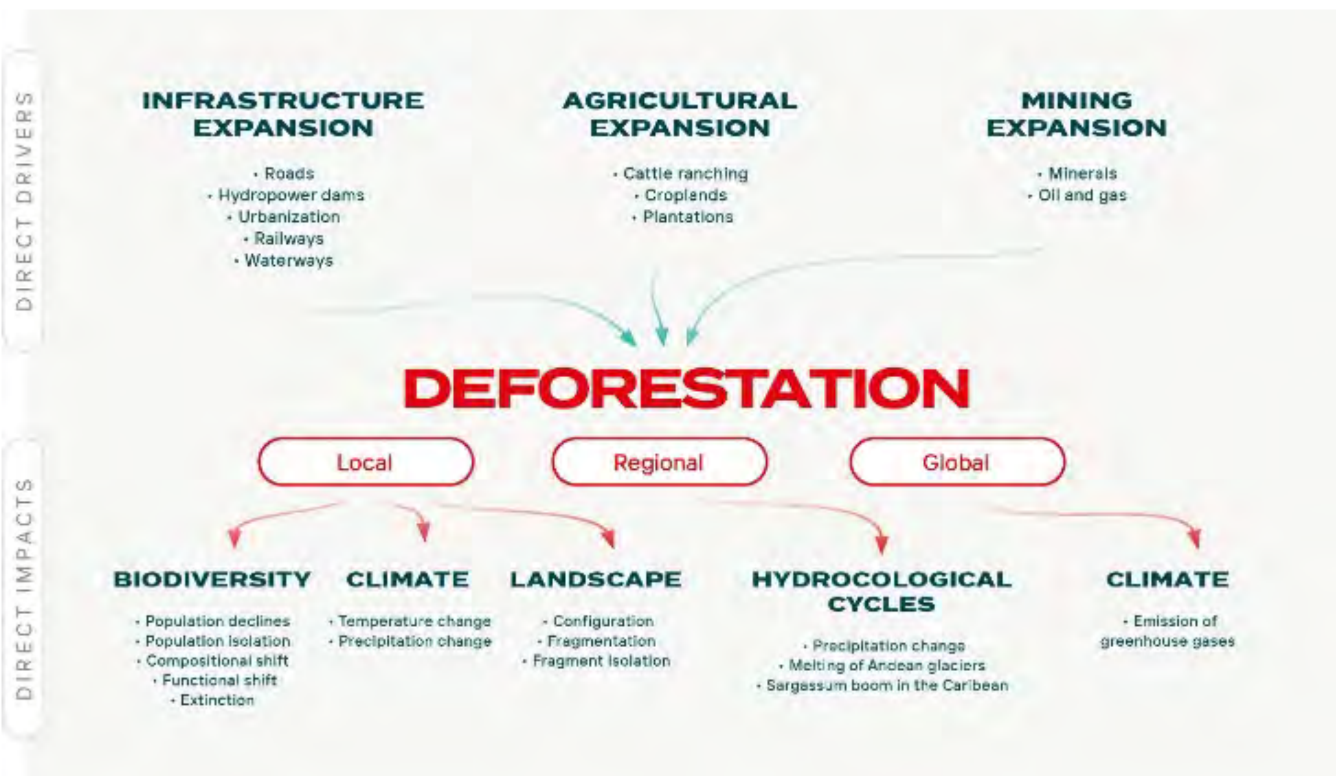


Figure 19.4 The direct drivers of deforestation and its direct impacts at local, regional, and global scales

Figure 19.5 Deforestation driven by road building, urbanization, and agricultural expansion, resulting in a fishbone pattern of deforestation. Images from the BR-163 Highway and the Transamazon Highway in the Brazilian Amazon.

areas, numerous secondary roads branching off the main highway were constructed by agricultural settlers, leading to the well-known pattern of fishbone deforestation (Fig. 19.5). In the sections below, we discuss each direct driver of deforestation individually, highlighting, whenever possible, how their relative importance differs across Amazonian countries.

Deforestation can lead to a wide range of direct ecological impacts, which are locally, regionally, and globally relevant. Of the local impacts, biodiversity loss is extremely concerning, with several species of trees, mammals, birds, reptiles, amphibians, and terrestrial invertebrates classified as globally threatened (IUCN 2021). The number of Amazonian threatened species is highly conservative, as the majority of Amazonian species have not even had their status assessed (Box 19.1). Although to date there is no record of a regional extinction, some may have already occurred, especially in plants and invertebrates, given the large number of species yet to be described in these taxa (Lees and Pimm 2015; Stork 2018; ter Steege *et al.* 2013). Fine-scale endemism may also contribute to undetected extinctions, as many species may only have very restricted geographic distributions (Fernandes 2013), occurring in very small areas (Box 19.2).

Forest fragmentation, or the subdivision of remaining forest cover into variable-sized forest patches, is another local impact of deforestation which reshapes landscape configuration. An increase in forest fragmentation is caused by continued deforestation (Armenteras Barreto *et al.* 2017; Broadbent *et al.* 2008; Laurance *et al.* 2018; Numata *et al.* 2017). Between 1999 and 2002, approximately 5,000 new fragments were created annually due to deforestation in the Brazilian Amazon (Broadbent *et al.* 2008). Although most Amazonian forests remain in large, contiguous blocks, there are over

Box 19.1 Why current tallies of threatened species in the Amazon are gross underestimates

To understand how many Amazonian species are threatened we first need to know how many species there are in the biome. It is estimated that 86% of existing species on Earth and 91% of species in the ocean still await formal scientific description; just 1.7 million species have been catalogued to date (Mora *et al.* 2011). The bulk of this undiscovered diversity is expected to be found in tropical forests like the Amazon. Undertaking the first step and putting names to life on Earth is the greatest impediment to understanding how much of that life is threatened with extinction. Global estimates of over one million threatened species (e.g. IPBES 2019) are derived from estimates of the total number of species that may exist combined with ratios of how many described species are threatened. For example, around 10% of described insects are known to be threatened with extinction.

The number of species officially listed as threatened in the Amazon is thus low for a variety of reasons. Firstly, we are unlikely to have described more than 10% of all the species in the biome. Secondly, even for those species that have been named, the Red Listing process disproportionately covers vertebrate species and not other species on the evolutionary tree of life. Even many vertebrate species which have been officially assessed have been classified as 'Data Deficient,' meaning there is insufficient information available to apply the criteria and evaluate their conservation status. The vast majority of described species have not been assessed, either because of a lack of information about their geographic distribution, responses to global change, or population trends, compounded by a lack of human resources to carry out the task of assessment and verification (IPBES 2019). Thirdly, taxonomy is an iterative process and genetic data increasingly point towards a mismeasure of Amazonian taxonomic diversity by uncovering multiple lineages within described species which have not shared genes for very long period of time (as much as millions of years), and which might be better treated at the species level. This taxonomic inflation (Isaac *et al.* 2004) tends to produce more 'new' restricted range species, which are thus more likely to meet Red List criteria if their ranges have suffered intensive habitat loss.

The current low level of 'officially' threatened species is thus primarily a product of a dearth of knowledge about how many species inhabit the Amazon biome and what proportion of this 'unknown' biodiversity is therefore threated. Secondarily it also reflects shortcomings in our knowledge of the response of 'known' species to habitat loss, fragmentation, and disturbance, and how their geographic ranges overlap with regions exposed to stressors. In summary, we currently do not yet know how many Amazonian species are threatened.

50,000 fragments between 1-100 ha (Haddad *et al.* 2015).

The distribution of small forest fragments across the Amazon is not even; rather, fragmentation is concentrated along the southern and eastern edges of the biome, along major roads and rivers, and around urban centers (Montibeller *et al.* 2020; Vedovato *et al.* 2016). Deforestation also promotes fragment isolation, with forest patches becoming more distant from one another as well as from large contiguous forested areas (de Almeida *et al.* 2020). While fragment size affects the maintenance of viable populations of both animals and plants, fragment isolation disrupts dispersion and movement. The smaller the fragment, the smaller its chances of sustaining the original pool of forest species (Laurance *et al.* 2011; Michalski *et al.* 2007; Michalski and Peres, 2005), with large-bodied animals and those that are highly dependent on forest habitat being particularly affected (Lees and Peres 2008; Michalski and Peres 2007). Fragment isolation is more harmful to species with low vagility, which are unable to cross open, non-forest matrices (Lees and Peres 2009; Palmeirim *et al.* 2020). To date, negative impacts of fragment size and/or isolation have been detected throughout the Amazon, affecting leaf bryophytes, trees, palms, birds, carnivores, and primates (Laurance *et al.* 2011; Michalski and Peres 2007). Forest fragments also experience a whole range of edge effects, which lead to their degradation (see Section 19.4.2).

Local temperature and precipitation are also affected by deforestation. Land surface temperature is 1.05-3.06°C higher in pastures and croplands than in nearby forests, with this difference becoming more pronounced during the dry season (Maeda *et al.* 2021). Furthermore, as forest cover decreases at landscape scales, the hotter the landscape becomes, such that landscapes with a lower number of remaining forest patches can be up to 2.5°C hotter than those with greater forest cover (Silvério *et al.* 2015). Forest loss also leads to reduced precipitation (Spracklen *et al.* 2012; Werth 2002), as 25-50% of Amazonian rainfall is recycled from forests (Eltahir and Bras 1994). Therefore, forest loss accrues a decrease in rainfall, increasing the risk of large-scale forest dieback (see Chapter 22 to 24). It is estimated that deforestation has already decreased precipitation by 1.8% across the Amazon (Spracklen and Garcia-Carreras 2015), although changes in rainfall patterns vary across the basin and between the wet and dry seasons (Bagley *et al.* 2014; Costa and Pires 2010). Additionally, widespread deforestation negatively influences precipitation outside the Amazon Basin, influencing regional hydrological cycles. A modeling study suggests that 70% of precipitation in the La Plata Basin; located in Argentina, Bolivia, Brazil, Paraguay, and Uruguay; depends on moisture recycled over the Amazon (Van Der Ent *et al.* 2010).

Regionally, Amazonian deforestation has surprising and very diverse impacts, such as accelerating glacier melting in the Andes and contributing to sargassum blooms in the Caribbean. The burning of recently felled forests as part of the deforestation process (Box 19.3) releases black carbon to the atmosphere. Smoke plumes then transport black carbon to the Andes, where it can be deposited over glaciers, speeding up glacier melt. This process is highly seasonal, peaking during high-fire months (Magalhães *et al.* 2019). Thousands of kilometers away, in the Caribbean Sea, recent sargassum blooms are likely influenced by anomalous nutrient inputs into the Atlantic resulting from Amazonian deforestation (Wang *et al.* 2019). Sargassum blooms negatively impact tourism and fisheries, and cause community shifts in seagrass meadows and increased coral mortality (Tussenbroek *et al.* 2017).

At a global scale, greenhouse gas emissions are the most-pronounced impact of forest loss in the Amazon. Between 1980 and 2010, the Amazon lost an estimated 283.4 Tg C annually due to deforestation, resulting in yearly emissions of 1040.8 Tg CO_2 (Phillips *et al.* 2017). Deforestation-related emissions are not homogeneous in space or time; for example, Brazil's annual emissions from Amazonian deforestation are eight times greater than those of Bolivia, the second largest emitter in the basin between 1980 and 2010 (Table 19.1). Overall, emissions have decreased in the region, being higher in the 1980s than the 2000s (Phillips *et al.* 2017).

Table 19.1 Estimated annual carbon loss due to deforestation in the Amazon between 1980-2010 (Phillips et al., 2017).

Country	Carbon loss (Tg C year^{-1})
Bolivia	28.6
Brazil	223.9
Colombia	6.5
Ecuador	2.5
French Guiana	1
Guyana	1
Peru	17.9
Suriname	1
Venezuela	1

9.3 Main drivers of deforestation and their associated impacts

19.3.1 Agricultural expansion

Across the Amazon, deforestation has been driven mainly by agricultural expansion, particularly cattle ranching (Nepstad *et al.* 2009), because of several public policies (See Chapter 14 and 15). In the Brazilian Amazon alone, it is estimated that 80% of deforested areas are occupied by pastures (Ministério do Meio Ambiente 2018). In the early 2000s, large-scale cropland expansion, principally soy, became increasingly important as a driver of deforestation. This pattern reversed (Macedo *et al.* 2012) due to extensive conservation policies, including the soy moratorium, and the creation of a number of protected areas in the regions of Brazil where most soy-related deforestation was taking place (Nepstad *et al.* 2014; Soares-Filho *et al.* 2010). Currently, soy expansion in the Brazilian Amazon occurs mostly on areas that were previously pastures, instead of directly replacing forests (Song *et al.* 2021). In Bolivia, however, soy is still expanding; the region of Santa Cruz has been identified as the largest deforestation hotspot in the Amazon, mainly due to forest conversion to soy fields (Kalamandeen *et al.* 2018; Redo *et al.* 2011). Since the mid-2000s, palm oil has become a growing threat to Amazonian forests, especially in Colombia, Ecuador, Peru, and the eastern part of the Brazilian Amazon (Furumo and Aide, 2017). Although palm oil plantations often replace other agricultural land uses, especially cattle ranching, it has been documented directly replacing primary forests (Castiblanco *et al.* 2013; de Almeida *et al.* 2020; Gutiérrez-Vélez and DeFries 2013). For example, between 2007 and 2013, 11% of deforestation in the Peruvian Amazon was driven by oil palm plantations (Vijay *et al.* 2018). Illicit crops, more specifically coca, is also a driver of deforestation, particularly in Colombia, but also in Bolivia, Ecuador, and Peru (Armenteras *et al.* 2006; Dávalos *et al.* 2016). However, its impact on forest loss is much smaller than that caused by licit commodities (Armenteras Rodríguez *et al.* 2013). Since 2016, following the peace agreement between the Colombian government and the Revolutionary Armed Forces of Colombia (FARC), the role of coca-driven deforestation has decreased, with areas previously in conflict being deforested for pasture, including inside protected areas (Clerici *et al.* 2020; Prem *et al.* 2020).

Direct impacts

Although croplands and pastures hold some animal species, the ecological communities in these areas are dramatically different from those of forests, both in terms of taxonomic and functional composition (Barlow *et al.* 2007; Bregman *et al.* 2016); with almost all forest-dependent species being lost. Among agricultural land uses, pastures hold significantly more taxonomic diversity than areas of mechanized agriculture (e.g. soy fields) for various taxa (Solar *et al.* 2015). Tree plantations also harbor an impoverished subset of forest species. For example, in an oil palm plantation in Peru, <5% of bird species were also found in forests (Srinivas and Koh 2016). In summary, the contribution of agricultural lands to Amazonian biodiversity conservation is negligible (Moura *et al.* 2013), highlighting the irreplaceable value of forests (Barlow *et al.* 2007).

Indirect impacts

In addition to GHG emissions during the deforestation process, pastures further contribute to emissions due to regular burning (Box 19.3) and bovine enteric fermentation (Bustamante *et al.* 2012). Significant changes in the physical and chemical properties of the soil, such as soil compaction and changes in nutrient concentration (Souza Braz *et al.* 2013; Fujisaki *et al.* 2015; Melo *et al.* 2017), are also a result of forest conversion to pastures and croplands in the Amazon. Pesticide and herbicide use in agricultural systems is often excessive in the region (Bogaerts *et al.* 2017; Schiesari *et al.* 2013), but the impacts of this in terrestrial ecosystems have neither been described nor quantified.

19.3.2. Infrastructure

19.3.2.1. Roads

Major official roads and highways, i.e. those built by the government, extend deep into the Amazon; only the western part of the basin is largely road free (Figure 19.6). Official roads, even if unpaved,

Box 19.2 Fine-scale endemism in Amazonian birds reveals threats of deforestation

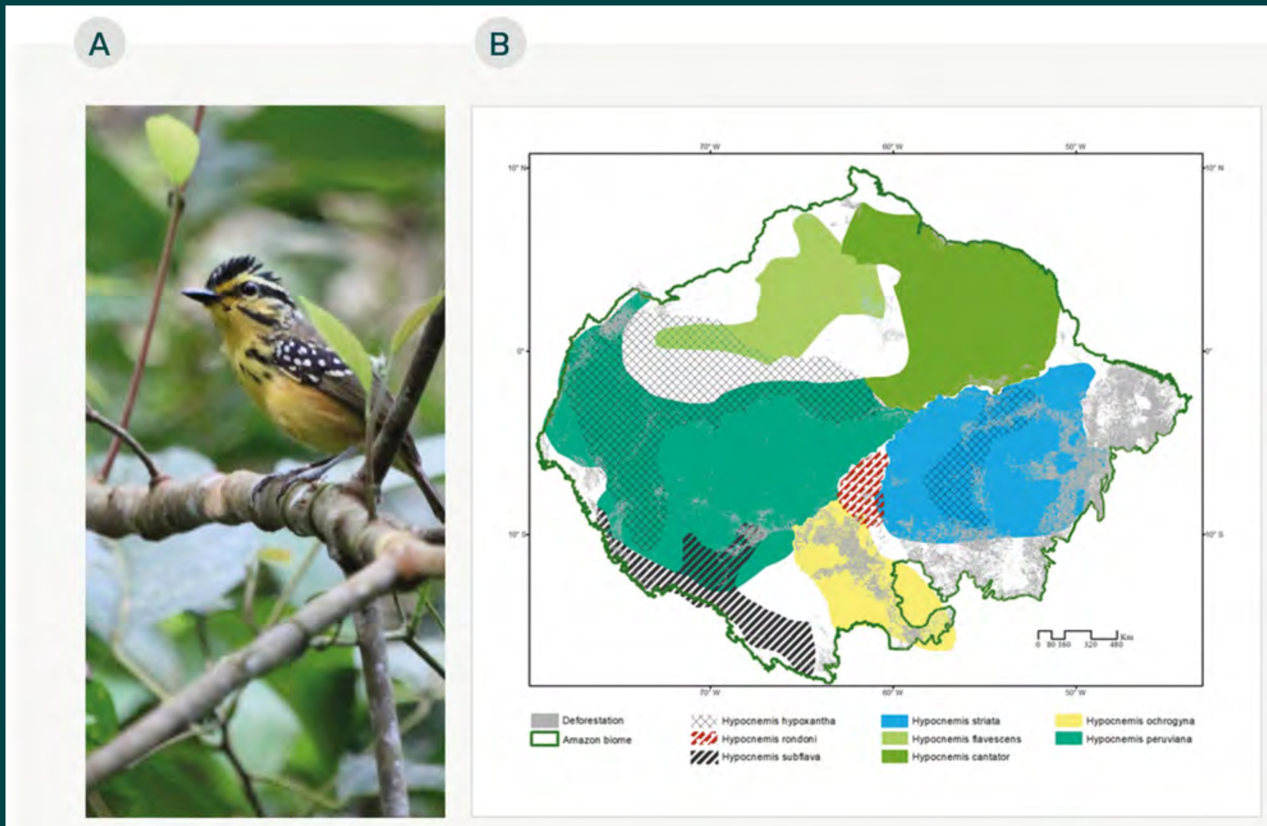


Figure 19.B2 There are two subspecies of Yellow-browed Antbird (*Hypocnemis hypoxantha*) which have disjunct Amazonian distributions. This is the eastern *ochraceiventris* subspecies and it is likely that this species will be subject to taxonomic revision in future. Photo taken in Belterra, in the Brazilian Amazon, by Alexander Lees.

Amazonian biodiversity is non-randomly distributed across the basin, with geographic discontinuities like large wide rivers conspiring alongside topoedaphic heterogeneity, climatic variation and biological interactions to delimit species ranges. Many species of vertebrate have long been recognised as being restricted to Amazonian 'areas of endemism' delimited by major rivers; with different 'replacement species' present on either side of these fluvial barriers. These areas of endemism are often viewed as planning units for conservation, including protected area designation (da Silva et al. 2005). Understanding patterns of endemism is however dependent on both how complete our biodiversity inventories are, and how refined our taxonomy of different groups is. For example, a revolution in avian taxonomy driven by the usage of molecular toolkits coupled with vocal characters has revealed previously unrecognised fine-scale cryptic diversity. This pointed towards indicated a mismeasure of Amazonian avian diversity because of a reliance on morphological characters to define species limits, characters which may be highly conserved in some lineages of rainforest birds (Fernandes 2013, Pulido-Santacruz et al. 2018). The impact of the usage of new quantitative criteria for species diagnosis has been an increase in the overall number of bird species in Amazonia and an increase in the number of threatened species – as 'splits' affecting formerly wide-ranging 'parent' species create multiple 'daughter' species with smaller range sizes. For example, a taxonomic revision of the 'Warbling Antbird' Hypocnemis cantator (Thamnophilidae) species complex by Isler et al. (2007) elevated six populations (two of which even occur in sympatry)

Box 19.2 ***continued***

- then regarded as subspecies - to species status based on vocal differences. This taxonomic decision was subsequently reinforced by molecular data (Tobias et al. 2008) and later a further member of this species complex - *Hypocnemis rondoni* was later described with a tiny range in the Aripuanã-Machado interfluve within the Rondonia area of endemism (Whitney et al. 2013). These discoveries and taxonomic rearrangements mean that several species in this complex have restricted ranges which overlap the Amazonian Arc of Deforestation and are thus threatened with global extinction – e.g. the Vulnerable *Hypocnemis ochrogyna*. Such fine-scale endemism is likely to be a common Amazonian biogeographic phenomenon which merits urgent consideration in systematic conservation planning efforts (Fernandes 2013).

often spawn networks of unofficial roads, i.e. those built by local actors, providing further access to previously inaccessible forests, resulting in the classic 'fishbone deforestation' pattern (Figure 19.5). In terms of total length, the network of unofficial roads is so extensive that it surpasses official ones (Nascimento *et al.* 2021).

Direct impacts

The impacts of roads on terrestrial wildlife in the Amazon are diverse and multi-faceted (Laurance *et al.* 2009). Their direct effects are dwarfed by their indirect impacts, but nonetheless remain important. First, roads lead to high levels of roadkill mortality. For example, over the course of 50 days of monitoring a 15.9 km stretch of road in Napo (in the western Amazon), 593 animals were killed, including reptiles, amphibians, birds, and mammals (Filius *et al.* 2020). Occasionally, roadkill includes threatened species, such as Harpy Eagles, Giant Anteaters, Giant Armadillos, Giant Otters, Red-faced Spider Monkeys, Lowland Tapirs, and Red-billed Toucans (de Freitas *et al.* 2017; Medeiros 2019). Given the approximately 40,000 km of official roads across the Amazon, roadkill is highly underreported and understudied. Second, roads can act as direct drivers of habitat fragmentation, isolating populations on either side (Lees and Peres 2009). Widths of just 12-25 m can restrict the movements of bird species adapted to the forest understory (Laurance *et al.* 2004; Laurance *et al.* 2009).

Indirect impacts

The greatest impacts of roads are indirect. The construction of official and, subsequently, unofficial roads increases land values, as it makes agriculture and ranching more profitable, since products can be transported to urban centers and ports (Perz *et al.* 2008). In turn, higher land prices lead to land speculation that motivates deforestation to secure land possession (Fearnside 2005). Roads also induce migration, leading to invasions and settlements (Mäki *et al.* 2001; Perz *et al.* 2007). As a result, the presence of roads is strongly associated with deforestation in the Brazilian (Laurance *et al.* 2002; Pfaff *et al.* 2007), Peruvian (Bax *et al.* 2016; Chávez Michaelsen *et al.* 2013; Naughton-Treves 2004), and Ecuadorian Amazon. However, in the case of Ecuador road construction is linked to oil concessions (Mena *et al.* 2006; Sierra 2000). The paving of official roads provokes direct deforestation along highways (Fearnside 2007; Asner *et al.* 2010) and induces displaced deforestation; pasturelands are often sold to be converted into more profitable croplands, such as soy, and ranchers who have sold their land move into rainforest areas to establish new ranches (Arima *et al.* 2011; Richards *et al.* 2014).

Roads also stimulate forest degradation, including selective logging (Amachar *et al.* 2009; Merry *et al.* 2009; Asner *et al.* 2006), as they provide machinery access (e.g. logging trucks, skidders) to areas that still contain valuable timber. The opposite can also be true; often loggers open small roads to extract

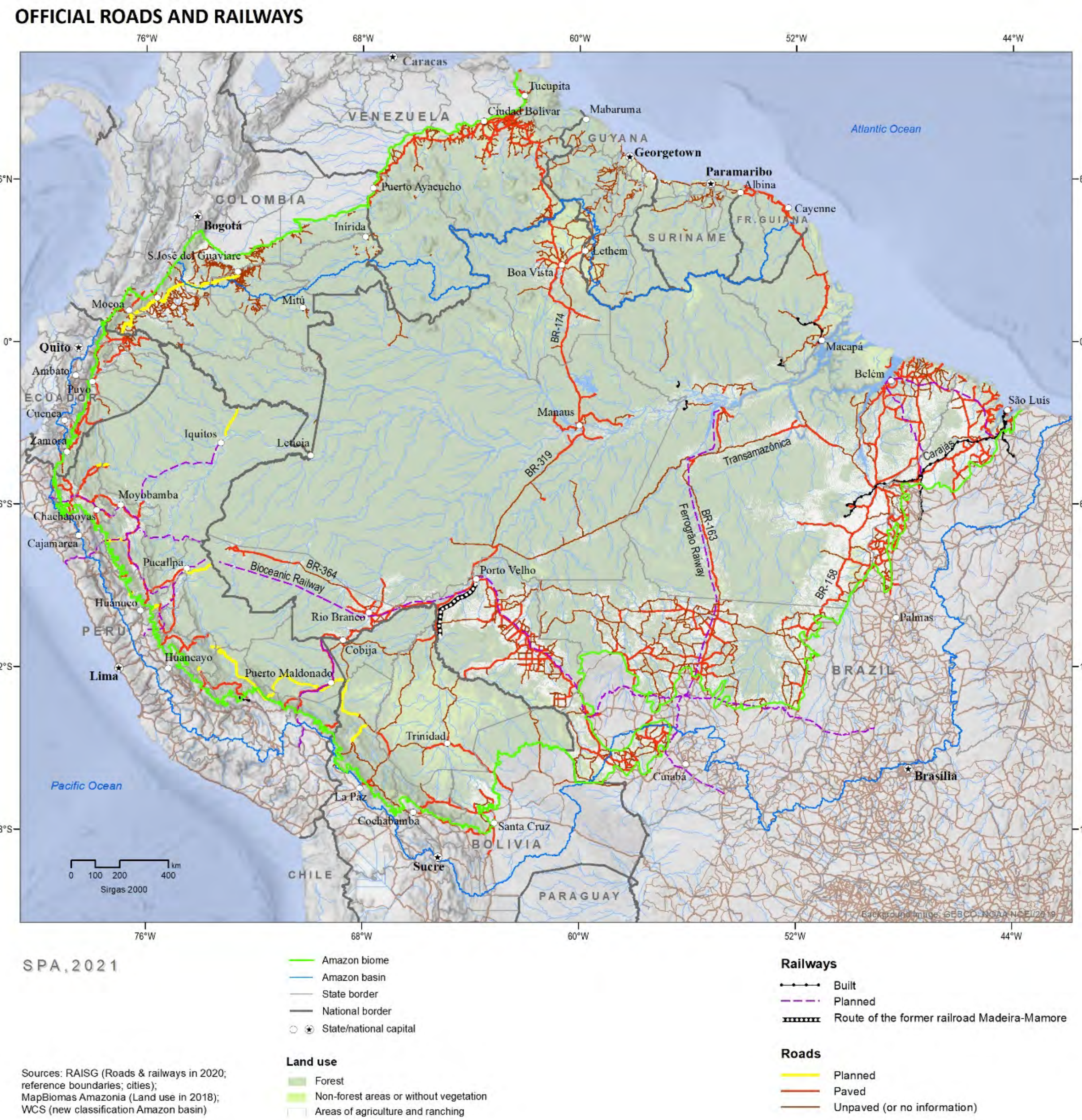


Figure 19.6 Planned (yellow), paved (red), and unpaved (brown) roads across the Amazon, as well as existing (black) and planned (purple) railways. The Amazon biome is outlined in green, while the Amazon Basin (the limit used in other chapters of this report) is outlined in blue.

Box 19.3 Fires, deforestation, and drought lead to forest degradation

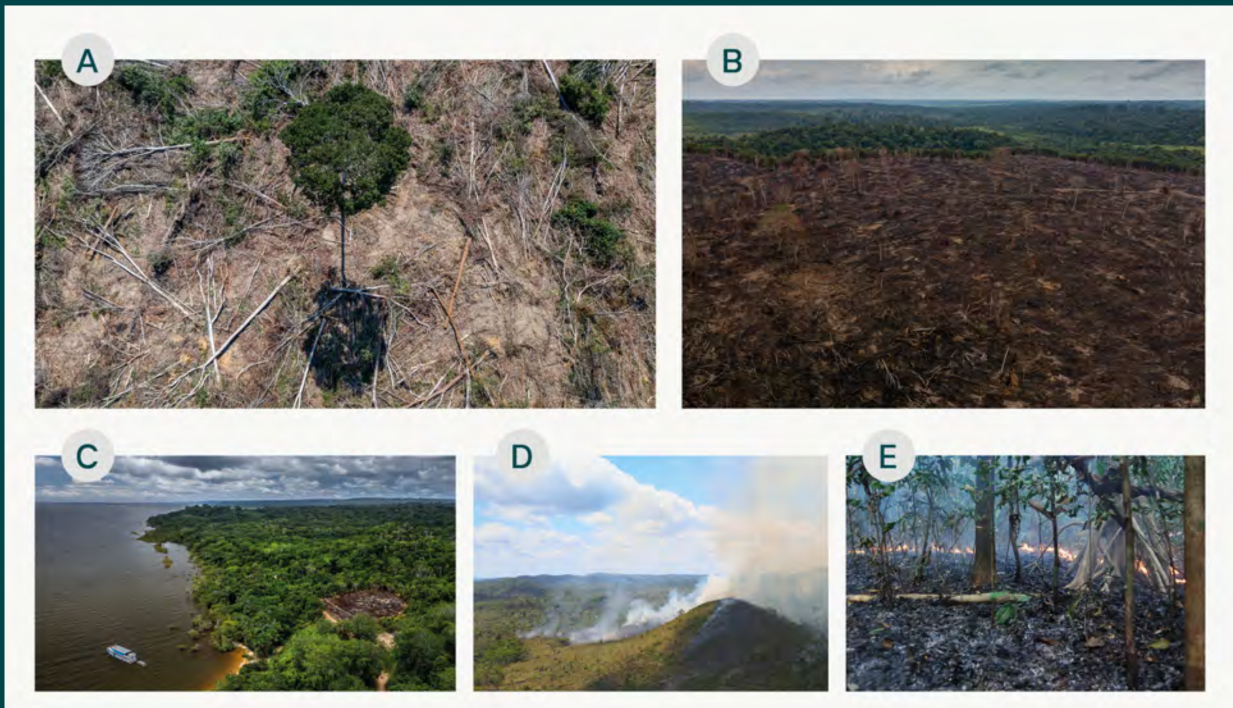


Figure 19.B3 A) An area recently deforested (Photo by Marizilda Cruppe/Rede Amazônia Sustentável; B) A large deforested area that has been recently burned (Photo by Flávio Forner/Rede Amazônia Sustentável); C) A small area deforested and burned for subsistence agriculture (Photo by Marizilda Cruppe/Rede Amazônia Sustentável; D) Fire in pastures (Photo by André Muggiati); E) Understory (Photo by Erika Berenguer).

Fires are an intrinsic part of the deforestation process in the Amazon (Barlow *et al.* 2020). First the land is cleared, and trees can be felled using a variety of methods, from chainsaws to bulldozers. Then, felled vegetation is left to dry for a period of a few weeks to a few months into the dry season. When the felled vegetation is dry, it is set on fire, transforming most of the biomass to ash. The land is then ready to be planted. Fires are also used in subsistence agriculture, which is often called slash-and-burn. Traditionally used by Indigenous Peoples and small landowners, fires are used to burn a small patch of land which has been recently deforested. After a few years of agricultural use, this area will be abandoned, and left as fallow, as the farmer rotates agricultural production to another fallow. Finally, fires are also used as a common management tool in pastures, to remove weeds and small trees and increase productivity. However, fires from deforestation, subsistence agriculture, or pastures can escape into surrounding agricultural areas, leading to economic losses as crops, fences, and buildings are burned (Cammelli *et al.* 2019). They can also escape to surrounding forests if it is a dry year, as leaf litter with <23% moisture can sustain a fire (Ray *et al.* 2005). Fires in Amazonian forests, or understory fires, tend to be of low intensity, with flame heights ranging between 10-50 cm, and slow moving, burning 300 m per day (Cochrane *et al.* 1999; Ray *et al.* 2005). Understory fires can be blocked by the canopy and hard to detect by remote sensing approaches (Pessôa *et al.* 2020). However, recent technological developments, such as the Visible Infrared Imaging Radiometer Suite (VIIRS) and the Continuous Degradation Detection (CODED) have been fundamental in mapping understory fires across the Amazon, thus helping to reveal the true extent of fires and overall forest degradation (Bullock *et al.* 2020; Oliva and Schroeder 2015; Schroeder *et al.* 2014).

target trees (Gutierrez-Velez and MacDicken 2008; Johns *et al.* 1996; Uhl and Vieira 1989), which can then drive additional degradation. Proximity to roads is also highly correlated with forest fires, even in non-drought years (Alencar *et al.* 2004). This is due to the influx of migrants and agricultural expansion surrounding roads (Figure 19.5), thus resulting in more deforestation and pasture-related fires, which can escape into forested areas (Box 19.3).

19.3.2.2 Hydropower dams

Substantial energy resources exist in the Amazon, some actively exploited and others as potential reserves (Ferreira *et al.* 2014). There are currently 307 hydropower dams either in operation or under construction, with proposals for at least 239 more (Figure 19.7). Of these, some are considered mega-dams, of >1 GW capacity. Hydroelectric dams not only disrupt aquatic ecosystems (Chapter 20), they also have severe consequences for terrestrial ones.

Direct impacts

Most hydropower dams require an area to be flooded, acting as a reservoir. Both floodplain (*várzea*) and upland (*terra firme*) forests are killed by reservoir flooding (Lees *et al.* 2016), resulting in high levels of CO_2 and CH_4 emissions due to the decomposition of submerged trees (Figure 19.8; see Chapter 20). Although seasonally flooded forests can survive several months under water, they die if flooded year-round. Forests bordering the reservoir also suffer stress, including reductions in the rates of photosynthesis of trees (dos Santos Junior *et al.* 2015). Depending on local topography, islands containing upland forests can be formed after flooding. Newly-formed islands suffer from edge effects and fragmentation, as they have been cut off from the rest of the previously contiguous forest. Reservoir islands have significantly different species composition of both fauna and flora than adjacent mainland areas (Tourinho 2020, Benchimol and Peres 2015), a pattern particularly pronounced on small islands, where large-bodied fauna become extinct (Benchimol and Peres 2020). Invertebrates are also negatively impacted by flooding; one study found that thirty years after the reservoir was filled, several islands completely lacked dung beetle species (Storck-Tonon *et al.* 2020). Dams also affect forests downstream; altered flood regimes can even impact forests 125 km away from the reservoir (Schongart *et al.* 2021), resulting in large-scale tree mortality (Assahira *et al.* 2017), leading to the loss of crucial habitat for a variety of organisms (e.g. arboreal mammals, birds, and plants) which can become locally extinct (Lees *et al.* 2016). Finally, dams can also affect the status of protected areas; for example, the planned São Luiz do Tapajós Dam resulted in part of Amazonia National Park being degazetted in Brazil (Fearnside 2015a).

Indirect impacts

The construction of hydroelectric dams also leads to indirect impacts; for example, the population attracted to the region boosts deforestation in the area surrounding the dam (Jiang *et al.* 2018; Velastegui-Montoya *et al.* 2020). Furthermore, dam construction often results in socio-economic problems, such as increases in violence and lawlessness, and the displacement and destruction of the livelihoods of both Indigenous and non-Indigenous communities (Athayde *et al.* 2019; Castro-Diaz *et al.* 2018; Moran 2020; Randell 2017).

19.3.2.3 Urbanization

Approximately 70% of Amazonians live in urban centers (Padoch, C. *et al.* 2008; Parry *et al.* 2014), with the largest city, Manaus, hosting >2.2 million inhabitants (IBGE 2021). Urban expansion is currently concentrated in small and medium cities (Richards and VanWey 2015; Tritsch and Le Tourneau 2016) and results from various processes, from rural-urban and urban-urban migration to displacement due to armed conflict and intrinsic population growth (Camargo *et al.* 2020; Perz *et al.* 2010; Randell and VanWey 2014; Rudel *et al.* 2002). See Chapter 14 for more details on historical migration to Amazonian cities.

Figure 19.7 Planned and active hydropower dams and waterways across the Amazon biome. The Amazon biome is outlined in green, while the Amazonian Basin (used in other chapters in this report) is outlined in blue. Sources: WCS Venticinque 2016; RAISG 2020.

Figure 19.8 Flooding of the reservoir of the Balbina dam in Brazil. a) Before (1986) and b) after (2020) the flooding. Source Google Earth.

Direct impacts

Urban and suburban sprawl increase deforestation (Jorge *et al.* 2020), especially in frontier settlements. Amazonian urban biodiversity is poorly studied, but is generally taxonomically depauperate and typically dominated by a small subset of common species found in secondary habitats (Lees and Moura 2017; Rico-Silva *et al.* 2021). As observed elsewhere, urbanization also influences the local climate, which becomes hotter (de Oliveira *et al.* 2020; Souza *et al.* 2016).

Indirect impacts

Many rural-urban migrants continue to consume forest resources, therefore playing a role in forest-use decisions (Chaves *et al.* 2021; Padoch, C. *et al.* 2008). For example, surveys of two Amazonian cities on the Madeira River showed that 79% of urban households consumed bushmeat, including terrestrial mammals and birds (Parry *et al.* 2014).

Animals hunted for urban consumption can be-sourced from forests located up to 800 kilometers away and frequently include threatened species, such as Black Curassow, Giant Armadillo, Gray Tinamou, Red-faced Spider Monkey, Lowland Tapir, Red-billed Toucan, and White-lipped Peccary (Bodmer and Lozano 2001; Bizri *et al.* 2020; IUCN 2021; Parry *et al.* 2010, 2014).

19.3.2.4 Railways and waterways

Across the Amazon, the density of railways and waterways is much lower than that of roads (Figures 19.6 and 19.7). As a result, there are few studies on the impacts of these forms of infrastructure on terrestrial ecosystems (See Chapter 20 for impacts of waterways on aquatic ecosystems).

Direct impacts

Opening railways in the Amazon results in deforestation and fragmentation of the forest that is cut by the rail line, impacting the movement of animals that cannot cross even narrow clearings (Laurance *et al.* 2009). There is currently no published investigation into the direct impacts of waterways on Amazonian forests.

Indirect impacts

The limited movement of passengers along railways mean that levels of adjacent deforestation are far lower relative to roads. However, railways can still indirectly induce deforestation. For example, between 1984 and 2014, approximately 30,000 km^2 of forests were lost in the area of influence of the Carajás Railway in the Brazilian Amazon (Santos *et al.* 2020). However, some of these impacts are hard to disentangle from that of roads built near some of the railway stations.

Railways present important risks for the future of the Amazon. The "Ferro Grão" Railway, also located in the Brazilian Amazon, would link soy areas in Mato Grosso (the southern Amazon) to the port in Miritituba on the lower Tapajós River, with access to the Amazon River (Figure 19.6). The lower freight costs of Mato Grosso's soy transported by the Ferro Grão Railway can be expected to contribute to the conversion of pasture to soybeans, possible leading to displaced deforestation, as seen elsewhere when roads were paved (Fearnside and Figureido 2016). Another proposed railway would connect Mato Grosso to the port of Bayóvar in the Peruvian state of Piura (Dourojeanni 2015). This railway, known as the "Railway to the Pacific" in Peru, could also contribute to soy expansion and displaced deforestation in Brazil. The same pattern of displaced deforestation is expected as a result of the proposed Tapajós and Tocantins waterways, which would stimulate pasture conversion to large croplands (Fearnside 2001).

19.3.3. Mining

19.3.3.1 Minerals

Mining is a major source of environmental impacts in the Amazon, with 45,065 mining concessions either under operation or waiting for approval, of which 21,536 overlap with protected areas and

Indigenous lands (Figure 19.9). While some minerals; such as bauxite, copper, and iron ore (Souza-Filho *et al.* 2021); are extracted through legal operations conducted by large corporations (Sonter *et al.* 2017), gold mining is largely illegal (Asner and Tupayachi 2017; Sousa *et al.* 2011). Despite its illegality, gold mining has become far from artisanal, and is now a semi-mechanized activity, employing large and expensive machinery such as prospecting drills and hydraulic excavators (Massaro and de Theije 2018; Springer *et al.* 2020; Tedesco 2013).

Direct impacts

Overall, the extent of mining-driven deforestation is far smaller than that caused by agricultural expansion (see Section 19.3.1). However, it still represents the main driver of forest loss in French Guiana, Guyana, Suriname and parts of Peru (Dezécache *et al.* 2017; Caballero-Espejo *et al.* 2018). For example, in Guyana, mining led to the loss of c. 89,000 ha of forests between 1990 and 2019, an area 18 times larger than that lost to agricultural expansion in the same period (Guyana Forestry Comission 2020). In Suriname, 71% of deforestation is attributed to mining (The Republic of Suriname 2019). In the southeastern Peruvian Amazon, approximately 96,000 ha were deforested due to mining between 1985 and 2017 (Caballero-Espejo *et al.* 2018), including areas inside the Tambopata National Reserve and its buffer zone (Asner and Tupayachi 2017). In a single year, deforestation due to gold mining in the Madre de Dios region resulted in the direct loss of c. 1.12 Tg C (Csillik and Asner 2020).

Another direct impact of mining is the potential biodiversity loss in one of the Amazon's smallest ecosystems, the cangas. This is a ferruginous savanna-like ecosystem associated with ironstone outcrops in the eastern Amazon (Skirycz *et al.* 2014). It originally occupied an area of 144 km^2, but 20% of this area has been lost to mining of iron ore (Souza-Filho *et al.* 2019). Despite the small area occupied, the Amazonian cangas has 38 endemic vascular plants, 24 of which are considered rare (Giulietti *et al.* 2019). The cangas is also rich in endemic cave-dwelling fauna (Giupponi and Miranda 2016; Jaffé *et al.* 2018). Little is known about the impacts of mining in this unique ecosystem. The direct and indirect impacts of mining on aquatic ecosystems and human wellbeing are addressed in Chapters 20 and 21, respectively.

Indirect impacts

Indirect impacts of mining activities are often greater than direct ones. In Brazil, for instance, mining was responsible for the loss of 11,670 km^2 of Amazonian forests between 2000 and 2015, corresponding to 9% of all deforestation in that period (Sonter *et al.* 2017), with effects extending 70 km beyond the boundaries of mining concessions. Mining also stimulates forest loss by motivating the construction of roads and other transportation infrastructure that leads to high levels of human migration and consequent deforestation (Fearnside 2019; Sonter *et al.* 2017). The Carajás Railway, in the Brazilian Amazon, is an example of this (see Section 19.3.2.4). Finally, mining can lead to increased logging and deforestation for charcoal production, especially to be used in pig iron production (Sonter *et al.* 2015).

19.3.3.2 Oil and gas

Oil and gas exploitation occur mainly in the western Amazon, where exploitation of crude oil started in the 1940s, and grew substantially from the 1970s onwards (Finer *et al.* 2009; San Sebastián and Hurtig 2004). Currently, 192 oil and gas leases are under production and 33 are being prospected; some of these overlap with protected areas and Indigenous lands (Figure 19.10).

Direct impacts

Major threats from hydrocarbon development include deforestation and oil spills, as has occurred on numerous occasions in Colombia, Ecuador, and Peru (Cardona 2020; San Sebastian and Hurtig 2004; Vargas-Cuentas and Gonzalez 2019). For example, in the northeastern Ecuadorian Amazon, 464 oil spills occurred between 2001 and 2011,

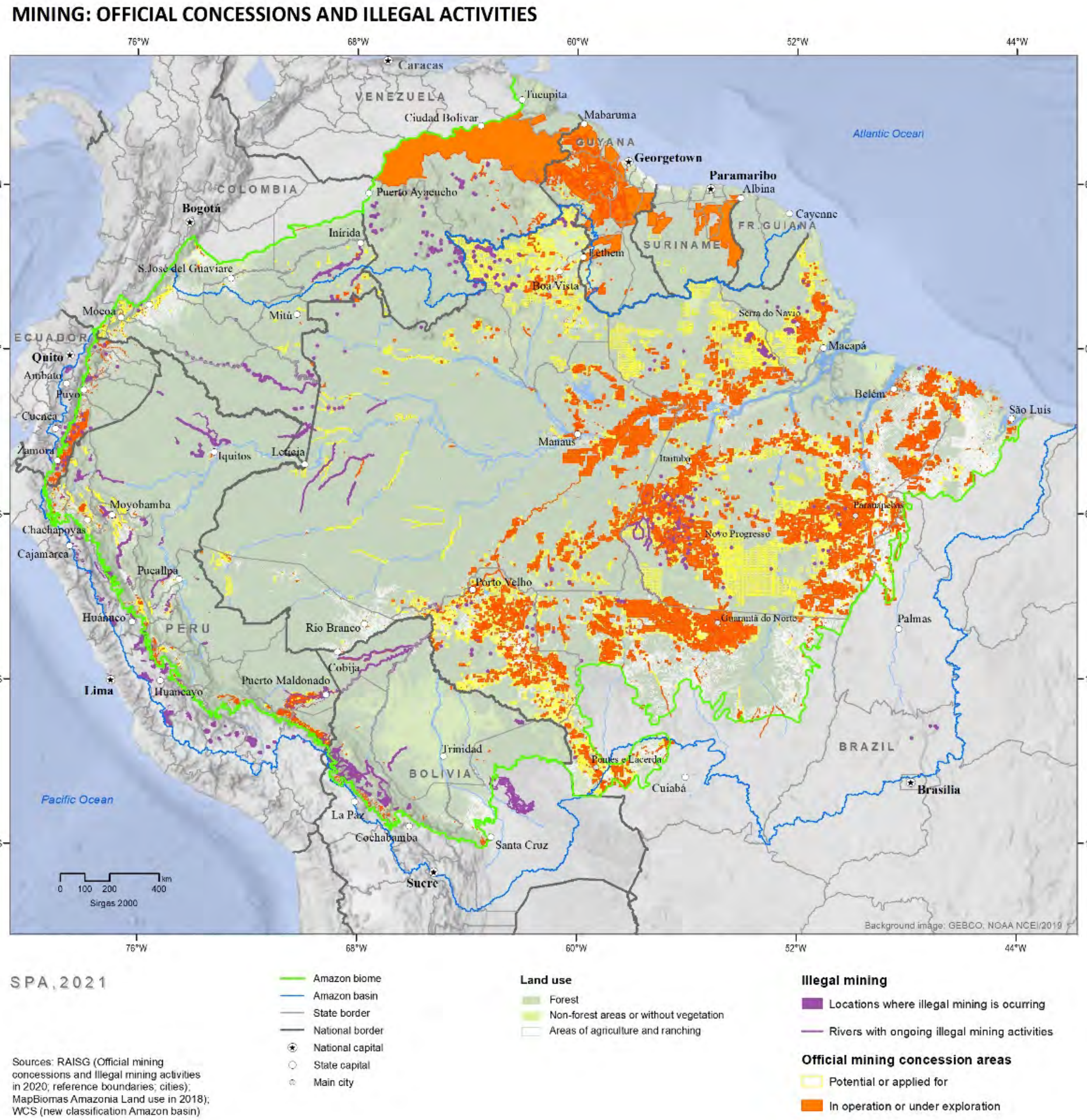


Figure 19.9 Illegal (purple) and legal mining that is either planned (yellow) or under production (orange) across the Amazon. The Amazon biome is outlined in green, while the Amazon Basin (used in other chapters) is outlined in blue. Sources: WCS-Venticinque 2016; RAISG 2020.

Figure 19.10 Oil and gas leases across the Amazon. The Amazon biome is outlined in green, while the Amazonian Basin (used in other chapters in this report) is outlined in blue. Sources: WCS-Venticinque 2016; RAISG 2020.

totaling 10,000 metric tons of crude oil released into the environment (Durango-Cordero *et al.* 2018). This corresponds to approximately 25% of the amount leaked in the Exxon Valdez oil spill. However, the number of oil spills across the Amazon is largely underestimated (Orta-Martínez *et al.* 2007). The impacts of oil spills on terrestrial ecosystems remain poorly understood. Nevertheless, it has been reported that Lowland Tapirs, Pacas, Collared Peccaries, and Red-brocket Deer consume soil and water contaminated by oil spilled from oil tanks and abandoned wells (Orta-Martínez *et al.* 2018). It is unclear how this consumption may affect animal populations.

Indirect impacts

As is the case of mineral exploitation, indirect effects of oil and gas exploitation on terrestrial ecosystems dwarf direct ones. The construction of a large road network to access oil fields has led to colonization of previously remote areas, especially in Ecuador, resulting in increased deforestation (Bilsborrow *et al.* 2004). Animal populations around these roads are negatively affected (Zapata-Ríos *et al.* 2006), with large and medium-sized mammals and game birds declining by 80% (Suárez *et al.* 2013). Some of these roads penetrate protected areas and Indigenous lands, where they have led to deforestation, habitat fragmentation, logging, overhunting, vehicle-wildlife collision, and soil erosion (Finer *et al.* 2009).

19.4 Degradation: An overview of direct drivers and impacts

Forest degradation is defined as the reduction of the overall capacity of a forest to supply goods and services (Parrotta *et al.* 2012), representing a loss in ecological value of the area affected (Putz and Redford 2010). While deforestation is binary (i.e. either the forest is present or absent), forest degradation is characterized by an impact gradient, ranging from forests with little, although significant, loss of ecological value, to those suffering with severe disruption to ecosystem functions and processes (Barreto *et al.* 2021; Berenguer *et al.* 2014; Longo *et al.* 2020). In total, c. 1 million km^2 of Amazonian forests were degraded by 2017 (Figure 19.11), equivalent to 17% of the biome, mostly in Brazil (Bullock, Woodcock, Souza, *et al.* 2020). These degraded forests are a persistent part of the landscape, as only 14% of them were later deforested (Bullock, Woodcock, Souza, *et al.* 2020).

Several anthropogenic disturbances act as direct drivers of forest degradation in the Amazon (Figure 19.12), such as understory fires, selective logging, edge effects, hunting, and climate change (Andrade *et al.* 2017; Barlow *et al.* 2016; Bustamante *et al.* 2016; Phillips *et al.* 2017). A forest can be degraded by the occurrence of a single or multiple disturbances (Michalski and Peres 2017; Nepstad *et al.* 1999). For example, a forest fragment experiencing edge effects may also be logged and/or burned (Figure 19.13). Between 1995 and 2017, 29% of degraded forests across the biome experienced multiple disturbances (Bullock, Woodcock, Souza, *et al.* 2020). Furthermore, climate change is an omnipresent driver of degradation, affecting all Amazonian forests, whether already degraded or not (see Chapter 24).

A disturbed Amazonian forest can be characterized as degraded due to significant changes in its structure, microclimate, and biodiversity, all of which impact ecosystem functions and processes. For example, understory fires, selective logging, and edge effects can lead to elevated tree mortality, increased liana dominance, greater presence of canopy gaps, decrease in forest basal area and carbon stocks, changes in stem density, and a decrease in the presence of large trees, accompanied by an increase in the occurrence of small-diameter individuals (Alencar *et al.* 2015; Balch *et al.* 2011; Barlow and Peres 2008; Berenguer *et al.* 2014; Brando *et al.* 2014; Laurance *et al.* 2006, 2011; Pereira *et al.* 2002; Schulze and Zweede 2006; Silva *et al.* 2018; Uhl and Vieira 1989). These structural changes can result in significantly higher light intensity, temperature, wind exposure, and vapor pressure deficit, as well as lower air and soil humidity (Balch *et al.* 2008; Kapos 1989; Laurance *et al.* 2011; Mollinari *et al.* 2019). These abiotic and bi-

Figure 19.11 Forests degraded (red). and deforested (White) across the Amazon Basin The Amazon biome is outlined in green, while the Amazonian limits used in other chapters in this report is outlined in blue. Sources: Bullock, Woodcock, Souza, et al., 2020; Mapbiomas 2020.

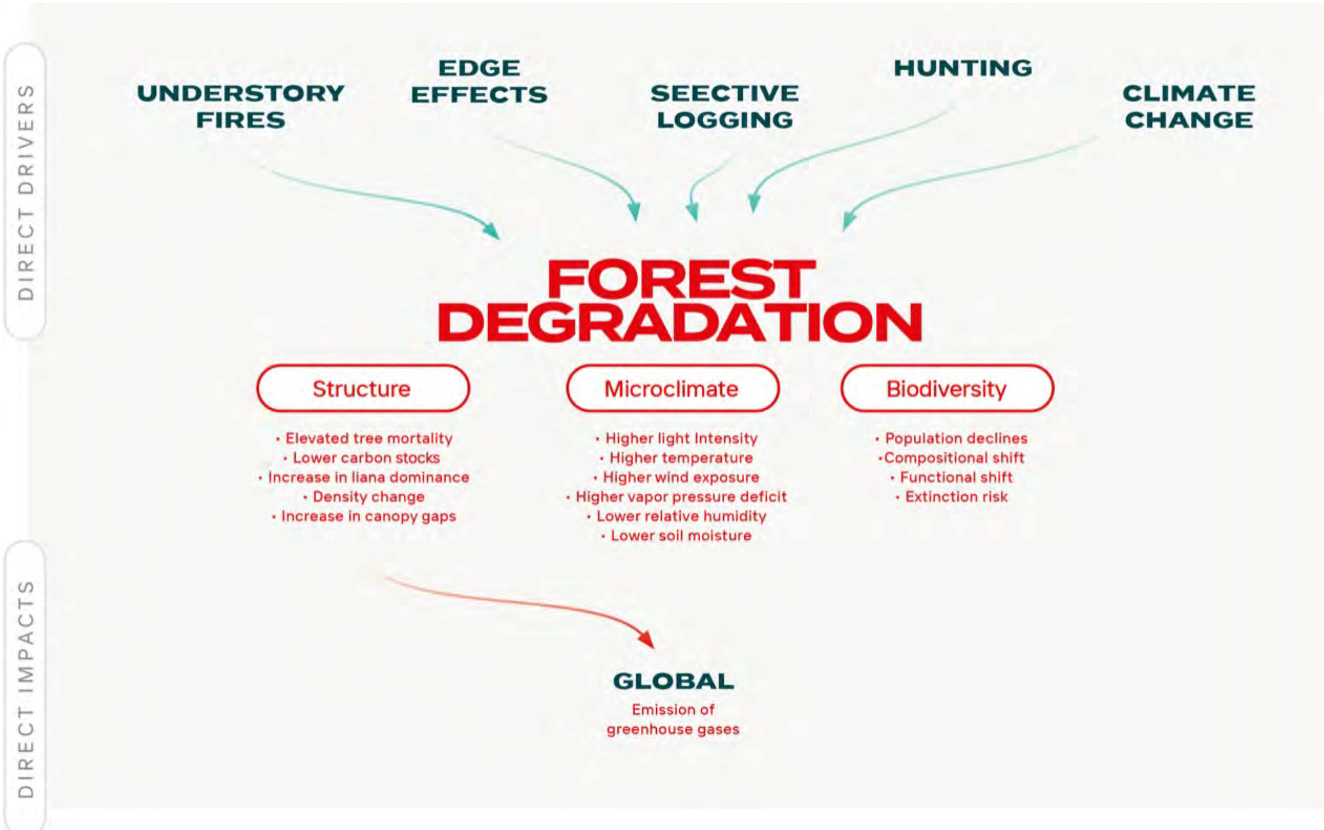


Figure 19.12 Direct drivers of forest degradation in Amazonia as well as their direct impacts at the local and global scales.

otic changes affect biodiversity, which is further impacted by hunting. Communities of both fauna and flora will experience compositional and functional shifts, with some species declining severely, leading to local extinctions (Barlow *et al.* 2016; de Andrade *et al* 2014; Miranda *et al.* 2020; Paolucci *et al.* 2016; Zapata-Ríos *et al.* 2009). The duration of the impacts of anthropogenic disturbances on Amazonian forests varies depending on the nature, frequency, and intensity of the disturbance; while logged forests may return to baseline carbon stocks within a few decades (Rutishauser *et al.* 2015), burned forests may never recover their original stocks (Silva *et al.* 2018). Recovery of degraded forests is also dependent on their landscape context, i.e. whether there are forests nearby that can act as sources of seeds and animals, thus speeding up recovery.

There is a large gap in our understanding of the regional impacts of forest degradation; a knowledge gap with an urgent need to be filled. Globally, the main impact of forest degradation is an increase in greenhouse gas emissions due to carbon loss (Aguiar *et al.* 2016). It is estimated that CO_2 emissions resulting from forest degradation already surpasses those from deforestation (Baccini *et al.* 2017; Qin *et al.* 2021).

19.4.1 Understory fires

In most years, and in most undisturbed forests, the high moisture load in the understory of Amazonian primary forests keeps flammability levels close to zero (Nepstad *et al.* 2004, Ray *et al.* 2005, 2010). However, thousands of hectares of forests burn across the basin every year (Aragão *et al.* 2018; Withey *et al.* 2018). These understory fires, also called forest fires or wildfires, spread slowly, have flame heights of 10-50 cm, and release little energy

Figure 19.13 A small forest fragment, surrounded by soy fields, which has been selectively logged and then burned during the 2015 El Niño, in Belterra, Brazil. Photo: Marizilda Cruppe/Rede Amazônia Sustentável.

(≤250 kW/m) (Brando *et al.* 2014, Cochrane 2003). However, their impacts can be enormous as Amazonian forests have not co-evolved with fires.

Direct impacts

Understory fires cause important long-term ecological impacts. They cause high levels of stem mortality, negatively affecting carbon stocks (Barlow *et al.* 2003; Berenguer *et al.* 2014; Brando *et al.* 2019), and forests take many years to recover. One study conducted across the Amazon estimated that burned forests have carbon stocks that are 25% lower than expected 30 years after fires, with growth and mortality dynamics suggesting recovery had plateaued (Silva *et al.* 2018). Fire impacts also vary regionally. Mortality rates tend to be lower in forests in the drier regions of the Amazon, potentially reflecting regional variation in bark thickness (Staver *et al.* 2020). Impacts are much higher in flooded forests than in *terra firme* (Box 19.4). In the south of the basin, in the ecotone between the Amazon and the Cerrado, native and exotic grass species have been observed to invade burned forests (Silvério 2013); a pattern not recorded elsewhere in the region. In the southwest of the basin, burned forests have experienced an increase in dominance by native bamboo species (Silva *et al.* 2021). Both grass and bamboo invasion significantly increase the flammability of these already burned forests (Dalagnol *et al.* 2018; Silverio *et al.* 2013).

High tree mortality caused by understory fires leads to significant taxonomic and functional changes in the plant community, which loses high-wood density climax species and sees a dominance of light-wood pioneer ones (Barlow *et al.* 2012; Berenguer *et al.* 2018). It is currently unknown whether burned forests will eventually return to their original plant community composition. Due to changes in forest structure and in the abundance of fruiting trees, fauna is also impacted by understory fires. For example, fires extirpate many forest specialist birds and mammals, while favoring species that occur in forest edges and secondary forests (Barlow and Peres 2004, 2006). Additionally, understory fires negatively affect the abundance of several orders of leaf-litter invertebrates, such as Coleoptera, Collembola, Dermaptera, Diptera, Formicidae, Isoptera, Hemiptera, and Orthoptera (França *et al.* 2020; Silveira *et al.* 2010). These changes are long-lasting even in continuous forests where there should be no barriers to recolonization (Mestre *et al.* 2013). All these direct impacts of a young secondary forest, with an open canopy and few large trees (Barlow and Peres 2008).

Future of fires and their impacts

Interactions between climate and land-use change across the Amazon can create the conditions needed for more widespread and intense fires (Malhi *et al.* 2008, de Faria *et al.* 2017, Brando *et al.* 2019). As the climate changes, we expect to observe increased frequency of extreme weather events and warmer climatic conditions (Le Page *et al.* 2017, de Faria *et al.* 2017, Fonseca *et al.* 2019). At the same time, deforestation continues to promote forest fragmentation and associated edge effects are much greater in forests that have burned multiple times, in which structure resembles more that (Alencar *et al.* 2006, Armenteras *et al.* 2017). In some regions of the Amazon, we can already observe how interactions among such factors have contributed to larger and more frequent

Box 19.4 Wildfire impacts on floodplain forests

Although Amazonian floodplain forests are inundated for several months every year, they are remarkably flammable when compared to *terra firme* forests, particularly in black-water rivers (Flores *et al.* 2014, 2017; Resende et al. 2014; Nogueira et al. 2019). Because of flooding, the forest litter takes longer to decompose and accumulates, forming a root mat (fine roots and humus) on the topsoil that can spread smoldering fires during extreme drought events (dos Santos and Nelson 2013, Flores et al. 2014). Compared to *terra firme* forests, the understory of floodplain forests is also slightly more open, allowing fuel to dry faster (Almeida et al. 2016). As a result, when wildfires spread, they can be intense, killing up to 90% of all trees by their root systems (Flores et al. 2014; Resende et al. 2014). After a single fire, forests can still recover slowly, but remain vulnerable to recurrent fires for decades. Along the middle Rio Negro, for instance, half of all burned forests were affected by another fire, which caused them to become trapped in an open vegetation state (Flores et al. 2016). Recent evidence reveals that after a first fire, the topsoil of floodplain forests begins to lose nutrients and fine sediments and gain sand. At the same time, tree composition shifts, with species typical of white-sand savannas becoming dominant, together with native herbaceous plants. In only 40 years, forests on clay soil are replaced by white-sand savannas due to repeated wildfires (Flores *et al.* 2021). Floodplain forests are therefore fragile and flammable ecosystems, and because they are widespread throughout the Amazon, they may potentially spread fires across remote regions (Flores et al. 2017) that could accelerate large scale tipping points (see Chapter 24). Plans to manage fire in the Amazon must take into account the existence of these flammable floodplain ecosystems, to prevent fires from spreading when the next major drought occurs.

understory fires that have burned close to 85,000 km^2 of primary forests in the southern Amazon during the 2000s (Morton *et al.* 2013, Aragão *et al.* 2018). As changes in climate and land use continue in the near future, they may trigger fires burning even larger areas (Le Page *et al.* 2017, Brando *et al.* 2020). Consequently, fires could become the main source of carbon emissions in the Amazon, surpassing those associated with deforestation (Aragão *et al.* 2018, Brando *et al.* 2020).

A major cause for concern is that the current transformations in forests caused by climate and land-use change will not only burn large areas, but also kill more trees than they currently do. In the southeast Amazon, for an increase of 100 kW/m in fire line intensity, tree mortality increased by 10% (Brando *et al.* 2014). With more edges and drier climatic conditions, we expect fire line intensity to greatly increase, potentially causing the mortality of many more trees, and subsequently resulting in even more CO_2 emissions. In addition, some projections point to a potential expansion of fire geography to historically wetter areas, a likely effect of the combination of climate and land-use change.

19.4.2 Edge effects

Between 2001 and 2015, around 180,000 km^2 of forest edges were created in the Amazon (Silva Junior *et al.* 2020). The resulting proliferation in edge habitat, often with no habitat 'core', is ubiquitous in farm-frontier landscapes in the Brazilian (Broadbent *et al.* 2008; Fearnside 2005; Numata *et al.* 2017; C. H. L. Silva *et al.* 2018), Bolivian (Paneque-Gálvez *et al.* 2013), Colombian, Ecuadorian, and Peruvian Amazon (Armenteras and Barreto *et al.* 2017).

Direct impacts

At local scales, increases in light intensity, air temperature, vapor pressure deficit, and wind exposure, accompanied by decreases in air humidity and soil moisture, result in desiccation around edges (Broadbent *et al.* 2008; Kapos 1989; Laurance *et al.* 2018), which may extend hundreds of meters into adjacent forests (Briant *et al.* 2010). This change in microclimate contributes to elevated tree mortality, which in turn lead to biomass collapses, especially within the first 100 m of a forest edge (Laurance *et al.* 1997; Numata *et al.* 2011). Across the Amazon, 947 Tg C were lost between 2001 and 2015 due to edge effects, representing a third of the losses from deforestation in the same period (Silva Junior *et al.* 2020). Carbon losses are not offset by tree growth or recruitment; forest edges suffer a drastic change in species composition, becoming dominated by lianas and trees of smaller size and with lower wood density, which store less carbon (Laurance *et al.* 2006; Michalski *et al.* 2007). Ultimately, the proliferation of pioneer trees causes forests close to edges to present higher tree densities than those further away (Laurance *et al.* 2011).

It is not only the flora that is directly impacted by edge effects; both vertebrate and invertebrate fauna also experience considerable compositional and functional shifts, with some species thriving while others decline (Bitencourt *et al.* 2020; Santos-Filho *et al.* 2012). Overall, generalist species are favored by edge habitats, while specialists become restricted to the forest core. This may lead to local extinctions of specialist species unable to adapt to new disturbed conditions, favoring edge and gap specialist species or even facilitating colonization and range expansion for non-forest species (Palmeirim *et al.* 2020; Mahood, Lees and Peres 2012; Rutt *et al.* 2019). For example, ungulates avoid forest edges, while rodents have similar abundances in forest edges or cores (Norris *et al.* 2008). Among invertebrates, a striking example is that of leaf-cutting ants; within the first 50 m of a forest edge, the density of colonies increases almost 20-fold when compared to the interior of the forest (Dohm *et al.* 2011).

Indirect impacts

Forest edges are more susceptible to other types of disturbance (Brando *et al.* 2019), especially understory fires (Armenteras, González, *et al.* 2013; Devisscher *et al.* 2016; C. H. L. Silva *et al.* 2018). This is mediated by changes in the structure and composition of the vegetation, in addition to the microclimatic alterations that occur when an edge is created (Cochrane 2003), which are exacerbated by climate change (Cochrane and Laurance 2008; Cochrane and Barber 2009). Fragmented forest regions in the basin experience a higher frequency of forest fires, including Bolivia (Maillard *et al.* 2020), Brazil (Silva *et al.* 2018; S. S. da Silva *et al.* 2018; Silvério *et al.* 2018), and Colombia (Armenteras, Barreto, *et al.* 2017; Armenteras, González, *et al.* 2013)

19.4.3 Logging

Timber production through selective logging is one of the most important activities in tropical forest areas (Edwards *et al.* 2014). The Pan-Amazonian countries represent 13% of the tropical sawnwood production, where Brazil alone is responsible for more than half (52%) of the production followed by Ecuador (11%), Peru (10%), and Bolivia (10%). Venezuela, Colombia, Suriname, and Guyana represent the remaining 17% (ITTO 2020) (Figure 19.14). The extent of logging activities in Amazonian countries is also large. In the Brazilian Amazon, selective logging affects an area as large as that deforested annually (Asner *et al.* 2005, 2009; Matricardi *et al.* 2020), concentrated mostly along the deforestation frontier and surrounding major logging centers (SFB and IMAZON 2010). Selective logging is the second most common driver of forest degradation in the Brazilian Amazon, behind only edge effects (Matricardi *et al.* 2020).

Direct impacts

The illegality of logging in the countries of the Amazon Basin is commonly associated with conventional logging practices, which differ from reduced-impact logging (RIL). Conventional logging extracts a higher amount of timber per hectare (e.g. volume and number of species) and does not follow a coherent infrastructure extraction plan which would allow less impact for future harvest (i.e. less roads and logging decks) (Lima *et al.* 2020; Sist and Ferreira 2007). Conventional logging practices increase soil compaction from unplanned skid trails (DeArmond *et al.* 2019), and have a larger impact on

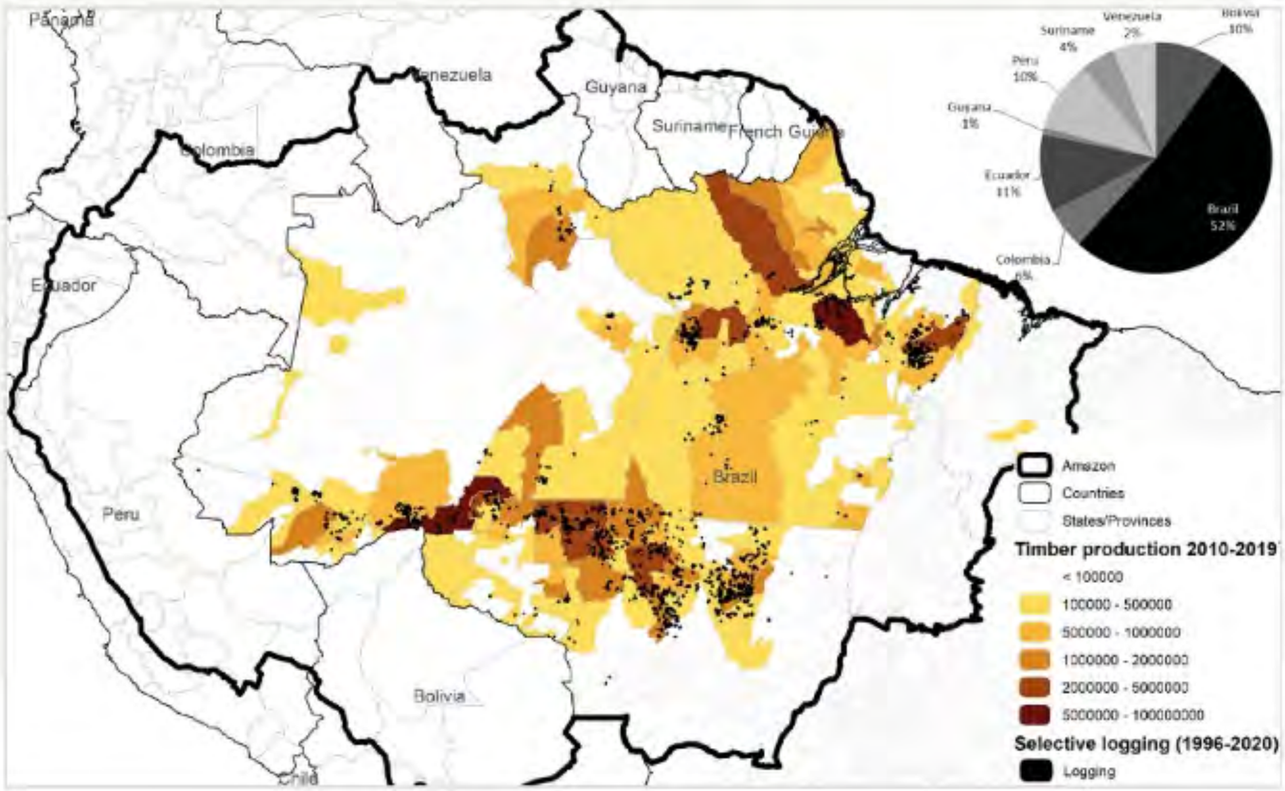


Figure 19.14 Selective logging across Amazonia. Pie chart – distribution of timber production in Amazonian countries (ITTO 2021). Map - legal timber production by Brazilian municipality from 2010 to 2019 (IBGE 2020).

reducing carbon stocks (Sasaki *et al.* 2016), increasing necromass and tree fall (Palace *et al.* 2007; Schulze and Zweede 2006), and enhancing CO_2 emissions (up to 30%) when compared with unlogged forest (Blanc *et al.* 2009; Pearson *et al.* 2014). In addition, conventional logging practices have greater impacts on biodiversity when compared to RIL, including reducing species abundance, richness, and phylogenetic and function diversity, mainly during the first years after logging (Azevedo-Ramos *et al.* 2006; Jacob *et al.* 2021; Mestre *et al.* 2020; Montejo-Kovacevich *et al.* 2018). Changes in species richness and abundance may in part be explained by post-logging increases in individuals' physiological stress (França *et al.* 2016). Ultimately, these lead to subsequent impacts on ecosystem processes; for example, in the Brazilian Amazon, selective logging led to the decline of dung beetle richness and significantly changed their community composition, which in turn decreased rates of soil bioturbation, a function performed by these animals (França *et al.* 2017). Distinct logging practices also impact ecosystem dynamics and services in logged forests in the Amazon. Logging affects energy and water fluxes due to changes in albedo and surface roughness caused by high levels of canopy openness, mainly in the short-term (1-3 years) (Huang *et al.* 2020). These practices also promote warmer temperatures inside the forest (Mollinari *et al.* 2019), and depending on the intensity of extraction, biomass recovery for further cutting cycles is compromised.

Indirect impacts

The road network created by selective logging provides access to new hunting grounds (Robinson *et* *al.* 1999), which can lead to declines in animal populations. Logging also facilitates the occurrence of understory fires; the intense canopy damage caused by logging activities leads to microclimate changes in the first two years following the logging operations (Mollinari *et al.* 2019). The hotter and drier forest is therefore more likely to sustain understory fires (Uhl and Vieira, 1989).

19.4.4 Hunting

Currently, there are ongoing population declines in many mammal, reptile, and bird species associated with over-harvesting, which are biased towards large-bodied species. The results of this defaunation can have profound consequences for species composition, population biomass, ecosystem processes, and human well-being in overhunted Amazonian landscapes.

Commercial exploitation of animal hides in the 20th century was intense; between 1904 and 1969, it is estimated that 23.3 million wild mammals and reptiles of at least 20 species were commercially hunted for their hides (Antunes *et al.* 2016). This commercial exploitation is now much reduced, although approximately 41,000 peccary skins (mostly Collared Peccary, *Pecari tajacu*) are exported for the fashion industry annually (Sinovas *et al.* 2017). Exploitation is now predominantly for food, with Peres *et al.* (2016) estimating that hunting affects 32% of remaining forests in the Brazilian Amazon (~1M km^2), with a strong depletion of large vertebrate populations in the vicinity of settlements, roads, and rivers (Peres and Lake 2003).

Direct impacts

Impacts vary across species depending on their life-history characteristics; taxa that are typically long-lived, with low birth rates, and long generation times are more vulnerable to local extinction (Bodmer *et al.* 1997). For example, in southeastern Peru, hunting resulted in the local extirpation of large primate species and reduced populations of medium-sized primates by 80% (Nuñez-Iturri and Howe 2007). Vulnerability to hunting may also be exacerbated by biogeographic quirks, with hunting representing a major threat to micro-endemic species like the Black-winged Trumpeter (*Psophia obscura*) or terrestrial species restricted to specific habitats which are more accessible like the Wattled Curassow (*Crax globulosa*), which is found only along more accessible river-edge forests. Habitat loss, fragmentation, and human-driven disturbances such as logging and forest fires interact synergistically with hunting in reducing and isolating populations that do not use the non-forest habitat matrix, inhibiting ‘rescue effects’ from neighboring forests and hence source-sink dynamics (Peres 2001). Additionally, there is evidence of sublethal impacts from hunting on Amazonian vertebrates, with lead being found in the livers of Amazonian game species (Cartró-Sabaté *et al.* 2019).

Although hunting represents the major driver of direct defaunation, there are other drivers of loss including human-wildlife conflicts arising from livestock depredations by Jaguar (*Panthera onca*) (Michalski *et al.* 2006) and Harpy Eagles (*Harpia harpyja*) (Trinca *et al.* 2008). The wildlife trade also impacts a diverse set of taxa; for example, live parrot exports average 12,000 birds annually, mostly wild-caught individuals from Guyana, Peru, and Suriname (Sinovas e al. 2017) and ~4,000 Night monkeys (*Aotus* sp.) were estimated to have been sold to a biomedical laboratory on the Colombian side of the tri-border region of the north-west Amazon (Maldonado *et al.* 2009). Direct depletion for the pet trade has a long history and likely drove regional extinction of species such as the Golden Parakeet (*Guaruba guarouba*) from as long ago as the mid-19th century (Moura *et al.* 2014). Although trade has been reduced by effective command-and-control strategies, it remains the main threat to regionally Critically Endangered species like the Great-billed Seed Finch (*Sporophila maximiliani*) (Ubaid *et al.* 2018).

Indirect impacts

Overhunting may have pervasive impacts on Amazonian forests by disrupting or entirely removing ‘top-down’ control on ecosystems that are mediated by large-bodied predators and herbivores, leading to widespread and potentially irreversible ecosystem alteration and to loss of resilience and function (Ripple *et al.* 2016). Overhunting disrupts the ecological interactions between plants and their seed dispersers, as some large mammals perform non-redundant seed dispersal services (Ripple *et al.* 2016). As a consequence, there is a shift in recruiting patterns of saplings in heavily hunted areas (Bagchi *et al.* 2018), with an increase in wind-dispersed and small-seeded species (Terborgh *et al.* 2008). This, in turn, could lead to a decrease in forests' future carbon stocks, as the species favored in hunted forests tend to have lower carbon storage capacity (Peres *et al.* 2016).

19.5 Conclusions

As of 2018, approximately 14% of the Amazon biome had been deforested, mainly due to the replacement of forests by pastures. Forest loss affects local temperature and precipitation, with increases in land surface temperatures and reductions in precipitation of up to 1.8% across the Amazon. Local extinctions are also a direct result of deforestation. The fact that there is no official record of a regional or global species extinction in the Amazon should bring no comfort, as a vast number of species remain to be described by science; it is possible, and even likely, that species are disappearing before they become known. Forest fires, selective logging, edge effects, and hunting put additional pressure on biodiversity, contributing to severe compositional shifts in remaining forests. The interactions between the multiple drivers of deforestation and forest degradation amplify their individual effects. An immediate halt to the drivers of deforestation and forest degradation is necessary to avoid further greenhouse gas emissions and biodiversity loss.

19.6 Recommendations

- Governments, the private sector, and civil society need to take urgent action to avoid further deforestation in the Amazon, particularly of primary forests. Avoiding loss of primary forest is by far the highest priority to avoid carbon emissions, biodiversity loss, and regional hydrological changes.
- Governments must close down markets for illegal products (e.g. timber, gold, and bush meat).
- Implement an integrated monitoring system for deforestation and forest degradation across the basin with comparable, transparent, and accessible datasets. Datasets can be generated through partnerships between governments and the scientific community. It is no longer acceptable for deforestation to be the sole focus of forest monitoring.
- Develop basin-wide environmental impact assessments for infrastructure, such as roads, waterways, and dams, as their impacts are not only local. Planning must account for the indirect impacts of infrastructure on surrounding ecosystems, as these can outweigh direct impacts.
- Licensing, concessions and permits for forest conversion and infrastructure development must be accessible across the Amazon Basin to support integration with ground and satellite-based monitoring systems, enabling supply-chain traceability and risk assessment of investments.
- Urbanization needs planning to replace the current, organic encroachment mode.
- Develop a fire risk monitoring system and an early warning system to prevent and combat forest fires, especially in years of extreme drought when fires are more likely to escape from non-forest land uses. These should be accompanied by programs stimulating alternative land-management techniques that do not use fire.
- Restrict logging concessions to companies employing reduced-impact logging techniques, in order to decrease forest flammability and promote a sustainable forest-based economy. It is crucial that logging concessions spare part of their territory to act as sources for recolonization of logged areas.

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Chapter 20

Drivers and impacts of changes in aquatic ecosystems

Pescadores vendem peixes frescos em suas canoas, no centro de Manaus (Foto: Bruno Kelly/Amazônia Real)

INDEX

Graphical Abstract

Figure 20.A Graphical Abstract

Drivers and Impacts of Changes in Aquatic Ecosystems

Philip M. Fearnside[a], Erika Berenguer[bc], Dolors Armenteras[d], Fabrice Duponchelle[e], Federico Mosquera Guerra[f], Clinton N. Jenkins[g], Paulette Bynoe[h], Roosevelt García-Villacorta[i], Marcia Macedo[e], Adalberto Luis Val[1], Vera Maria Fonseca de Almeida-Val[1], Nathália Nascimento[j]*

Key Messages

- Over the last four decades, and especially over the last two, many Amazonian aquatic ecosystems have become less connected and more polluted.
- Prior to the massive impacts of dams built over the past four decades, overexploitation of plant and animal species was the most significant factor causing aquatic ecosystem degradation in the Amazon Basin. This degradation continues to advance.
- The spatial distribution of impacts on biodiversity and ecological processes is uneven.
- Agricultural and industrial waste and sewage contaminate Amazonian waters.
- Mercury contamination from gold mining (legal or not) is a major environmental and public-health concern.
- Hydroelectric dams block fish migrations and the transport of sediments and associated nutrients, as well as altering river flows and oxygen levels.
- Deforestation greatly affects the physical and chemical characteristics of watercourses and when agriculture replaces forests can release fertilizers, herbicides, and other pollutants into the water, as well as sediments from soil erosion.
- Petroleum extraction and resulting oil spills can have catastrophic impacts on aquatic ecosystems.
- The biological productivity of aquatic ecosystems is affected both downstream and upstream of these impacts.

Abstract

The Amazon's aquatic ecosystems are being destroyed and threats to their integrity are projected to grow in number and intensity. In this chapter we review a number of these threats. Hydroelectric dams (307 existing or under construction) have changed almost every aspect of Amazonian aquatic ecosystems, and many more dams are planned (239), posing threats to the region's enormous aquatic biodiversity and fisheries resources. By blocking fish migrations dams affect important commercial species, as well as the flow of sediments and nutrients that sustain aquatic food chains and support fish populations. By altering stream flows and flooding regimes, dams and their reservoirs also disrupt downstream ecosystems,

[a] Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Brazil, pmfearn@inpa.gov.br
[b] Environmental Change Institute, School of Geography and the Environment, University of Oxford, OX1 3QY, Oxford, UK
[c] Lancaster Environment Centre, Lancaster University, LA1 4YQ, Lancaster, UK
[d] Ecología del Paisaje y Modelación de Ecosistemas ECOLMOD, Departamento de Biología, Facultad de Ciencias, Universidad Nacional de Colombia Sede Bogotá, Colombia
[e] Institut de Recherche pour le Développement, 44 bd de Dunkerque, Immeuble Le Sextant CS 90009, F-13572 Marseille cedex 02, France
[f] Fundación Omacha, Colombia
[g] Florida International University, Department of Earth and Environment & Kimberly Green Latin American and Caribbean Center, Miami, FL 33199, United States of America
[h] University of Guyana, Guyana
[i] Centro Peruano para la Biodiversidad y Conservación (CPBC), Iquitos, Perú
[j] Universidade Federal do Espírito Santo - UFES, Instituto de Estudos Climáticos, Vitória, Espírito Santo, Brazil.

including flooded forests and the floodplain lakes that are essential for breeding of many fish species. The low-oxygen (anoxic) conditions found near reservoir bottoms cannot be tolerated by many fish species. They also favor the formation of highly toxic methylmercury and the production of methane, a powerful greenhouse gas. Small dams and reservoirs can have substantial impacts that are often even greater than large dams on a per-Megawatt (MW) or per-hectare basis. In Brazil the definition of "small" dams has progressively increased from less than 10 to 30 to 50 MW, opening an expanding loophole in the environmental licensing system. Overharvesting of fish for both food and the ornamental trade has depleted fish stocks and altered their ecological roles. Native species are threatened by invasive species that escape from aquaculture operations and potentially from proposed inter-basin river diversions. Deforestation changes the chemical and physical properties of streams, including releasing natural deposits of heavy metals (such as mercury from erosion) and eliminating aquatic species that inhabit watercourses in Amazonian forests. Pollution sources include toxins from agriculture and industrial and urban waste, such as plastic; mercury; transition metals like Cu, Cd, Pb, and Ni; urban sewage; and various forms of toxic waste. Oil spills have had disastrous consequences in Ecuador and Peru. Gold mining releases large amounts of sediments, in addition to releasing mercury and provoking the clearing and degradation of floodplain forests. Roads contribute to the fragmentation of streams and river tributaries as well as generating sediments through soil erosion, in addition to the sediment from the deforestation that roads provoke. Navigational waterways cause multiple impacts on rivers converted to this use, particularly affecting the reproduction habitats of freshwater species. Climate change impacts aquatic ecosystems through increased temperature and extreme droughts and floods. Interactions among drivers mean many of these impacts are even more harmful to aquatic ecosystems. The authors of this chapter recommend that no more hydroelectric dams with installed capacity ≥10 MW be built in the Amazon, that investments in new electricity generation should be redirected to wind and solar sources, and that all environmental assessments should incorporate synergistic and cumulative impacts in their analyses. In addition to the ecosystem impacts that are the subject of this chapter, the extraordinarily great social impacts of Amazonian dams (Chapter 14) lead to the same conclusion. Fortunately, countries like Brazil have abundant undeveloped wind and solar potential.

Keywords: Climate change, dams, fish, invasive species, mercury, oil spills, pollution, river diversion, toxic waste, waterways

20.1 Introduction

The Amazon's rivers and streams reflect the landscapes through which they flow. The great Amazon limnologist Harald Sioli (1984) explained that "The big rivers receive their waters from a dense network of Igarapés, streams and brooklets. The total length of their courses exceeds more than a thousand times that of the Amazon; this implies an intimate contact of the Amazon aquatic system with its terrestrial surroundings and a determining influence of the latter on the chemistry and biology of the small watercourses." This influence reflects not only geological differences such as those that produce the region's white-, black- and clear-water rivers, but also the effects of human activity. These watercourses are often compared to a person's blood or urine - the subject of medical testing to identify problems in a human body. In the same way, the deteriorating health of a terrestrial or aquatic ecosystem will be reflected in the quality and quantity of the water flowing from its hydrographic basin.

The sheer magnitude of the flows in the Amazon reflect the region's global significance, annually discharging 6.6 trillion cubic meters of fresh water to the oceans, along with 600-800 million tons of suspended sediments (Filizola and Guyot 2011). The Amazon's aquatic biodiversity is also globally significant. So far, 2406 fish species have been described (Jézéquel *et al.* 2020), although hundreds more remain to be described such that the actual number is likely to be above 3,000 species (Val 2019). Described floodplain tree species total 918 (Wittmann *et al.* 2006). As mighty as the Amazon River is, its aquatic ecosystems are also fragile (e.g., Castello *et al.* 2013a). The multiple threats these ecosystems face are the focus of this chapter.

Amazonian rivers and streams connect distant parts of the vast Amazon Basin, and impacts originating at any given location may be felt thousands of kilometers away. A dam altering downstream sediment flows, for example, can affect ecosystems all the way to the Atlantic Ocean and even in the Amazon's estuary. Likewise, a dam blocking migratory species causes upstream effects reaching all the way to the Amazon's headwaters in the foothills of the Andes. The same is true for other drivers of change in freshwater systems (Figure 20.1); overharvesting of fish stocks (both commercial and ornamental species) can disrupt aquatic food webs; introduction of invasive species can disturb native species communities, causing habitat loss; and deforestation can alter water quality, temperature, and climate at various scales. Water pollution (e.g., agricultural and industrial wastes, plastics, medicines, oil spills, and transition metals such as mercury) can have widespread and cumulative effects, as can infrastructure such as dams, roads, river diversions, and waterways. Other factors include urban and industrial growth, agriculture, and regional climate change. These drivers have synergistic interactions among themselves and, when acting together, can amplify each other's impacts (Costa *et al.* 2011; Anderson *et al.* 2018; Athayde *et al.* 2019; Castello and Macedo 2016; Silva *et al*. 2019). The construction of dams, for example, inevitably results in the construction of roads, which in turn may increase deforestation for pasture and commodity crops such as soy (Fearnside 1989; Guerrero *et al.* 2020). These land-use changes ultimately result in the pollution of rivers and streams, be it from the large-scale use of fertilizers and agricultural chemicals, the formation of toxic methylmercury in reservoirs, or rapid population growth from migration spurred by dam construction. These multiple impacts on aquatic ecosystems threaten the Amazon's enormous aquatic biodiversity, as well as the health and well-being of many Amazon residents who depend on fisheries and other aquatic resources for their livelihoods (see Chapter 21).

Aquatic systems in the Amazon are environmentally diverse and include many characteristics that can pose unique challenges for aquatic organisms. Among these are habitat heterogeneity, different river types (such as white-, black- or clear-water), and dramatic seasonal flood events (i.e., flood pulses) when rivers overflow their banks and invade adjacent forests, creating habitats such as *várzeas* (white-water floodplains) and *igapós* (black-water swamps) that are essential for feeding and nurturing fish (Barletta *et al.* 2010). Water-quality indicators, such as dissolved oxygen, temperature, electrical conductivity, and pH, may also vary seasonally and spatially depending on the drainage area (e.g., the Andes, Guiana, and Brazilian shields), requiring aquatic organisms to adjust to changing conditions. These challenges have favored the evolution of adaptive strategies at all levels of biological organization (Junk *et al.* 1989; Campos *et al.* 2019; Val 2019; Piedade *et al*. 2000). Fish and other aquatic animals have evolved strategies to cope with extreme environments (e.g., water with low oxygen, high acidity, low ion concentrations, and high temperatures) and high seasonal variability in food resources, resulting in high biotic diversity (Val *et al.* 2006; Val and Almeida-Val 1995; Zuanon *et al*. 2005).

Interactions between extreme habitat conditions and anthropogenic disturbance are driving many organisms to their physiological limits; adaptations to their natural environment do not always promote survival under anthropogenic stresses. An emblematic example is the effect of oil spills on fish. Among the many strategies Amazonian fish have developed to cope with low oxygen is the ability exploit the water-air interface that, in the case of an oil spill, increase their contact with pollutants concentrated at the top of the water column

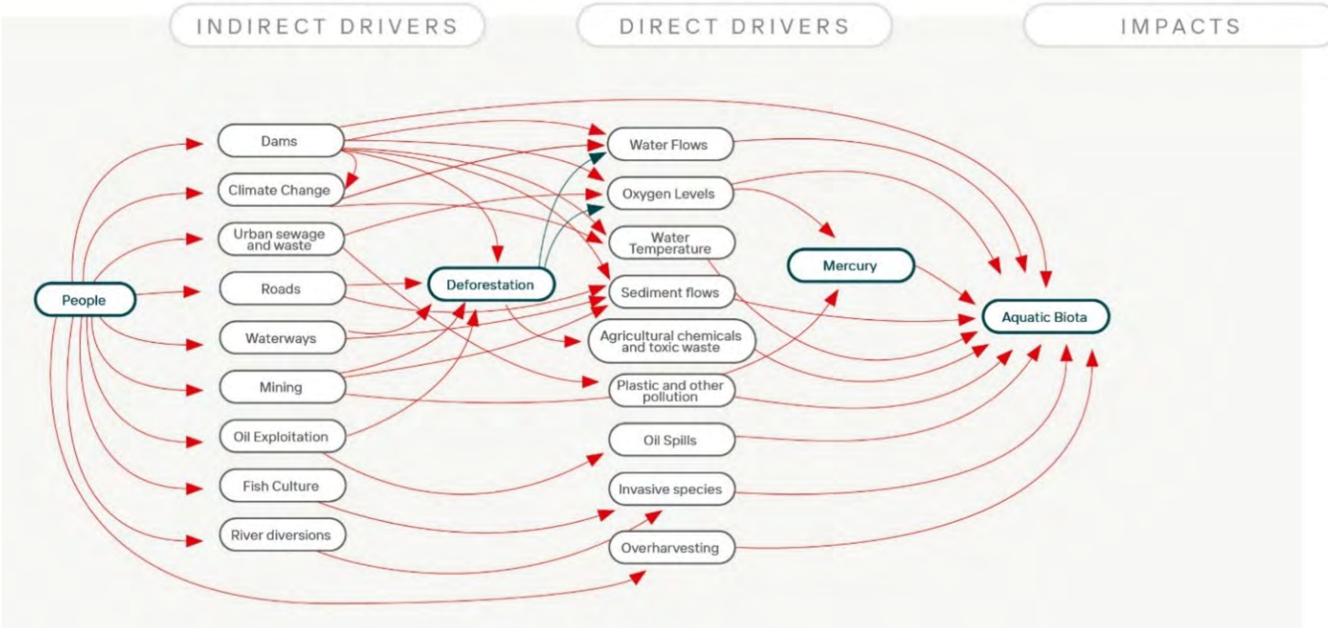

Figure 20.1 Flowchart of relationships among drivers leading to impacts on aquatic life.

(Val and Val 1999; Dos Anjos *et al.* 2011; Souza *et al.* 2020).

The interactions among the different drivers of degradation in aquatic systems are summarized in Figure 20.1. This chapter begins with a discussion of hydroelectric dams because of their very large and diverse impacts in the region, and the many connections between dams and other drivers of change in aquatic ecosystems. It then reviews the effects of overharvesting, invasive species, pollution, mining, roads, river diversions, waterways, and climate change on Amazon aquatic systems. The chapter concludes with a discussion of synergistic effects among drivers, followed by conclusions and recommendations.

20.2 Infrastructure

20.2.1 Dams

20.2.1.1 Existing dams and future plans

We identified 307 dams that exist or are under construction and 239 that are planned or projected (Figure 20.2). These numbers vary in the literature (Finer and Jenkins 2012; Lees *et al.* 2016; Almeida *et al.* 2019) due to differences in the areas covered, inconsistent definitions of what constitutes a "planned" dam (especially for small dams), and variable information across the eight countries and one overseas territory comprising the Amazon Basin. Plans for future hydroelectric dams are also continually in flux.

"Small" dams have less hydrological impact than large dams in absolute terms, but relative to their installed capacity for energy generation they have a significantly greater impact (Timpe and Kaplan 2017). Since 2016, "small" hydroelectric dams have been defined in Brazil as those with less than 50 MW of installed capacity; the limit was 30 MW from 2004 to 2016, and 10 MW before 2004. Dams in this category are exempt from federal environmental licensing and can be built with (generally less-rigorous) state licensing, thus motivating both the expansion of this loophole by redefining "small" dams and a rapidly increasing number of "small" dams in the Brazilian Amazonia. The definition of "small" dams varies widely among countries, with 10 MW being "increasingly recognized as the international standard" (Couto and Olden

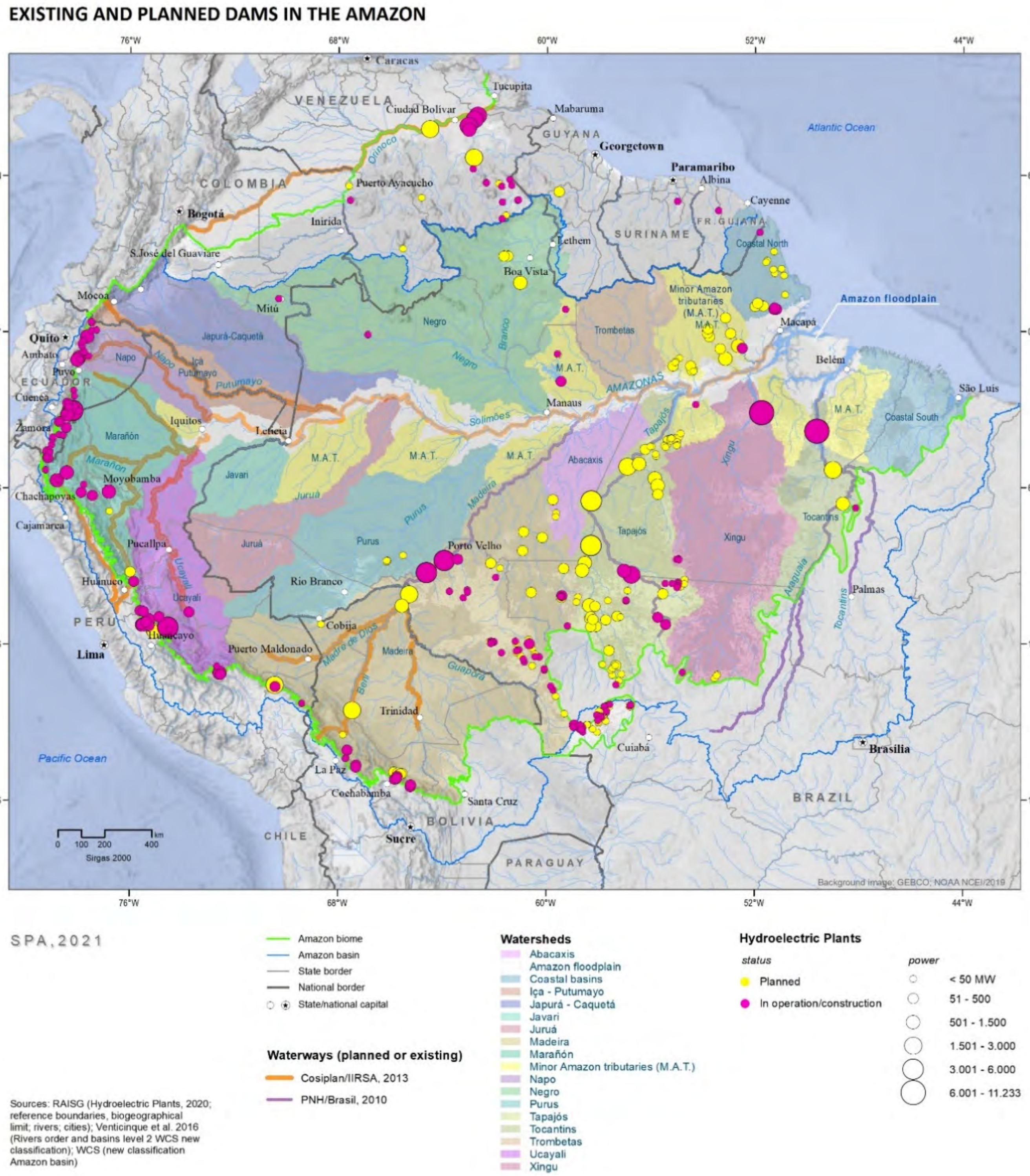

Figure 20.2 Existing and planned hydroelectric dams and waterways in the Amazon. Currently there are 307 dams existing or under construction, and 239 planned or projected (total = 546).

2018). Brazil's relaxing its definition to include dams up to 50 MW represents a significant setback in environmental control.

20.2.1.2 Fish communities

Hydroelectric dams negatively impact fish communities both above and below the reservoir due to habitat loss and severe changes in the hydrological regimes of flooded forests (Ribeiro and Petrere 1988; Ribeiro *et al.* 1995; Santos *et al.* 2018). The conversion of a stretch of river from running water (lotic) to still water (lentic) either eliminates or greatly reduces the populations of many species, few of which are adapted to the new environment (Agostinho *et al.* 2016). Fish communities become structurally and functionally different from the pre-dam baseline (Araújo *et al.* 2013; Arantes *et al*. 2019a, b), with one of the most evident impacts being the impediment of both upstream and downstream migration (Pelicice *et al*. 2015a). Only some of the highly diverse migratory fish species are able to use fish passages (Pelicice and Agostinho 2008). The famous "giant catfish" of the Madeira River (*Brachyplatystoma* spp.) is among those that have not been able to use the passages in the large Santo Antônio and Jirau Dams in the Brazilian Amazon, although they are physically able to climb the passages if placed inside them (Figure 20.3). This is because the instinct of the fish during their annual migration to spawn in the headwaters is to swim up the main channel of the river, not to enter small streams like the ones imitated by the passages. Although not yet documented for the Amazon, basin-wide extirpations of migratory species have occurred in many rivers of the world due to ineffective fish ladders (see Pringle *et al.* 2000; Freeman *et al.* 2003). Amazonian dams and their ineffective fish passages have already seriously disrupted the migration routes of many fish species, resulting in declining fisheries both above and below the dams and in changes in assemblage structure and functional traits of fish communities (review in Duponchelle *et al.* 2021). Ineffective fish ladders in the Amazon have caused declines of migratory species at the Santo Antônio Dam on the Madeira River in Rondônia (Hauser *et al.* 2019) and the Lajeado Dam on the Tocantins River in the state of Tocantins (Agostinho *et al.* 2007, 2012). In other cases, no fish passage was provided, as at the Coaracy Nunes Dam on the Araguari River in Amapá (Sá-Oliveira *et al*. 2015a), the Samuel Dam on the Jamari River in Rondônia (Santos 1995), and the Tucuruí Dam on the Tocantins River in Pará (Ribeiro *et al.* 1995). The resulting loss of fisheries has severe social impacts."

Figure 20.3 The various species of "giant catfish" in the Madeira River are already heavily impacted by the Santo Antônio and Jirau Dams that have blocked their annual spawning migration since 2011. Source: Kileen (2007). Photograph: Russell Mittermeier

20.2.1.3 Aquatic mammals, reptiles, amphibians, and insects

Many other aquatic taxa are affected by hydroelectric dams (Lees *et al.* 2016). For example, dams can cause the fragmentation of populations of dolphins, amphibians, and reptiles (especially larger ones such as caimans and turtles). Dams can also affect these animals indirectly – e.g., they can decrease prey availability for dolphins (Salisbury 2015; Araújo and Wang 2015). Population fragmentation by dams disrupts gene flow and can result in small and therefore vulnerable populations (Gravena *et al.* 2014; Paschoalini *et al.* 2020).

The beaches on which turtles often lay their eggs are commonly flooded by dam-altered hydrology (Alho 2011). This occurs not only in the reservoir area itself (Norris *et al.* 2018), but also in downstream areas where water levels vary depending on power generation (Salisbury 2016). A number of planned dams are particularly threatening to turtles (Gonzales 2019). For instance, on the Rio Branco in Roraima the planned Bem Querer Dam (Fearnside 2020a) is likely to impact downstream turtle breeding beaches (e.g., Nascimento 2002). On the Trombetas River in Pará, the dam that is planned to be the centerpiece of the Barão do Rio Branco Project announced by Brazil's current presidential administration (The Intercept 2019) would be just upstream of one of the Amazon's largest turtle-breeding beaches, the "*tabuleiro do Jacaré*" (e.g., Forero-Medina *et al*. 2019; Zwink and Young 1990).

In a study of frogs at the Santo Antônio Dam on the Madeira River, the composition of species assemblages present near the natural river margin before reservoir flooding did not re-establish on the new margin up to four years after the reservoir was filled (Dayrell *et al.* 2021). Frog species richness near the new margins increased by 82% one year after filling, but this percentage had declined to 65% by four years after filling and showed "no tendency to return to the original assemblage."

Dam impacts on aquatic insects vary; species that depend on fast-moving water lose habitat with the creation of reservoirs and thus decrease in abundance; while others that breed in the standing water of a reservoir, such as mosquitos, can undergo population explosions. At the Tucuruí Dam, in Brazil's Pará state, up to 39% of the reservoir was covered by macrophytes (aquatic plants) in the first years after impoundment (Lima *et al.* 2000), providing breeding sites for mosquitos in the genus *Mansonia* (Fearnside 2001). The resulting "mosquito plague" caused many of the people who had been resettled near the reservoir to abandon their lots and initiate a new hotspot of deforestation elsewhere (Fearnside 1999). Conversely, *Anopheles* mosquitos (the vectors of malaria) diminished in abundance after completion of the Tucuruí Dam (Tadei *et al.* 1991). At the Samuel Dam (in Brazil's state of Rondônia) *Culex* mosquitos exploded dramatically and *Anopheles* mosquitos, which were already abundant before construction of the dam, are also believed to have increased (Fearnside 2005) (Chapter 21).

Alteration of flows downstream of dams can also impact aquatic insects drifting in the water (Castro *et al*. 2013; Patterson and Smokorowski 2011) and those that inhabit the edges of the river, such as mayflies (Ephemeroptera) (Kennedy *et al.* 2016). Changes in substrate composition (i.e., from coarse to fine substrates) downstream of dams is also known to negatively affect aquatic insects (Wang *et al.* 2020).

20.2.1.4 Reservoir stratification

Reservoirs commonly stratify into layers with colder water at the bottom and a division (thermocline) at 2-10 m depth separating the warmer and colder layers. Water does not mix between the two layers. Oxidation of organic material at the bottom consumes oxygen to produce CO_2 until oxygen is no longer available, after which decomposition must end in methane (CH_4). Stratification is essentially universal in storage dams such as Tucuruí on the Tocantins River (Figure 20.4). In run-of-river dams, stratification will depend on the velocity with which the water moves through the reservoir. In run-of-river dams where the main channel remains free of stratification, as at the Santo Antônio Dam on the Madeira River, bays and flooded tributaries can still stratify (Fearnside 2015a).

Underwater biomass decomposition leads to the emission of both CO_2 and CH_4. One ton of methane has an impact on blocking the passage of infrared radiation that is 120 times that of a ton of CO_2 while it remains in the atmosphere (Myhre *et al.* 2013). If we are to stay within either of the Paris Agreement's limits (mean global temperature "well below 2°C" or below 1.5°C above the preindustrial mean), then the impact of CH_4 in terms of CO_2-equivalents must be considered on a 20-year basis, which essentially triples the impact of hydroelectric dams on global warming (Fearnside 2015b, 2017a,b). The impacts of different green-

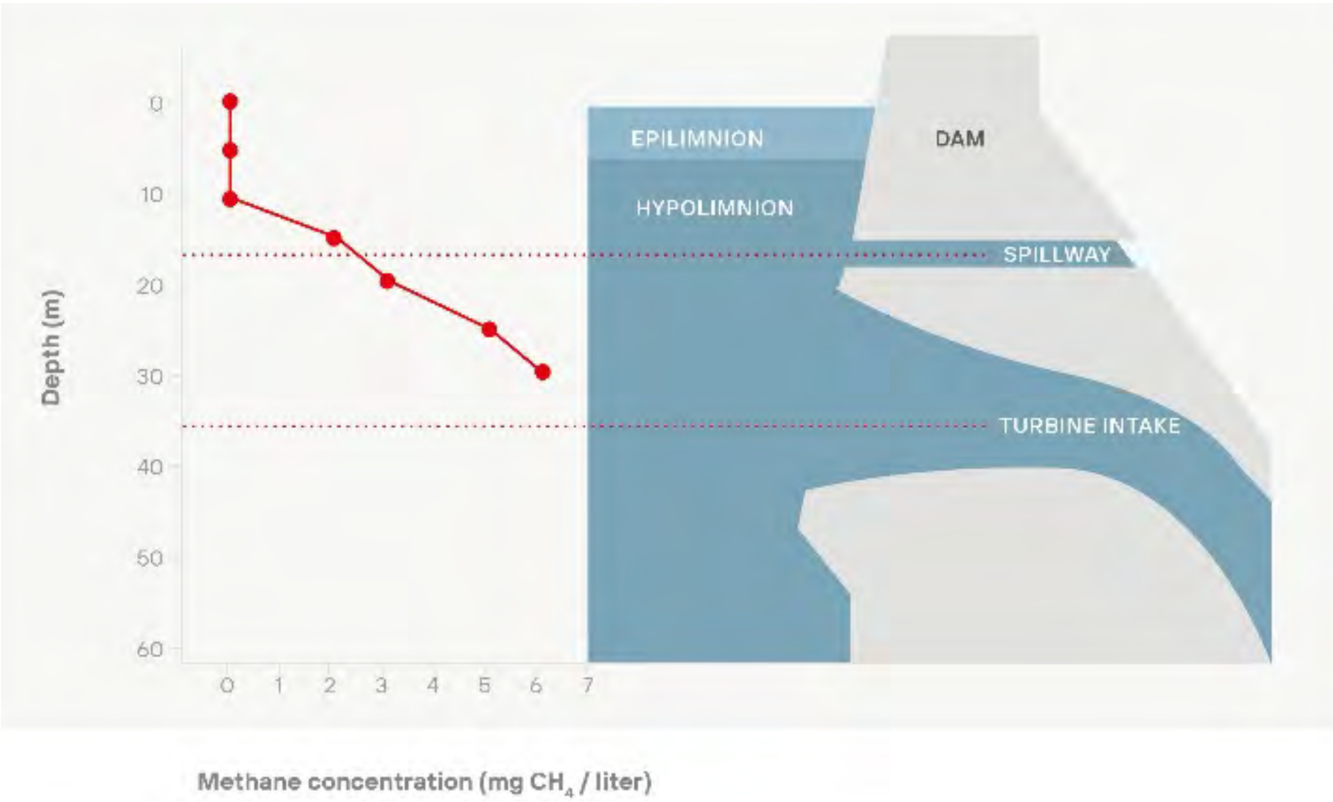

Figure 20.4 Reservoir stratification in the Tucuruí reservoir. In the bottom water (hypolimnion) oxygen is depleted and methane (CH4) levels increase with depth, reaching high levels at the levels of the spillways and turbine intakes. Source: Fearnside and Pueyo (2012).

house gases are expressed in terms of CO_2 equivalents based on global-warming potentials (GWPs), which represent the effect on global temperature over a given time horizon from emitting one ton of the gas relative to the simultaneous emission of one ton of CO_2. Considering the 20-year GWPs from the IPCC's 5th Assessment Report, 25% of lowland dams would emit even more CO_2 equivalents per megawatt-hour generated than a coal-fired power plant, and 40% of them would emit more than generation from natural gas (Almeida *et al.* 2019). The result would be even worse for Amazonian dams if emissions from the water passing through the turbines and spillways were included in these calculations. Box 20.1 explains the contribution of Amazonian dams to greenhouse-gas emissions.

Considerable uncertainty exists in calculating greenhouse-gas emissions (i.e., CO_2, CH_4 and N_2O) from dams on the scale of the Amazon as a whole. There is much variation from dam to dam with reference to key variables such as the depth of water at the intakes of the turbines and spillways, the average turnover time of water in the reservoir, and the existence of bays and other areas in the reservoir where turnover times are much longer than the average (Fearnside 2013a, 2015a). For example, run-of-river dams emit less than storage ones because they have smaller reservoirs with faster water turnover times and less variation in water level. However, run-of-river dams can still emit methane even if the water flow is sufficient to prevent stratification in the main channel of the river because the tributaries and bays stratify, and methane produced in them reaches the spillways and turbines to be emitted downstream (Fearnside 2015a; see also Bertassoli Jr *et al.* 2021). Another key aspect in the variation in dam-related emissions is dam location; lowland dams (eleva-

BOX 20.1 Greenhouse-gas emissions from Amazonian dams

Greenhouse-gas emissions from Amazonian dams include both methane produced in stratified reservoirs and CO_2 from trees killed by flooding (Figure B20.1). The dead trees subsequently decay and release greenhouse gases (i.e., Abril et al. 2013; Fearnside 1995, 2002a, 2005). In addition, trees near the edges of reservoirs suffer stress from the high water table, causing mortality (dos Santos Junior et al. 2013, 2015; Fearnside 2009). The large amount of initial biomass when a reservoir is flooded (which is especially high in tropical forests), in addition to the presence of easily oxidized labile carbon in the soil, leads to young reservoirs being larger emitters than older ones (Barros et al. 2011). After these carbon pools are depleted, emissions decline but do not fall to zero (Fearnside 2009, 2016).

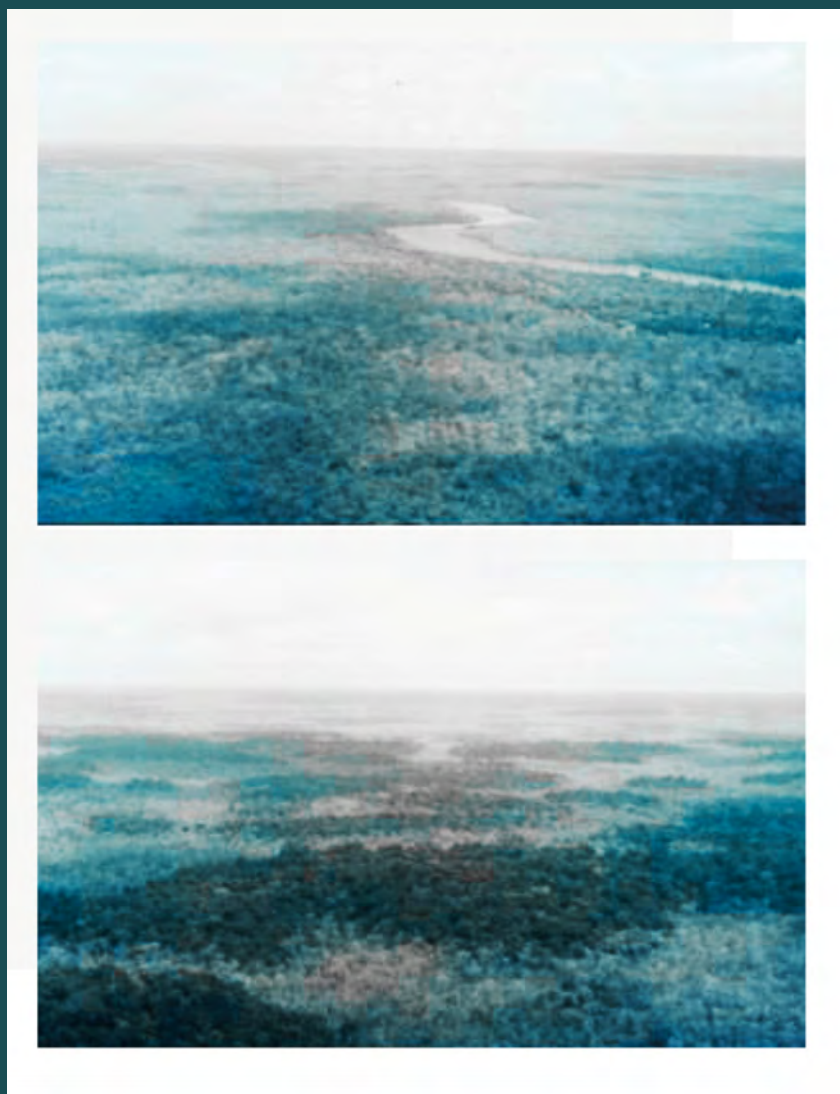

Figure B20.1 Some of the approximately 100 million trees (diameter > 10 cm) killed in the shallow reservoir behind the Balbina Dam. The light-colored trees are dead. The reservoir has over 3,000 islands (bottom panel), increasing the impact on emissions from tree mortality, as well as the fragmentation impact on terrestrial fauna. Source: Fearnside 1989. Photographs: Philip Fearnside.

tion <500 m) produce more than triple the emissions per megawatt-hour generated than dams at higher elevations (Almeida *et al.* 2019). Similarly, tropical dams have higher emissions than those at higher latitudes (Barros *et al.* 2011). Because a substantial amount of information is needed about each dam in order to estimate greenhouse-gas emissions, it is difficult to make valid regional, national, or global estimates. Simple extrapolation based on installed capacity, which has been done in various global estimates, is insufficient.

Emissions resulting from the reservoir surface tend to be the only ones considered when evaluating the impacts of dams on climate change, which greatly underestimates total dam emissions (e.g., Brazil 2004). Reservoir surfaces can emit gases both by diffusion and by bubbling (ebullition). Diffusion is a large source in the first two years after reservoir filling, but subsequently declines in importance (Dumestre *et al.* 1999). Bubbling is greater in shallow parts of the reservoir, and it occurs at irregular intervals, with short periods of intense bubbling interspersed with long periods with few bubbles (Lima 2002). The treatment of these effects in calculating annual emissions from a reservoir can have dramatic effects on the calculated impact (Pueyo and Fearnside 2011; Fearnside and Pueyo 2012). The often-neglected emissions from turbines and spillways ("downstream emissions") are critical (Fearnside 2013a, b, 2015a). Downstream emissions, which are largely proportional to water flow, are generally greater than those from the reservoir surface, which are proportional to reservoir area. This is the case of the Petit Saut Dam in French Guiana, which has much more data on emissions than any other Amazonian dam (Delmas *et al.* 2001; Abril *et al.* 2005). In Balbina, which has a large reservoir and little water flow, surface emissions are slightly larger than downstream emissions, whereas in Tucuruí, which has approximately the same reservoir area as Balbina but much more water flow, downstream emissions predominate (Fearnside 2002a; Kemenes *et al.* 2007, 2011, 2016).

In the first years after impoundment there is normally an explosion of floating and rooted aquatic plants (macrophytes) due to a flush of nutrients in the water when the soil and litter are first flooded and from leaves dropped by dying trees. The macrophytes add to the oxygen depletion provoked by decay of the flooded vegetation. The macrophyte cover subsequently declines to lower levels, as occurred at Tucuruí and Balbina (Fearnside 1989, 2001). Lower oxygen content in a reservoir as compared to the running water of the natural river is one of the changes that cause populations of most of the original fish species to either disappear or be reduced to minimal levels, being replaced by a different and less-diverse assembly of species (Sá-Oliveira *et al*. 2015a,b).

20.2.1.5 Alteration of sediment flows

Dams reduce sediment flows by retaining sediments in reservoirs (Fearnside 2013c). Downstream, reduced sediment load results in scouring, where erosion of the riverbanks and bottom accelerates (Santos *et al.* 2020). Reduction in sediment flow deprives the downstream river of the nutrients associated with sediment particles. In the Madeira River, sediment transport downstream of the Santo Antônio and Jirau Dams decreased by 20% compared to pre-dam quantities (Latrubesse *et al.* 2017), which may have contributed to the observed sharp decline in fish catches downstream of the dams (Lima *et al.* 2017; Santos *et al.* 2020). Because suspended particulate organic matter and aquatic macrophytes are the base of the food chain of the lower Amazon (Arantes *et al.* 2019c), reduction of sediment loads by Andean dams are likely to have far-reaching consequences for aquatic food webs by reducing nutrient supplies and thereby affecting primary production (Forsberg *et al.* 2017). Along with reduced oxygen, reduced nutrient flows may have contributed to the collapse of fish and freshwater shrimp populations below the Tucuruí Dam (Odinetz Collart 1987), an impact these populations have never recovered from (Cintra 2009).

Reducing sediment flows also impacts aquatic biota by modifying river geomorphology. Andean tributaries provide over 90% of the sediment budget of lowland rivers in the Amazon Basin (Filizola and Guyot 2009), playing critical roles in geomorphological processes such as river meandering and floodplain formation (Dunne *et al.* 1998; Meade 2007; McClain and Naiman 2008; Constantine *et al.* 2014). Interfering with these processes disrupts the lateral connectivity between river channels and floodplains and ultimately reduces fish yields (Forsberg *et al.* 2017; Almeida *et al.* 2020). The fishes' seasonal use of floodplains has essential nursery and feeding roles (Bayley 1995; Nilsson and Berggren 2000; Castello *et al.* 2015; Hurd *et al.* 2016; Bayley *et al.* 2018).

Impacts from reduction of sediment flows are especially problematic in white-water rivers. In some cases, the process of dam construction can have the opposite effect of temporarily increasing sediment loads in clear-water and black-water rivers, which is also damaging. In either case, dam-induced downstream modifications affect fishes' longitudinal upriver spawning migrations (Agostinho *et al.* 2004, 2008; Lytle and Poff 2004; Bailly *et al.* 2008). These migrations are affected by modifying the physical and chemical cues to which fish have adapted (Freitas *et al.* 2012; McIntyre *et al.* 2016; Timpe and Kaplan 2017). This impact is in addition to the catastrophic effect of physical blockage of migration routes by dams.

20.2.1.6 Alteration of streamflow

Storage dams can cause downstream flow changes over longer periods than run-of-river dams, but the large variation in daily or hourly time scales for run-of-river dams can also provoke significant changes in streamflows (Almeida *et al.* 2020). Alteration of flow patterns in the river below a dam has multiple effects on downstream ecosystems. Timpe and Kaplan (2017) related ecological impacts to hydrological measures within four groups of hydrological parameters: 1) frequency and 2) duration of high and low pulses (flood pulses), and 3) the rate and 4) the frequency of water condition (level) changes. Other impacts on streamflow occur when the reservoir is filling, such that downstream river stretches dry out during all or part of the filling period. The Balbina Dam was an extreme case, with flow stopped for over a year (Fearnside 1989). The Belo Monte Dam produces a similar effect that is permanent and on a grand scale; water flow is greatly reduced in a 130-km stretch known as the "big bend of the Xingu River" (*Volta Grande do Rio Xingu*), with 80% of the river's annual flow diverted (Figure 20.5).

Modifications in the hydrological regime directly impact aquatic biodiversity. Fish behavior, especially as related to migration and reproduction, is attuned to flow changes, and false signals caused by dams can induce fish to behave in ways that jeopardize their reproductive success (Agostinho *et al.* 2004; Bailly *et al.* 2008; Freitas *et al.* 2012; Vasconcelos *et al.* 2014; Nunes *et al.* 2015; McIntyre *et al.* 2016). Reduction in water flow also negatively affects ornamental species, such as the zebra pleco (*Hypancistrus zebra*), which is threatened with extinction in the wild due to the Belo Monte Dam (Gonçalves 2011). In addition, alteration of flow and of river stages (height of the water level) can also affect turtle reproduction on river beaches, as is reported by Indigenous people for beaches below the Teles Pires and São Manoel Dams in the Tapajós Basin.

Flooded forests are impacted by the construction of mega-dams by increasing tree mortality due to extreme flooding (Resende *et al.* 2019; Oliveira *et al.* 2021). In the Uatumã River below Brazil's Balbina Dam, streamflow alterations resulted in the death of 12% of the swamp (*igapó*) forest along a 125-km stretch of river below the dam (Assahira *et al.* 2017; Schöngart *et al.* 2021). During years with high rainfall the water level no longer reaches the minimum of the natural river, leaving trees in low topographic positions underwater beyond their tolerance limits (Figure 20.6).

Figure 20.5 The Belo Monte hydroelectric project has diverted water from the "Volta Grande" (big bend) of the Xingu River, a 130-km stretch between the two dams that comprise the project. Source: Watts (2019). Photograph: Fábio Erdos/The Guardian.

Figure 20.6 *Igapó* (black-water swamp forest) killed by alteration of water levels downstream of the Balbina Dam. Photo: Jochen Schöngart, INPA.

20.3 Roads

Amazonian roads are often built without adequate passages for water, such as culverts or bridges, which results in the fragmentation of small tributaries and seasonal streams. Roads can act as dams, and their impact is especially strong for seasonal streams, with roads causing ponding along the road, blocking the passage of aquatic life and disrupting stream connectivity. On Brazil's BR-319 (Manaus-Porto Velho) highway such blockages impede the seasonal migration of stream fishes (Stegmann *et al.* 2019). Roads also influence water quality and sediment deposition in aquatic systems. A study of 82 of the 242 points at which watercourses intersect BR-319 showed higher water turbidity downstream, as compared to upstream, of the road crossings (Maia 2012). A road without accompanying deforestation in Brazil's state of Amazonas resulted in sediment from erosion of the roadbed and from dust raised by truck traffic that had notable effects on the community of aquatic insects in nearby streams, reducing richness and density in all functional groups, especially shredder species (Couceiro *et al.* 2011). One factor contributing to this is the burial of fallen leaves under the sediments, making these unavailable to insects in the shredder functional group (Couceiro *et al.* 2011). This reduces an important input to the base of the trophic pyramid in the aquatic ecosystem.

20.4 Navigational waterways and river diversions

Navigational waterways (Figure 20.7) have severe impacts on aquatic ecosystems. One is the dynamiting and removal of rocky habitats in order to allow barges to pass unimpeded. Many species of fish are endemic to these habitats and could go extinct when they are removed (e.g., (Zuanon 2015). The planned removal of the extensive rock outcrops of the Pedral do Lourenço upstream from Marabá on the Tocantins River in the Brazilian Amazon would have these effects on a large scale (Higgins 2020).

In addition to removing rock outcrops, dredging of river channels to ensure yearlong navigability results in deepening shallow zones and removing woody debris (Castello *et al*. 2013a) that can hold rich, endemic fish fauna (Hrbek *et al.* 2018). Populations of these species are unlikely to recover once their specific habitat has been removed. In the Peruvian Amazon a project has recently been contracted for implanting the roughly 2,700-km Hidrovía Amazónica (Anderson *et al.* 2018; Bodmer *et al.* 2018). Recent field data on fluvial sediment movements and fish biodiversity in the Marañon and Ucayali Rivers in the Peruvian Amazon suggest that the Hidrovía Amazónica project could significantly alter river-channel morphology and consequently impact fish diversity and productivity on which local economies depend. Measurements of sediment transport in these rivers have shown that the filling time of the riverbed is very fast, with an average transport of 1.3 million tons of total sediments per day (Centro de Investigación y Tecnologia del Agua CITA 2019).
Among the most critical impacts that the Hidrovía Amazónica would cause to the Peruvian Amazon's fish biodiversity, habitats, and fishery resources are (i) contamination of rivers due to fuel and oil spills from dredging vessels, (ii) disturbance of local and regional fish migrations, (iii) impact on fish spawning and refuge habitats, (iv) impact on the abundance of fish populations, (iv) mortality of fish eggs, larvae, and juveniles, (v) disturbance of the natural floods along the river banks, and (vi) impacts on fish productivity (García-Villacorta 2019). Other potential consequences are the degradation or destruction of breeding and feeding grounds, particularly for detritivorous species.

20.5 Overharvesting

20.5.1 Aquatic fauna harvested for human consumption

The unsustainable exploitation of plant and animal species has long been a significant factor in degrading aquatic ecosystems in the Amazon Basin (Castello *et al*. 2013a, Chapter 15). Most large, high-valued fish species, such as the giant pira-

Figure 20.7 Existing and planned waterways across the Amazon biome. Sources: Fearnside 2002b, 2014a; Mariac *et al*. 2021

rucu or paiche (*Arapaima* spp.), which is already on the CITES II list of endangered species (Castello and Stewart 2010; Castello *et al.* 2015), the large fruit-eating tambaqui or gamitana, *Colossoma macropomum* (Isaac and Ruffino 1996; Campos *et al.* 2015), and many of the largest catfishes (e.g., Isaac *et al.* 1998; Ruffino and Isaac 1999; Petrere *et al.* 2004; Alonso and Pirker 2005; Córdoba *et al.* 2013) are considered overfished in their natural distribution areas. In several places, local management programs are in place and fisheries are under systematic control, as is the case with participatory management of *Arapaima* fishing in the Mamiraruá Sustainable Development Reserve in Brazil (IDSM 2021) and the Pacaya-Samiria National Reserve in Peru (Kirkland *et al*. 2020).

Overfishing is no longer restricted to large, highly sought species, it also affects several of the smaller Characiformes species that now dominate fish landings, such as *Prochilodus nigricans* (Catarino *et al.* 2014; Bonilla-Castillo *et al.* 2018) *Psectrogaster* spp. (García-Vásquez *et al.* 2015), *Triportheus* sp, *Osteoglossum bicirrhosum*, and *Mylossoma duriventre* (Fabré *et al.* 2017). This is particularly visible around large cities, such as Manaus and Iquitos, which can cast defaunation shadows of over a thousand kilometers, as evidenced for tambaqui (Tregidgo *et al.* 2017; Garcia *et al*. 2009). The progressive replacement in fisheries of large, long-lived species by smaller species with faster turnover is a well-described phenomenon known as "fishing down" (Welcomme 1995, 1999), or "fishing down the food web" when an associated decline in trophic levels is observed in the exploited species (Pauly *et al.* 1998).

Most commercial and overexploited fish species in the Amazon Basin are migratory, traveling from a few hundred to several thousand kilometers (Barthem and Goulding 2007; Goulding *et al*. 2019). Migratory species account for over 90% of fisheries landings in the Amazon Basin, generating incomes of over US $400 million (Duponchelle *et al.* 2021). Although the proportion of migratory species is slightly lower in unmonitored subsistence fisheries, which represent at least as much volume as the landed commercial fisheries (Bayley 1998; Crampton *et al.* 2004), they still dominate the catches (Batista *et al.* 1998; Castello *et al.* 2011; Castello *et al*. 2013b). Migratory fishes are the species most at risk from the growing anthropogenic activities threatening the Amazon's aquatic ecosystems (review in Duponchelle *et al.* 2021).

Fish overharvesting could have indirect negative effects on terrestrial plant biodiversity and conservation because many commercial species have frugivorous diets and play key roles in dispersing seeds (ichthyochory) and in seed germination processes (review in Correa *et al*. 2015a). This is further aggravated by the fact that larger fish, which are the main targets for fisheries, are also the most effective seed-dispersal agents (Correa *et al*. 2015a,b; Chapters 3 and 4).

Modern aquaculture could contribute to the conservation of endangered species, which are overharvested. Most of the aquaculture farms around major Amazon cities have only recently begun operation and focus on much-consumed species. Tambaqui is the native fish species most frequently farmed in Brazil (Araújo-Lima and Goulding 1998; de Oliveira and Val 2017). Pirarucu (*Arapaima*) and some other fish species, such as matrinchã (*Brycon amazonicus*), are also farmed. The major challenge to fish farming in the Amazon is feeding because local production of fish feed is limited. Other inputs, such as ice and rock salt, can also be difficult to obtain. The improvement of transportation and other conditions would also contribute to the use of by-products (such as leather) from these fish species. Other aquatic groups, such as turtles, are illegally harvested for sale as food (Salisbury 2016). Dolphins are under severe pressure from the practice of killing them to use their flesh as fish bait, especially for the piragatinga or mota catfish (*Callophysius macropterus*), and caimans are also killed for this purpose (Brum *et al.* 2015).

20.5.2 Ornamental fish

The aquarium trade is a growing, multi-billion-dollar industry (Andrews 1990; Stevens *et al.* 2017). Fish are among the most popular pets in the world (Olivier 2001), and the harvesting of wild specimens for the international ornamental trade is a major conservation issue (Andrews 1990; Chao and Prang 1997; Moreau and Coomes 2007) The Amazon Basin accounts for ~10% of the global trade of freshwater ornamental fish, with Brazil, Colombia, and Peru as the major exporters; in 2007, the total declared (greatly underestimated) export value from these three countries was around US $17 million (Monticini 2010). Although artificial breeding could be beneficial for the conservation of aquarium species (King 2019), nearly all specimens exported from South America are taken directly from the wild (Olivier 2001). There is no up-to-date published estimate of the overall number of Amazonian fish species exploited by the ornamental trade, but about 700 species are exported from Brazil (IBAMA 2012), >100 from Colombia (Ortega Lara *et al.* 2015) and >300 from Peru (Gerstner *et al.* 2006). These lists share many species, but widespread species may also hold cryptic diversity (e.g., Estivals *et al.* 2020). These figures are probably underestimates, as many different species can be exported under a single name (Moreau and Coomes 2007). Therefore, a conservative estimate could consider that between 700 and 1,000 species of fish are exploited by the ornamental trade in the Amazon Basin.

One major impact of the ornamental trade is that it favors invasion of exotic species and their associated parasites (Chan *et al.* 2019; Gippet and Bertelsmeier 2021). The effects of the ornamental trade on natural fish populations in the Amazon, however, remain poorly studied. Anecdotal information suggests population collapses or declines under exploitation pressure at some locations in the Rio Negro for discus (*Symphysodon discus*) (Crampton 1999) and cardinal tetra (*Paracheirodon axelrodi*) (Andrews 1990; Chao and Prada-Pedreros 1995). In the Peruvian Amazon, exploitation for the ornamental trade has led to reductions in ornamental species at study locations by over 50% in fish abundance, diversity, and biomass (Gerstner *et al.* 2006).

The cardinal tetra is the number-one export species in the ornamental fish trade in Brazil, accounting for 68% of the total value of Brazilian ornamental fish exports (Anjos *et al*. 2018). The cardinal tetra inhabits the middle and upper Rio Negro, and its trade corresponds to 60% of the economy of the municipality of Barcelos. However, fishery data have yet to be collected to better evaluate the effects of this artisanal fishery on fish populations. Based on information from fishers and the data obtained from sampling ornamental fish (fish caught per area sampled), the world economic collapse that began in 2008 directly affected the gross amount of exported ornamental fish (mostly cardinal tetra).

After the 2008 global financial crisis there was a decrease in both the number of people involved in exploiting ornamental fish and in the catch volume. In fact, the decrease in the 2010s, followed by another economic crisis, ended the boom in ornamental fish export from Brazil. Considering bycatch (other species caught together with the target species), ornamental fisheries would not be sustainable without an observatory group comprising the fisher community, dealers, and researchers. The observatory program is viable for the ornamental fish market and can increase sales by emphasizing fish preservation and the well-being of the local communities that are still active in this trade in a manner similar to what occurred with fair-trade coffee (Zehev *et al.* 2015).

Owing to the increasing exploitation of ornamental fish, the silver arowana (*Osteoglossum bicirrhosum*) has been placed on the Red Book list in Colombia (Mojica *et al*. 2012), and this species may also be threatened in Peru (Moreau and Coomes 2006, 2007). Export of this species for ornamental purposes is prohibited in Brazil (Lima and Prang 2008).

20.6 Invasive Species

The introduction of invasive fish species worldwide is responsible for the homogenization of aquatic fauna, driven especially by a few species, such as *O. niloticus*, *C. carpio* and *P. reticulata* (Villéger *et al*. 2011; Toussaint *et al*. 2016a,b), all of which have been introduced into the Amazon. Invasive species are used for farming, cultivation of ornamental species, and recreational fishing (Lima-Junior *et al*. 2018). Fish introduced to the lakes and reservoirs of the Brazilian Amazon often belong to predatory species (*Cichla* spp., *Astronotus* spp. And *Pygocentrus nattereri*), contributing to the reduction in abundance or loss of native fish species, with whole-ecosystem consequences such as loss of native species' habitats, decrease of local species due to the many invasive species that eat native fish species' eggs, and competition for food, leading to changes in species composition and to modifications of food-webs (Zaret and Payne 1973; Latini and Petrere 2004; Pelicice and Agostinho 2009; Pelicice *et al*. 2015b; Fragoso-Moura *et al*. 2016). In Andean watercourses in Bolivia and Peru the introduction of the predatory rainbow trout *Oncorhynchus mykiss* resulted in local extirpation or greatly reduced abundance of native *Astroblepus* spp. (Ortega *et al*. 2007; Van Damme *et al*. 2011). In the lake Titicaca system, introduced rainbow trout (*Oncorhynchus mykiss*) and pejerrey (*Odonthestes bonariensis*) resulted in the extinction of *Orestias cuvieri* and in declines in many other native species (Anderson and Maldonado-Ocampo 2011; Ortega *et al*. 2007; Van Damme *et al*. 2009).

Sport fishing and collection for ornamental and aquaculture purposes have motivated the introduction of tilapia (*Oreochromis niloticus*), guppy (*Poecilia reticulate*), and common carp (*Cyprinus carpio*), but their impacts are still poorly investigated (Ortega et al., 2007; Anderson and Maldonado-Ocampo 2011; Van Damme *et al*. 2011; Gutiérrez *et al*. 2012; Doria *et al*. 2020). In 2020, the Brazilian government authorized and initiated the promotion of raising tilapia in cages in reservoirs (Charvet *et al*. 2021), despite the fact that tilapia can affect native species through competition and spread of diseases (Deines *et al*. 2016). If tilapia populations become dense, they can release enough phosphorus into the water to cause eutrophication, which leads to widespread fish mortality, as has already occurred in lakes outside the Amazon (Starling *et al*. 2002).

The proliferation of hydroelectric dams in the Amazon makes the region more vulnerable to invasive species, as dams facilitate invasive fish species. For example, specialist species adapted to running water progressively disappear from the newly created reservoirs upstream of dams and, if eurytopic native species (species able to tolerate a wide range of ecological conditions) cannot take their place, then the niche is often taken by alien species (Liew *et al*. 2016). This is facilitated by potential tilapia entry into reservoirs; in addition to the recently legalized rearing of tilapia in cages in reservoirs in Brazil, many aquaculture farms are installed close to reservoirs and fish may escape when water is drained from the ponds.

The introduction of some Amazonian predatory fish species into regions outside their original range can have major effects on local fish communities. This is the case for tucunaré (*Cichla* spp.) and pirarucu or paiche (*Arapaima* spp.) (Miranda-Chumacero *et al*. 2012). A recent review revealed 1,314 records of non-native fish species (in 9 orders and 17 families), in the Amazon Basin since the first record in 1939, with a sharp increase in the last 20 years (75% of occurrences) (Doria *et al*. 2021). Non-native species were mainly introduced by the ornamental trade, or for aquaculture and sport-fishing. The most widespread non-native species were *Arapaima gigas* (outside of its native range), *Poecilia reticulata,* and *Oreochromis niloticus*. Overall, our current understanding of impacts of invasive fish species in the Amazon remains limited due to a paucity of studies (Frehse *et al*. 2016; Doria *et al*. 2021).

20.7 Deforestation

Deforestation is a driver of aquatic degradation that can have effects that differ between the directly impacted areas and areas downstream; local deforestation can have regional consequences. At the small to medium scale, deforestation usually results in increased runoff and discharge; for example, deforestation resulted in a 25% increase in discharge in large river systems such as the Tocantins and Araguaia Rivers, with little change in precipitation (Coe *et al*. 2009). At a larger scale, atmospheric feedbacks (reduced precipitation caused by decreased evapotranspiration) can change the water balance, not only in the basins where deforestation has occurred but throughout the entire Amazon via atmospheric circulation (Coe *et al*. 2009).

By increasing water runoff and sediment loads carried by the rivers, deforestation typically alters geomorphological and biochemical processes downstream with consequences for soil erosion and the biological productivity of aquatic ecosystems (Neill *et al*. 2001; Coe *et al*. 2009; Deegan *et al*. 2011; Iñiguez-Armijos *et al*. 2014; Ilha *et al*. 2018). For example, stronger floods result in the washing out of substrate and associated production of the benthos on which migratory detritivores feed (Flecker 1996). Decreased water transparency reduces algal and zooplankton production in floodplain lakes, which are important feeding and nursery areas for most fish species (Bayley 1995; Pringle *et al*. 2000).

The chemical properties of streams flowing through pastures are radically different from those of streams in neighboring forests (Krusche *et al*. 2005; Neill *et al*. 2006; Deegan *et al*. 2011). Solutes in groundwater are also affected, thereby contributing to changes in stream chemistry (Williams *et al*. 1997). Direct exposure to sun and changes in temperature, oxygen, chemical content, and bottom substrates greatly affect aquatic fauna (da-Silva Monteiro Júnior *et al*. 2013). Increased water temperatures and reduced oxygenation during the dry period can be lethal to fish (Winemiller *et al*. 1996).

Cardinal tetras are sensitive to increased temperatures (Fé-Gonçalves *et al*. 2018). The two congeneric species of cardinal tetras are distributed in inter-fluvial areas in the upper part of the Rio Negro Basin and inhabit two distinct environments with different vegetation covers and temperatures (Marshall *et al*. 2011). The water temperatures of these environments differ by less than 2°C but coincide with the maximum thermal limits for both species (Campos *et al*. 2017). Small characins are usually found in small, forested *terra firme* (upland) streams. The increase in water temperature caused by deforestation will therefore affect fish species living in streams in deforested areas. Overall, severe disturbances in fish communities can result because many species live in streams with temperatures close to their critical tolerance limits (Campos *et al*. 2018).

In small streams, deforestation reduces the availability of large instream wood, which plays critical roles in the structure, diversity, and abundance of fish communities, thus impacting fisheries and ecosystem functions (Wright and Flecker 2004). Loss of smaller debris could impact the benthic insects and macroinvertebrates that fish eat. Recent studies have demonstrated negative impacts of deforestation on fishery yield (Castello *et al*. 2018) and fish species richness, taxonomic diversity, abundance (Lobón-Cerviá *et al*. 2015; Arantes *et al*. 2018), biomass, and functional diversity (Arantes *et al*. 2019a). All these impacts can be reduced if riparian forests are maintained; for example, if an area is converted to pasture but a forested strip is left along the margins of waterbodies, these waterbodies will be less affected (de Paula *et al*. 2021). The wider the strip, the less the impact on aquatic ecosystems; for example, in the eastern Amazon the percentage of forest cover within 100 m of a stream is closely related to macroinvertebrate diversity in the stream (de Paula *et al.* 2021). Even a small fraction of forest loss in a catchment is sufficient to transform communities of benthic invertebrates and vertebrates (mainly fish) in Amazonian streams (Brito *et al*. 2020; Campos *et al*. 2018). Reducing forest cover by only 6.5% within 50 m of a stream is enough to cross thresholds for aquatic invertebrates (Dala'corte *et al.* 2020). Furthermore, a forest border protects stream banks from erosion, prevents destruction of the stream bed, maintains cooler temperatures, and helps maintain better water quality. In Brazil, the legal requirement for such protection has been greatly reduced since 2012, when the country's Forest Code was replaced by a law that redefines the water level from which the required forest border is measured, changing the basis for measurement from the maximum to the minimum level of the river. This eliminated almost all requirements for protection along most medium and large Amazonian rivers due to their great annual variation in water level.

20.8 Pollution

20.8.1 Agricultural chemicals

Expansion of chemical-intensive crops such as soybeans and oil palm increases the risk of water contamination from agricultural chemicals. The expansion of soybean production in the southern Amazon is of particular concern due to the heavy use of herbicides, including glyphosate (e.g., Roundup©). There are few direct measurements of Amazonian watercourses. A 2016 review on pesticides in Brazilian freshwaters found no studies in the country's Amazon biome (Albuquerque *et al*. 2016). A 2020 study in the area near Santarém, where soybeans are expanding, sampled watercourses and/or groundwater at 28 sites, detecting glyphosate at 11 sites at levels between 1.5 and 9.7 µg/L (Pires *et al*. 2020). The presence of pesticides in aquatic animals indicates water contamination, as in the case of organochlorine pesticides in fish in the Tapajós River (Mendes *et al*. 2016), turtles in the Xingu River (Pignati *et al*. 2018), and Amazon River dolphins in the Solimões (Upper Amazon) and Madeira Rivers (Lailson-Brito Jr. *et al*. 2008). The same dolphins also had polychlorinated biphenyls in their blubber (Lailson-Brito Jr. *et al*. 2008; Torres *et al*. 2009).

In Brazil, several hundred agricultural chemicals have been newly authorized for use under the current administration, many of which are banned in other countries (Ferrante and Fearnside 2019). Pesticides, herbicides, and medicines and other drugs (including endocrine disrupters) are released into the environment. For many compounds, the period of time they remain in the environment is still undetermined. Transition metals and other pollutants in Amazonian aquatic communities may affect local fish species differentially due to their respiration, reproduction, trophic position, and metabolic characteristics, which vary among different fish assemblages (Duarte *et al*. 2009; Braz-Mota *et al*. 2017). In Venezuelan streams, for example, particulate or dissolved compounds coming from agricultural effluents resulted in strong water de-oxygenation through micro-organismal decomposition and, subsequently, in the loss of fish species (Winemiller *et al*. 1996). By killing mostly adult fish, these relatively localized effects have potentially long-term consequences (Braz-Mota *et al*. 2017). The herbicide glyphosate and the pesticide Malathion have been shown to cause metabolic and cellular damage in fish exposed to concentrations lower than their 50% lethal concentrations (LC_{50}) (Silva *et al*. 2019; Souza *et al*. 2020).

Laboratory experiments on fish have shown that glyphosate and other herbicides cause damage to the liver and gills, as well as DNA breakage and increased expression of oncogenes (Braz-Mota *et al*. 2015; Silva *et al*. 2019; Souza *et al*. 2020). Field observations on frogs monitored before and after these herbicides were applied in an area in the central Amazon revealed that two species (*Scinax ruber* and *Rhinella marina*) developed malformations that were not present before the herbicide application or at a location 600 m from the application site. In addition, three previously abundant *Leptodactylus s*pecies became locally extinct (Ferrante and Fearnside 2020).

20.9 Oil spills and toxic waste

The western part of the Amazon Basin has large oil reserves (Chapter 19). Crude oil spills and untreated toxic waste from oil and gas exploitation are notorious in the Amazon portions of Ecuador (Jochnick *et al*. 1994) and Peru (Kimerling 2006; Orta Martínez *et al.* 2007; Yusta-García *et al*. 2017) (Figure 20.8). In the Ecuadorian Amazon between 1972 and 1992, 73 billion liters of crude oil was discharged into the environment, 1.8 times the 41 billion liters released by the Exxon Valdez disaster in Alaska (Sebastián and Hurtig 2004; Kimerling 2006). Over this period, 43 billion liters of produced water (oilfield brine) was also released, which contains salts that disrupt fish migrations (Kimerling 2006)**.**

Oil is toxic to fish (Sadauskas-Henrique *et al*. 2016), and oil-associated contamination can have far-reaching impacts on Amazonian aquatic communities because the oil can disperse over the entire downstream network (Yusta-García *et al*. 2017). Oil extraction produces large amounts of toxic mud and produced water, which in Peru and Ecuador have been routinely released into the environment rather than being pumped back into wells (Kimerling 2006, pp. 450-453; Moquet *et al*. 2014). This brine has both high salt concentrations and a variety of toxic substances (including heavy metals), in addition to significant amounts of oil. Concentrations of hydrocarbon-related toxins have been found in Ecuadorian streams up to 500 times higher than those allowed by regulations in Europe (Sebastián and Hurtig 2004).

Figure 20.8 Oil leaks from a submerged pipeline in Peru. Source: Fraser (2014).

The effects of oil can last for decades, as seen following a spill of 11 billion liters of crude into the Coca and Napo Rivers in Ecuador in 1987; as of 2006, the affected rivers had not recovered their fish biodiversity (Kimerling 2006, p. 458). Oil spills also greatly impact aquatic invertebrate communities, reducing both abundance and species richness, as shown by studies in streams and floodplains affected by oil near Manaus, Brazil (Couceiro *et al*. 2006, 2007a).

Extraction of oil and natural gas near the Urucu River, in the western part of the Brazilian Amazon, is a concern due to potential impacts on adjacent waterbodies. Although the oil company responsible (Petrobras) ensures that all safety operation protocols are being observed, there is always the possibility of an oil spill. Oil pumped from the Urucu wells travels in large barges down the Solimões (Upper Amazon) River from Coarí to Manaus, where it is refined (Figure 20.9).

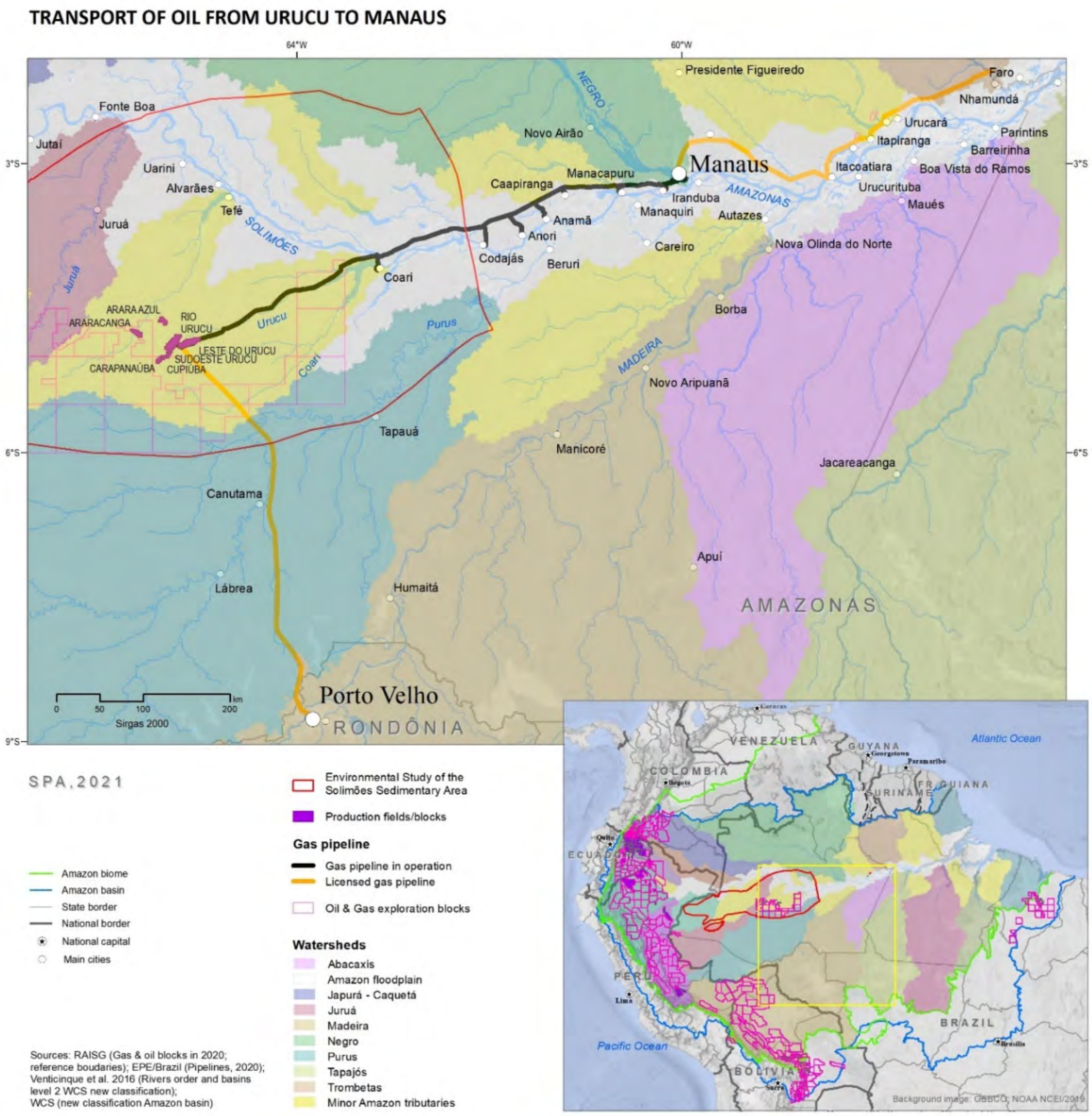

Figure 20.9 Transport of oil by pipeline from Urucu (RUC) to Coarí and then by barge from Coarí to Manaus. The inset map shows oil project areas throughout the Amazon.

Amazon fishes have evolved in hypoxic water and have developed many strategies to either breathe air or take water from the film at the top of the water column, which is richer in oxygen (Val *et al.* 1998; Soares *et al.* 2006). As mentioned above, these strategies threaten air-breathing fish if oil spills occur (Val and Almeida-Val 1999).

Brazil's proposal for the Solimões Sedimentary Basin oil and gas project is rapidly moving forward and will open a vast "strategic influence area" covering 47 million hectares (larger than the US state of California) to exploitation in the western Brazilian Amazon (Fearnside 2020b) (Figure 20.10). Within this area, wells would be located at the most-promising locations (green lines in Figure 20.10) where seismic surveys have already been completed. Rights to the first drilling blocks have already been sold to Rosneft, a Russian company that Greenpeace-Russia accuses of causing over 10,000 oil spills throughout the world (Fearnside 2020c). This oil and gas project also carries a substantial risk of improving road access to the vast "trans-Purus" region between the Purus River and Brazil's border with Peru, resulting in deforestation of the last great block of intact forest in the Brazilian Amazon (Fearnside et al. 2020; see also the views of Brazil's Ministry of Mines and Energy in Brazil EPE 2020a,b; Fearnside 2020b,c; Vieira 2020a,b).

20.10 Mining

Gold mining, much of which is illegal, is widespread in the Amazon Basin (Figure 20.11). In Brazil it occurs in rivers such as the Tapajós,

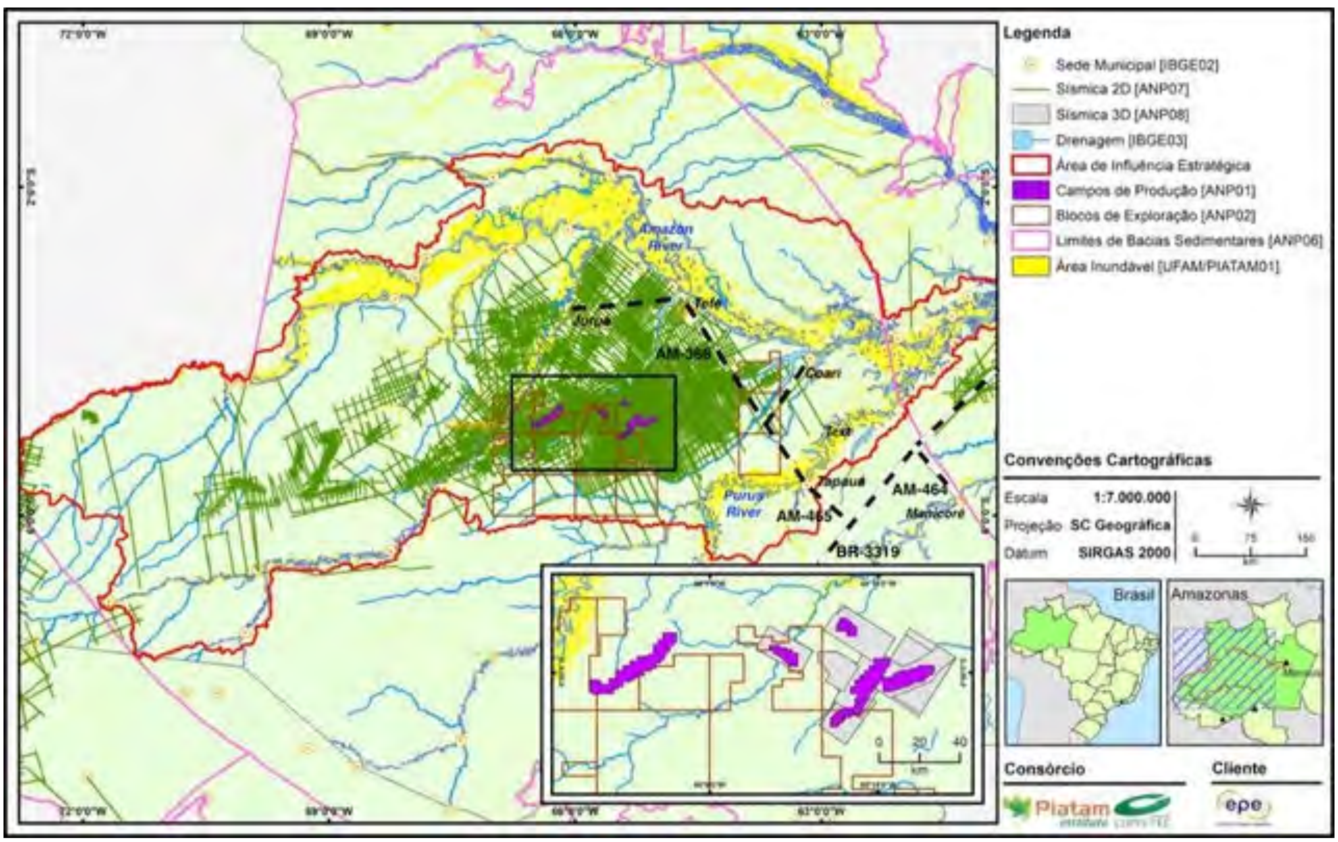

Figure 20.10 Brazil's proposed "Solimões Sedimentary Basin" oil and gas project. The purple areas are the Urucu production field where wells are currently in production. The thin green lines represent locations for future drilling where seismic surveys have already been carried out. The proposed project's "Strategic Influence Area," delimited by the red line, covers 47 million hectares (larger than the US state of California). Source: Brazil, EPE (2020a, p. 65).

Tocantins, Madeira, Xingu, Negro, Amapari, and Solimões or Upper Amazon (Figure 20.12; Roulet *et al*. 1999; dos Santos *et al.* 2000); in Bolivia in the Madeira, Beni, and Iténez Rivers (Pouilly *et al*. 2013); in Colombia in the Putumayo, Caquetá, Guanía, Vaupés, and Inirída Rivers (Nuñez-Avellaneda *et al*. 2014); in Ecuador in the Nambija River, and in French Guiana along the tributaries of the Black River (Barbosa and Dorea 1998). Illegal invasion of Indigenous areas in Brazil by gold miners (*garimpeiros*) has long been a major impact on these areas (Figure 20.13), including their aquatic ecosystems. A bill that would legalize these and other activities in Indigenous areas has the potential to greatly increase these impacts (Branford and Torres 2019; Villén-Pérez *et al*. 2020; Ferrante and Fearnside 2021). It is estimated that more than 200,000 tons of mercury have been shed by gold mining in the Brazilian Amazon since the late 19th Century (Bahía-Oliveira *et al*. 2004).

Gold mining is estimated to account for 64% of the mercury entering Amazonian aquatic systems (Roulet *et al*. 1999, 2000; Artaxo *et al*. 2000; Guimaraes *et al*. 2000). The remaining amount comes from runoff from natural deposits that are eroded by deforestation (33%) and atmospheric emissions resulting from deforestation and forest fires (3%) (Roulet *et al*. 1999; Souza-Araújo *et al*. 2016). On the basin scale, the dynamics of mercury involve abiotic physical processes (i.e., downstream transport of sediments). Elemental mercury can then be turned into toxic methylmercury by specific bacteria in anoxic environments, such as those created at the bottom of reservoirs (Section 20.2.1.4) or in thermally stratified natural lakes and rivers.

Methylmercury enters aquatic food webs and bioaccumulates in successively higher trophic levels (Morel *et al*. 1998; Ullrich *et al*. 2001). Vertebrate populations that have accumulated mercury migrate upstream, including both fish migrations for spawning and side migrations in the floodplains (Molina *et al*. 2010; Nuñez-Avellaneda *et al*. 2014; Mosquera-Guerra *et al*. 2019). High concentrations of total mercury (Hg) and methylmercury (MeHg) in aquatic trophic networks have been documented since the 1980s (Martinelli *et al*. 1988; Lacerda 1997; Lacerda and Salomons 1998).

soil independent of human activities; since Amazonian soils are ancient, they have slowly accumulated mercury that is injected into the atmosphere by volcanic eruptions and deposited by precipitation worldwide. Fish consumption by the Amazon's human communities causes some of the world's highest recorded mercury levels in human hair, along with associated health issues (Passos and Mergler 2008). Through fish consumption, humans also bioaccumulate mercury (Chapter 21).

Among endangered species, high concentrations of mercury have been reported in the giant otter (*Pteronura brasiliensis*) in Brazil (Dias Fonseca *et al*. 2005); in the Amazon River dolphin (*Inia geoffrensis*) in Colombia, Brazil, and Bolivia (Rosas and Lethi 1996; Mosquera-Guerra *et al*. 2015, 2019); and in the gray river dolphin (*Sotalia fluviatilis)* in Brazil (Mosquera-Guerra *et al*. 2019). Along the coast of the Amazon, mercury was also found in tissues of the coastal dolphin (*S. guianensis*) (de Moura *et al*. 2012). Effects of mercury on small cetaceans include liver abnormalities and serious disorders in the kidney and brain (Augier *et al*. 1993). Elsewhere, the combination of mercury with other pollutants in small cetaceans resulted in sensory deficits, behavioral deficiency, anorexia, lethargy, reproductive disorders and death of fetuses, as well as deficiencies in the immune system that facilitate the appearance of pneumonia and other infectious diseases (Cardellicchio *et al*. 2002). It remains unknown whether the same impacts are occurring in Amazon River dolphins and marine dolphins.

Preparations for large-scale industrial mining operations are rapidly moving forward (Arsenault 2021). The Canadian mining company Belo-Sun is preparing a massive operation just downstream of the Pimental Dam (part of the Belo Monte complex on the Xingu River). The operation would extract

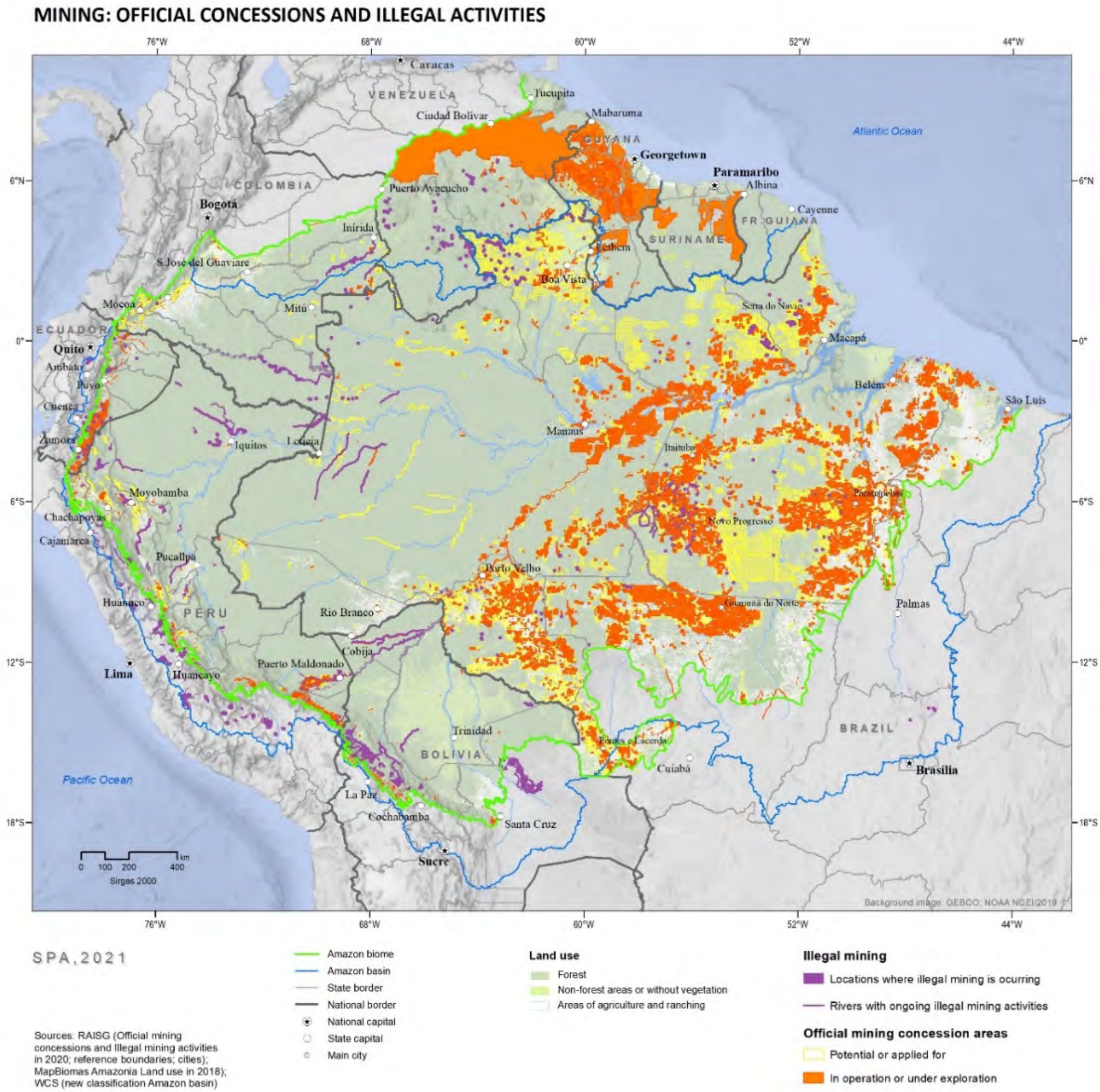

Figure 20.11. Official mining concessions and illegal activities.

Figure 20.13 Mining in Yanomami Indigenous Territory in 2020. Source: Chico Batata - Greenpeace).

Figure 20.12 Sediment from gold mining enters the Tapajos River at its confluence with the Crepuri, one of several tributaries in central Pará discharging sediments from gold mining into the Tapajós. Source: Guimarães (2020). Photograph: Jean R.D. Guimarães.

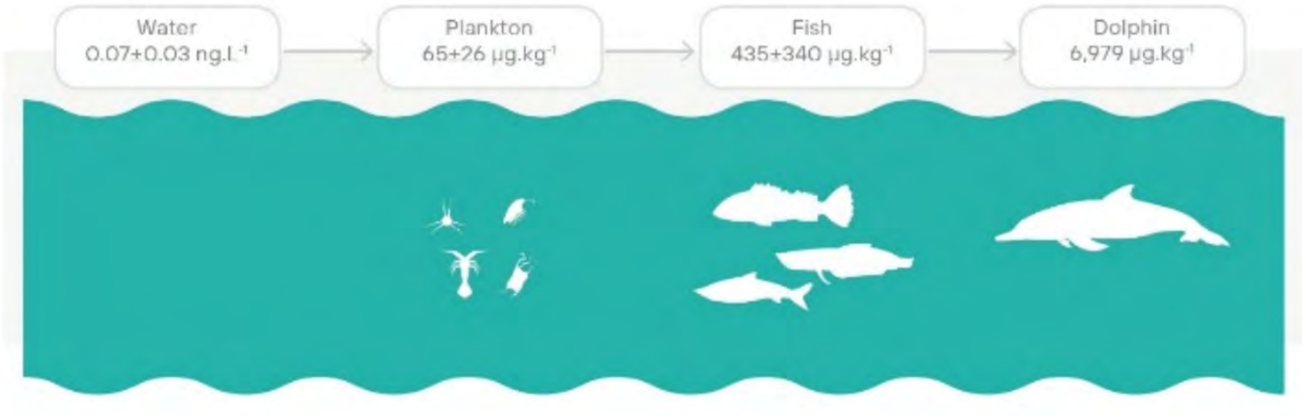

Figure 20.14 Bioaccumulation of mercury in the Rio Negro. Adapted from Kasper (2018).

gold from two open-pit mines beside the *Volta Grande* (Big Bend) stretch of the river that is already heavily impacted by reduced water flow due to the Belo Monte complex. Risks include tailings dams, cyanide use, and demand for large amounts water from the already insufficient flow of the *Volta Grande* (Emerman 2020). The 44 m high tailings dam will remain indefinitely, although the mine is estimated to be exhausted after 17 years of operation. Were the tailings dame to rupture, it could provoke a catastrophe equal to the 2015 Mariana disaster on the Rio Doce in Minas Gerais (Tófoli *et al.* 2017), and release over 35 million m^3 of tailings containing cyanide (Emerman 2020).

Bauxite mining and the processing of ore to produce alumina and then aluminum can release fine toxic particles known as "red mud" into aquatic ecosystems. At the Mineração Rio do Norte bauxite mine on the Trombetas River in Pará, a large lake (the Lago Batata) was completely filled with 24 million tons of this mud in the 1980s, killing virtually all aquatic life (Soares 2015; Borges and Branford 2020). In 2018, a holding pond for red mud burst at the Norsk Hydro alumina plant in Barcarena, Pará (Fearnside 2019). Water was contaminated as far away as Abaetetuba, 48 km from the alumina plant (Barbosa 2018).

20.11 Urban sewage and plastic waste

Urban sewage greatly affects aquatic invertebrates, reducing both abundance and species richness, as shown by a series of studies in 20 streams in the Manaus area (Couceiro *et al.* 2006, 2007a,b, 2011; Martins *et al.* 2017). The effect varies by taxonomic group, which allowed an index of pollution severity to be developed using aquatic insects as bioindicators (Couceiro *et al.* 2012). Streams in Manaus are also contaminated with a variety of hydrocarbons both from biomass burning and petroleum (de Melo *et al.* 2020).

Streams in Manaus have been found to contain human pharmaceuticals, as well as traces of cocaine, but these are diluted below detection limits after entering the major rivers (Thomas *et al.* 2014; de Melo *et al.* 2019). Pollution with pharmaceutical compounds can affect fish (dos Santos *et al.* 2020) and macrophytes (Otomo *et al.* 2021). Pharmaceutical pollution is a growing threat to aquatic environments throughout Latin America, including Amazonian countries (Valdez-Carrillo *et al.* 2020). Samples taken at 40 sites along the Amazon River and major tributaries in Brazil found 30-40 compounds near major cities and 1-7 compounds in the Amazon River far from cities (Fabregat-Safont *et al.* 2021). A different survey at 40 sampling sites along the Amazon River, three tributaries (Negro, Tapajós and Tocantins Rivers), and four cities found that chemical pollution can cause long-term effects in 50–80% of aquatic species near urban areas (Rico *et al*. 2021).

Large amounts of plastic are discarded in Amazonian rivers and streams (Figure 20.15), and the presence of microplastics has now been detected in river sediments (Gerolin *et al*. 2020), in the sand of a beach on the coast of the Amazon region, and in a river beach in the Ecuadorian Amazon (Lucas-Solis *et al.* 2021; Martinelli Filho and Monteiro 2019). Microplastics have also been found in fish species from all trophic levels, including 13 species from the Xingu River (Andrade *et al*. 2019) and 14 from the Amazon estuary (Pegado *et al*. 2018). Micro- and nanoplastics have impacts on aquatic ecosystems, including serving as carriers for persistent organic pollutants (POPs) (Besseling *et al*. 2019) and transferring chemicals that can provoke hepatic stress in fish (Rochman *et al*. 2013). They can also affect mammals (Rubio *et al*. 2020). Many cities, towns, and municipalities across the basin do not have plastic and waste management in place, and this remains as an important challenge to be tackled by policy makers for the conservation of healthy freshwater ecosystems in the region. The Amazon River is estimated to discharge 32,000-64,000 tons of plastic into the Atlantic Ocean annually (Lebreton *et al*. 2017). The Amazon River has also been identified as a major source of organic plastic additives in the water of the tropical North Atlantic (Schmidt *et al*. 2019).

20.12 Interactions among drivers

Although most drivers of degradation in aquatic ecosystems have been discussed separately, several are highly correlated, often interacting, and aquatic organisms will have to cope with some combination of these drivers. The impacts of land-cover change, global climate change, dams, and mining have interactions that are causing large-scale degradation of the Amazon's freshwater

Figure 20.15 Plastic waste discarded in a stream in Manaus in 2021. Source: Rodrigo Duarte/Greenpeace.

ecosystems, and current development trends imply dramatic increases in these impacts (Castello and Macedo 2016).

Several of the drivers discussed here can directly or indirectly promote deforestation. Hydropower dams induce road construction, which in turn lead to increased deforestation and agriculture, which often also result in more deforestation (Finer and Jenkins 2012; Chen *et al.* 2015; Lees *et al.* 2016; Forsberg *et al.* 2017; Anderson *et al.* 2018). As already explained, regulation of hydrological cycles by dams will isolate large portions of floodplains, which will likely be exploited for agriculture, further increasing deforestation (Forsberg *et al.* 2017).

Similarly, the planned waterway in the Tapajós sub-basin is likely to encourage further deforestation directly through increased soy production in Mato Grosso. Soy plantations cause aquatic ecosystems to receive runoff containing fertilizers, herbicides, pesticides, and sediment from soil erosion (Section 20.6.1). Waterways also reduce transportation costs and induce replacement of pasture by soy, resulting in indirect land-use change, where cattle ranchers sell their land to soy farmers and move to other parts of the Amazon, clearing forest for cattle pasture (Arima *et al.* 2011; Fearnside 2015c) (see Chapters 14 and 15).

One impact of waterways is that they serve to justify hydroelectric dams regardless of how severe the impacts may be. Without a complete sequence of dams on a river, the entire waterway would cease to function because barges cannot pass rapids and waterfalls, which are eliminated by reservoirs. The Tocantins/Araguaia waterway (Fearnside 2002b) and the Tapajós waterway (Fearnside 2015c) both serve as examples. In the case of the Madeira River, a plan for 4,000 km of waterways in the Amazon portion of Bolivia, intended to transport soybeans, was used as an argument in the viability study for Brazil's Santo Antônio and Jirau Dams (Fearnside 2014a,b).

Exploitation of new sources of energy, such as oil, usually require road construction, hence deforestation (Anderson *et al.* 2018; Fearnside 2020b). Oil exploitation also has strong combined effects with dams, devastating aquatic biota where these drivers intersect (Anderson *et al.* 2019). Indirect effects of oil exploitation, such as road building and consequent deforestation, can lead to fragmentation of aquatic connectivity or habitat loss for migratory species, further aggravating the effects of dams and waterways. In the Peruvian Amazon, the Interoceanic Highway has had a dual impact on the rivers and associated terrestrial ecosystems. As shown by satellite imagery, this road promoted land-use change due to agricultural expansion in the north, while at the same time facilitating access to previously pristine forests along the Malinowsky and Inambari Rivers for the extraction of alluvial gold (Finer *et al.* 2018; Sánchez-Cuervo *et al.* 2020).

Climate-induced increases in the severity of droughts and lengthening dry seasons will lead to further deforestation and fires (Malhi *et al.* 2009). The effects of climate change will also interact with other anthropogenic impacts. Warming trends will increase water temperatures, increasing the toxicity of pollutants to organisms and bioaccumulation of mercury in aquatic food webs (Ficke *et al.* 2007; Val 2019). The expected trend of declining discharges in the Amazon Basin, except in the western part (Sorribas *et al.* 2016; Farinosi *et al.* 2019), could result in fish biodiversity loss of up to 12% in the Amazon Basin and 23% in the Tocantins Basin (Xenopoulos *et al.* 2005). Droughts and decreased river discharge are also expected to impact fish community composition, population size and structure, reproduction, and recruitment (Poff *et al.* 2001; Lake 2003; Freitas *et al.* 2013; Frederico *et al.* 2016).

Increased temperatures and reduced oxygen concentrations resulting from reduced water volumes are expected to be detrimental for many aquatic organisms, including fish (Lake 2003; Ficke *et al.* 2007; Frederico *et al.* 2016; Nelson and Val 2016; Gonçalves *et al.* 2018; Lapointe *et al.*

2018; Campos *et al.* 2019). In adult organisms, energy is allocated to growth, reproduction, and maintenance metabolism (Val and Almeida-Val 1995; Almeida-Val *et al.* 2006; Wootton 1998). The surplus energy spent in compensating for increased thermal conditions will therefore come at the expense of growth and reproduction, and it is likely to increase susceptibility to disease (Ficke *et al.* 2007; Freitas *et al.* 2012; Oliveira and Val 2017; Costa and Val 2020). Higher temperatures are also expected to favor eutrophic conditions and to stimulate macrophyte development in floodplain lakes, modifying food-web dynamics and affecting the fish that depend on them (Ficke *et al.* 2007).

Global warming and reduced oxygen availability result in shrinking body size in many organisms (Sheridan and Bickford 2011), and this is also expected in fishes (Cheung *et al.* 2013; Oliveira and Val 2017; Pauly and Cheung 2018; Almeida-Silva *et al.* 2020), which could impact fisheries across the region. Declining body sizes under global warming could lead to ecosystem alteration through a trophic cascade for predatory species (Estes *et al.* 2011), or through disruption of carbon flows for detritivorous species (Taylor *et al.* 2006) and consequent decreased recruitment because reproductive output is proportional to body size in most fishes. Expected climate-driven reductions of fish size will also further accelerate the fishing-induced size decreases that have already been observed for commercial species.

Fragmentation of river networks by hydroelectric dams and other infrastructure will constrain potential range shifts of aquatic species to cope with expected temperature rise under climate change (Myers *et al.* 2017). Range shifts of fish to higher altitudes as a result of climate change have already been documented, and river fragmentation by dams will block this form of adaptation (Herrera-R *et al.* 2020). Andean aquatic species will likely be particularly impacted because most dams have been built or are planned on Andean tributaries (Forsberg *et al.* 2017; Anderson *et al.* 2018; Tognelli *et al.* 2019).

20.12 Conclusions

Rivers provide connections between widely separated aquatic and terrestrial ecosystems through flows of water, sediment, and nutrients, and through fish migrations. Fragmenting rivers therefore has consequences that are far-reaching (and often international).

Clean, free-flowing rivers and their interacting floodplain ecosystems generate ecosystem services that are important at local, regional, and global scales (e.g., fisheries for food security, sediment transport, and carbon sequestration).

Aquatic ecosystems are particularly prone to cumulative or synergistic impacts. These include the effects of multiple dams on rivers and the combined impacts of changes in river flows, oxygen levels, water temperatures, and levels of pollution.

20.13 Recommendations

- Dams with installed capacity ≥10 MW should not be built in the Amazon. Dams with installed capacity <10 MW which would power a single town or village can be built with the proper environmental licensing and using a risk-based approach. Rather than building Amazonian dams, energy policy should prioritize electricity conservation, halt exports of energy-intensive products, and redirect investment in new electricity generation to wind and solar sources.
- Dams with installed capacity <10 MW have significant impacts and should not be built to feed national or regional grids. The severe cumulative effect of blocking multiple tributaries with these dams should also be considered.
- Decision making processes on infrastructure projects should be reformed such that direct and indirect environmental and social impacts are compiled and democratically debated before decisions are made.
- Selected watersheds throughout the Amazon need to be preserved for research, long-term monitoring, and protection of genetic and species diversity. These watersheds will also

maintain ecological communities that can be needed for recovery efforts.

- Rivers and streams should be protected by an adequate forest border when surrounding land is converted to other uses.
- Better regulation and monitoring of exotic species is needed, especially for fish culture. Interbasin water diversion projects, which inevitably lead to introduction of exotic species, should be avoided.
- Adequate controls are needed on urban sewage, plastic pollution, mercury and other heavy metals, and on the use of agro-chemicals.
- Control of sediments and waste from mining is needed.
- Alluvial mining must be banned across the Amazon Basin to preserve aquatic biodiversity, floodplain forests, and human health.
- Regional governments and municipalities must prioritize the cleaning of sewage water in order to preserve the health of aquatic biota and human populations.
- Because aquatic resources are not private property, they require cooperative arrangements to manage their use (including the exclusion of outside fishing vessels) and enforcement of restrictions on overharvesting.
- Proper accounting of the greenhouse-gas emissions of Amazonian dams is needed.

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Amazon Assessment Report 2021

Chapter 21

Human well-being and health impacts of the degradation of terrestrial and aquatic ecosystems

Queimadas em Rio Branco, no Acre, 2020 (Foto: Sérgio Vale/Amazônia Real)

INDEX

Graphical Abstract

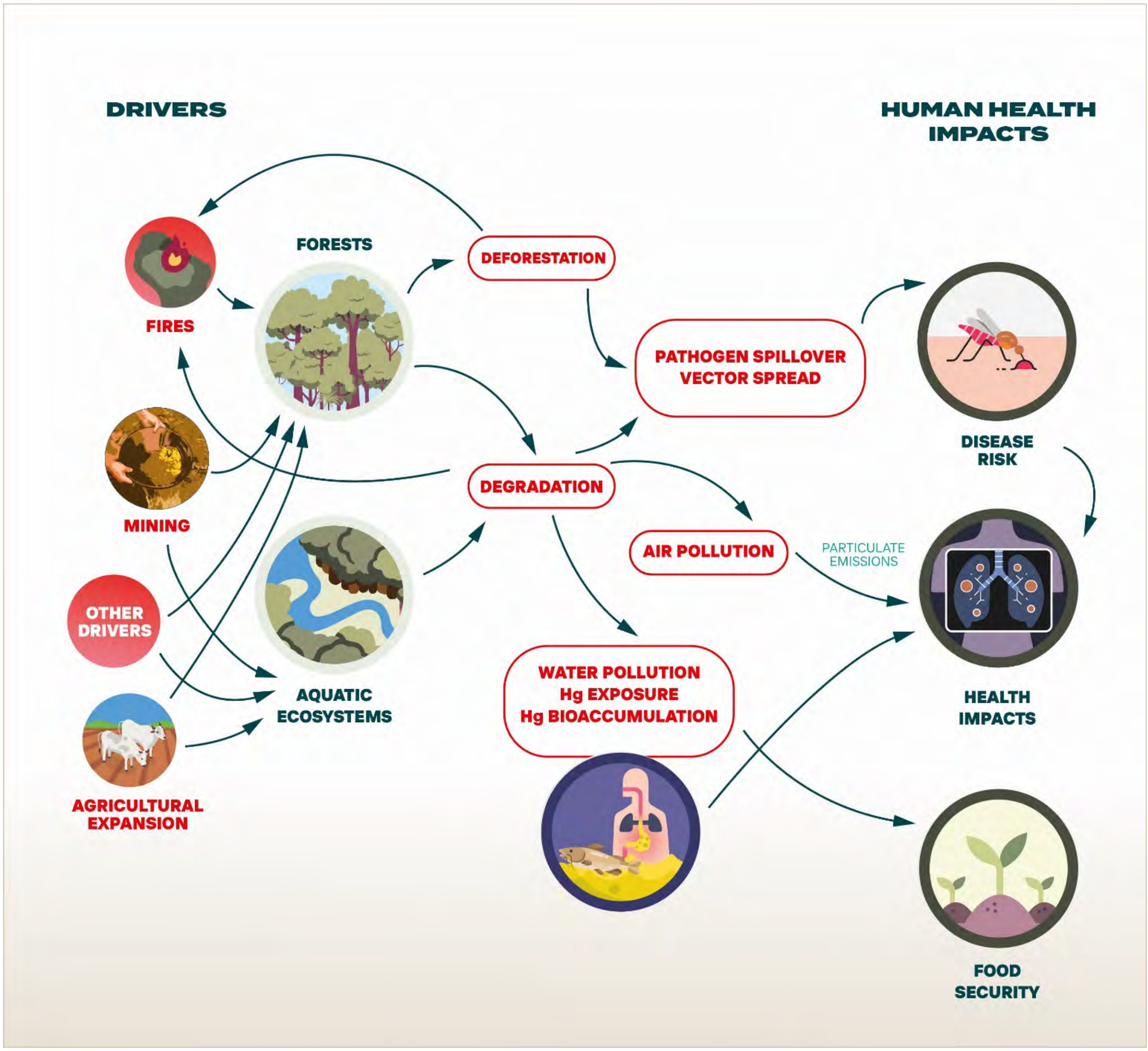


Figure 21.A Graphical Abstract

Human Well-being and Health Impacts of the Degradation of Terrestrial and Aquatic Ecosystems

Dolors Armenteras[a], Erika Berenguer[bc]*, Cecilia S. Andreazzi[d], Liliana M. Dávalos[e], Fabrice Duponchelle[f], Sandra Hacon[d], Andres G. Lescano[g], Marcia N. Macedo[h], Nathália Nascimento[i]*

Key Messages

- Substantial evidence exists that environmental degradation can have acute and chronic impacts on human health.
- Outbreaks and increased incidence of different emerging, re-emerging, and endemic infectious diseases in the Amazon are associated with environmental changes, driven by a range of factors such as rapid human population growth, urbanization, and/or economic development activities. Deforestation and associated degradation of forest and aquatic ecosystems may facilitate the spread of infectious diseases and increase the likelihood of emergence of new zoonotic diseases. The short- and long-term health impacts of fire-related air pollution and mercury contamination from deforestation, dams, and mining activities are also well-described.
- Although we don't know all of the detailed mechanisms of how synergistic impacts work, the evidence to date suggests an urgent need for action to avoid severe and persistent declines in human health and well-being due to environmental degradation throughout the Amazon.

Abstract

Terrestrial and aquatic ecosystems are the basis for ecosystem services, which play a crucial role in people's livelihoods, human well-being, and health. Some of the most relevant and challenging current health problems in Amazonia are associated with deforestation and degradation of terrestrial and aquatic ecosystems, including the risk of contracting infectious diseases, respiratory and cardiovascular problems caused by exposure to smoke from forest fires, and mercury (Hg) contamination due to mining. Emergent, re-emergent, and endemic infectious diseases in the Amazon have all been associated with environmental changes driven by rapid human population growth and/or socioeconomic transition. Yet the relationship between forest conversion and fragmentation and the incidence of infectious disease is complex, scale-dependent, and heavily modulated by socio-ecological feedbacks. Amazonia is also a region of exceptionally high (yet poorly known) diversity of viruses and viral hosts, exacerbating the risks of potential zoonotic spillovers. Another major environmental and public health concern in the Amazon basin is mercury contamination resulting from gold mining, hydropower dams and deforestation. Not only are Amazon basin communities exposed to high Hg concentrations at risk of toxicological contamination, but environmental effects on fisheries and wildlife are seen throughout Amazonia. As a result, communities with high levels

[a] Ecología del Paisaje y Modelación de Ecosistemas ECOLMOD, Departamento de Biología, Facultad de Ciencias, Universidad Nacional de Colombia Sede Bogotá, Colombia, armenterasp@unal.edu.co
[b] Environmental Change Institute, School of Geography and the Environment, University of Oxford, OX1 3QY, Oxford, UK. erika.berenguer@ouce.ox.ac.uk
[c] Lancaster Environment Centre, Lancaster University, LA1 4YQ, Lancaster, UK
[d] Instituto Oswaldo Cruz (IOC), FIOCRUZ, Av. Brasil, 4365, Manguinhos, Rio de Janeiro RJ, 21040-900, Brazil
[e] State University of New York at Stony Brook, 100 Nicolls Rd, Stony Brook NY 11794, United States.
[f] Institut de Recherche pour le Développement (IRD), MARBEC (Univ Montpellier, CNRS, IFREMER, IRD), Montpellier, France.
[g] Universidad Peruana Cayetano Heredia, Latin American Center of Excellence for Climate Change and Health, San Martín de Porres, Peru.
[h] Woodwell Climate Research Center, Falmouth, USA / Amazon Environmental Research Center (IPAM), Brasilia, Brazil
[i] Universidade Federal do Espírito Santo - UFES, Instituto de Estudos Climáticos, Vitória, Espírito Santo, Brazil

of fish consumption present some of the world's highest recorded Hg levels. The impact of fires is also a big concern, since they emit large quantities of particulate matter and other pollutants that degrade air quality and affect human health, especially among vulnerable groups in the Amazon. Here we demonstrate that environmental degradation is also a socio-economic issue, affecting the health of millions of Amazonians and compromises the quality of life and human health of future generations.

Keywords: human well-being, human health, environmental degradation, pollution, tropical disease.

21. 1 Introduction

According to the World Health Organization (WHO), health is "a state of complete physical, mental and social well-being", going beyond the absence of disease or illness (World Health Organization 1947). Enjoying a clean and sustainable environment is critical for human health and well-being (European Environment Agency 2020) and preserving crucial regions, such as the Amazon Basin, is central to achieving this goal. However, quantifying the risks and impacts of environmental degradation to human health poses several methodological challenges, particularly when considering complex issues, such as mental health or social well-being. For example, the loss of culture, language, and traditions of Indigenous populations and traditional communities undoubtedly have a profound long-term impact on the well-being of already vulnerable populations (Athayde and Silva-Lugo 2018; Damiani 2020), but these impacts are hard to measure. On the other hand, there is a substantial body of literature that specifically addresses the impacts of deforestation and environmental degradation on physical health (Ellwanger 2020; White and Razgour 2020), which will be the focus of this chapter. Here, we address physical health problems in the Amazon resulting from deforestation and the degradation of terrestrial and aquatic ecosystems, focusing on the risks of contracting infectious diseases, respiratory problems caused by fires, and mercury contamination due to pollution from illegal and legal gold mining activities.

There are multiple drivers of deforestation and overall environmental degradation in the Amazon, including agricultural expansion, logging, fires, mining, urban expansion, and hydropower dams, among others (Kalamandeen 2018; Piotrowski 2019). The type and level of degradation associated with each activity can have specific impacts on infectious disease transmission, particularly zoonotic and/or vector-borne diseases (Ellwanger 2020). They may also contribute to other health problems such as respiratory syndromes, waterborne diseases, and malnutrition (food insecurity). Processes related to these activities can have additional, often compounding impacts on well-being, many of which are beyond the scope of this chapter. For example, illegal logging and mining can lead to forced labor and human trade, drug use, and an increase in HIV and sexually transmitted diseases (Wagner and Hoang 2020). Increased population density in urban settings facilitates the transmission of respiratory infections, as seen with COVID-19 (Rader 2020) – which can be further exacerbated by poor air quality and exposure to smoke from biomass burning. Uncontrolled urbanization and the lack of sanitation and urban planning can also increase the incidence of arboviruses and diarrheal diseases in growing Amazonian cities (Viana 2016; Lowe 2020). Finally, environmental degradation and urbanization can lead to food insecurity by undermining diverse, sustainable diets (Sundstrom 2014).

21. 2 Impacts of deforestation on the diversity and spread of diseases

Environmental changes in the Amazon -- particularly shifts in climate, microclimates, and land use -- have been repeatedly linked to the increased risk (and incidence) of emerging and re-emerging infectious diseases. Emerging diseases are those that have recently been discovered, while re-emerging diseases are those that were controlled in the past but have emerged as a problem once again. The incidence of emerging and re-emerging infectious diseases in the Amazon is expected to rise with increased deforestation and anthropogenic climate change, but there are important factors and differences depending on the dynamics of each infectious agent. For example, vector-borne diseases such as malaria have received much attention because of their incidence, events of re-emergence, and important socio-ecological determinants of transmission and control. In contrast, the potential for emerging zoonotic diseases, particularly of viral origin, has received far less attention (Box 1). Surveillance for wildlife viruses has revealed the Amazon to be a hotspot of coronavirus diversity (Anthony 2017), for example, with essentially unknown risks for spillover to human populations. Rabies is perhaps the best documented viral zoonotic disease in the region (Gilbert 2012). Finally, while the risk of zoonotic acquisition of infectious diseases such as yellow fever is well-documented, less is known about the risk of environmental change generating human-to-wildlife spillbacks, establishing wildlife reservoirs for other arboviruses (e.g., the causal agents of dengue fever, chikungunya, and zika) (Valentine 2019), or even of SARS-CoV-2 (Botto 2020). Here, we summarize the literature on the association between environmental change and risks from emerging and re-emerging infectious diseases in the Amazon.

21.2.1 Malaria

Decades of work on deforestation and malaria in the Amazon have yielded evidence for non-linear, scale-dependent relationships with disease incidence (Laporta 2019), and important feedbacks from disease incidence to deforestation (MacDonald and Mordecai 2019). Analyses of the density of *Anopheles darlingi*, the main malaria vector in South America, show a positive relationship with recent deforestation (Vittor 2006, 2009; Burkett-Cadena and Vittor 2018), suggesting that forest clearing could increase the risk of malaria near forest edges. In regions with consolidated human settlements, however, the incidence of malaria is positively correlated with forest cover (Valle and Clark 2013; Valle and Tucker Lima 2014). This apparent nonlinearity can be explained in part by *A. darlingi*'s ecology, which favors forest edges, translating into increased malaria risk in both newly deforested areas (Barros and Honório 2015; Terrazas *et al.* 2015) and forest patches in urban areas. Malaria transmission has been associated with several factors: (1) legal and illegal mining with high human exposure to mosquito bites, human movement and extensive environmental changes (Ferreira and Castro 2016); (2) expansion of agricultural frontiers, leading to deforestation, land-use changes and human invasion in forested areas (Chaves *et al.* 2018), (3) discontinuity of malaria control programmes in poorly accessed remote areas (Terrazas *et al.* 2015); and (4) ecological factors, which can drastically increase vector abundance, such as fish farms in rural, periurban and urban areas (dos Reis *et al.* 2015).

Socioeconomic factors, including the hours of human activity and migration patterns, may also play important roles in modulating risk and disease outcomes. For example, crepuscular activities before dawn or at sunset were associated with higher risk of malaria in the Peruvian Amazon (Andersen 2000), highlighting strong interactions between vector ecology and human activities. Likewise, at a different spatial scale, the presence of both gold mining and higher rural incomes were linked to higher malaria incidence in Brazil (Valle and Tucker Lima 2014), demonstrating how rapid environmental change coupled with economic development can increase exposure to vectors of infectious diseases. Finally, at the scale of the Brazilian Amazon as a whole, recent work suggests a complex, bidirectional relationship between malaria risk and deforestation. Although deforestation significantly increased malaria transmission (a 10% increase in deforestation led to a 3.3% increase in malaria incidence), a high malaria burden simultaneously reduced forest clearing (a 1% increase in malaria incidence led to a 1.4% decrease in deforestation). The latter was presumably associated with changes in human behavior, economic activity, migration, and settlement, and the strength of the interaction attenuated as land use intensified (MacDonald and Mordecai 2019). Such complex socioecological feedbacks are still poorly understood, but they underscore the intimate relationship between environmental change and human health.

21.2.2 Chagas

Although less studied than anophelines that transmit malaria, the vectors for Chagas disease (i.e., the triatomine bugs *Rhodnius* and *Triatoma*) also respond to environmental changes. At the interface between human settlements and forest habitats. Chagas vectors appear to have quickly adapted to makeshift settlements, leading to a positive correlation between forest fragmentation and disease incidence (Brito 2017). Urbanized environments, however, are not completely exempt from transmission despite the lack of forest cover. This is because Chagas may be acquired orally via ingestion of contaminated fruit juices, such as açaí and bacaba. It is still unclear whether these juices become contaminated due to the presence of bug feces or because infected bugs themselves are mixed in with the fruit during food preparation (Valente 2009; Beltrão 2009; Sousa Júnior 2017). Thus, new forest settlements experience sylvatic Chagas cycles, but more urbanized settlements —which would be expected to have lower vector abundances due to higher temperatures and low forest cover (Brito 2017) — experience outbreaks from a different epidemiological mechanism (Ellwanger 2020).

21.2.3 American Cutaneous Leishmaniasis

Socioecological interactions are also evident for Leishmaniasis, another important and neglected vector-borne disease in the Amazon. Like malaria, environmental factors such as deforestation may correlate positively with the incidence of Cutaneous Leishmaniasis (Olalla 2015; Gonçalves-Oliveira 2019), but at least one study has found decreasing incidence as a function of forest loss (Rodrigues *et al.* 2019). Socioeconomic factors, and a strong dependence on longer-term landscape trajectories might explain these conflicting results. For example, across Amazonian municipalities, cutaneous leishmaniasis decreases with health

Box 21.1 Neglected Viruses in the Amazon
Cecilia S. Andreazzi

Outbreaks of febrile disease and hemorrhagic fevers have fostered virology research in the Amazon region and provided opportunities to find new viruses in humans and animals. Arthropod-borne viruses (arboviruses) research in the Amazon region started in the beginning of the 20th century, led by the Rockefeller Foundation research program to understand and control yellow fever (Downs 1982). Over the past seven decades, studies conducted in the Brazilian Amazon have already isolated and characterized around 220 different arboviruses species, which is remarkable considering that there are around 500 species registered in the International Catalog of Arboviruses (Medeiros *et al*. 2019). Several evidence of orthohantaviruses and mammarenaviruses have also been identified in the Amazon region (Gimaque *et al*. 2012; Fernandes *et al*. 2020; Delgado *et al*. 2008; Terças-Trettel *et al*. 2019; Medeiros *et al*. 2010; Oliveira *et al*. 2014). Such large numbers of viruses can be explained by the large biodiversity of both arthropod vectors and vertebrate hosts, as well as by the huge variety of ecological conditions that maintain and promote virus biodiversity (Rosa 2016; Medeiros *et al*. 2019). Despite the enthusiastic efforts of Latin American scientists (Rosa 2016), such viruses are underdiagnosed and neglected by health systems, despite being the most common infections among the world's poorest people (Hotez *et al*. 2008). Here, we describe some of these viruses found in Amazonia in more detail and evaluate the possibility of disease emergence in the region.

Arboviruses are generally transmitted by arthropod vectors to their vertebrate host and circulate among wild animals, serving as reservoirs in the sylvatic life cycle. The most frequent hematophagous arthropods that may serve as arbovirus vectors include mosquitoes, ticks, sandflies, midges, and

Box 21.1 Neglected Viruses in the Amazon (cont.)

possibly mites (Medeiros *et al*. 2019). Through spillover transmission from enzootic amplification cycles, humans can be infected as incidental and dead-end hosts (Vasconcelos *et al*. 1991). By contrast, some arboviruses undergo an urban cycle involving humans as amplifying hosts and have caused several epidemics in urban areas (Medeiros *et al*. 2019). Most of the arboviruses that cause human/animal diseases belong to the *Togaviridae, Flaviviridae, Reoviridae and Rhabdoviridae* virus families and to the *Bunyavirales* order (Figueiredo 2007; Kuhn *et al*. 2020). Infections in humans and animals could range from subclinical or mild to encephalic or hemorrhagic, with a significant proportion of fatalities. Thirty-six arboviruses have been associated with human disease in the Amazonian region; seven of them are important in public health and are involved in epidemics. They are dengue, Chikungunya, Zika, Mayaro, Oropouche, Rocio, and yellow fever viruses (Rosa 2016). Other important arboviruses are those associated with encephalitis, which in the Amazon are represented by the equine encephalitis viruses (Eastern, Western, and Venezuelan) and the Saint Louis encephalitis virus. Aside from these, several other arboviruses have been isolated from cases of acute febrile illness, including many species of the orthobunyavirus genus (Ellwanger *et al*. 2020; Vasconcelos *et al*. 2001).

Viral hemorrhagic fevers are highly lethal diseases that produce hemorrhagic disorders and fluid leakage syndromes, with or without capillary damage, which affect the liver, kidneys, and central nervous system (Bausch and Ksiazek 2002). Viral transmission to humans occurs through the bite of an infected arthropod (which includes some arboviruses), or inhalation of particles from the excreta of infected rodents (Figueiredo 2006). More than 25 different viruses from six families are related to hemorrhagic fevers worldwide. In the Amazon region, *Flaviviridae* (hemorrhagic dengue / dengue shock syndrome and yellow fever), *Arenaviridae* (arenavirus hemorrhagic fevers) and *Hantaviridae* (hantavirus pulmonary syndrome) hemorrhagic fevers deserves special attention (Figueiredo 2006).

As unsustainable economic activities increasingly expand over the Amazon, so does the risk of contact between humans and vectors/reservoirs of zoonotic disease agents including arboviruses, orthohantaviruses, mammarenaviruses and rabies. There is evidence showing that construction of the Tucuruí hydroelectric dam in the Tocantins River led to the emergence of almost 40 arboviruses, 30 of them described for the first time after the dam construction (Vasconcelos *et al*. 2001). Experts list a number of viruses of concern that have the potential to emerge or increase incidence in the Amazon due to increased human migration and interference in the region. Those include the *Flaviviridae* (yellow fever, dengue, and hepatitis C viruses), *Bunyavirales* (orthohantavirus, Oropouche, and some hemorrhagic fever viruses), *Rhabdoviridae* (rabies virus), *Togaviridae* (Chikungunya and Mayaro viruses), *Papillomaviridae* (human papillomavirus), *Hepadnaviridae* (hepatitis B virus), *Orthomyxoviridae* (Influenza virus), *Coronaviridae* (severe acute respiratory syndrome coronavirus), *Kolmioviridae* (Hepatitis delta virus), and *Retroviridae* (human T-cell lymphotropic virus) (do Vale Gomes *et al*. 2009). One of the main challenges involved in early detection, prevention, and mitigation of emerging viruses in the Pan-Amazonian region is the lack of molecular diagnosis in the syndromic surveillance of febrile diseases. Many infections result in similar symptoms and because there is a high diversity of prevalent viruses such as Dengue, it is crucial to improve local health units, implementing sentinel areas and systematic monitoring of viral circulation in humans, vectors, and reservoirs. An integrated surveillance, monitoring and networking system with strong intersectoral collaboration and coordination between animal, human health and environmental sectors is necessary to prevent, control, and mitigate emerging diseases (Andreazzi *et al*. 2020).

system effectiveness (Rodrigues *et al.* 2019). The introduction of domestic animals into recently settled areas may also contribute to the acclimation of vectors to human landscapes, increasing disease risks from deforestation (Rosário 2016). Thus, nonlinear relationships between forest loss and disease risk are mediated by their interactions with a diverse vector fauna and local health systems.

21.2.4 Emergence of new diseases

Surveillance efforts to identify hotspots of zoonotic coronaviruses with spillover potential have flagged the Amazon as a region with an exceptionally high, yet poorly known, diversity of viral hosts and viruses (Anthony *et al.* 2017). Increased human population densities also increase the potential for zoonotic spillovers (Olival *et al*. 2017). Risk predictions were originally based on bat species richness, after finding both alpha- and beta-coronaviruses in a few bat species, notably the virus subfamily including the human pathogens that cause SARS, MERS and SARS-CoV-2 (Anthony *et al.* 2017). Other viruses also circulate in the Amazon region and present serious risks of widespread outbreaks, including the Rocio, Oropouche, Mayaro and Saint Louis arboviruses (Vasconcelos 2001; Araújo 2019) as well as hantaviruses (Guterres 2015) and arenaviruses (Bausch and Mills 2014). Given the scant record, our understanding of the potential for land-use change to increase spillover risk remains limited.

Nevertheless, global surveillance for viruses of zoonotic potential offers key lessons for preventing future zoonotic spillovers. Because the diversity of viruses in wild animal populations is vast, but spillover potential for most viruses is limited, close surveillance of infectious diseases in the human population is an effective way to avert future pandemics (Holmes 2018; Carlson 2020). Region-wide improvements to public health services, would also reduce the burden of well-known pathogens such as *Plasmodium* or *Leishmania*, and are necessary to reduce the risk of viral emergence from wild populations. While the Amazon harbors a hyper diverse range of hosts and diverse communities of viruses of unknown human pathogenic potential, preventing a catastrophic pandemic requires implementing strategies that will improve human health more broadly.

One global coronavirus pandemic, COVID-19 has reminded the world about the risks of zoonotic spillovers. However, the potential for spillback from humans to wildlife is just as important for biodiversity (Nuñez *et al*. 2020). Decades of research on vector-borne arboviruses have already revealed the consequences of spillback. Outside the Amazon, in Espírito Santo (Brazil), a yellow fever outbreak killing dozens of non-human primates prompted an early public health response to vaccinate people (Fernandes 2017). Although a chain of transmission has not been established among wild primates, sylvatic mosquitoes harboring the recently introduced Chikungunya and Zika viruses have been documented, indicating a plausible risk to wildlife (Valentine 2019). The finding that endemic *Aotus* Night-Monkeys do not contract dengue after exposure to infected mosquitoes in Iquitos suggests that dengue transmission remains confined to humans and insect vectors rather than generating a sylvatic cycle (Valentine 2019). As with the risk of zoonotic emergence, averting the establishment of zoonotic reservoirs for arboviruses requires sustained investments in public health, including the necessary tools to diagnose the diversity of viruses circulating in the human population. As the COVID-19 crisis has revealed, public health infrastructure is woefully inadequate throughout the Amazon (de Castro 2020; Navarro 2020), emphasizing the need to consider socioecological risks arising from human migration, contact with wildlife and disease vectors, and deforestation.

21.3 Impacts of mercury contamination from mining on human health

Between 2000 and 2010, the price of gold quadrupled, stimulating gold mining activities in Amazonia (Swenson 2011; Alvarez-Berríos and Aide 2015), with severe environmental consequences for terrestrial and aquatic ecosystems in the region

(See Chapter 19 and Chapter 20, respectively). Gold mining sites are commonly associated with contamination by several elements, including arsenic (As), cobalt (Co), lead (Pb), manganese (Mn), and zinc (Zn) (Filho and Maddock 1997; Pereira 2020). These elements are associated with a variety of adverse health effects elsewhere, including childhood mortality. However, the impacts of these elements and compounds on human health in Amazonia are still largely unknown. It is estimated that there are 453 illegal mining sites in the Brazilian Amazon and more than 2500 for the entire Amazonian basin (Basta *et al.* 2021; RAISG 2020). The main impact of gold mines on human health is mercury (Hg) contamination – a result of both legal and illegal mining. Communities living near gold mining operations are exposed to harmful Hg concentrations released during gold extraction and discharged into waterways, soils, and the atmosphere (Gibb and O'Leary 2014). Once the inorganic metallic mercury is released by anthropogenic activities, it is transformed into its more toxic organic form (methylmercury, MeHg) by specific bacteria, usually in anoxic conditions. This process of mercury methylation allows MeHg to enter aquatic food webs, where it may accumulate in individual organisms (bioaccumulation) or be magnified as it moves into higher trophic levels (e.g., biomagnification in predatory fish) (Morel 1998; Ullrich 2001) and can affect fish that are of great importance for food security of local communities (Diringer 2015), (Box 2).

Despite the lack of systematic analyses, studies from Colombia, Peru, and Bolivia over the course of the last 20 years have documented mercury poisoning even in remote Indigenous populations. Kayabi populations from the Teles Pires River, in the Brazilian Amazon, presented 12.7 μg/g of mercury in their hair, while the Munduruku from the Tapajós River, also in the Brazilian Amazon, presented levels ranging between 1.4 to 23.9μg/g (Dórea *et al.* 2005; Basta *et al.* 2021). The internationally recommended limit of hair mercury concentration varying from 1-2 μg/g (WHO 1990). Similar studies were conducted in populations in the Caquetá River basin in the Colombian Amazon, with 79% of individuals with mercury levels in their hair greater than 10 μg/g (Olivero-Verbel 2016).

Further, mercury exposure can be toxic even at very low doses, and the toxicological effects of MeHg are of special public health concern, given its capacity to cross the placenta and the blood-brain barrier (Rice 2014). MeHg reaches high levels in both maternal and fetal circulation, with the potential to cause irreversible damage to child development, including decreased intellectual and motor capacity (Gibb and O'Leary 2014). Studies investigating associations between Hg levels in hair and neuropsychological performance found strong links between mercury and cognitive deficiencies in children and adolescents across the Amazon, including the Madeira (Santos-Lima 2020) and Tapajós rivers in Brazil (Grandjean 1999) and the Madre de Dios region in Peru (Reuben 2020). The World Health Organization recommends the monitoring of MeHg concentration in pregnant women's hair and argues that the level of 10 μg/g or above can increase the risk of fetal neurological effects (Alhibshi 2012). Hg can also impact the health of adults, as it affects the nervous, digestive, renal, and cardiovascular systems. Central nervous system effects include depression and extreme irritability; hallucinations and memory loss; tremors affecting the hands, head, lips, and tongue; blindness, retinopathy, and optic neuropathy; hearing loss; and a reduced sense of smell (WHO 2008). Minamata disease was recently confirmed in Amazonian communities -- a result of exposure to high levels of MeHg, with symptoms including tremors, insomnia, anxiety, altered tactile and vibration sensations, and visual perimeter deficit.

21.4 Impacts of forest fires on air quality and human health

Both deforestation and forest fires emit large quantities of particulate matter and other pollutants to the atmosphere. This degrades air quality, affecting human health, especially among vulnerable groups, such as young children (Smith 2015). The dry season is the most critical period for pop-

Box 21.2 Food security and fisheries

Fabrice Duponchelle, Sebastian Heilpern, Marcia Macedo, David McGrath

Fish historically have great societal importance as one of the main sources of protein and other essential animal-derived nutrients (e.g., fatty acids, iron, zinc) for people of the Amazon (Veríssimo 1895). They accounted for up to 75% of the vertebrate species consumed in early human settlements (750 to 1020 A.D.) in Brazil, for example (Prestes-Carneiro *et al.* 2016). The long cultural and socioeconomic dependence on fish is also illustrated by the fact that fishing was one of the first subsistence and economic activities in the Amazon (Furtado 1981; Erickson 2000; Blatrix *et al.* 2018). Today, even outside professional fisher communities, most Amazonians living in riverbank cities and riverine communities have some members of the family engaged in this activity (Cerdeira *et al.* 2000; Agudelo Córdoba *et al.* 2006; Doria *et al.* 2016). Fishing is not always a core activity but can complement other productive activities that sustain livelihoods such as farming, animal husbandry, and harvesting of natural products (Agudelo Córdoba *et al.* 2000; Cerdeira *et al.* 2000). Floodplain fisheries often act as safety nets for many Indigenous and poor rural communities who turn to fish more than to forest products when faced with adversity (Coomes *et al.* 2010).

The importance of fish to Amazonians is also emphasized by some of the world's highest consumption rates, although they can vary substantially across river basins (Isaac and Almeida 2011); with conservation status and isolation of the region (Isaac *et al.* 2015; Van Vliet *et al.* 2015); or with cultural and regional preferences (Begossi *et al.* 2019). The average per capita rate ranges from 30-40 kg year^{-1} for urban populations and from 70-200 kg year^{-1} for rural populations (Batista 1998; Isaac and Almeida 2011; Doria *et al.* 2016; Doria *et al.* 2018; Isaac *et al.* 2015). These per capita rates are well above the world average of ~ 20 kg year^{-1} (Tacon and Metian 2013) and the recommendation by the World Health Organization of 12 kg year^{-1}.

Estimates indicate that ~ 600,000 tons year^{-1} of fish are consumed in the Brazilian Amazon (Isaac and Almeida 2011) and 29,000 tons year^{-1} in the Colombian Amazon (Agudelo Córdoba 2015). This represents three times the total commercial landings reported for the Amazon basin as a whole (173,000 to 199,000 tons year^{-1}, Bayley and Petrere 1989; Barthem and Goulding 2007). Although part of this consumption could be accounted for by marine fisheries and aquaculture in the large Amazonian cities, these figures clearly indicate that in the Amazon basin (as in other tropical freshwater fisheries), unreported subsistence catches are strongly underestimated (Fluet-Chouinard *et al.* 2018) and may be of the same order of magnitude as commercial fish landings (Tello-Martín and Bayley 2001; Crampton *et al.* 2004). Another figure illustrates the importance of fish for the food security of Amazonian people: in the Brazilian Amazon alone, the fisheries sector directly employs 168,000 people and generates a total yearly income of up to US $200 million (Petrere 1992; Barthem *et al.* 1997).

Although declines in total fish biomass have yet to be documented conclusively, signs of overexploitation are evident in changes to fish biodiversity. In Brazil, for example, large tambaqui are virtually absent near urban centres (Tregidgo *et al.* 2017). These ongoing changes in biodiversity have two implications for food security. First, changes in species composition reflect a sequential replacement of large and high-biomass species such as catfish and boquichico with smaller, faster growing species. This pattern of "fishing down a size" could result in declining long-term resilience, and eventual biomass collapses (Heilpern *et al.* 2021a). The second implication for food security is that fish provide people with a variety of nutrients beyond protein, but they vary in nutritional quality (Tacon and Metian

Box 21.2 Food security and fisheries (cont.)

2013; Khalili Tilami and Samples 2018; Hicks *et al.* 2019). By changing biodiversity, anthropogenic threats to freshwater ecosystems may affect both the amount of nutrients available to people and the probability of meeting nutritional adequacy (Heilpern *et al.* 2021a).

Increased urbanization in the Amazon basin is also shifting food habits. While riverine communities still consume high amounts of wild-caught fish and some bushmeat, urban and peri-urban communities are consuming higher proportions of aquaculture-fish, chicken and other derivative products (Nardoto *et al.* 2011; Van Vliet *et al.* 2015, Pettigrew *et al.*, 2019, Oestreicher *et al.* 2020). Such changes in the food habits of Amazonian people, together with reduced diversity in the fish species consumed, could exacerbate existing nutritional deficiencies since farmed animal foods can have lower nutritional value, particularly omega-3 fatty acids and minerals (e.g., iron, selenium; Heilpern *et al.* 2021b, Pettigrew *et al.* 2019).

The shift to domesticated sources of animal foods has another profound implication for food security – a shift from subsistence, wild-caught foods to foods that are more capital intensive and depend on access to cash. Because they are less affordable, this shift can ultimately affect livelihoods and access to healthy diets. Compounding these issues, the nutritional transition to a more industrialized diet is also associated with higher fat and sugar intake, which can exacerbate the dual burden of malnutrition and obesity playing out through the Amazon.

ulation exposure to smoke from fires - particulate matter levels during these months (Figure 1) are usually well above the World Health Organisation's recommended levels. Emergency room visits increase during the dry season, especially among children under the age of 10. They are positively correlated with PM2.5 concentrations (i.e., particulate matter <2.5 micrometers in diameter), which correspond to fine particles present in smoke (Mascarenhas 2008). Fine particles can remain in the atmosphere for up to one week and may be transported far downwind to urban areas, where they may impact the health of populations far from the fire origin (Freitas 2005; Liana Anderson and Marchezini 2020).

Other components of smoke are PM10 (i.e., particulate matter <10 micrometers in diameter), soot and Black Carbon – all of which are also very toxic to humans. PM10, for example, has the potential to cause DNA damage and cell death (Alves 2020), leading to the development of PM10-mediated lung cancer (Alves *et al.,* 2017). These inhalable particles were classified as class 1 carcinogens in 2016 (IARC Working Group on The Evaluation Of Carcinogenic Risks To Humans; International Agency For Research On Cancer 2016). They can penetrate the alveolar regions of the lung, pass through the cell membrane, reach the bloodstream, and accumulate in other organs. PM2.5 and Black Carbon are associated with reduced lung function in children 6 to 15 years old (Jacobson 2012; 2013; 2014). School children from municipalities with high levels of deforestation, and therefore exposed to deforestation fires and smoke, have a high asthma prevalence (Rosa *et al.* 2009; Farias *et al.* 2010). Smoke can also affect children's well-being indirectly, for example, by reducing outdoor time and, thus, compromising cognitive development. Pregnant women are also highly vulnerable to smoke pollution. Silva *et al.* (2014) showed that exposure to PM2.5 and carbon monoxide (CO) from biomass burning during the second and third trimesters of pregnancy increased the incidence of low birth weight by 50%. This is consistent with previous studies demonstrating that the exposure of pregnant women to deforestation and forest fires during pregnancy may increase the risk of premature birth and jeopardize the child's development.

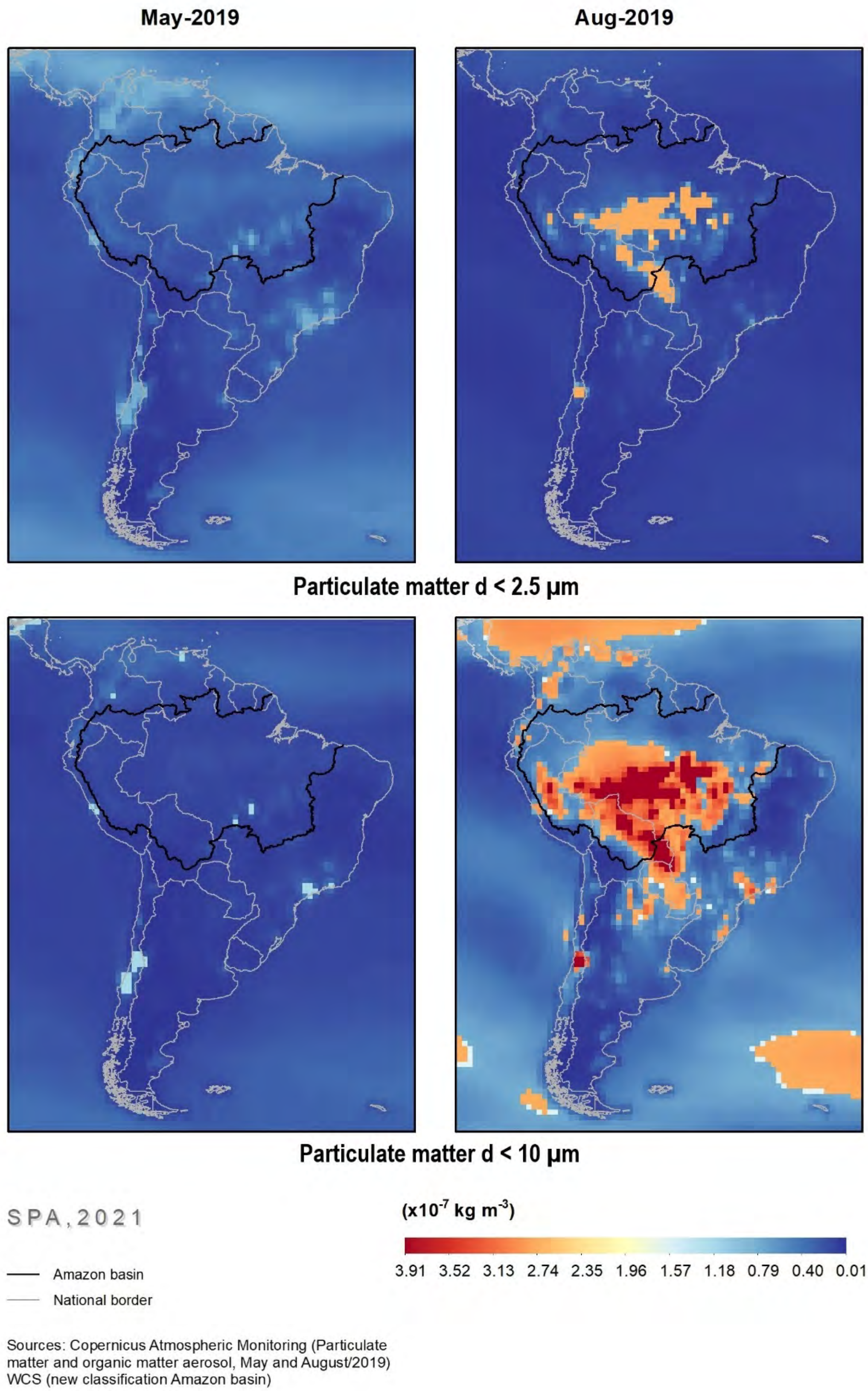


Figure 21.1 Smoke plume and particulate matter circulation (PM2.5, PM10) over South America and Amazonia (black limits - limit adopted by SPA for the Amazon basin) in May 2019 (left panels) and August 2019 (right panels). Sources: Copernicus (2020) and WCS-Venticinque *et al.* (2016).

21.5 Interactions between impacts

The drivers of terrestrial and aquatic ecosystem degradation in the Amazon can have synergistic impacts on human well-being. Interactions among drivers and impacts of degradation are complex phenomena affecting people and biodiversity via multiple, context-specific pathways. For example, gold mining and logging introduce environmental degradation that facilitates the transmission of vector-borne diseases such as malaria (Galardo 2013; Adhin 2014a; Sanchez 2017), Leishmaniasis (Rotureau 2006; Loiseau 2019), Hantaviruses (Terças-Trettel 2019) and even Chagas disease (Almeida 2009). Historically, such activities also attract large numbers of immigrants from non-endemic regions (Godfrey 1992), many of whom are susceptible and immunologically naïve (Bury 2007). If large outbreaks and epidemics take place, insecticide and antimicrobial resistance can follow if drug use is not controlled (Adhin 2014b).

Insecticide resistance arising from excessive use of pesticides in croplands (Schiesari and Grillitsch 2011) can spill over to other vector populations as well (Schiesari 2013). New ecological niches are created that pave the way for the introduction of disease vectors that are well-adapted and can sustain diseases over the long term (Vittor 2006, 2009). Heavy metal poisoning, alcohol and drug use and abuse, prostitution, and human trafficking can further exacerbate conditions, decreasing human well-being (Terrazas *et al.* 2015). Local Indigenous populations are affected, and many are displaced and forced to leave or clash with illegal settlers (Terrazas *et al.* 2015). Variations of these scenarios have been observed clearly in Madre de Dios, Peru, the Guiana Shield, the various gold mining sites in the Brazilian state of Pará, and in Yanomami Lands in Roraima, Brazil (Reuters 2021; Terrazas 2015). Countless areas of the Amazon replicate similar conditions at a smaller scale.

Land transformation for agriculture creates a similar setting for the encroaching of "frontier" malaria (Bourke *et al.* 2018) and possibly Leishmaniasis. Several studies have shown that populations close to forest edges, such as those engaged in gold mining (Hacon 2020) are at higher risk of contracting infectious diseases due to their increased contact with vectors and hosts (Ellwanger 2020). Over time, large-scale industrial agriculture exacerbates climate change, increases contamination by pesticides (Schiesari and Grillitsch 2011; Schiesari 2013), and reduces the diversity of the food supply. These factors contribute to the double burden of malnutrition and increased risk of obesity and cardiovascular disease later in life (Oresund 2008).

Roads and even rivers eventually facilitate the transit of *Aedes* mosquitoes to colonize small and previously difficult-to-reach towns and settlements (Guagliardo 2014; Sinti-Hesse 2019). Forest fire exposure introduces acute respiratory conditions and can also induce long-term vulnerabilities such as asthma (D'Amato 2015; Rappold 2017). Among cases of Covid-19 (Box 3), many of these comorbidities have severely increased the risk of adverse outcomes and may have contributed to the devastating impact of the pandemic in the Amazon basin (Filho 2017).

Many of the synergies described above have been in place for decades. For example, the gold rush in Madre de Dios dates back to the 1930s. Such synergies have often magnified the inequities that historically plagued the Amazon basin within each country (Dávalos 2020). What is different today is the magnitude and scale of degradation already inflicted, their cumulative effects, and the declining potential to reverse these processes. Decades of degradation have led the Amazon to a critical point today, generating an urgent need to implement integrated strategies and actions for addressing these challenges. The recent growth in the number and extent of drivers of deforestation has further contributed to this critical scenario.

26.6 Uncertainties and knowledge gaps

Complex relationships prevent broad generalizations about the comprehensive impact of environmental degradation on human well-being and health. While extensive evidence exists, it is often

Box 21.3 The impact of COVID-19 in the Amazon region

Cecilia S. Andreazzi, Tatiana C. Neves and Cláudia T. Codeço

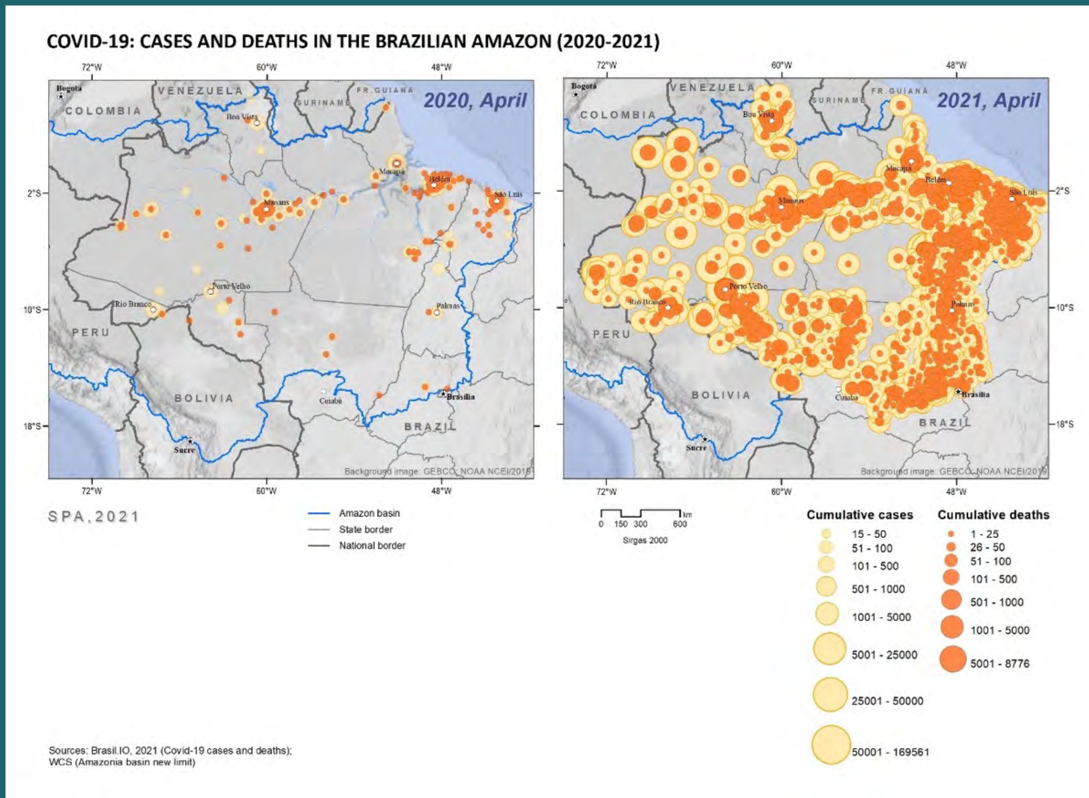
In December 2019, after investigations on a sudden increase in the number of pneumonia cases in the city of Wuhan, Hubei province, China, it was discovered a new emergent respiratory viral disease caused by a previously unknown coronavirus, the severe acute respiratory syndrome-coronavirus-2 (SARS-CoV-2). The new coronavirus disease-2019 (COVID-19) epidemic rapidly evolved to a Public Health Emergency of International Importance. On March 11, 2020, due to its geographical spread across different continents with sustained human transmission, the World Health Organization declared the COVID-19 pandemic. SARS-CoV-2 reached the Amazon region in Ecuador on March 7 and by the end of March, almost all the Pan Amazonian countries were already affected (Ramírez *et al.* 2020). In all those countries, the Amazon region accounted for most of the cases and deaths, led by Brazil, Ecuador, and Colombia (Ramírez *et al.* 2020). The COVID-19 epidemic severely impacted the Amazon, highlighting the region's social and environmental vulnerabilities (Codeço *et al.* 2020). Although the Amazon region encompasses many countries which adopted distinct policies to control the COVID-19 pandemic, the social and economic vulnerabilities of the populations living in this region share great similarities. Brazil holds the largest territorial area of Amazonia and the dynamics of COVID-19 spreading in the Brazilian Amazon is a good proxy of its dynamics in this region - in only four months since its arrival, this region reached a total of 32.259 confirmed cases and 1.957 deaths (Buss *et al.* 2020; Hallal *et al.* 2020).

The disproportionate impact of the COVID-19 epidemic in the Amazon region (Figure 1) is strongly related to access to health assistance (Codeço *et al.* 2020, Bezerra *et al.* 2020). Most of the population, including Indigenous Peoples, quilombolas and riverine communities (Codeço *et al.* 2020), need to travel long distances, and even across borders, to access health services (Canalez *et al.* 2020, Nicolelis et al. 2021). The Amazon region shows one of the lowest per capita numbers of Intensive Care Unit (ICU) beds. In Ecuador, for example, the departments in the Amazon region had only 10 ICU beds per 100,000 inhabitants (Navarro *et al.* 2020).

In Brazil, the number of per capita ICU beds exclusive for COVID-19 patients (Figure 2) was lower in the Amazon region (2.20 ICU/100,000 inhabitants), in comparison with the non-Amazonian regions (3.06 ICU/100,000 inhabitants). This number remained lower even after actions to increase the number of beds in response to the ongoing COVID-19 pandemic (Figure 2). The precarious health system and the high dependence on health services present only in large cities played a major role in the dynamic of the COVID-19 pandemic in Amazonia, with high numbers of incidence and mortality, and overburdened health and funeral systems.

COVID-19 infection rapidly spread from Amazonian cities to rural and forest communities (Codeço *et al.* 2020), marking the rapid interiorization of COVID-19 in the Amazon region when compared to other regions in Brazil (Figure 3). The disease spread occurred hierarchically, jumping over geographic scales because of the high connection among ports and airports, from larger cities (*e.g.* Manaus) to smaller towns. Across Amazonia, there is a dense network of waterways with overcrowded boats and intense flow to the larger cities for services, provisioning of goods, and business. These boats favor viral transmission and the spread of COVID-19 (Aleixo *et al.* 2020). The consequences of these mobility and behavioral patterns on COVID-19 spreading and evolution remains unclear, but studies suggest they might have played a role in the emergence of new variants (Naveca *et al.* 2021).

Box 21.3 The impact of COVID-19 in the Amazon region (cont.)



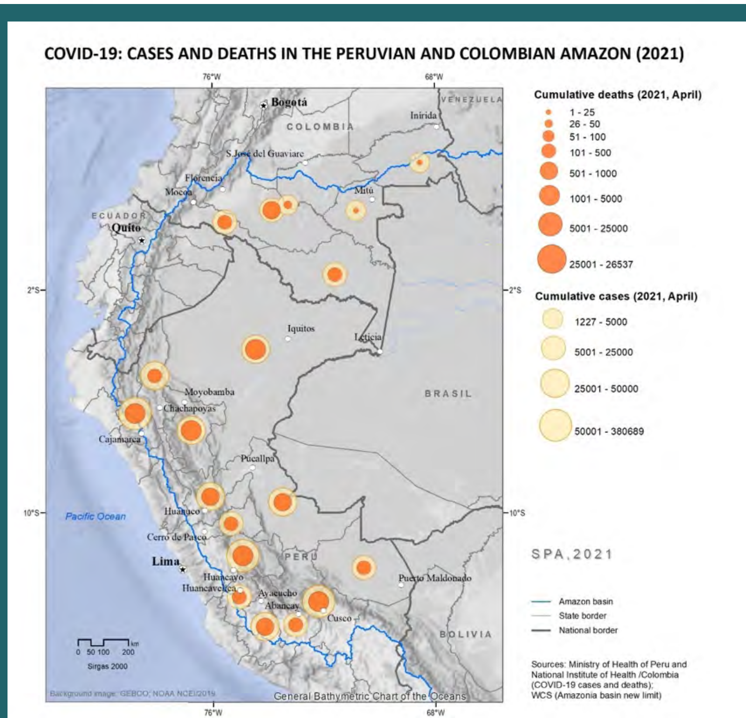


Figure 21.B3.1 COVID-19 cases and deaths in the Brazilian, Colombian and Peruvian Amazon. Sources WCS-Venticinque *et al.* (2016); Brasil.IO.;Ministry of Health of Peru and National Institute of Health Colombia.

Box 21.3 The impact of COVID-19 in the Amazon region (cont.)

Figure 21.B3.2 Boxplot showing lower Intensive Unit Care for COVID-19 per capita in health macro regions in the Legal Brazilian Amazon compared to other other Brazilian regions, both in early and late 2020. Data Source: Brazilian National Register of Health Establishments (CNES), Ministry of Health.

The COVID-19 pandemic showed a time-lagged spatial dynamic among the urban and rural Amazonian municipalities in Brazil and two waves in early and late 2020. Increased transmission periods correlate to varying levels of adoption of nonpharmaceutical interventions, such as social distancing measures and the use of face masks. A genomic epidemiology study (Naveca *et al.* 2020) investigated the successive lineage replacements of Sars-Cov-2 in the Amazonas state and the emergence of new variants of concern, in special the P.1 virus, a more transmissible variant coincident with the second wave of COVID-19. The authors suggest that the adopted levels of social distancing were able to reduce Sars-Cov-2 effective reproductive number but were insufficient to control the COVID-19 pandemic. Uncontrolled transmission and high prevalence provide the conditions for the diversification of viral lineages, especially when mitigation measures were relaxed (Naveca *et al.* 2020).

COVID-19 propagation patterns in Brazil clearly evidentiate the large disparities in quantity and quality of health resources and income among regions. Despite the evident severe public health emergence, there was a failure in the coordination of control actions, in part due to the governamental denial of the seriousness of the pandemic (Castro *et al.* 2021). The absence of mobility restrictions and total disregard to social distancing and lockdown policies contributed to the successive collapses in the health system, mortuaries and cemeteries (Ferrante *et al.* 2020). The excess of deaths included not only COVID-19 cases, but also a large fraction of patients affected by prevalent diseases that are endemic and epidemic in the Amazon region, such as malaria and dengue (Navarro *et al.* 2020, Torres *et al.* 2020), and those affected by chronic diseases such as hypertension, obesity, diabetes, cardio-

Box 21.3 The impact of COVID-19 in the Amazon region (cont.)

vascular and chronic respiratory diseases, which are also prevalent in the region and require prompt health assistance (Horton 2020).

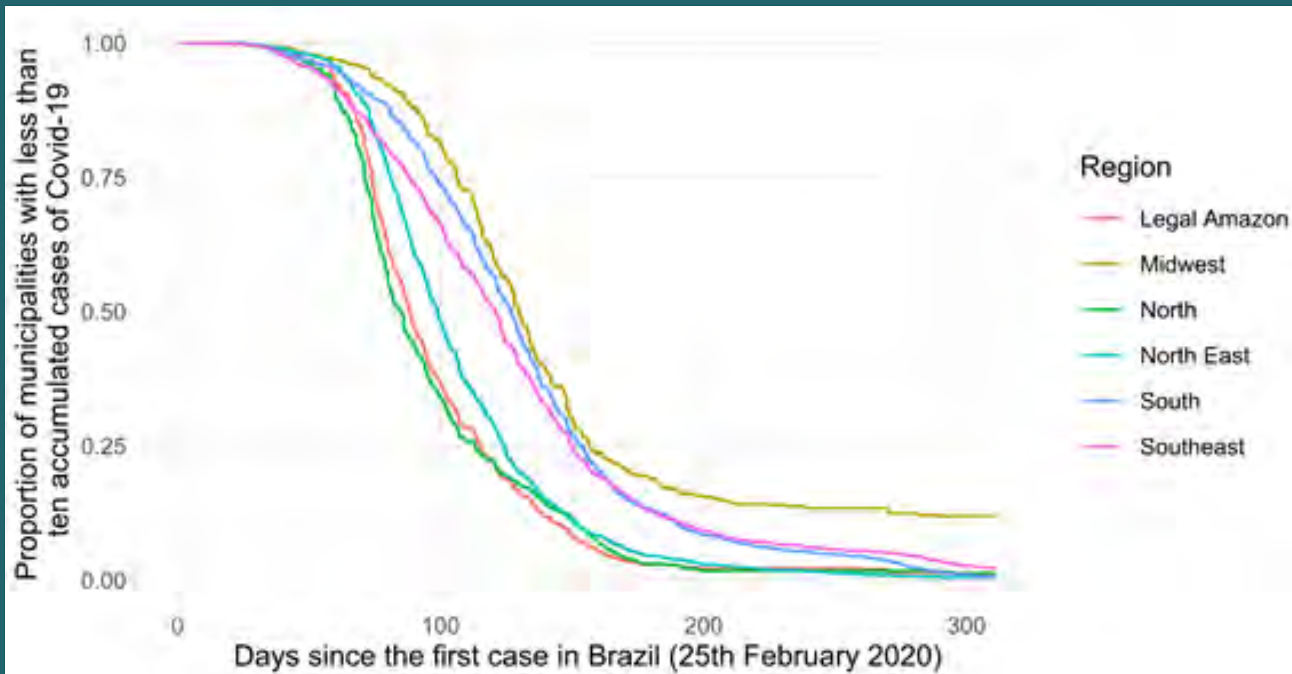


Figure 21.B3.3 Proportion of municipalities with less than ten accumulated cases of COVID-19 among the Legal Brazilian Amazon and geographic regions. The North region (in green - all of which is part of the Amazon) had the fastest rate of spread of covid, with 50% of municipalities being reached in 90 days since the start of the epidemic; followed by the Legal Brazilian Amazon (in red), includes a state located in the Midwest and part of a Northeastern state. The Southeast (in pink), South (in dark blue) and Midwest (in light brown) regions, respectively, spent more than 100 days (after the first case in Brazil) to have half the municipalities with ten or more accumulated COVID-19 cases. Even in late 2020, after more than 300 days, the Midwest region still has more than 10% of its municipalities with less than ten accumulated COVID-19 cases. Data source: Brasil.IO (https://brasil.io/home/)

limited to specific settings using a "case study" research approach (Magliocca *et al.* 2018). Characterizing these complex relationships requires both more detailed studies and studies that cover broader temporal and spatial scales, as illustrated by research on the relationships between Malaria incidence and deforestation. Furthermore, there is a great need to expand research beyond physical health to broaden our understanding of how environmental degradation affects the mental health of rural and urban Amazonians.

Analyzing and predicting diverse impacts interacting at various scales requires broad, flexible conceptual frameworks. Ecosystem approaches can be valuable to better understand the interactions, synergies, and overall complexities inherent in the relationships among forest loss, water resource degradation, and human health. Similarly, multidisciplinary research combining fields such as earth observation, data science, mathematical modelling, economics, social sciences, and anthropology will be critical to quantify these knowledge gaps and address uncertainties. Because the Amazon is highly heterogeneous, studies of the impacts of environmental degradation on human health and well-being are needed at different levels of geographic granularity. These range from Amazon-wide and country-level models to estimates for specific locations and issues of individual health and well-being. Similarly, models at different timescales will improve our perspectives on these complex issues. Such information is crucial for effectively guiding decision making at all levels.

21.7 Conclusions

- Degradation of terrestrial and aquatic ecosystems generates complex chain reactions with a range of impacts on human health and well-being increasing existing structural inequality.
- Disease outbreaks and the increased incidence of emerging, re-emerging, and endemic infectious diseases in the Amazon are associated with a range of environmental changes. The relationship between forest conversion and fragmentation and the incidence of infectious disease is complex, scale-dependent, and often modulated by socioecological feedbacks.
- Certain disease vectors (e.g., Malaria vector *Anopheles darlingi*, Chagas vector *Rhodnius*, and Leishmania vector *Lutzomya*), can increase along deforestation frontiers. However, the spatial matrix, abundance of domestic animals and specific human activities modulate the disease burden in complex ways.
- Although the burden of malaria and Cutaneous Leishmaniasis may decrease in structured urban areas, heavily urbanized settings in the Amazon can provide niches that facilitate the spread of other arboviruses transmitted by vectors such as *Aedes aegypti* and *Aedes albopictus.*
- Emerging diseases associated with the zoonotic spillover of hantaviruses and arenaviruses have been linked to specific deforestation activities
- Mercury contamination from mining activities has been shown to produce neurological, motor, sensory, and cognitive declines in exposed Amazonian populations. Unless addressed now, mercury toxicity will have lasting effects on future generations, given the scale and growth of mining activities; the processes of bioaccumulation and biomagnification; and specific health impacts on developing embryos and youth.
- The complex interactions and negative synergies between different impacts of both terrestrial and aquatic degradation and their pathways are not clearly understood yet. Moreover, there is a need to understand the relationship between the individual and cumulative impacts of different environmental disturbances.

21.8 Recommendations

- Given the important influence of socio-ecological factors on disease burden, improving human health in the Amazon will require uncovering all environmental risks, managing landscapes, and promoting equitable solutions.
- To reduce the risk of viral emergence from wild populations, region-wide improvements to public health services (including access, environmental sanitation, and health facilities) and close surveillance of infectious diseases in human population are necessary.
- Prevention of infectious diseases also requires a robust monitoring system focused on the circulation of pathogens in the environment (water, soil, and sediments), as well as populations of disease vectors and animal reservoirs.
- Complex interactions between drivers of deforestation and ecosystem degradation and the resulting disease burden in the Amazon region need to be further investigated. It is particularly important to emphasize the role of deforestation and climate change in the modelling of vector- borne diseases.
- Tailored public health strategies are needed to target each specific problem, but these measures require better integration of actions across different sectors and spheres of society.
- Innovative methods and approaches are needed to address the challenge of the broader, cumulative impacts of forest and aquatic ecosystem degradation on human health.
- It is necessary to recognize that the Amazon Basin is crucial for human subsistence, especially for traditional communities and Indigenous Peoples who depend on the Amazon's nat-

ural resources for their survival.

- Efforts are necessary to formulate legitimate participatory management policies, developed in an intercultural framework (e.g., Indigenous, academic, and institutional) to enhance strategies for climate resilience, sustainability, food security, and human health. Promoting socially just and culturally sensitive practices can be achieved through action-oriented research where academia and community actors jointly develop practical solutions.

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Amazon Assessment Report 2021

Chapter 22

Long-term Variability, Extremes, and Changes in Temperature and Hydro Meteorology

Cheia do rio Negro no centro de Manaus 2021 (Foto: Alberto César Araújo/Amazônia Real)

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Graphical Abstract

Observed and projected changes in the Amazon show that current climate and hydrology tendencies can be differentiated both spatially and temporally, exhibiting two seesaw spatial patterns, one north-south and the other west-east, and an intensification of the wet and dry seasons. In the present, the northwestern Amazon shows an increase in rainfall and runoff, while in the southern part it is the opposite. The region, including the central and eastern Amazon, does not show a significant rainfall trend as a whole. However, observations suggest an increase in rainfall extremes and intensification of droughts and floods, with little overall change in mean annual river discharges. Temperature records show an overall warming of the Amazon in recent decades, especially from the year 2000 to the present over the eastern Amazon. Evapotranspiration (ET) is reduced in the southern Amazon, probably as a result of land-use change, but uncertainties are still high due to the lack of systematic observations across the basin. This analysis is based on a literature review of findings based on different observational, reanalysis, and satellite datasets of rainfall, temperature, and river discharge records, and different methodologies (parametric and non-parametric techniques), leading to different levels of confidence, consistency, and magnitude of trends.

Projections show a drier and warmer climate in the eastern Amazon, leading to an increase in evapotranspiration. The western Amazon will also experience warmer conditions, but rainfall is expected to increase, due to more intense rainfall events, leading to increasing runoff and decreasing evapotranspiration in the northwestern Amazon. However, in the Amazon-Andes region, the spatial resolution of the CMIP5 models is insufficient to reproduce the main atmospheric features and projections show high uncertainties.

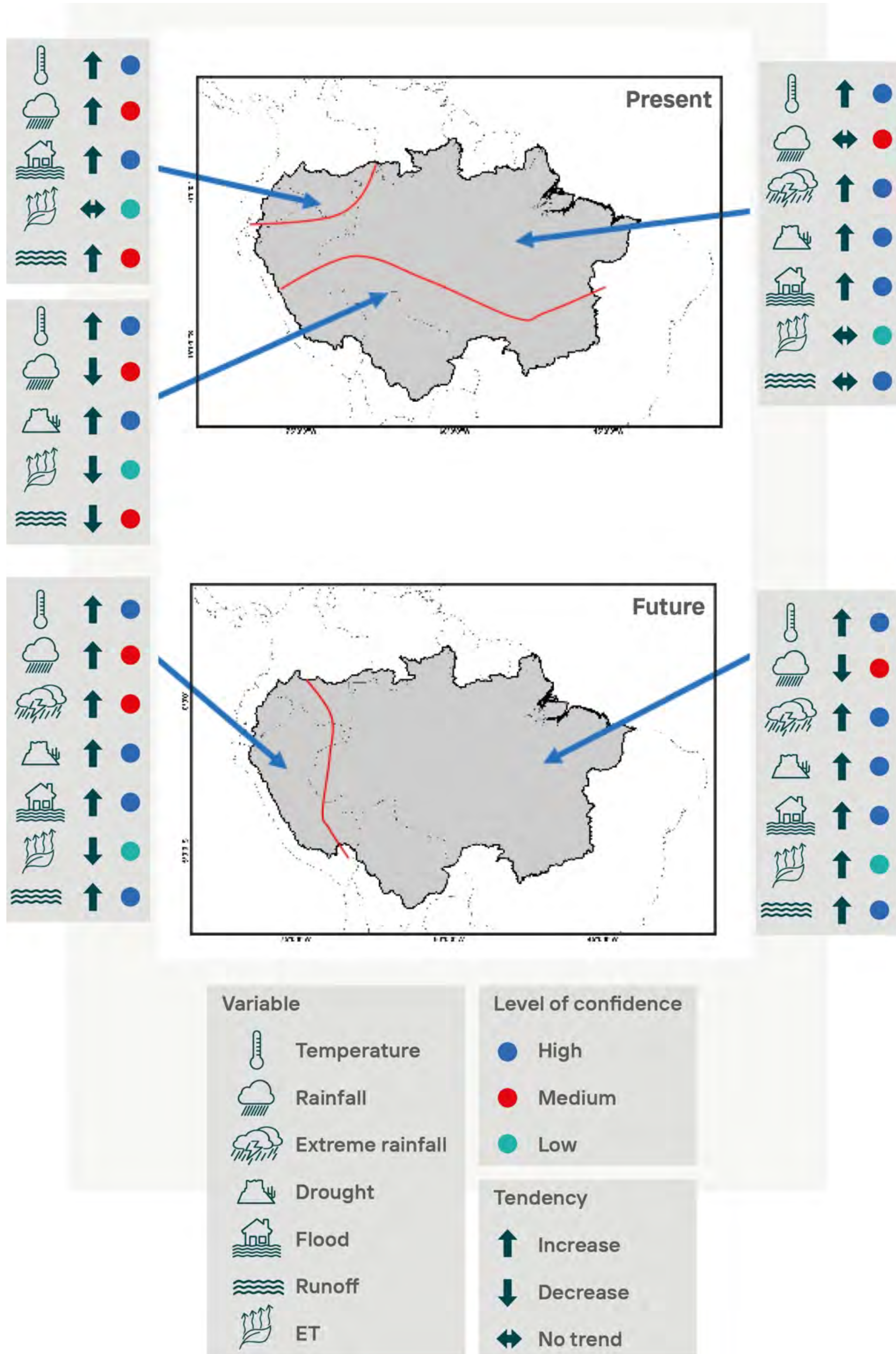

Figure 22.A Summary of observed and projected changes of climate in the Amazon, based on several studies (see Magrin *et al.* 2014; Marengo *et al.* 2018, and references quoted therein). The level of confidence in future projections is determined by the level of convergence among model signals of change from CMIP5 (Kirtman *et al.* 2013) and CMIP6 (Cook *et al.* 2020) models.

Long-term variability, extremes and changes in temperature and hydro meteorology in the Amazon region

Jose Antonio Marengo[a], Jhan-Carlo Espinoza[b], Rong Fu[c], Juan Carlos Jimenez Muñoz[d], Lincoln Muniz Alves[e], Humberto Ribeiro da Rocha[f], Jochen Schöngart[g]*

Key Messages

- Recent intensification of the Amazon's hydrological extremes are due to intensification of interannual variability; the flood return period has increased from 20 years during the first half of the 20th century to 4 years since 2000; regional discharges (Q) have increased in the northwestern Amazon during the high-water season (1974-2009) and decreased in the southwestern Amazon during the low-water season (1974-2009).
- Recent severe droughts are linked to the El Niño-Southern Oscillation (ENSO) and/or Tropical North Atlantic (TNA) sea surface temperature (SST) anomalies. The Indian Ocean also plays a role. SST indices based on the EN3.4 region along the central-equatorial Pacific Ocean do not provide enough information about impacts due to different El Niño (EN) types.
- Lengthening of the dry season and changes in the frequency and intensity of extreme drought episodes are probably the most important threats for society, Amazonian ecosystems, and wildlife. Current data show that the dry season has expanded by about 1 month in the southern Amazon since the mid-1970's.
- Warming over the Amazon is clear, but the magnitude of the warming trend varies with the dataset. The warming trend is more evident from 1980, and enhanced since 2000, with 2015-16 and 2020 among the warmest years in the last three decades.
- The climate change fingerprint is still difficult to determine due to the short duration of climate records; therefore, climate modeling studies simulating Amazonian deforestation show significant reductions in rainfall over the Amazon, affecting regional hydrology and thus increasing the vulnerability of ecosystem services for the local and regional population in and outside the Amazonian region.

Abstract

This chapter discusses observed hydroclimatic trends and also projections of future climate in the Amazon. Warming over this region is a fact, but the magnitude of the warming trend varies depending on the datasets and length of period used. The warming trend has been more evident from 1980, and further enhanced since 2000. Long-term trends in climate and hydrology are assessed. Various studies have reported an intensification of the hydrological cycle and a lengthening of the dry season in the southern

[a] National Center for Monitoring and Early Warning of Natural Disasters CEMADEN, Estrada Doutor Altino Bondesan, 500 - Distrito de Eugênio de Melo, São José dos Campos/SP, CEP:12.247-060. jose.marengo@cemaden.gov.br
[b] Institut des Géosciences de l'Environnement (IGE) - Institut de Recherche pour le Développement (IRD), 70 Rue de la Physique, Bat. OSUG- B. Domaine Universitaire 38400 Saint Martin d'Heres, France.
[c] Department of Atmospheric and Oceanic Sciences, University of California-Los Angeles, 520 Portola Plaza, Math Sciences Building, 7127, Los Angeles CA 90095, USA
[d] Global Change Unit (GCU) of the Image Processing Laboratory (IPL), Universitat de València Estudi General (UVEG), C/ Catedrático José Beltrán 2, 46980 Paterna, Valencia, Spain.
[e] Earth System Science Center/National Institute for Space Research, Av. dos Astronautas, 1758 - Jardim da Granja, Brazil.
[f] Departamento de Ciências Atmosféricas/ Instituto de Astronomia, Geofísica e Ciências Atmosféricas/ Universidade de São Paulo, Rua do Matão, 1226, São Paulo SP 05508-090, Brasil
[g] National Institute for Amazon Research (INPA), Department of Environmental Dynamics, 2936, Av. André Araújo, Manaus, Amazonas 69067-375, Brazil

Amazon. Changes in floods and droughts largely due to natural climate variability and land use change are also assessed. For instance, in the first half of the 20th century extreme flood events occurred every 20 years. Since 2000, there has been 1 severe flood every 4 years. During the last four decades, the northern Amazon has experienced enhanced convective activity and rainfall, in contrast to decreases in convection and rainfall in the southern Amazon. Climate change in the Amazon will have impacts at regional and global scales. Significant reductions in rainfall are projected for the eastern Amazon. This will have consequences for regional hydrology, and consequently, increasing vulnerability of ecosystem services for the local and regional population in and outside the Amazon.

Keywords: Amazon, climate change, land-use change, warming, moisture transport, drought, floods, climate models, climate variability, climate trends

22.1 Introduction

This chapter provides an updated review of literature on climate and hydrology in the Amazon basin, including classic and new studies developed in the recent decades, with the objective to answer key questions relevant to the current and future functioning of the Amazon forest as a regulator of local and regional climate: What are current trends in hydrometeorology, moisture transport, and temperature in the Amazon? Are there signals of intensification or alteration of the hydrological cycle? Is this due to climate variability or human induced climate change? What about the length of the dry season? Is there an increasing variability of droughts and floods in the Amazon? If so, are they due to El Niño (EN), the Tropical Atlantic, land use change, or a combination of factors? How did EN and drought vary in the past as suggested by paleoclimate records? What are the expected changes to the Amazonian climate due to increasing greenhouse gases (GHG) and deforestation? What would be the impacts at the regional and global scales?

22.2 Long Term Variability of Temperature and Extremes: Warming Trends

Several studies have identified positive air temperature trends in the Amazon, with the magnitude dependent on the data (stations or gridded based data, reanalyzes or satellite observations), methodologies (linear and non-linear), length of the climate records, region, and season of the years. An early study by Victoria *et al*. (1998) used station data for the Brazilian Amazon and quantified an increasing trend of +0.56ºC/century during 1913-1995. Malhi and Wright (2004) study trends in temperature over Amazonian tropical forests. They use the Climate Research Unit (CRU) dataset for 1960-1998, and for the subperiod 1976-1998. They identify positive temperature trends, that were steeper in 1976-1998 for the region. Jiménez-Muñoz *et al*. (2013) updated the analysis provided by Malhi and Wright (2004) by using the European Center for Medium Range Forecast Reanalysis ECMWF reanalysis (ERA-Interim) for 1979-2012, and also Moderate-Resolution Imaging Spectroradiometer (MODIS) remote sensing data from the 2000s. They identify warming patterns that vary seasonally and spatially. Strong warming over southeastern Amazon was identified during the dry season (July to September), with a warming rate of +0.49ºC/decade during 1979-2012, according to the ERA-Interim data (Gloor *et al*. 2015).

A summary of these studies and the tendencies for the entire Amazonian basin or at the regional level are summarized in Table 22.1. For the purpose of this work, the northern and southern Amazon are defined as the basin north and south of 5ºS, respectively. This definition considers the difference in seasonal rainfall cycles and the fact that the dry season south of 5ºS may have months with precipitation lower that 100 mm, which does not occur north of 5ºS (See Chapter 5).

All data show that the recent two decades were the warmest, though there are some systematic differences among the trends estimated by different data.

Table 22.1 Summary of studies dealing with temperature trends in the Amazon. It includes region of the Amazon, period of data, type of data, magnitude of the trend and reference.

Region	Period	Data used	Trend	Reference
Brazilian Amazon	1913-1995	Station	+0.56 °C/century	Victoria *et al.* (1998)
Western and Central Amazon	1960-1998	CRU	-0.15 °C/decade	Malhi and Wright (2004)
Northeastern Amazon	1960-1998	CRU	+0.1 °C/decade	Malhi and Wright (2004)
All Amazon	1976-1998	CRU	+0.26 °C/decade	Malhi and Wright (2004)
Southern Amazon	1976-1998	CRU	+0.4 °C/decade	Malhi and Wright (2004)
Northeastern Amazon	1976-1998	CRU	+0.2 °C/decade	Malhi and Wright (2004)
Brazilian Amazon	1961-2000	Station	+0.3° °C /decade	Obregon e Marengo (2007)
Tocantins River basin	1961-2000	Station	+1.4 °C /decade	Obregon e Marengo (2007)
All Amazon	1979-2012	ERA-Interim	+0.13 °C/decade	Jiménez-Muñoz *et al.* (2013)
All Amazon	2000-2012	ERA-Interim	+0.22 °C/decade	Jiménez-Muñoz *et al.* (2013)
Southeastern Amazon (July-September)	2000-2012	ERA-Interim	+1.22 °C/decade	Jiménez-Muñoz *et al.* (2013)
Southeastern Amazon (July-September)	2000-2102	MODIS	+1.15 °C/decade	Jiménez-Muñoz *et al.* (2013)
All Amazon	1980-2013	CRU	+0.7 °C	Gloor *et al.* (2015)
Southeastern Amazon (July-September)	1973-2013	Station	+ 0.6◦C	Almeida *et al.* (2017)
All Amazon	1950-2019	CRU, GISS	+ 0.6◦C	Marengo *et al.* (2018)
Bolivian Amazon	1965-2004	Station	+0.1 °C/decade	Seiler *et al.* (2013)
Peruvian Amazon	1965-2007	Station	+0.09 °C/decade	Lavado-Casimiro *et al.* (2013)
Manaus	1980-2015	Station	+0.5 ˚C	Schöngart and Junk (2020)

The EN year 2015/16 was the warmest year followed by EN year 1997/98 (Almeida et al., 2017; Marengo et al., 2018). Analyses of temperature data from CRU and ERA 20C/ERA-Interim reanalysis showed that 2016 was the warmest since 1850, with warming up to +1ºC annually, and months surpassing +1.5 ºC (Jiménez-Muñoz et al., 2016). Later analyses will show that 2020 was the among the five warmest from the recent decades.

Historical records show an increasing trend for all seasons. A greater warming rate was detected for June-August (JJA) and September-November (SON) seasons (Figure 22.1). A contrasting West-East pattern is observed. Warming rates were almost twice over eastern Amazon that over to western Amazon. Warming for 1980-2020 is higher than that for the period of 1950-1979, especially over eastern Amazon. This recent increase on the warming rate is not observed over southwestern Amazon during December-February (DJF) and March-May (MAM), with even a slight reduction on the warming rate for the period 1980-2019. However, trends for the period 1950-1979 are not statistically significant.

Warm (cold) anomalies correspond to El Niño (La Niña, or LN) events, but this link is more clearly evidenced in the case of warming due to EN than cooling due to LN. Significant, anomalously warm temperatures were recorded over the last two decades (2000-2019), especially over the eastern Amazon. Higher warming rates over the eastern Amazon are attributed to the effects of land cover change, and subsequent alteration of the energy balance (Davidson *et al.* 2012). Land cover alone also plays a role over the southeastern Amazon, where tropical forests are bordered by other land covers such as Cerrado and pastures. In contrast, the western Amazon is influenced by the Andes barrier and a transition from montane tropical forests to lowland forests, where temperature trends decline with elevation (Malhi *et al.* 2017).

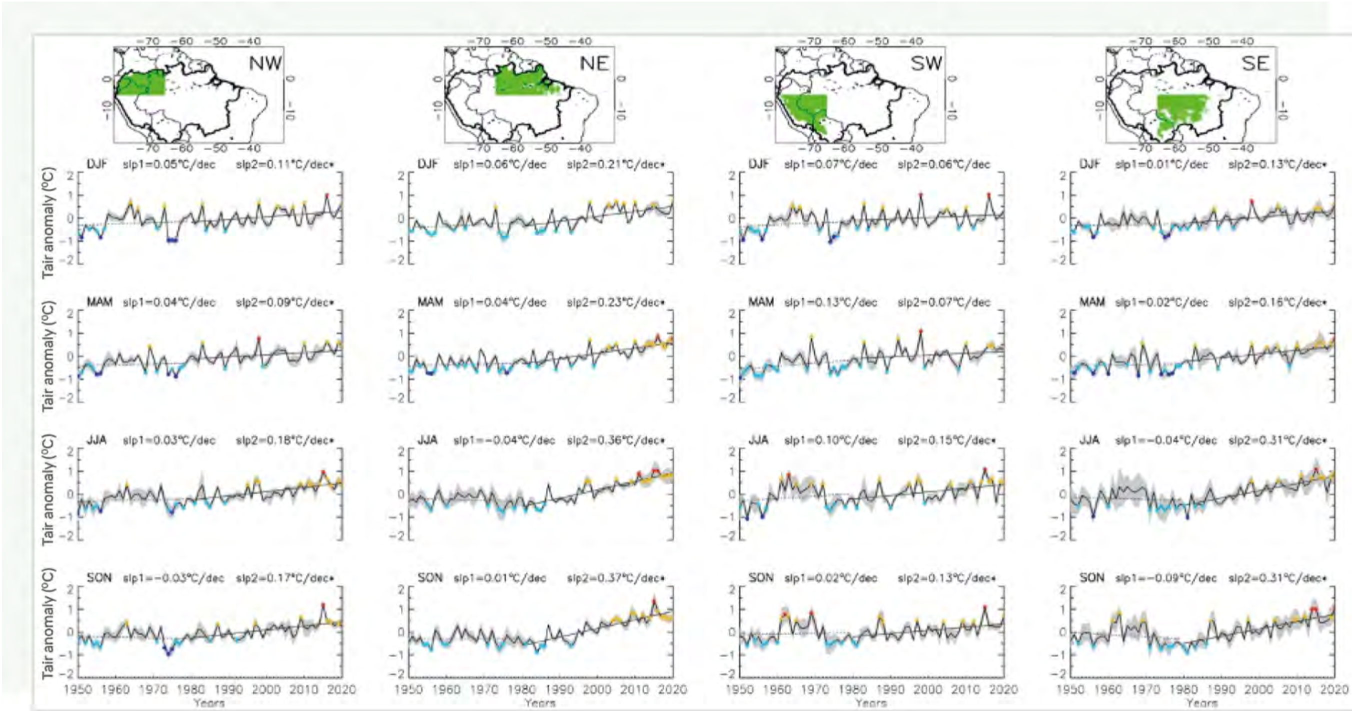

Figure 22.1 Temporal series of seasonal (DJF, MAM, JJA, SON) air temperature anomalies over different sectors of the Amazon (NW, NE, SW, SE) using data from the CRU Version 4 (CRUTS4) data for the reference period 1981-2010. Orange and red circles indicate temperature anomalies that surpass 1 standard deviation (σ) and 2σ, respectively, whereas light blue and dark blue circles indicate temperature anomalies below -1σ and -2σ, respectively. Linear trends for the period 1950-1979 and 1980-2020 are represented by a dashed line and a continuous line, respectively. Values of the slope for these two periods (slp1, slp2) are also included.

Local observations show that the average monthly temperatures in Manaus rose 0.5˚C during the period 1980-2015, and the minimum and maximum monthly temperatures 0.3˚C and 0.6˚C, respectively, in relation to the long-term average for the period 1910-1979. The highest temperatures recorded in Manaus since 1910 occurred during the dry season (September) of the year 2015. Strong EN events, as in 1997/98 and 2015/16, have a strong influence on air temperatures in the central region of the Amazon basin (Jiménez-Muñoz *et al.* 2016). In September 2015, the monthly average daily mean maximum and minimum temperature were 2.2-2.3˚C higher compared to the same month's averages for the previous five years (2010-2014). The average maximum temperature for October 1997 was 3.1˚C above this month's average for the previous five years 1992-1996 (Schöngart and Junk 2020). Gatti *et al.* (2021) found similar annual mean warming trends for the whole Amazon (1.02 ±0.1°C) consistent with the global average (0.9°C) between 1979 and 2018. However, warming trends differ between months, and the largest increases were observed for the dry season months of August, September, and October ASO (1.37±0.15˚C).

A recent study by Khanna *et al.* (2020) intercompares temperature trends from different datasets over the tropics. They show significant differences among datasets but a strong warming trend in wet climate regions such as the Amazon. Surface warming over these regions is amplified because of the positive radiative effect of high clouds and precipitable water in trapping upwelling longwave radiation. This suggests a dominant role of atmospheric moisture in controlling the regional surface temperature response to GHG warming.

Other temperature indices also corroborate the warming trend over the Amazon (Dunn *et al.* 2020). A positive trend in the number of warm nights and reduction in the number of cool nights was detected, particularly in the last decade. The highest trend in warm days was observed during the JJA season. This behavior may be attributed to a combination of low seasonal/interannual temperature variability with land-use change effects. Seiler *et al.* (2013) reported a warming rate over Bolivia of 0.1ºC/decade during the period of 1965-2004, with this warming rate more pronounced over the Andes and during the dry season (JJA). Similarly, Lavado-Casimiro *et al.* (2013) found a significant warming trend in mean temperature of 0.09ºC/decade during 1965-2007 in the Peruvian Amazon-Andes transition zone.

The overall conclusion is that warming over the Amazon region is a fact. The warming trend is better evidenced from 1980, and it is enhanced from 2000, where three exceptional droughts occurred in 2005, 2010, and 2015/16. Warming in 2015-2016 reached 1.2ºC, while in 2019-2020 warming was 1.1ºC, becoming the second warmest since 1960 in the Amazon. The warming trend varies depending on the dataset (station, gridded data sets, reanalysis or satellite derived), the time period for which the trend was computed, and the spatial scale (the whole Amazon or sub-regional). Because of the different climate regimes over the Amazon, the warming trend is also seasonally and regionally dependent. The seasonal and spatial distribution of trends (with a strong warming in the southeast Amazon) is consistent with the climatic gradient across the Amazon from continuously wet conditions in the northwest (with low warming rates) to long and pronounced dry seasons in the southeast Amazon with high warming rates (Section 22.3.2).

Box 22.1 Warming in the Amazon region

Warming over the Amazon basin is a fact, but the magnitude of the warming trend varies with the dataset used and the length of the temperature records. Intercomparisons among temperature trends from different datasets shows significant differences among datasets, but overall, all datasets show widespread warming in recent decades over Amazon basin, with higher warming rates during the dry seasons (roughly, from June to September) (see Figure Box 22.1).

Warming rates also vary with the time period considered. Hence, early studies in 1998 quantified a warming of +0.56ºC/century during 1913-1995 in the Brazilian Amazon using station data, whereas more recent studies using other data sets (station data, gridded data, reanalysis and remote sensing estimates) evidenced an increasing warming in southern Amazon during the dry season, at a rate of +0.49 ºC/decade during 1979-2012. A contrasted spatial pattern between eastern Amazon and western Amazon is also observed, with eastern Amazon (and especially southeastern Amazon) providing a warming rate almost twice as higher than western Amazon. This may be attributed to effects of land cover change and interactions with fire and drought.

Warming trends for the recent period 1980-2019 are higher than trends over the period 1950-2019. The warming trend is better evidenced from 1980, and it is enhanced from 2000, where three exceptional droughts occurred in 2005, 2010 and 2015/16. All temperature datasets show that the recent two decades were the warmest, with El Niño year 2015/16 as the warmest year followed by El Niño year 1997/98. The year 2016 may have reached the highest value of the anomaly in the last century, up to +1ºC annually, with particular months surpassing +1.5 ºC. Other temperature indices also corroborate the warming trend over the Amazon, with increases in the number of warm nights and decreases in the numbers of cool nights, especially over the last decade. One of the strongest trends in warm days was observed over the Amazon in all seasons, but especially during the winter dry season.

In the light of the above discussion, future warming of the Amazon in 4°C or higher may induce changes in the hydrological cycle and in the functioning of the forest. Evaluating the consequences of such substantial climatic change, several negative effects in the Amazon can be anticipated, including short-term hydrological changes similar to the events associated to the extreme 2005, 2010 and 2016 droughts, and longer time-scale modifications of broad scale characteristics such as different biome distribution.

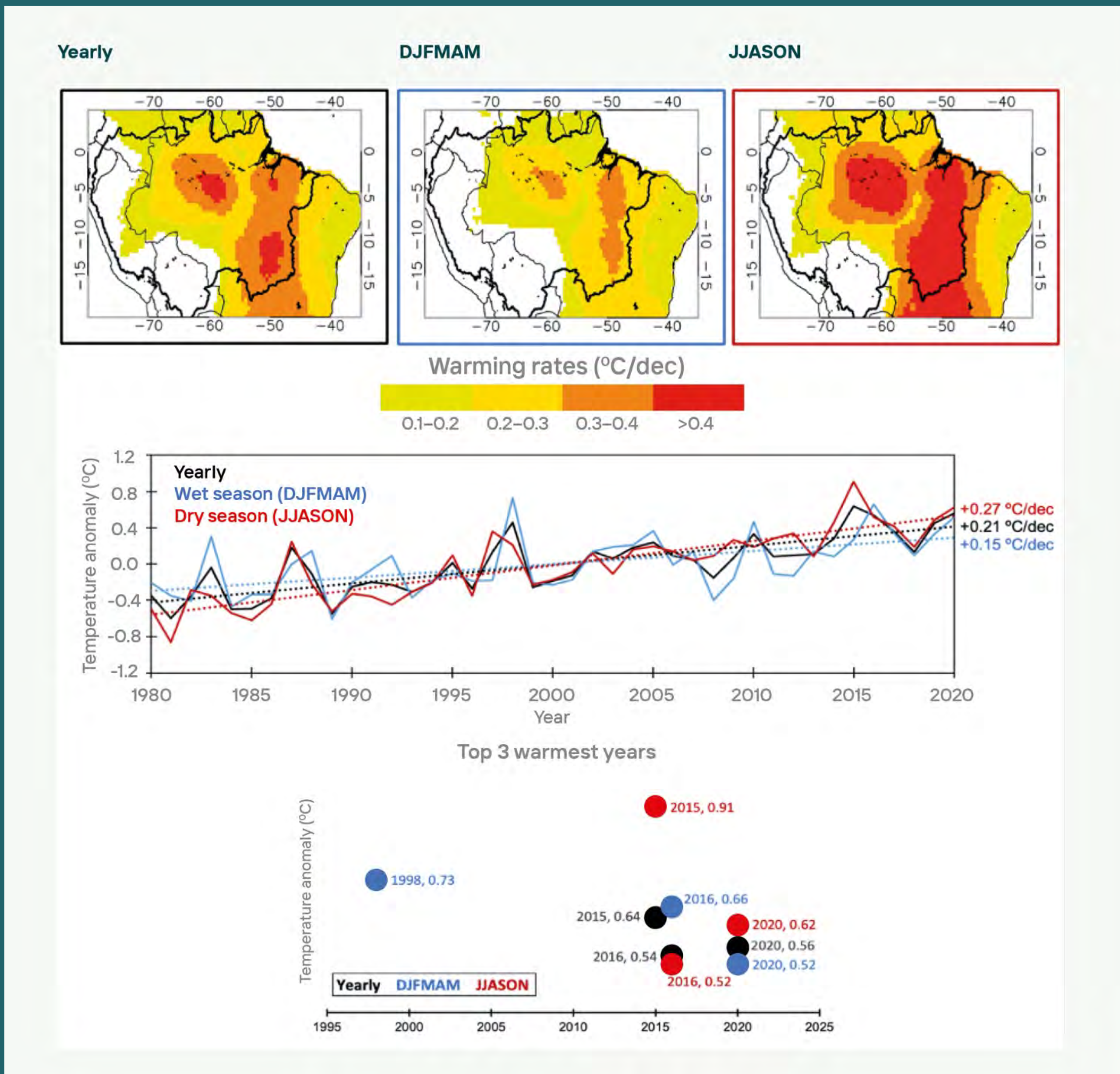

Figure Box 22.1 Temporal series of air temperature anomalies over the Amazon forests (broadleaf evergreen forest land cover class) from 1980 to 2018 using the last version of the CRUTS dataset (v4.04). Temporal series have been extracted at yearly level (black) and half-yearly levels (first half of the year, DJFMAM, in blue, and second half of the year, JJASON, in red). Dashed lines indicate the linear trend, including also the value of the trend in °C per decade.

22.3 Long-Term Variability of Hydrometeorology of the Amazon and Andean-Amazon Region

22.3.1 Long-term variability and trends of rainfall and rivers

Paleoclimate records based on pollen, speleothems, charcoal, lake and flood sediments, archeological sites, and tree rings were used to reconstruct Amazonian climate. There are indications that the region was affected by severe drought events. These were longer and probably of stronger magnitude than any observed in the instrumental period. Parsons *et al*. (2018) found that the region has regularly experienced multi-year droughts over the last millennium. Meggers (1994) suggests the occurrence of prehistoric mega-EN events around 1500, 1000, 700, and 500 B.P. (before present) influenced tributaries in the Amazon and flood-sediments from the north coast of Peru. Granato-Souza *et al*. (2020) used tree-ring chronologies of *Cedrela odorata* from the eastern Amazon (Paru River basin), to reconstruct wet season precipitation totals for 1759-2016. They show remarkable drought events in the past such as an 18-year drought period (1864–1881), that includes also the EN event 1877-1879.

Historical trends in Amazonian precipitation have been reported in the literature. These vary considerably among studies, depending on the dataset, time series period and length, season, and region evaluated (Malhi and Wright 2004; Espinoza *et al*. 2009; Fernandes *et al.* 2015; Marengo *et al.* 2018). For recent periods, most rainfall records start in the 1960s. The short period of record keeping hampers the quantification of long-term trends in the Amazonian region. Various rainfall datasets (e.g., Climate Research Unit, Global Precipitation Climatology Center [GPCC], Global Precipitation Climatology Project [GPCP], Climate Hazards Group InfraRed Precipitation with Station data [CHIRPS], Tropical Rainfall Measuring Mission [TRMM], satellite and reanalysis products) rely on few rain stations with short records and low spatial coverage. These datasets have been “gap-filled” by interpolation and satellite data estimates. The fact that these studies consider different periods in their tendency analysis complicates the identification of a consistent, long-term precipitation trend in the Amazon and its subregions.

Extremes of interannual rainfall and river variability in the Amazon can be, in part, attributed to sea surface temperature variations in the tropical oceans. This manifests as the extremes of the El Niño-Southern Oscillation in the tropical Pacific, and the meridional SST gradient in the Tropical North Atlantic. No unidirectional total rainfall trends have been identified in the region as a whole. However, at regional and seasonal level the situation may be different (Espinoza *et al*. 2009; Satyamurty *et al*. 2010; Almeida *et al*. 2017; Marengo *et al*. 2018). Long-term, decadal variations linked to natural climate variability have significant influence on rainfall trends because most of the rainfall records over the Amazon are only available up to four decades. Decadal changes in Amazonian precipitation have been attributed to phase shifts of the Pacific Decadal Oscillation (PDO), Interdecadal Pacific Oscillation (IPO), and Atlantic Multidecadal Oscillation (AMO) (Andreoli and Kayano 2005; Espinoza *et al*. 2009; Aragão *et al*. 2018). Fernandes *et al*. (2015) show that rainfall decadal fluctuations over the western Amazon vary closely with those of the north-south gradient of tropical and subtropical Atlantic SST. This is also evident in the 250-yr record of reconstructed precipitation totals from tree-ring data (Granato-Souza *et al*. 2020).

Studies analyzing rainfall trends in the Amazon for the past four decades show a north-south opposite trend, including increasing rainfall in the northern Amazon and diminution in the southern Amazon. These trends may be a consequence of the intensification of the hydrological cycle in the region (Gloor *et al*. 2013; Barichivich *et al*. 2018; Garcia *et al*. 2018). This intensification means increased climate variability, reflected by the increase in recent extreme hydro-climatic events due to stronger northeast trade winds that transport moisture into the Amazon (such as is observed in Figure 22.2 a). Alves (2016) detected a statistically significant negative rainfall trend in the southern Amazon at the dry-to-wet season transition during 1979–2014. Recent work by Espinoza *et al*. (2019a) shows that while the southern Amazon exhibits negative trends in total rainfall and extremes, the opposite is found in the northern Amazon, particularly during the wet season. Wang *et al*. (2018) combine both satellite and *in situ* observations and reveal changes in tropical Amazonian precipitation over the northern Amazon. According to these authors, rainfall has significantly increased by +180 to +600 mm in the wet season during the satellite era (1979 to 2015). Due to increasing rainfall in the northern Amazon, the overall precipitation trend on a basin scale showed a 2.8 mm/year increase for the 1981–2017 period (Paca *et al*. 2020).

Water level data for the Rio Negro at Manaus, close to its confluence with the Solimões (Amazonas) River, started being recorded in September 1902 (Figure 22.2). The mean amplitude between annual maximum (floods) and minimum (droughts) water levels is 10.22 m (1903-2015) (Schöngart and Junk 2020). Barichivich *et al*. (2018) indicate a significant increasing of daily mean water level of about 1 m over this 113-yr period. Furthermore, the authors observed a fivefold increase in severe flood events resulting in the occurrence of severe flood hazards over the last two decades in the central Amazon (2009, 2012-2015, 2017, 2019) and droughts in 2005, 2010, and 2015-16. During the last three decades, the mean amplitude of water levels at Manaus increased. The Rio Negro rose by almost 1.5 m compared to the period before (Schöngart and Junk 2020). This growth is mainly caused by a basin-wide increase in river runoff during the wet season and a slight decrease in discharge during the dry season, defined as the intensification of the hydrological cycle (Gloor *et al*. 2013), although trends vary substantially among subbasins (Espinoza *et al*. 2009; Gloor *et al*. 2015).

As seen in previous sections, the intensification of the hydrological cycle in the Amazon has been reported in several studies. Substantial warming of the tropical Atlantic since the 1990s plays a central role in this trend (Gloor *et al*. 2013; Wang *et al*. 2018). The warming of the tropical Atlantic increased atmospheric water vapor, which is imported by trade winds into the northern Amazon basin. This raises precipitation and discharge, especially during the wet season (Gloor *et al*. 2013, 2015; Heerspink *et al*. 2020). The simultaneous cooling of the equatorial Pacific during this period increased differences in sea level pressure and SSTs between both tropical oceans, resulting in a strengthening of the atmospheric circulation that induces rainfall, with the trade winds and deep convection over the Amazon, referred as the Walker circulation. This circulation represents a direct cell zonally oriented along the equator induced by the contrast between the warm waters of the western Pacific and the cooler waters of the eastern Pacific (McGregor *et al*. 2014; Gloor *et al*. 2015; Barichivich *et al*. 2018).

River discharge records at the Negro, Solimões, Madeira, and Amazon rivers show significant negative trends ($p<0.05$) during low-water periods since the mid-1970s (Espinoza *et al*. 2009; Lavado-Casimiro *et al*. 2013; Marengo *et al*. 2013; Gloor *et al*. 2015; Molina-Carpio *et al*. 2017). These studies show floods in the four rivers as indicated by their maximum water levels reached in 2014. Additionally, it can be observed that the maximum water level of the Rio Negro (Manaus) in 2005 was 28.10 cm above the long-term average (1903-2015). Finally, a weak positive trend can be noticed in the levels at Manaus and Óbidos since the late 1980's (Figure 22.2).

Hydroclimatic trends in the Andean-Amazon region are highly sensitive to the specific region and period considered. Long-term information is generally available from 1970 or 1980 onwards from a low-density meteorological network. Such low density and short records make it particularly difficult to identify clear trends in rainfall in most of the inter-Andean valleys of the upper Amazon basin (Lavado-Casimiro *et al*. 2013; Carmona and Poveda 2014; Posada-Gil and Poveda 2015; Heidinger *et al*. 2018). In various northern Andean-Amazon basins, precipitation trends have opposite signs (Carmona and Poveda, 2014; Pabón-Caicedo

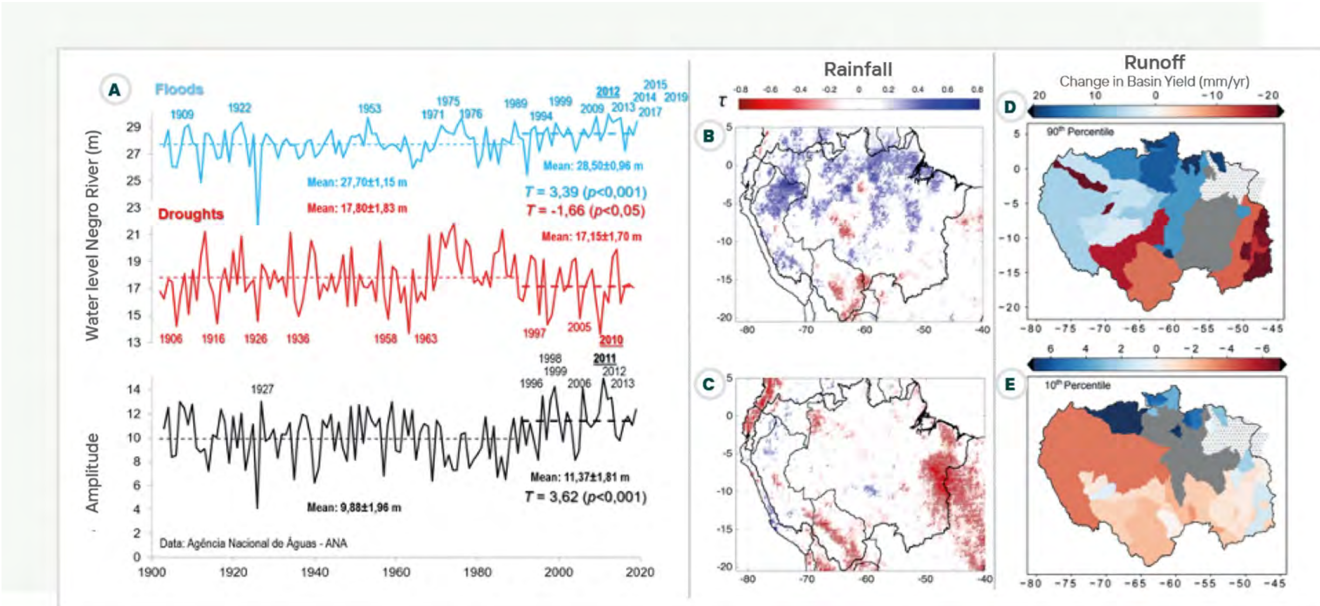

Figure 22.2 a) Maximum (floods, blue) and minimum (droughts, red) annual water level variability of the Rio Negro at Manaus (1903-2020). Years corresponding to extreme hydrological events are indicated. The annual water level amplitude (droughts minus floods) is displayed in black. Adapted from Schöngart and Junk (2020) based on data from the Brazilian National Agency of Waters (ANA). b) Spatial distribution of Kendall coefficient values (p<0.05 are indicated with a dark dot) showing the trend for 1981–2017 wet day frequency (>10 mm/day) during March-May season. c) As b, but for rainy days (>1 mm/day) during September-November season. b) and c) use CHIRPS data. Adapted from Espinoza *et al.* (2019a). © Climate Dynamics. Reprinted by permission from Springer Nature. d) and e) slope of change in 90th and 10th percentile runoff (mm/yr), respectively, for the 1980-2014 period. Areas in grey represent no significant trend and areas with black dots represent no data. From Heerspink *et al.* (2020). © Journal of Hydrology: Regional Studies. CC license.

et al. 2020). However, in the Amazon lowlands of Colombia, Ecuador and northern Peru, precipitation has been increasing since the 1990s, as observed in most of the Amazon basin north of 5˚S (Espinoza *et al.* 2009; Wang *et al.* 2018; Jimenez *et al.* 2019; Paca *et al.* 2020), where a growth in rainfall of around 17% has been documented during the wet season (Espinoza *et al.* 2019a).

Increasing rainfall over this region has been related to an intensification of the Walker and Hadley cells. This enhances convergence and convective activity towards the equator (e.g., Arias *et al.* 2015; Espinoza *et al.* 2019a). Consequently, since the mid-1990s, river discharge in the main northwestern tributaries of the Amazon River shows higher values during the high-water season (e.g., Caquetá-Japurá and Marañón rivers, Figures 22.2 and 22.3). In Santo Antonio do Iça station (Caquetá-Japurá river) a discharge increase of 16% was reported during the high-water season for the 1992-2004 period compared to the 1974-1991 period (Espinoza *et al.* 2009; Posada-Gil and Poveda 2015). Increasing rainfall and discharge in the northwestern Andean-Amazon region contribute to an intensification of extreme floods in the main channel of the Amazon River in Brazil over the last three decades (Barichivich *et al.* 2018).

In the southern part of the Peruvian Andean-Amazon basins decreasing rainfall has been documented since the mid-1960s (e.g., Silva *et al.* 2008; Lavado-Casimiro *et al.* 2013; Heidinger *et al.* 2018), and consequently, discharge diminution was reported during the low-water season in the rivers that drain from the south, such as the Ucayali River in Peru. Annual discharge diminution was also detected downstream at Tamshiyacu (Amazonas

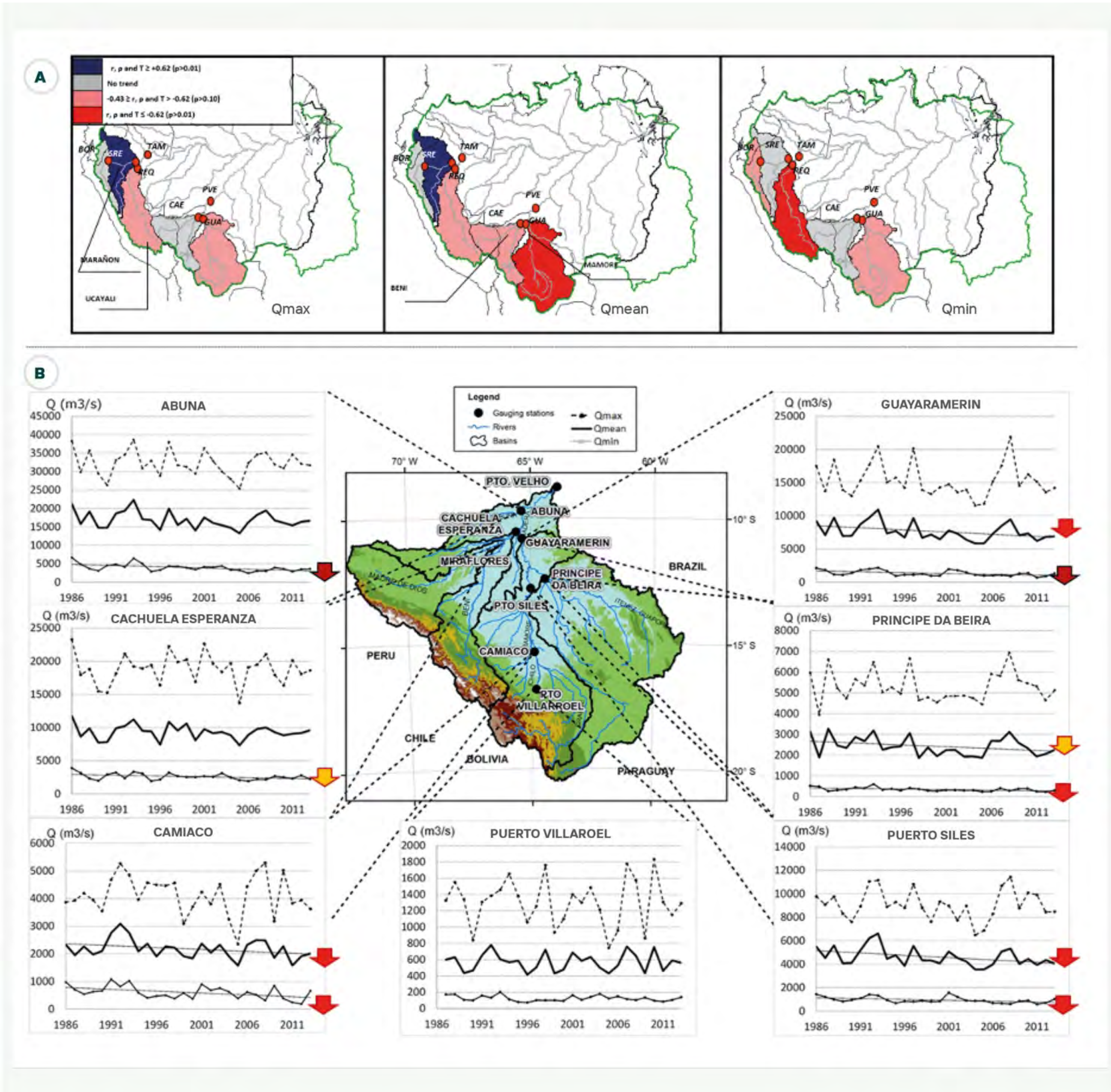

Figure 22.3 Discharge trends in Ecuadorian, Peruvian, and Bolivian Amazon-Andean rivers: a) Discharge trends for the annual maximum (Q_{max}, left panel), the mean annual (Q_{mean}, middle) and the annual minimum discharge (Q_{min}, right) computed in Borja (BOR) and San Regis (SRE) stations in Marañón river, Requena (REQ, Ucayali), Cachuela Esperanza (CAE, Beni) and Guayaramerin (GUA, Mamoré) for the 1990-2005 period. The colors indicate the sign and the strength of the trends estimated using Pearson (r), Spearman rho (ρ) and Kendall Tau (T) coefficients. Adapted from Espinoza *et al.* (2009) based on data from SNO-HYBAM observatory. © Journal of Hydrology. Reprinted by permission from Elsevier. b) 1985-2013 evolution of Q_{max}, Q_{mean}, and Q_{min} in the main rivers of the Bolivian Amazon. Arrows indicate negative trends at $p<0.1$ (yellow), $p< 0.05$ (red) and $p<0.01$ (black red) of significant levels. Adapted from Molina-Carpio *et al.* (2017) based on data from SNO-HYBAM observatory.

River in Peru) and Tabatinga (upper Solimões River in Brazil) stations (e.g., Lavado-Casimiro *et al.* 2013; Posada-Gil and Poveda 2015; Marengo and Espinoza 2016; Ronchail *et al.* 2018; Heerspink *et al.* 2020). For instance, as a result of rainfall diminution, discharge during the low water season at the Tabatinga station, which drains rainfall over the Andean-Amazon basins, diminished by 14% in the 1969-2006 period (Lavado-Casimiro *et al.* 2013).

In the Bolivian Amazon, a positive rainfall trend was identified in the 1965–1984 period, and a diminution of rainfall for the 1984-2009 period (Seiler *et al.* 2013). Rainfall diminution since the 1980s is mainly observed in the southern part of the Bolivian Madeira basin, involving the Mamoré and Guaporé basins (Figure 22.3). Related to rainfall changes, river discharge during the low-water season at the Porto Velho station in the upper Madeira river shows a significant diminution of around 20% since the 1970s (Espinoza *et al.* 2009; Lopes *et al.* 2016; Molina-Carpio *et al.* 2017). Discharge diminution at Porto Velho station was detected for the 1974-2004 period (before the start of operations at the Santo Antonio and Jirau hydropower plants) and confirmed for the 1967-2013 period. Discharge diminution is also observed in the Mamoré and Guaporé rivers (southern tributaries of the Madeira river) at the Principe da Beira (Guaporé), Puerto Siles (Mamoré), Guayaramerín (Mamoré) and Abuña (upper Madeira) stations for the 1985-2013 period (Molina-Carpio *et al.* 2017). The period analyzed here was before construction of the Santo Antonio and Jirau hydropower dams along the Madeira river's main channel. Discharge diminution over this region is related to rainfall diminution and a lengthening of the dry season in the southern Amazon (see Section 22.3.2).

For the Tocantins and Itacaiúnas basin, no significant trend was observed in rainfall patterns. However, in the Tocantins River, a significant decrease in discharge was observed during the high-water season for the period 1980-2014 (Heerspink *et al.* 2020; Figure 22.2). In the Itacaiúnas River there was a significant upward trend observed in the minimum (baseflow). This may be attributed to increasing deforestation and land use change (Oti and Ewusi 2016). This conclusion is based on the non-existence of trends in both the maximum and mean flow patterns of the Itacaiúnas River, the lack of change in rainfall patterns, and the significant upward trend in the minimum (baseflow) of the Itacaiúnas River but not the Tocantins River. Studies by Timple and Kaplan (2017) show the impact of the Tucurui hydropower dam resulting in an increase of minimum water levels and decline of maximum water levels during the operational period in contrast to pre-dam conditions.

Previously, Costa *et al.* (2003) compared discharge of the Tocantins River (upstream of Tucurui dam) during periods with small and large deforestation in the catchment area. They found that deforestation increased the maximum water discharge and that it occurred earlier in the season, as compared to the period of reduced deforestation. The authors compared monthly discharge of the Tocantins River between periods with small (1949-1968) and substantial (1979-1998) land-use changes in the catchment area. Between both periods the authors observed a growth of 24% in annual mean discharge and of 28% of discharge during high-water period, although no significant difference in rainfall was observed between both periods. Other factors leading to changes in the hydrological cycles are related to land-use changes, such as large-scale deforestation in the catchment areas for agriculture and cattle ranching (Costa *et al.* 2003; Davidson *et al.* 2012, Heerspink *et al.* 2020; see also Chapters 19, 23 and 24).

Massive and abrupt changes of streamflow regimes are expected from hydroelectric power plants which change the hydrological cycle downstream of the dams, resulting in complex spatiotemporal disturbances of floodplains downstream of dams (Anderson *et al.* 2018; Resende *et al.* 2019). Multiple dams are under construction or planned for the Tapajós, Xingú, Tocantíns-Araguaia, Marañón, and many other river basins in the Amazon. These will have cumulative and cascading effects on the downstream hydrological cycle (Timpe and Kaplan

2017).

These disturbances affect the integral functioning of floodplains, leading to massive losses of biodiversity and environmental services, to the detriment of the welfare of Indigenous peoples, local communities, and society at large (see Chapter 20). Synergies of land-use and climate changes can be expected, especially for the southern tributaries, such as the Madeira, Tapajós, Xingú, and Tocantins-Araguaia basins, which experienced high deforestation rates of their catchments in recent decades, construction of several hydroelectric dams, and increasing dry season length (Timpe and Kaplan 2017).

In summary, the above-mentioned studies have documented the key role of hydroclimatic variability in the Andean-Amazon and lowland Amazonian rivers, such as the upper Madeira, upper Solimões, Caquetá-Japurá, Tocantins, and Negro rivers for a broad understanding of the hydrological system of the entire Amazon basin. This includes seasonal and interannual time scales, as well as long-term hydrological trends, extreme events, and atmospheric and surface water balances (e.g., Builes-Jaramillo and Poveda 2018).

22.3.2 Variability of the rainy and dry season

The rain falling in wet seasons helps the forest survive dry seasons as water is readily available in soils and roots (see Chapter 7). Dry seasons in the Amazon have become more intense in recent years leading to greater forest loss and increasing fire risk. Various studies have shown evidence of lengthening of the region's dry season, primarily over the southern Amazon, since the 1970s (Marengo *et al.* 2011, 2018; Fu *et al.* 2013 and references therein). This tendency can be related to the large-scale influence of meridional SST gradients across the North and South Atlantic, or the strong influence of dry season ET in response to a seasonal increment of solar radiation (Fu and Li 2004; Butt *et al.* 2011; Lewis *et al.* 2011; Dubreuil *et al.* 2012; Fu *et al.* 2013; Alves 2016; Marengo *et al.* 2018), a poleward shift of the southern hemispheric subtropical jets (Fu *et al.* 2013), and an equatorward contraction of the Atlantic Intertropical Convergence Zone (ITCZ) (Arias *et al.* 2015). Arias *et al.* (2015), Espinoza *et al.* (2019b) and Leite-Filho *et al.* (2019) identified rainfall diminution in the southern part of the Peruvian, Brazilian, and Bolivian Amazon basin during the dry season, that is associated with a delay in the onset of the South American Monsoon System (SAMS) and enhanced atmospheric subsidence over this region (Espinoza *et al.* 2019b; Leite-Filho *et al.* 2019). Indeed, these atmospheric changes are also related to increased dry season length documented over the southern Amazon basin since the 1970s.

Various studies have also investigated rainfall seasonality, showing changes in recent decades. The rainy season in the southern Amazon now starts almost a month later than it did in the 1970s, as shown by Marengo *et al.* (2011) (Figure 22.4). In the drought years 2005, 2010, and 2016, as well as in previous droughts, the rainy season started late and/or the dry season lasted longer (Marengo *et al.* 2011; Alves 2016). Fu *et al.* (2013) quantified this apparent lengthening of the dry season, with an increment of about 6.5 $\pm$2.5 days per decade over the southern Amazon region since 1979. During the 2015/16 drought, the onset of the rainy season in 2015 occurred 10-15 days later than the normal onset date. Gatti *et al.* (2021) show that annual mean precipitation has not significantly changed, but similar to temperature trends, August-October precipitation has decreased by 17%, enhancing the dry-season/wet-season contrast.

The length of the dry season also exhibits interannual and decadal-scale variations linked to natural climate variability, apparently related to the 1970's climate's shift (Figure 22.5). Wang *et al.* (2011), Alves *et al.* (2017), and Leite-Filho *et al.* (2019) suggest that land-use change influence dry season length in the Amazon, with a longer dry season and a late onset of the rainy season. A longer dry season and late onset of the rainy season may have direct impacts on the risk of fire and hydrology of the region, enhancing regional vulnerability to drought. Wright *et al.* (2017) highlight the mechanisms by

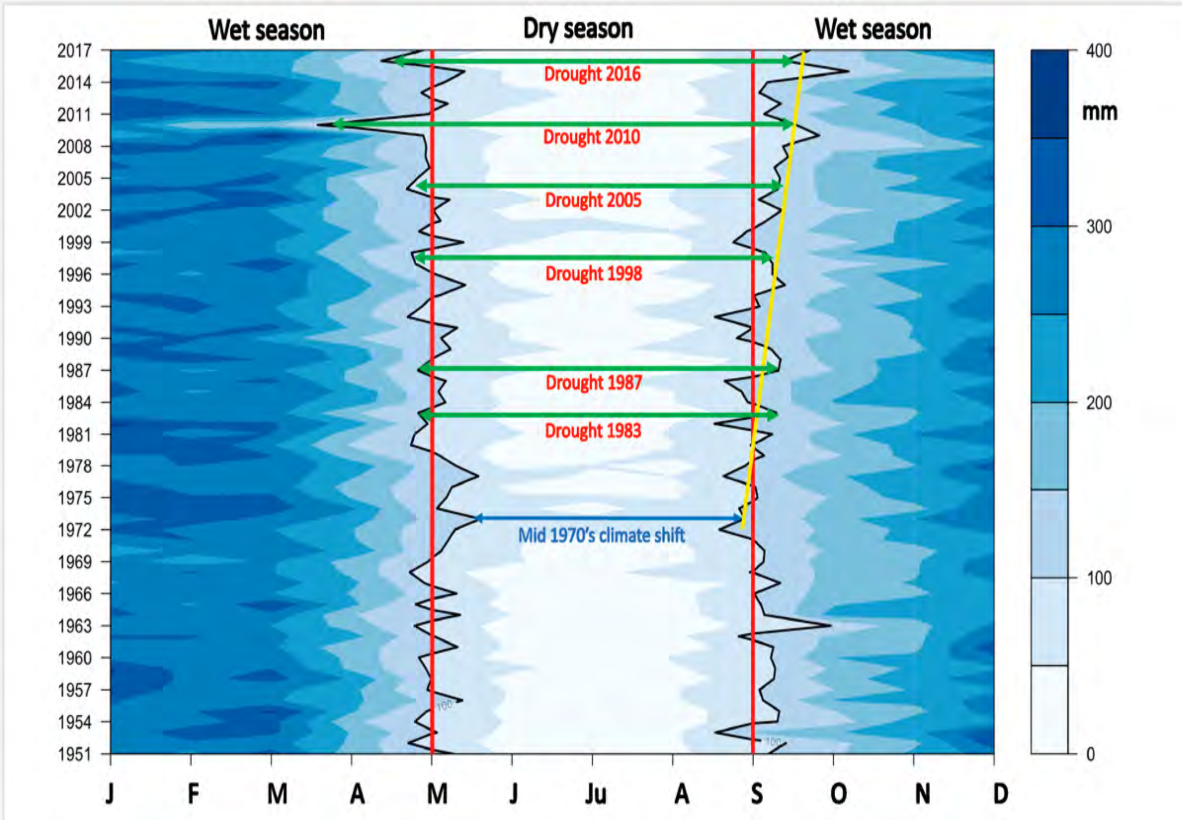

Figure 22.4 Hovmoller diagram showing monthly rainfall from 1951 to 2017 for the southern Amazon (mm/month). The isoline of 100 mm/month is an indicator of dry months in the region (Sombroek 2001). Drought years are indicated with green lines. Red lines show the average onset and end of the rainy season (Marengo *et al.* 2018, © Frontiers in Earth Science). Yellow line shows the tendency for a longer dry season after the mid 1970's climate shift. This climate shift detected in 1976–1977 shows a cold-to-warm sea surface temperature shift in the tropical Pacific Ocean, which has been associated with a phase change of the Pacific Decadal Oscillation index (Jacques-Coper and Garreaud 2015).

which interactions among land surface processes, atmospheric convection, and biomass burning may alter the timing of the onset of the wet season (Zhang *et al.* 2009). Furthermore, they provide a mechanistic framework for understanding how deforestation and aerosols produced by late dry season biomass burning may alter the onset of the rainy season, possibly causing a feedback that enhances drought conditions (Costa and Pires 2010; Lejeune *et al.* 2016). Recent work by Agudelo *et al.* (2018) and Arias *et al.* (2020) show that longer dry seasons in the southern Amazon are also related to enhanced atmospheric moisture content over the Caribbean and northern South America, changes in moisture transport, and moisture recycling in the southern Amazon. This may be due to an enhanced contribution of water vapor from oceanic regions, and the growth of surface moisture convergence over the equatorial region linked to warm surface temperature anomalies over the tropical Atlantic.

The analysis of 40 years of temperature and precipitation data over the Amazon by Gatti *et al.* (2021) shows the relationship between deforestation extent, decreases in precipitation, and increases in temperature, mainly during the dry season, with different trends observed for the east-

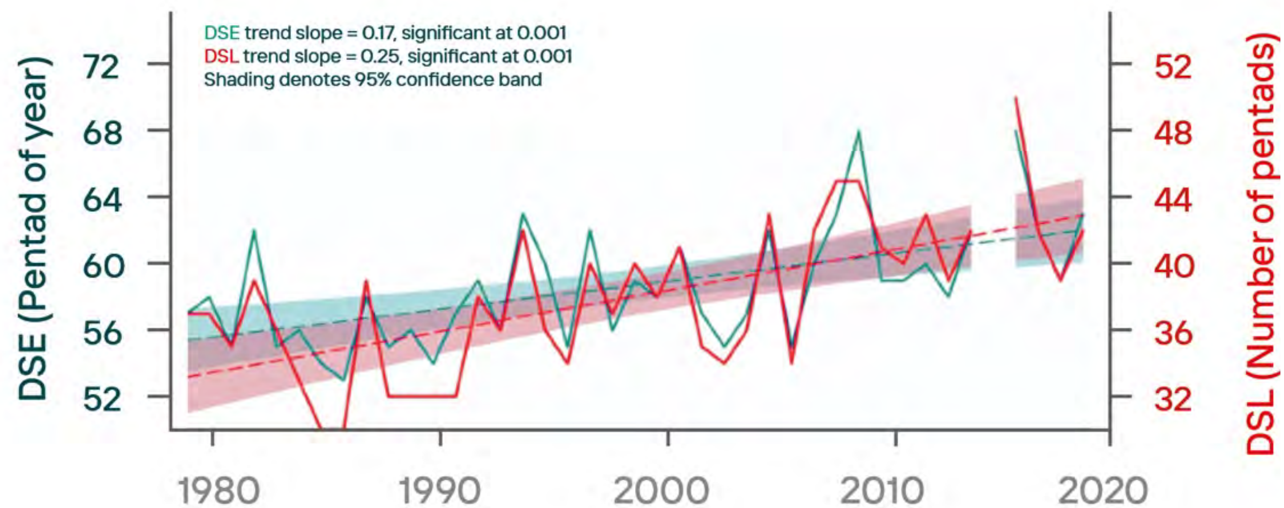

Figure 22.5. Annual time series of the dry season length (DSL, red line) and dry season ending (DSE, blue line) dates (in unit of pentad or 5-day) over southern Amazon how an increase of dry season length at the rate of 12.5±2.5 days per decade of due to a delay of dry season ending at the rate of 8.8±2.5 days per decade for the period of 1979-2019. On the left axis, the 55th pentad corresponds to September 2–7 of the calendar date, and the 70th pentad corresponds to December 10–15. The DSL and DSE are derived from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) daily rainfall data. The linear trend is determined by a least-square fitting. Trends are significant ($p<0.01$) and the shades show the 95% confident

ern, western, and whole Amazon.

The reasons for the delayed onset of the wet season are not completely understood, and the authors add evidence to the idea that deforestation is probably playing a role (Wright *et al.* 2017). Leite-Filho *et al.* (2019) show a delay of wet season onset by about 4 days per decade for each 10% of deforested area relative to existing forested area. Such an interaction between ET and rainfall could further reduce ET and enhance dryness over the Amazon. Staal *et al.* (2020) relate observed fluctuations in deforestation rates to dry-season intensity and find that deforestation has contributed to the increasing severity of dry seasons in Bolivia, southern Brazil, and Peru, and how this leads to greater forest loss.

22.3.3 Historical droughts and floods and ENSO or Tropical Atlantic Influences

It is well known that the strong interannual variability of rainfall over the Amazon basin has direct impacts on the water balance of the Amazon River (e.g., Tomasella *et al.* 2011). As a consequence of this variability, the Amazon basin is affected by recurrent droughts and floods of variable intensity. Drought not only implies a shortage of precipitation, but it is also almost always associated with an increase in surface air temperature. Most of the severe droughts in the Amazon region are EN-related (Cai *et al.* 2020). However, in 1963, 2005, and 2010, the Amazon was affected by a severe drought that was not El Niño-related, as most of the rainfall anomalies that have happened in southwestern Amazon are driven by sea surface temperature anomalies in the TNA (Table 22.2). In fact, during the last 20 years the three “megadroughts" (2005, 2010, and 2015/16) (Jiménez-Muñoz *et al.* 2016; Marengo and Espinoza 2016) were events classified at the time as “one-in-a-100-year events”. Past mega-droughts were registered in 1925–1926, 1982–1983, and 1997–1998, mainly driven by El Niño (Marengo *et al.* 2018 and references quoted in). In contrast, “mega-floods” were detected in 2009, 2012, and 2014 (Marengo and Espinoza 2016 and references quoted in), and currently in 2021. Most of these events have been related to EN, LN, or to warm TNA (Table 22.2). However, the very unusual wet 2014 austral summer period located on the eastern slope of the Peruvian and Bolivian Andes has been associated with warm anomalies in the western Pacific-Indian Ocean and over the subtropical South Atlantic Ocean (Espinoza *et al.* 2014).

Table 22.2 History of droughts and floods in the Amazon, indicating whether they are related to El Niño, La Niña or SST conditions in the tropical Atlantic. References listed in the table are from studies that assess causes and impacts of droughts or floods in the region. EN= El Niño, LN=La Niña, TNA=Tropical North Atlantic, TSA=Tropical South Atlantic, SSA=Subtropical South Atlantic, IP=Indo-Pacific Ocean. Updated from Marengo and Espinoza (2016), Marengo *et al.* (2018) and Espinoza *et al.* (2019 a, b).

Year	Extreme seasonal event	Causes
1906	Drought	EN (E and C indices suggest a strong CP event in 1905, and weak EP and CP events in 1906)
1909	Flood	?
1912	Drought	EN-E
1916	Drought	EN
1922	Flood	?
1925-26	Drought	EN
1936	Drought	?
1948	Drought	EN
1953	Flood	weak LN
1958	Drought	EN
1963-64	Drought	warm TNA
1971	Flood	LN?
1975	Flood	LN?
1976	Flood	LN
1979-81	Drought	warm TNA
1982-83	Drought	EN-E + warm TNA
1989	Flood	LN (Cold anomalies were higher in the CP region)
1995	Drought	EN-C + warm TNA
1997-98	Drought	EN-E + warm TNA
1999	Flood	LN (Cold anomalies over CP region)
2005	Drought	warm TNA (+moderate EN-C)
2009	Flood	warm TSA
2010	Drought	EN-C + warm TNA
2012	Flood	LN + warm TSA
2014	Flood	warm IP + warm SSA
2015-16	Drought	EN-C (also strong EN-E in 2016), warm TNA

Recent studies have documented different “types” of ENSO events, for instance with warm SST anomalies in the eastern Pacific (EP or E) or in the central equatorial Pacific (CP or C) (Cai *et al.* 2020). The role of the different ENSO types (E vs C) and TNA over the observed spatial patterns of drought in the Amazon are evidenced in Figure 22.6 through linear regression of precipitation anomalies versus the E, C, and TNA indices. During austral summer (DJF), EN events inhibit precipitation over wide areas of the northeastern Amazon, with similar pattern for E and C indices. However, the signal of the C index is stronger than the E index, particularly over the Andean-Amazon region. In contrast, the role of TNA is evidenced during the austral autumn (MAM), with a characteristic north-south dipole (wetness over the northern Amazon and dryness over the southern Amazon). Dryness induced by warm TNA temperatures is also observed during the austral spring (SON), but the signal observed in this season is weaker than the signal observed during the austral autumn. Although ENSO and TNA are the main drivers of droughts over the Amazon, some recent events were not fully explained by the contribution of these two oceanic regions (Jimenez-Muñoz *et al.* 2019). In the case of EN 2015/16, dry conditions were observed over some Amazonian regions even after E, C, and TNA contributions were removed, which may be attribute to an anthropogenic factor, among other causes (Erfanian *et al.* 2017). Other studies revealed that Amazonian droughts are most related to one dominant pattern across the entire region, followed by north-south and east-west seesaw patterns (Builes-Jaramillo *et al.* 2018; Builes-Jaramillo and Poveda 2018).

Observed extreme climatic events in the region, such as droughts and floods, or changes in the rainy and dry seasons, augmented fire risk with associated impacts on climate, health, and biodiversity; these suggest an increase in climate variability in the region (Aragão *et al*. 2018, and references quoted in). This could be an indicator of the intensification of the hydrological cycle in the Amazon, observed in the last decades by Gloor *et al.* (2013) and Barichivich *et al.* (2018), and partly explained by changes in moisture transport coming from the tropical Atlantic, presumably caused by SST-induced northward displacement of the ITCZ (Marengo *et al.* 2013, 2018; Gimeno *et al.* 2020).

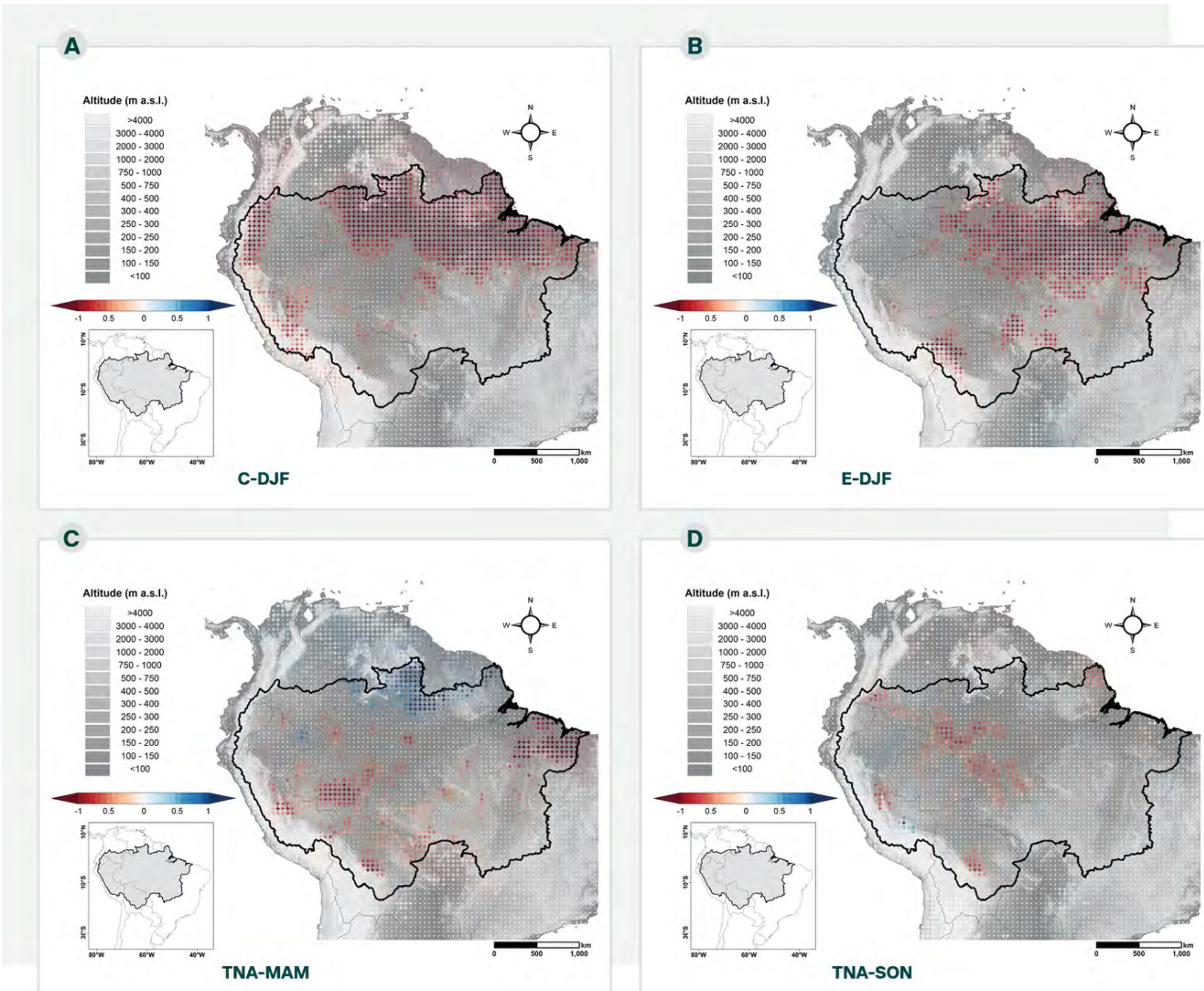

Figure 22.6 Slope of the linear regression coefficient between standardized SST indices (E, C, TNA) and precipitation anomalies for different seasons. Values are in mmday^{-1} per standard deviation. Pixels at the 95% confidence level are marked. Regions colored in red (blue) indicate a reduction (increase) in precipitation with increasing (decreasing) warm (cold) SST anomalies over the Eastern Pacific (E), Central Pacific (C) or Tropical North Atlantic (TNA) regions.

Furthermore, in the beginning of the 21st-century there has been an unprecedented number of extreme drought events; this is related to the large-scale conversion of forests to pasture and cropland over the last decades across the region, altering the land–atmosphere interface and contributing to changes in the regional and local hydrological cycle (Zemp *et al*. 2017a, b; Garcia *et al*. 2018).

22.3.4 Changes In evapotranspiration and possible land-use change

Precipitation and ET recycling are strongly correlated in the Amazon. About 48% of ET returns to the ground as precipitation, and about 28% of the precipitation falling in the basin originated as ET (van der Ent *et al*. 2010). A review by Kunert *et al*. (2017) shows an estimated 25–56% of the precipitation falling on Amazon forests results from local to regional recycling within the ecosystem (see Chapter 7).

Deep-rooted vegetation pulls up soil moisture recharged during the wet season to maintain ET at the same level in the dry season (da Rocha *et al*. 2004; Juárez *et al*. 2007; Costa *et al*. 2010), with an increase of ET during the late dry season (Rocha *et al*. 2009b; Sun *et al*. 2019). Constant or even elevated ET during the dry season is central for maintaining relatively humid atmospheric moisture and initiating the increase of rainfall during the dry to wet season transition (Li and Fu 2004; Wright *et al*. 2017). In addition, ET, especially over the southern Amazon, provides moisture for the downwind region, including the Andean mountains, and helps buffer again droughts across the Amazon (Staal *et al*. 2018).

Changes in ET are influenced by climate variability, forest type, and forest conversion to crop/pasture (da Rocha *et al*. 2009a; Costa *et al*. 2010). Indeed, surface net radiation is the main control of ET year-round, especially over the wet equatorial Amazon, but also affecting other regions where surface conductance is greatly affected, generally the eastern, southern, and southeastern transitional tropical forests towards the boundary of the Cerrado biome. The degree of these influences can vary regionally. For example, Costa *et al*. (2010) and Rodell *et al*. (2011) have shown that surface radiation is the main controller of ET in the wet equatorial Amazon, whereas stomatal control is an important controller in regions with strong dry seasons (such as the southern Amazon).

The influences of climate variability such as ENSO on ET have been observed directly by flux measurements and indirectly by satellites. For example, flux tower measurements have shown that the 2002 EN reduced ET by 8% in the southern Amazon (Vourlitis *et al*. 2015). Satellite based estimates of ET using the moisture budget approach also showed reductions of ET and rainforest photosynthesis during the 2015/2016 EN over the Solimões and Negro basins (e.g., Sun *et al*. 2019). Land use has a strong impact on ET, especially during the dry season. Flux tower measurements show an ET reduction over pastures as compared with two forest sites in the eastern Amazon (Santarem) from about 24% to 39% in the wet season and between 42% to 51% in the dry season, whereas in the southern Amazon (Rondônia) the reduction was less than 15% in the dry season and not significant in the wet season, as summarized in da Rocha *et al*. (2009b). Alternatively, satellite-based ET models estimated a reduction of ET in the dry season from 28% (Silva *et al*. 2019) to as much as 40% (Khandy *et al*. 2017) in the southern Amazon, whereas in the wet season the difference was not significant (Silva *et al*. 2019). The mechanisms of ET reduction resulting from changes in land cover, for example as occurs when forest is replaced by crops, or even in fragmented forests, are to some extent well-known, which supports a decrease of ET in the southern Amazon, particularly in regions affected by deforestation (including the so-called Arc of Deforestation). However, ET models over the Amazon basin do not always show consistent results, which leads to low confidence on the temporal trends of ET. Therefore, it is difficult to extract a clear conclusion on ET trends over the Amazon basin based on literature review (Wu *et al*. 2020).

Changes of ET, especially during the dry season, have a significant impact on rainfall and wet season onset. For example, in terms of the surface energy balance, the relationship between sensible heat (used to warm or cool the air) and latent heat (used to evaporate or condensate atmospheric moisture), known as the Bowen ratio, during the dry season has strong impact on interannual variation in the onset of the wet season (Fu and Li 2004). The augmented surface dryness and resultant convective inhibition energy during the dry season is a leading contributor to the delaying of wet season onset over the southern Amazon in the past several decades (Fu *et al.* 2013). Shi *et al.* (2019) further show that the 2005 drought reduced dry season ET and contributed to the delay of wet season onset in 2006. Thus, the response of ET to drought could have a legacy impact on rainfall of the following wet season.

22.3.5 Long-term variability of atmosphereic moisture transport, moisture recycling from the Amazon, and inflences on southeastern South America and Andean region hydrology

On average the Amazon rainforest receives about 2000-2500 mm of rain each year. Much of this water comes sweeping in on winds from the Atlantic Ocean, but the forest itself provides a substantial part of rainfall (Salati and Vose, 1984) as water evaporates or transpires from leaves and blows downwind to fall as rain elsewhere in the forest. Furthermore, the forest itself influences cloud formation and precipitation by producing secondary organic aerosols. These are formed by photooxidation of VOCs or condensation of semi- and low VOCs on primary biological aerosols (e.g., bacteria, pollen spores) or biogenic salt particles (Andreae *et al.* 2018).

Moisture transport into and out of the Amazon basin has been studied since the 1990s using a variety of upper air and global reanalysis datasets, as well as data from climate model simulations. During the wet season in particular, moisture is exported from the Amazon basin and transported via so called "aerial rivers" to regions outside the basin (Arraut *et al.* 2012; Poveda *et al.* 2014; Gimeno *et al.* 2016, 2020; Marengo *et al.* 2004, 2018; Molina *et al.* 2019). These aerial rivers represent the humid air masses than come from the tropical Atlantic and gain more moisture due to water recycling of the forest when crossing the Amazon (see Box 7.1 from Chapter 7). The aerial river to the east of the Andes contributes to precipitation over southern Brazil and the La Plata River basin via the South American Low Level Jet East of the Andes (SALLJ). During the major drought in the southern Amazon in the summer of 2005, the number of SALLJ events during January 2005, at the height of the peak of the rainy season, was zero, suggesting a disruption of moisture transport from the tropical North Atlantic into the southern Amazon during that summer. The SALLJ transports large amounts of moisture from the Amazon basin towards the subtropics of South America and intense mesoscale convective systems and heavy precipitation frequently develop near its exit (Zipser *et al.* 2006; Rassmussen and Houze 2016).

Evapotranspiration from the Amazon basin contributes substantially to precipitation regionally, as well as over remote regions such as the La Plata basin and the tropical Andes (Zemp *et al.* 2014; Staal *et al.* 2018; Gimeno *et al.* 2019). Montini *et al.* (2019) developed a new climatology of the SALLJ with a focus on the central branch. They showed significant increases in the SALLJ in recent decades in the northwesterly moisture flux, especially in austral spring, summer, and fall, which have possibly enhanced precipitation and extremes over southeastern South America. Additionally, the SALLJ in the central Andes shows decreasing frequency during MAM. Jones (2019) shows substantial growth in the activity of the SALLJ northern branch in the last 39 years and explains the dynamical reasons for that. This expansion in activity is observed in the frequency and intensity of the SALLJ in the northern Andes.

At the interannual time scale, transport during a weak and a strong monsoon in the Amazon basin is distinctly different. For the South American monsoon, the DJF transport was 28.5×10^7 kg s^{-1} in the dry year 2004–2005 and 45.1×10^7 kg s^{-1} in the wet year 2011–2012, in contrast to the climatological value of 31.4 x10^7 kg s^{-1} (Costa 2015). Reducing atmospheric moisture transport and respective recycling of precipitation due to deforestation and land-use change in climate-critical regions may induce a self-amplified drying process which would further destabilize Amazon forests in downwind regions, i.e., the south-western and southern Amazon region, but also reduce moisture export to southeastern Brazil, the La Plata basin, and the Andean mountains (Zemp *et al.* 2017a; Staal *et al.* 2018). Land-use change in these regions may weaken moisture recycling processes and may have stronger consequences for rainfed agriculture and natural ecosystems regionally and downwind than previously thought. These authors further identify growth in the fraction of total precipitation over the La Plata basin from 18–23% to 24–29% during the wet season as well as 21–25% during the dry season, driven by moisture from the Amazon basin. They also show that the south-western part of the Amazon basin is not only a direct source of rainfall over the subtropical La Plata basin, but also a key intermediary region that distributes moisture originating from the entire Amazon basin towards the La Plata basin during the wet season.

Previous work by Nobre *et al.* (2009) showed that large-scale Amazon deforestation can severely reduce local rainfall through the cooperative processes of local reduction of evapotranspiration and enhanced atmospheric subsidence over the Amazon, due to increased ENSO activity associated with Amazonian deforestation. In addition, Staal *et al.* (2018) show that around 25–50% of annual rainfall in the tropical Andes originates as transpiration from Amazonian trees. Land-use change in these regions may weaken moisture recycling processes and may have stronger consequences for rainfed agriculture and natural ecosystems regionally and downwind than previously thought (Zemp *et al.* 2014). Removal of forests increases temperature, reduces evapotranspiration, and has been shown to reduce precipitation downwind of deforested area (Nobre *et al.* 2016; Staal *et al.* 2018).

22.4 Change Scenarios in the Amazon: Local and Remote Causes and Influences

This section summarizes future changes in temperature and precipitation across the Amazon, considering the temporal means and extremes. It assesses future projections derived from the global climate models (GCMs) participating in phase 5 of the Coupled Model Intercomparison project (CMIP5) for two representative concentration pathways (RCPs), RCP4.5 representing moderate and RCP8.5 representing high emissions of GHG by the end of the twenty-first century (2081-2100), relative to the present day (1986-2005). CMIP5 GCMs have been used widely for studying future climate over the Amazon (e.g., Gulizia and Camilloni 2015; Joetzjer *et al.* 2013). These studies show that temperature is generally better simulated than precipitation in terms of the amplitude and phase of the seasonal cycle and the multi-model mean is closer to observations than most of the individual models. For precipitation, all the models, in particular those from CMIP5, have been found to be able to simulate the Amazon's recent past climate reasonably well, although the GCMs show large errors in representations of regional rainfall patterns and their controlling processes.

Annual mean temperature is projected to augment everywhere. Averaged over the Amazon, warming projected in a RCP4.5 scenario is about 2ºC higher than the present day, whereas in RCP8.5 scenario, temperature increases will continue, reaching more than 6ºC by the late 21st century (Figure 22.7). This could have a negative effect on forest health and on its functioning in the regional and global climate. However, large uncertainties still dominate the hypothesis of an abrupt, large-scale shift of the Amazon forest caused by climate change (Lapola *et al.* 2018).

Over the basin as a whole, the changes in rainfall projected by the ensemble mean are mixed over the Amazon, varying by season, and showing that rainfall change impacts in the form of floods or droughts tend to increase under higher concentration scenarios. Despite rather low confidence in the

CMIP5 ensemble mean projections of precipitation, some consensus can be found in the literature. There is high confidence that annual mean precipitation will decline in the Amazon, which is more pronounced in the east and south of the Amazon over the 21st century (Figure 22.8); small changes in rainfall are projected under a moderate emission scenario. In line with observed historical precipitation trends, dry season length is also expected to expand over the southern Amazon (Bois-

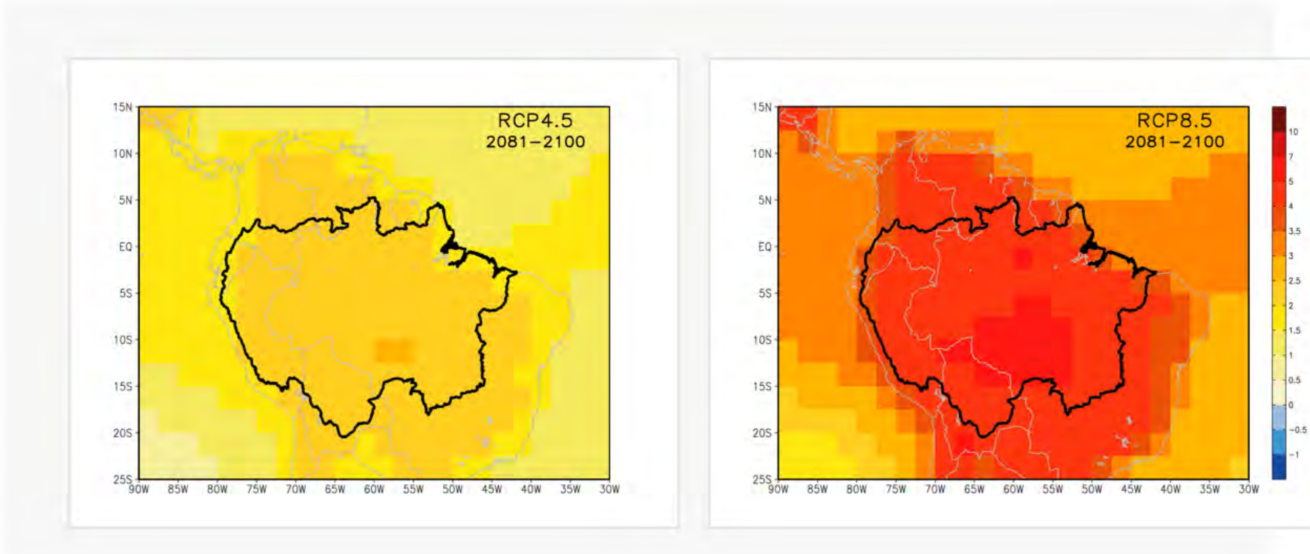

Figure 22.7 Multi-model CMIP5 average percentage change in annual mean near-surface air temperature relative to the reference period 1986–2005 averaged over the period 2081–2100 under the RCP4.5 and 8.5 forcing scenarios.

ier *et al.* 2015).

Spracklen and Garcia-Carreras (2015) assessed relevant peer-reviewed literature published over the last 40 years on analyses of models simulating the impacts of Amazon deforestation (deforested areas varied from 10% to 100%) on rainfall. Results show that more than 90% of simulations agree on the sign of change and deforestation's influences on regional rainfall as simulated by the model; in general, deforestation leads to a reduction in rainfall. However, there are some differences between models, mainly in term of amplitude, magnitude, and predictability that is strongly dependent on the spatial and temporal scales being considered.

There is also generally model agreement for an increase in precipitation for the end of the 21st century over the northwestern Amazon (Colombia, Ecuador and the north of Peru) (Schoolmeester *et al.* 2016). In the Peruvian-Ecuadorian Andean-Amazon basins (Marañón basin), Zulkafli *et al.* (2016) show an increasing seasonality of precipitation under RCP 4.5 and 8.5 scenarios. This study also suggests an augmented severity of the wet season flood pulse. On the other hand, in the southern Peruvian and Bolivian Amazon, a reduction of precipitation is expected during the dry season, where a longer dry season is also projected (e.g., Fu *et al.* 2013; Boisier *et al.* 2015). Consequently, Siqueira-Junior *et al.* (2015 and references therein) projected diminution in runoff in the Bolivian Amazon and Southern Peruvian Amazon during the low-water season for the middle and end of the 21st Century. In summary, while a great deal of uncertainty exists regarding future rainfall projections over the Andean-Amazon region, most studies show that an intensification of the hydrological cycle is likely to occur in this region, with intensification of wet conditions in the north and dry conditions in the south, as observed during the last decades (Section 22.3).

Analyzing projected changes, Minvielle and Garreaud (2011) documented a future reduction in easterly winds at 200hPa during the austral summer, which could translate into reduced rainfall in the Andes-Altiplano (-10% to -30%) and probably over the highest region of the upper Amazon by the end of the 21st century. In addition, glaciers are an important water source for cities in the upper Andes (Buytaert *et al.* 2017) and unprecedented glacial retreat is currently observed, with an acceleration since the late 1970s (Rabatel *et al.* 2013). Air

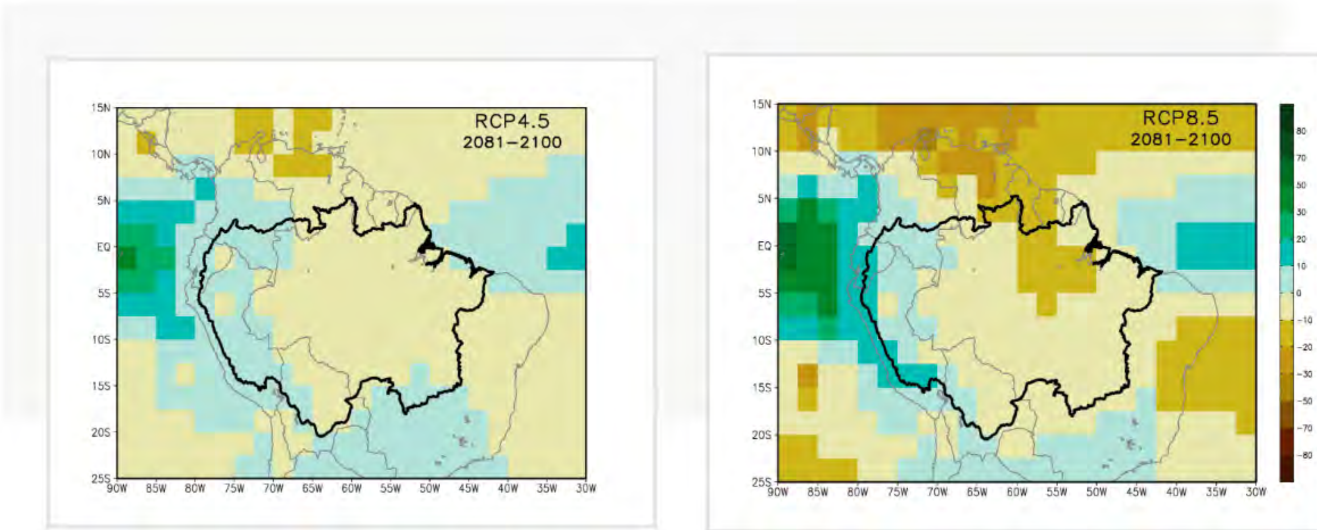

Figure 22.8 Multi-model CMIP5 ensemble percentage change in annual mean precipitation relative to the reference period 1986–2005 averaged over the period 2045–2081–2100 under the RCP4.5 and 8.5 forcing scenarios.

temperature is expected to increase by the end of the 21st century (Vuille *et al.* 2015) and many glaciers could disappear, which will increase the risk of water scarcity in upper Andean valleys.

Recent studies have revealed the strong dependence of Andean hydroclimatology on the Amazonian rainforest (e.g., Espinoza *et al.* 2020 and cited articles). Indeed, loss of Amazonian rainforests will probably affect the entire hydrological cycle over both the Amazon basin and the Andes by changing moisture advection and regional atmospheric circulation (Segura *et al.* 2020).

The most serious impacts of climate change are often related to changes in climate extremes. There is general model agreement for an increment in precipitation for the end of the 21st century over the northwestern Amazon, while annual mean precipitation is projected to decline in the future in the eastern Amazon under a high emission scenario (Figure 22.9). The differences in magnitude between the moderate emission scenario (RCP4.5) and the high emission scenario (RCP8.5) are even greater (on the order of 10%) in the eastern and southern Amazon and can be expected to lead to a change in the likelihood of events such as wildfires, droughts, and floods. The maximum number of consecutive dry days (CDD) is projected to increase substantially (Figure 22.9a). The projected changes indicate not only more frequent CDD, but also increases in intense precipitation as shown by the maximum five-day precipitation accumulation (RX5day) index, a strong contributor to floods (Figure 22.9a) (Seneviratne *et al.* 2021; Ranasinghe *et al.* 2021; Gutiérrez *et al.* 2021).

It is also important to note that the impacts of deforestation are frequently reflected in changes in the amount, intensity, and frequency of precipitation. Alves *et al.* (2017) conducted a modeling study to examine possible connections between changes in land cover in the Amazon and the spatiotemporal variability of precipitation in South America. They also found more extreme precipitation events and, as compensation, a longer dry season. Lan *et al.* (2016) found no signals of a higher frequency of intense precipitation events over the Amazon rainforests but found a widespread decline in precipitation over the Amazon (especially over the eastern Amazon) from 1981 to 2100, although trends were mostly not statistically significant at the 95% confidence level (Student's t-test). Declines in trends for evapotranspiration, total runoff, and available

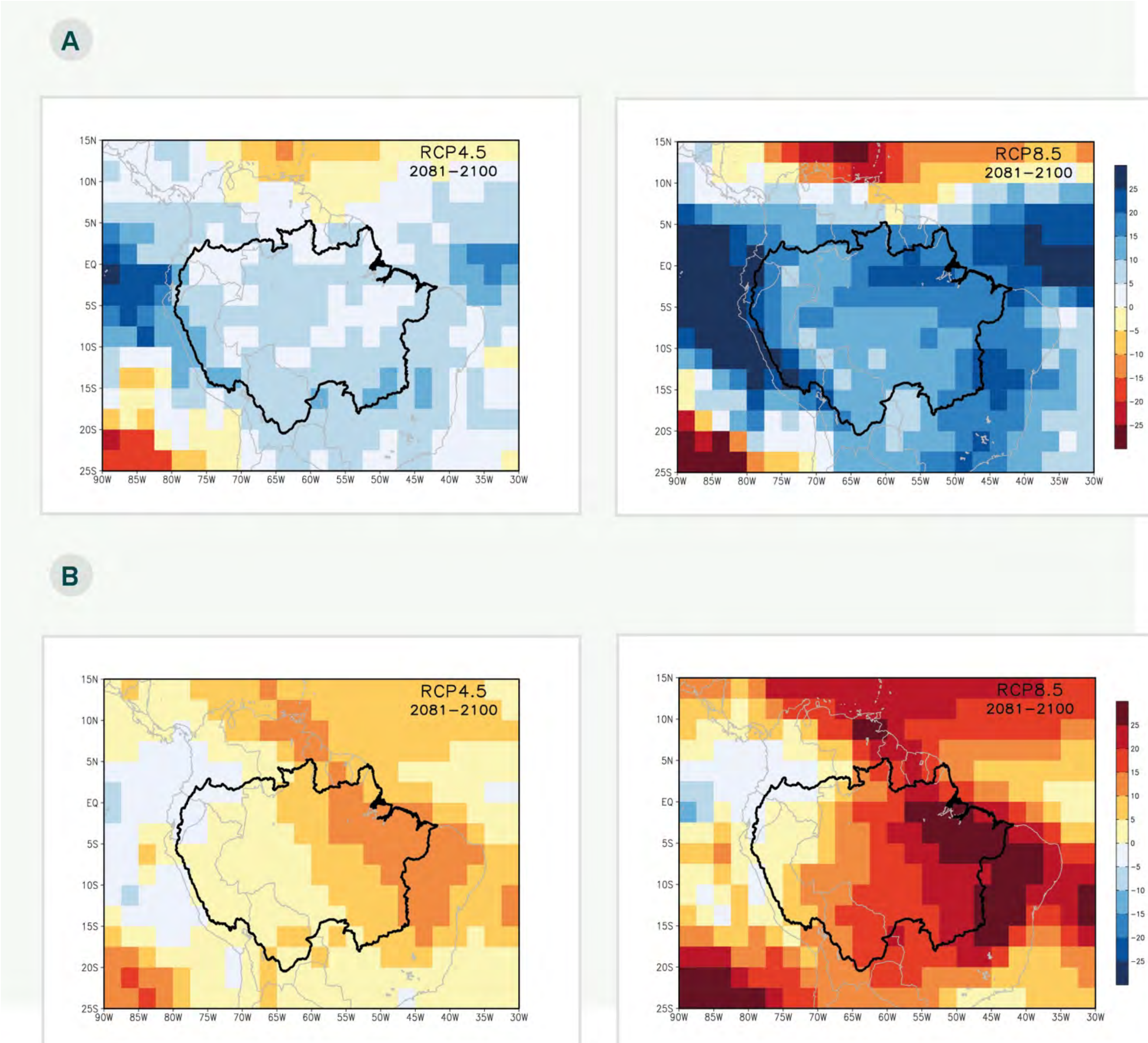

Figure 22.9 (a) Projected percent changes in annual RX5day, the annual maximum five-day precipitation accumulation and (b) projected change in annual CDD, the maximum number of consecutive dry days when precipitation is less than 1 mm, over the 2081–2100 period in the RCP4.5 and 8.5 scenarios (relative to the 1986–2005 reference period) from the CMIP5 models.

water were also observed.

Decreases in precipitation are countered by declines in evapotranspiration and total runoff, leading to an almost neutral trend in the terrestrial water flux over the Amazon (Figure 22.9b). Results also indicated that soil moisture will become lower over the Amazon in the future (1981-2000 vs 2181-2100), and the seasonal range of total soil moisture will become larger (Kirtman *et al.* 2013).

The ratio of runoff to precipitation indicated dramatic changes from June to September over the Amazon for the period 2081-2100, which is attributed to low amounts of precipitation and runoff, and with more reduced precipitation than reduced runoff. These results are also supported by Zaninelli *et al.* (2019), with less humid conditions with decreasing surface runoff over the southern and southeastern Amazon for the period 2071-2100.

Mohor *et al.* (2015) suggest climate change is likely to reduce discharges in the Madeira, Tapajós, and Xingú river basins. Such reduction is largely related to decreasing precipitation and increasing temperature, that favours an increased ET and discharge reduction. In general, for the scenarios considered in these hydrological simulations, a larger decreasing precipitation scenario also has a stronger increase in temperature, which explains the rates of change in discharge. Results suggest that for strong temperature warming, i.e., higher than 4°C, discharges are more sensitive to precipitation changes than that for weak temperature increase. However, climate sensitivity largely varies between basins, affected by surface characteristics and the basin's scale. Hydrologic projections considering the conversion of tropical forests to pasture and farming were carried out by Siqueira-Junior *et al.* (2015) and Guimberteau *et al.* (2017), applying potential scenarios for land-use and land-cover change in Amazonian basins, showing that augmented deforestation in the basins results in lower rates of evapotranspiration and higher runoff generation, which counterbalances the climate change effects on streamflow.

The Amazonian forest's ability to provide environmental services is threatened by anthropogenic forcing at various scales, such as deforestation, fire, global and regional climate change, and extreme events (see Chapters 19, 23 and 24). Such services include maintenance of biodiversity, water cycling, evaporative cooling, and carbon stocks. These services have a much greater value to human society than do the timber, beef, and other products that are obtained by destroying the forest (Nobre *et al.* 2016). Perhaps one of the most valuable services provided by the Amazon forest is water. Evapotranspiration from the forest across the basin provides moisture for the downwind region, including the Andean mountains, helps buffer again droughts across the Amazon, and also contributes to rainfall in the southern Amazon, Pantanal, and La Plata basin. In these downwind regions a suppression of moisture transport from the Amazon may lead to rainfall reductions and warmer temperatures, increasing the risk of drought and fire, as well as water, food, and energy insecurity in regions to the south of the Amazon.

For instance, during the water crises in Sao Paulo in 2014-2015, atmospheric moisture coming from the Amazon did not reach southeastern Brazil in the summer of 2014, reducing rainfall almost 50%. The higher temperatures and increased human water use, together with reduced rainfall, triggered a water crisis that lasted until 2015 (Nobre *et al.* 2006). In the summer of 2019, 2020, and 2021 the summer rainy season the in Pantanal was very weak, with moisture transport from the Amazon. Reduced rainfall in the west central and southeastern Brazil induced drought in the region, increased the risk of fire, and lowered river levels in the basin (Marengo *et al.* 2021) and this is also reflected in the water crisis situation that is affecting these regions in 2021. Reducing atmospheric moisture transport and respective recycling of precipitation due to deforestation may induce a self-amplified drying process which would further destabilize the Amazon forests. However, the droughts in Sao Paulo and the Pantanal were related to atmospheric circulation anomalies and cannot be attributed to deforestation in the Amazon or to climate change.
Future climate scenarios project progressively higher warming that may exceed 4°C in the Amazon in the second half of the century, particularly during the dry season (Sampaio *et al.* 2019). Model projections show that this moisture flux from the Amazon to the La Plata basin may be also reduced, and there is a possibility that these environmental services provided by the Amazon now may also be affected in a warmer and drier future.

The new CMIP phase 6 (CMIP6) simulations agree on the sign of decreasing future rainfall trends in the Amazon, with droughts projected to increase in duration and intensity under global warming (Ukkola *et al.* 2020). Specially, CMIP6 models show drying across the eastern and southern Amazon in the 21st century (Parsons *et al.* 2020), and most CMIP6 models agree on future decreases in soil moisture and runoff across most of the Amazon in all emissions scenarios (Cook *et al.* 2020).

Under different global warming scenarios, the Amazon, particularly the central Amazon, is projected to experience a 75% increase in the number of hot days and a decrease in Rx5day. This region is also projected to have increased droughts (Santos *et al.* 2020). Lastly, Oliveira *et al.* (2021) show that the combined effects of large-scale Amazon deforestation and global warming can subject millions of people in the Amazon region to a heat stress index beyond the level of survivability by the end of the 21st century. Furthermore, their results indicate that the effects of deforestation alone are comparable to those of the worst-case scenarios of global warming under the RCP8.5 scenario.

Recent work by Baudena *et al.* (2021) identified that loss of tree transpiration from the Amazon causes a 13% drop in column water vapor, and could result in a 55%–70% decrease in precipitation annually. They conclude that although the effects of deforestation may be underestimated, forest restoration may be more effective for precipitation enhancement than previously assumed. Furthermore, Oliveira *et al.* (2021) showed through numerical simulations with the Brazilian Earth System Model that the combined effects of climate change under the RCP8.5 scenario and large-scale Amazon deforestation can impact annual rainfall over the central portion of the Amazon Basin with a reduction of up to 70% of its annual rainfall total.

22.5 Conclusions

Long-term instrumental records for climate and streamflow (>80 years) have a low spatial coverage across the continental-sized Amazon basin, which limits our ability to assess the spatial and temporal variability and changes of precipitation and temperature.

Our trend studies demonstrate that there is no unidirectional signal towards either wetter or drier conditions over the entire Amazon during the period of the observational records. However, for specific regions there are consistent trends. In general, the size and direction of the trends depend on the details of dataset used, such as the length of rainfall datasets, if there are breaks in the record, and if and how they are aggregated. For surface temperature, while warming appears in all datasets, the magnitude of it depends on the length of the observational period. However, all datasets show that the last 20 years have been the warmest in the Amazon, with some datasets suggesting that 2020 may be the warmest year over particular sections of the basin. In a region where measurements are very scarce, the uncertainty in the size and direction of any temperature trend is high.

An intensification of the hydrological cycle in the region has been observed in various studies (Gloor *et al.* 2013; Barichivich *et al.* 2018; Wang *et al.* 2018), and this is reflected by the increase in recent extreme hydro-climatic events (Marengo and Espinoza 2016, and references quoted in). During the last four decades, various studies show an enhancement of convective activity and increases in rainfall and river discharge over the northern Amazon and decreases of these hydroclimate variables over the southern Amazon (Paca *et al.* 2020, and references therein).

Our current interpretation of water cycle and trends in the Amazon is still limited by the lack of complete long-term and homogeneous historical climate and river data in different sub-basins. At interannual time scales ENSO and TNA have played an important role in temperature and rainfall variability. At large scale, teleconnections with anomalies of Pacific and Tropical and Subtropical Atlantic SSTs, as represented by the AMO, PDO, and others, have shown impacts on rainfall anomalies. These oceanic influences have been confirmed by dendroclimatic or stable isotopes studies that reconstruct past climatic and hydrological features in the basin. The role of vegetation and land use in the region on hydrological and temperature variability has been demonstrated by modeling as well as observational studies.

As shown by model projections, large-scale deforestation and the prospects of global climate changes can intensify the risk of a drier and warmer Amazon. Changes in seasonal distribution, magnitude, and duration of precipitation may have significant impacts on Amazon hydrology and other sectors, since rainfall reductions will occur predominantly in dry and transition seasons. While land-use change is the most visible threat to the Amazon ecosystem, climate change is emerging as the most insidious threat to the region's future.

A summary of observed and projected changes in the Amazon are shown in the graphical abstract of this chapter. The observed tendencies can be different in the western and eastern Amazon, and the projected changes suggest a drier and warmer climate in the east, while in the west rainfall is expected to increase in the form or more intense rainfall events. The level of confidence is determined by the level of convergence among model signals of change from CMIP5 models (Kirtman *et al.* 2013).

22.6 Recommendations

Our knowledge of temperature and rainfall trends is limited because of the lack of complete, homogeneous, and long-term climate records to identify changes in extremes, such as droughts and floods, due to increasing interannual climate variability. Furthermore, the most important changes in the hydroclimate system are happening in the transition between the dry and the rainy seasons, with a warmer, longer, and dryer dry season, which has important ecological and hydrological consequences. Future studies should focus on this particular transition season. This limitation leads to considerable uncertainty in determining the recent intensification of the hydrological cycle in the Amazon, and how it compares to other intensifications of the hydrological cycle that may have occurred in the past. There is an urgent need to rescue data and integrate it among Amazon countries, with free access for the scientific community. High-resolution climatic and hydrological gridded datasets for the Amazon should be generated by means of a cooperation between state and national meteorological services, international climate agencies, universities, and private datasets.

When considering the policy and practical implications of our assessment, it is important to note that despite the fact that the CMIP5 and CMIP6 models simulated some aspects of the observed present-day climate reasonably well, key processes, such as evapotranspiration, clouds and precipitation, vegetation, and climate feedbacks are highly uncertain and poorly represented in the current generation of GCMs. Because the climate projection does not represent well the complex synergetic and antagonistic effects linking climate to land-use change, model projections likely have considerable uncertainty, particularly for rainfall projections. With increased field experiments and high-resolution models, we will be able to enhance understanding and modeling of complex interactions, and where improvements should be made. The increase in extreme droughts may cause extremely low water levels and an elevated tree mortality due to fires, which are more pronounced at the edges between vegetated and non-vegetated areas, due to relation between land-use change and fire.

Last but not least, there is a strong need for better education of local people as well as policy and decision makers on climate, hydrology, and the atmospheric sciences, especially the impacts of land-use and climate change on their livelihoods. Traditional and cultural knowledge are also invaluable sources of climate-proxy information. In sum, we have to improve ground monitoring, data accessibility and quality, research infrastructure, and climate model development. Furthermore, model development and calibration at key research centers and universities working with climate modelers in the region can promote collaboration among scientists. These efforts may need support from national and/or international funding agencies.

Climate and land use changes are pushing the Amazon closer to its projected "bio-climatic tipping point" (Lovejoy and Nobre 2018) faster than any other tropical forests, especially in the eastern and southern Amazon basin. This is despite large uncertainties in precisely defining thresholds for tipping points (see Chapter 24).

22.7 References

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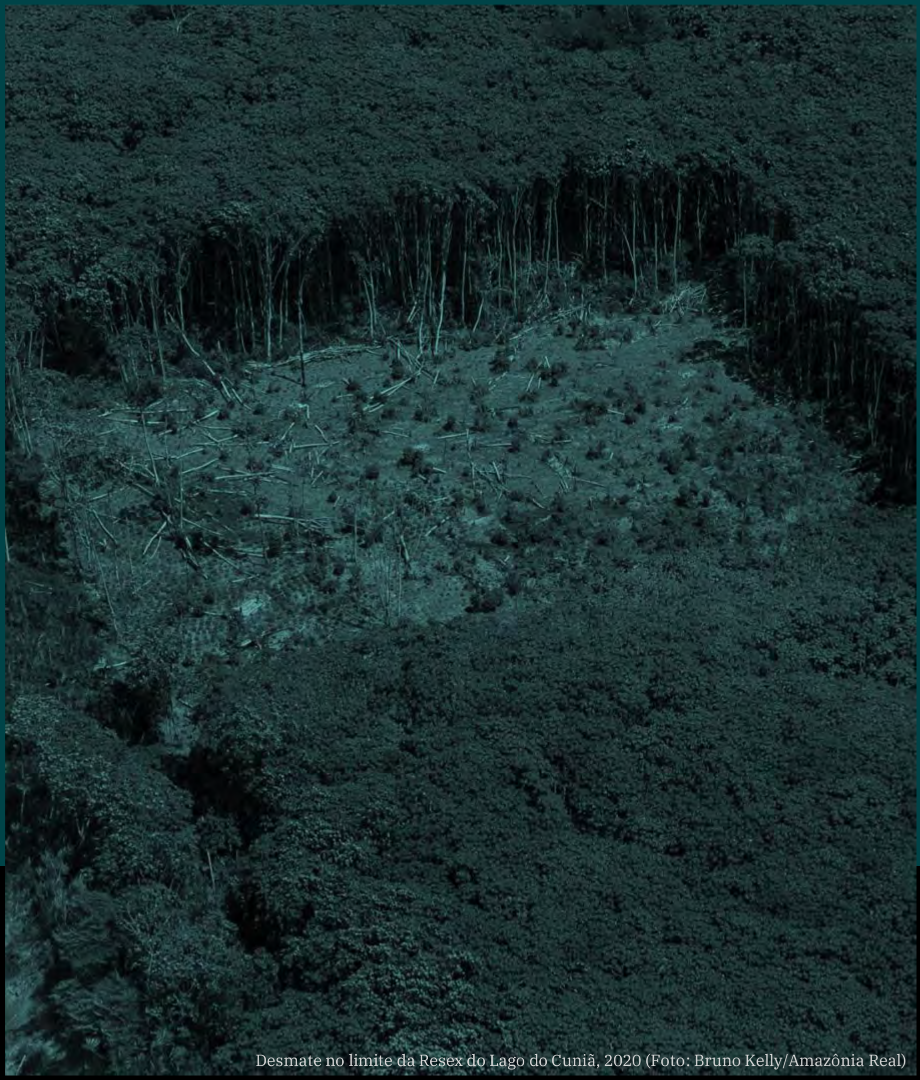
Chapter 23

Impacts of deforestation and climate change on biodiversity, ecological processes, and environmental adaptation



Desmate no limite da Resex do Lago do Cuniã, 2020 (Foto: Bruno Kelly/Amazônia Real)

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Graphical Abstract

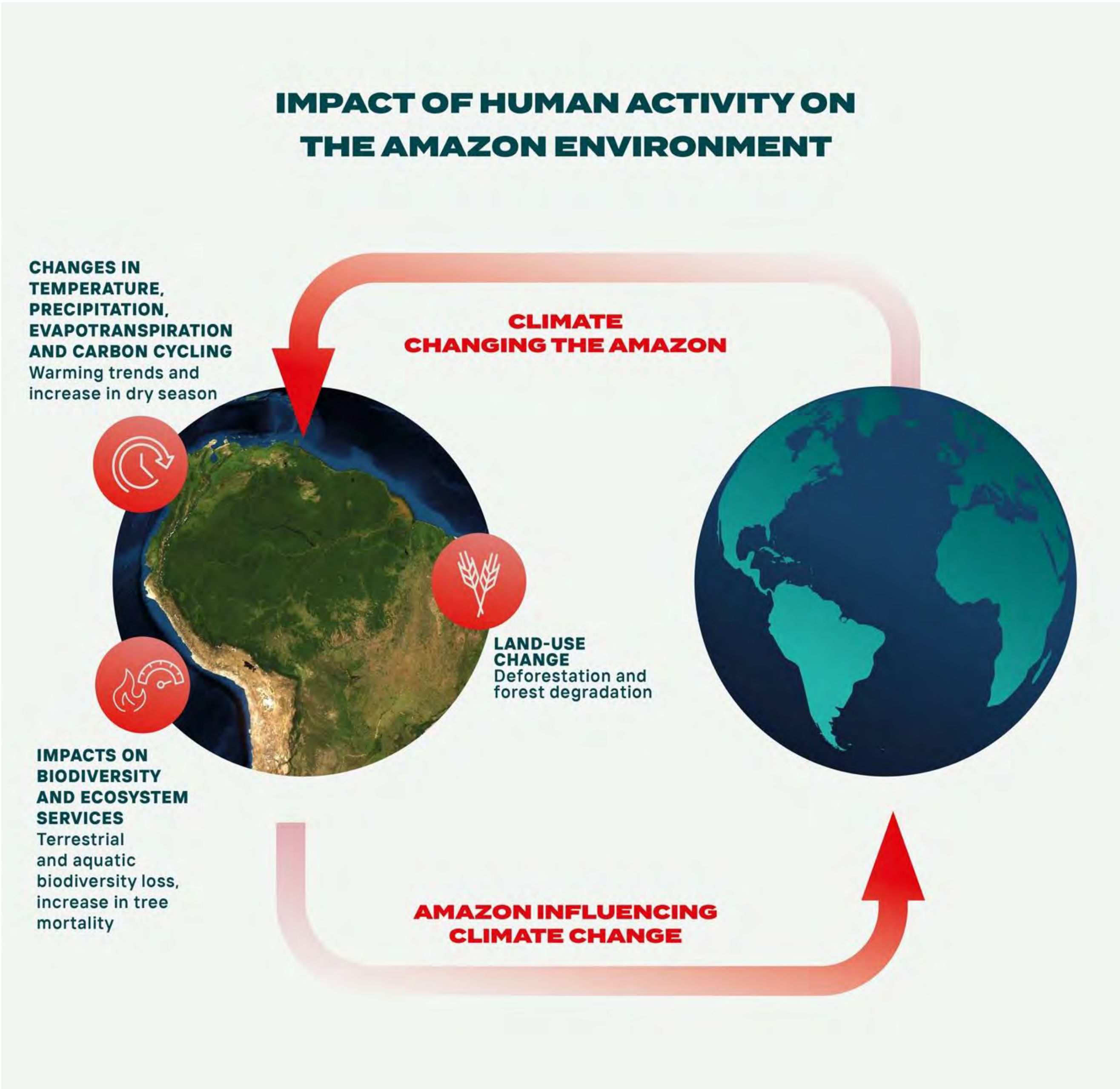

Figure 23.A Impact of human activities on the Amazon environment. Global climate changes affect the Amazon through temperature increase, altered precipitation patterns and climate extremes, leading to increased tree mortality and terrestrial and aquatic biodiversity loss. This, coupled with land-use change through deforestation and degradation, reduces evapotranspiration, changes carbon cycling dynamics, decreases the resilience of the ecosystems, and leads to further biodiversity loss and tree mortality, emitting greenhouse gases that impact not only the regional, but the global climate. On the other side, Amazonian deforestation enhances climate change.

Impacts of Deforestation and Climate Change on Biodiversity, Ecological Processes, and Environmental Adaptation

Paulo Artaxo[a,b], Vera M.F. Almeida-Val[c], Bibiana Bilbao[d], Paulo Brando[e], Mercedes Bustamante[f], Michael T. Coe[g], Sandra Bibiana Correa[h], Francisco Cuesta[i], Marcos Heil Costa[j], Fernando Miralles–Wilhelm[k], Norma Salinas[l], Divino Vicente Silvério[m], Adalberto Luis Val[c].*

Key Messages

- The Amazon is one of the world's most at-risk regions, with a possibility that over 90% of species could be exposed to unprecedented temperatures by 2100.
- Knowledge gaps on carbon balance are significant, including the role of forest degradation and natural photosynthesis enhancements. To close these gaps, remote sensing of CO_2 measurements, ground-based tower flux data, aircraft measurements, and modeling tools must be integrated.
- Reducing emissions from biomass burning is critical to minimize the negative impacts on ecosystems and human health.

Abstract

Climate change is already impacting critical mechanisms of the functioning of the Amazon's ecosystems. The observed increase in temperature, precipitation changes, and increase in climate extremes affect ecosystem services, carbon uptake, and the duration of the dry season, among other effects. It also affects biodiversity, selecting species that can adapt quickly to the changing climate, including freshwater fish and other ectothermic groups able to do the same. In particular, fisheries' yields are important to food security and have been impacted by climate change in unpredictable ways. Moreover, projections indicate that climate change will have significant adverse impacts on pollination and seed dispersal, essential ecosystem services for the maintenance of natural and agricultural ecosystems because of changes in species distributions, and decoupling of biotic interactions. Rainfall in the Amazon is sensitive to seasonal and interannual variations in sea surface temperature, as well as El Niño and La Niña. The increase in intensity and frequency of droughts and floods have important impacts on carbon cycling. Levels of water at Óbidos have significantly increased over the last 30 years, and the runoff of the Xingu catchment has risen by 10%, possibly owing to 40% deforestation in the Xingu catchment. The Amazon was a strong carbon sink in the 1980s, and recent measurements show a much weaker carbon sink in the forests. The mean net carbon uptake for the 1990s was -0.59 ± 0.18 Pg C y^{-1}, and the decade of 2010s had a carbon uptake of -0.22 ± 0.30 Pg C y^{-1}. In dry years, such as 2005 and 2010, the forest loses carbon to the atmosphere, increasing greenhouse gas concentrations. Increases in climate extremes are reducing carbon uptake by

[a] Institute of Physics, University of São Paulo, Rua do Matão 1371, CEP 05508-090, São Paulo - SP, Brazil, artaxo@if.usp.br.
[b] Research Center for Greenhouse Gas Innovation – RCGI, Engineering School, University of São Paulo, Brazil.
[c] Instituto Nacional de Pesquisas da Amazônia, Av. André Araújo, 2936, Manaus - AM, 69067-375, Brazil.
[d] Universidad Simón Bolívar, Apartado 89000, Caracas 1080, Venezuela.
[e] Instituto de Pesquisa Ambiental da Amazônia, Brazil.
[f] University of Brasília, Brasilia, Federal District, 70910-900, Brazil.
[g] Woodwell Climate Research Center, 149 Woods Hole Road, Falmouth, MA, United States, 02540-1644.
[h] Mississippi State University, 775 Stone Blvd, Mississippi State, MS 39762, United States.
[i] Universidad de las Americas, De Los Colimes esq, Quito 170513, Ecuador.
[j] Viçosa Federal University, Av. Peter Henry Rolfs, s/n - Campus Universitário, Viçosa - MG, 36570-900, Brazil.
[k] University of Maryland, College Park, MD 20742, United States.
[l] Pontifical Catholic University of Peru, Av. Universitaria 1801, San Miguel 15088, Peru.
[m] Universidade Federal Rural da Amazônia, Estr. Principal da Ufra, 2150 - Curió Utinga, Belém - PA, Brazil.

the Amazonian ecosystem. Biomass-burning emissions have significant negative impacts on the ecosystem, such as high ozone concentrations that affect the stomatal opening and human health. Aerosols from biomass burning alter the radiation balance, increasing diffuse radiation compared with direct radiation affecting carbon cycling. The increase in surface albedo associated with deforestation changes surface temperature and energy partitioning. Forest degradation could be as crucial as deforestation in terms of carbon emissions. Our current scientific understanding points to Amazonian forests becoming increasingly susceptible to wildfires and droughts. Feedbacks between climate change and Amazonian ecosystems' functioning are substantial and must be better known and quantified, especially for carbon and water vapor feedback. We need more integrated studies involving biodiversity loss with the changing climate, including resilience. Additionally, there is a need for a comprehensive network of Amazonian environmental observations to provide society with diagnostic capabilities of the changes that terrestrial and aquatic ecosystems are already undergoing.

Keywords: Impacts of climate change, hydrological cycle, biodiversity, carbon cycling, precipitation, fisheries

23.1 Impacts of climate change on biodiversity, including forest dynamics, carbon cycling, freshwater, and coastal ecosystems

Terrestrial ecosystems and climate interact in complex ways through changes in climate forcing and multiple biophysical and biogeochemical feedbacks across different spatial and temporal scales. Climate change impacts tropical forest ecosystems in various ways, but the attribution is not always clear because the climate system's natural variability can be large. Precise characterization of hydroclimate variability in the Amazon on various timescales is critical to understanding the link between climate change and biodiversity (Cheng *et al.* 2013). The temperature, precipitation, and climate extremes are increasingly changing in tropical and Amazonian forests. The large biodiversity of the Amazon somewhat helps to protect the forest, but there are limits and thresholds for the environmental impacts. The complex forest dynamics are closely coupled to the carbon and water cycling, and changes in a single component affect the whole structure. Geologically, the Andean uplift was crucial for the evolution of Amazonian landscapes and ecosystems (see Chapters 1 and 2). Current biodiversity patterns are rooted deep in the pre-Quaternary period (Hoorn *et al.* 2010). Amazonian paleoclimate studies help to understand the formation and evolution of this rich environment and show evidence that human impact on the Amazonian ecosystems could have been substantial over the last few millennia (Maezumi *et al.* 2018; Maksic *et al.* 2019; Cordeiro *et al.* 2014; Anhuf *et al.* 2006).

Freshwater ecosystems also interact with the whole ecosystem in complex ways, and in the case of the Amazon, the Basin houses unparalleled aquatic biodiversity. Regarding fish, more than 2,400 species (see Chapter 3), from old to modern groups, inhabit all kinds of water bodies, such as small streams, lakes, and large rivers, and many are adapted to challenging conditions. Some of these fish species are important protein sources for local people (see Chapters 15 and 30). Other species are essential to maintain the biological equilibrium of local systems and floodplain forests' natural regeneration. However, the current challenging conditions of particular water bodies, such as low pH, high temperature, and low dissolved oxygen, could be worsened by the ongoing climate changes. As many fish species already live near their physiological limits, environmental impacts on those water characteristics would impact the local aquatic biota (Braz-Mota and Almeida-Val 2021)

This chapter will discuss the observed and predicted impacts of climate change in the Amazonian terrestrial and aquatic ecosystems. We will focus on the impacts on biodiversity, ecosystem services, carbon cycling, fisheries, and biomass burning emissions. All these aspects are closely linked, as shown in the schematic in Figure 23.1.

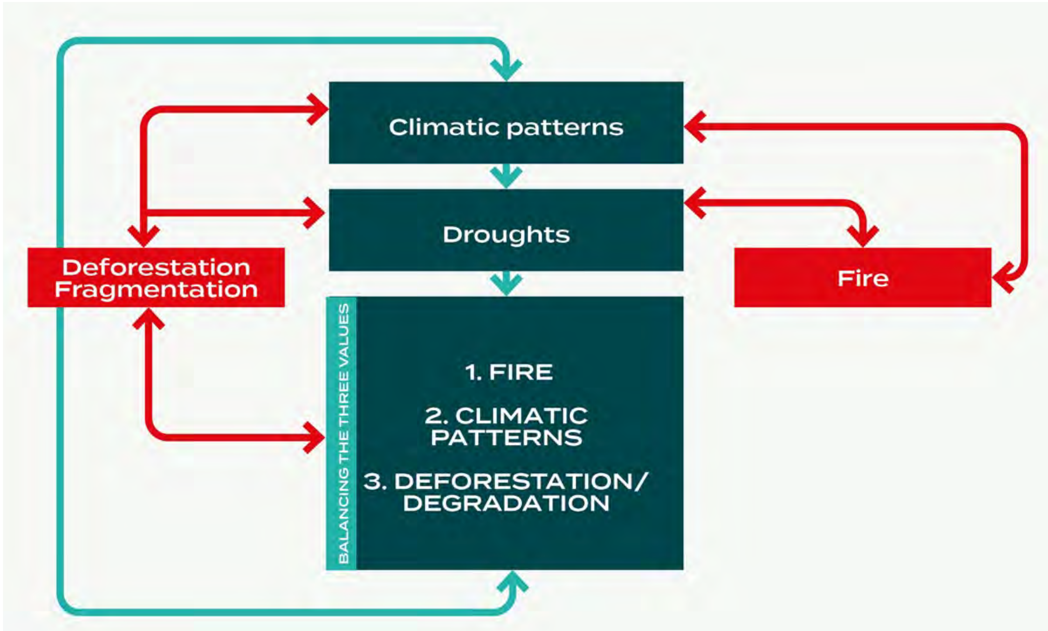

Figure 23.1. Links between climate, deforestation, forest degradation, and fire impacts on the Amazonian ecosystems. In order to establish solid public policies on land-use change, it is necessary to have an integrated view of the main drivers and impacts. Adapted from Luiz Aragão.

23.1.1 Changes in biodiversity driven by climate change and deforestation

23.1.1.1 Lowland forests

An increasing body of literature indicates that global climate change can affect the future distribution of biodiversity and the composition of ecological communities, species range sizes, extinction probabilities, and species' local richness. Several paleoclimate studies have reported changes in biodiversity and ecological communities associated with climate change over a range of time scales (Anhuf et al. 2006; Cheng et al. 2013; Cordeiro et al. 2014). Climate variability associated with internal (such as ocean/atmosphere/land coupling) and external forcing (such as solar activity or volcanism) has altered ecosystems for thousands of years. But, over the last 20,000 years, the Amazon has had relatively stable climate.

Although deforestation and forest degradation are currently the most significant threat to biodiversity in the Amazon (see Chapters 19 and 20), climate change is becoming an increasingly relevant driver. Climate change and deforestation combined could cause a decline of up to 58% in Amazon tree species richness by 2050. Species may lose an average of 65% of their original environmentally suitable area, and a total of 53% are considered threatened (Gomes *et al.* 2019). Some Amazon regions are more likely to be affected by the synergetic impacts of deforestation and climate changes: eastern Amazon may suffer up to 95% of forest loss by 2050, followed by southwestern (81%) and southern Amazon (78%). Furthermore, there is the influence of wildfire in the interactions between deforestation and climate change (Gomes *et al.* 2019).

The floristic and functional compositions of well-preserved lowland Amazonian forests have been changing according to records of long-term inventories covering 30 years. Among newly recruited trees, drought-tolerant genera have become more abundant, whereas the mortality of wet tolerant genera has increased in plots where the dry season has intensified most (Esquivel-Muelbert *et al.*

2019). The results suggest a slow shift towards a drier Amazon, with changes in compositional dynamics (recruits and mortality) consistent with climate change drivers. The increase in atmospheric carbon dioxide (CO_2) is driving tree communities towards large-statured species. Despite the impacts of climate change on the forest composition, the long generation times of tropical trees imply a lagged response of tree diversity to climate change (Esquivel-Muelbert *et al.* 2019).

Although climate change affects biodiversity, plant trait diversity may enable the Amazon forests to adjust to new climate conditions protecting the Amazon's ecosystem functions (Sakschewski *et al.* 2016; see also Chapter 24). However, the risks to biodiversity will increase over time with anthropogenic climate change progression, with future projections of potentially catastrophic global biodiversity loss. Projections (from 1850 to 2100) of temperature and precipitation to estimate the timing of exposure of a large group of species to potentially dangerous climate have indicated that future disruption of ecological assemblages would be abrupt (Trisos *et al.* 2020) because of the simultaneous exposure of most species to climate conditions beyond their realized niche limits. Under the Intergovernmental Panel on Climate Change (IPCC) shared socioeconomic pathway SSP5-8.5 (high emissions), such events will affect tropical forests in the following decades.

Despite the lower level of warming relative to temperate regions, exposure is most significant in the tropics. Little historical climate variability and shallow thermal gradients mean that many species occur close to their upper realized thermal limits throughout their geographic range. The Amazon is one of the regions (together with the Indian subcontinent and Indo-Pacific) most at risk, with more than 90% of species in any assemblage exposed to unprecedented temperatures by 2100 (Trisos *et al.* 2020).

23.1.1.2 Lowlands connectivity with highlands

Amazon harbors one of the world's most diverse biological communities (see Chapters 2–4), and migration towards wetter and colder habitats as the lowlands become warmer is predicted for many species. Being the most extensive and highest mountain range on the continent, the Andes may represent the only refuge for many Amazonian species, potentially resulting in a net loss of species in lowland forests (Colwell *et al.* 2008).

Lowland Amazonian species are likely to be highly vulnerable to climate change because of their narrow thermal niche. Some areas in the Andes may increase in species richness owing to the immigration of lowland species. However, these gains may be offset by other threats to biodiversity, such as habitat loss. In parts of the northern Andes, climate-driven shifts of bird, mammal, and amphibian species are predicted to lead to minimum average gains of 21–27% in species richness, based on two emissions scenarios according to Nakicenovic and Swart (2000) (Lawler *et al.* 2009).

Because most tropical species might migrate to habitats that match their ecological requirements in response to climate change, protecting lowlands' connectivity to the cooler highlands may provide an escape route for many species from the megadiverse Amazon and Andean foothills. The forest belts are typically subdivided into upper montane (2,500 m to timberline) and lower montane (1,500 to 2,500 m). However, very few elevational gradients of intact habitat extend from the lowlands on either side of the Andes to the tree line or above. Because forests often remain in isolated belts at intermediate elevations, many species will face rising temperatures, forcing them to shift upslope. Simultaneously, they are pushed downslope by the expansion of human population centers and the advancing agricultural frontier.

23.1.1.3 Aquatic ecosystems

A significant effect of climate change on the function of aquatic ecosystems and their biodiversity (see Chapter 3) is the disruption of the natural hydrological cycle owing to unusually low and high peaks in water levels during extreme drought and flood events (Marengo and Espinoza 2016; see also Chapter 22). Such extreme events affect plants and animals, causing changes at multiple levels, from individuals and populations to communities and ecosystems, at local and regional scales. In central Amazon's floodplains, the extreme drought event of 2005 affected detritivore curimatids' health (*branquinhas*), leading to thinner fish relative to their body length (Correia *et al.* 2015). It also caused shifts in fish abundance and the composition of fish communities, which were noticeable a decade later (Röpke *et al.* 2017). In the western Amazon, the extreme drought of 2010 caused significant declines in wading birds, river dolphins, and fish populations (Bodmer *et al.* 2018). In contrast, extreme flood events in 2009 and 2011–2015 caused a 95% population decline of ground-dwelling mammals and altered predator-prey interactions. Such long-lasting reductions in game-wildlife abundance shifted local Indigenous people's hunting effort to fishing and increased local fishing pressure during the flood period (Bodmer *et al.* 2018).

Higher future sea levels will have important impacts on aquatic systems in Amazonia. Marine waters would be driven deep into the Central Amazon, altering shorelines, habitats, microclimates, and regional rainfall patterns (see Chapter 1). This large marine incursion would convert large areas of lowland Amazon rainforest to nearshore estuarine and marine habitats and possibly drive many species to extinction.

Many fish species in the Amazon are migratory (see Chapter 3), and their ability to migrate is threatened by climate change. Goliath catfishes (*Brachyplatystoma rousseauxii, B. platynemum, B. juruense,* and *B. vaillantii*) undertake the longest documented migrations of freshwater fish on Earth (Barthem *et al.* 2017). From headwater spawning habitats in/or near the Andean piedmont of Bolivia, Colombia, Ecuador, and Peru to nursery habitats in the Amazon Estuary on the Atlantic Ocean, their migratory journeys can expand to 11,600 km when older juveniles of *B. rousseauxii* return to their places of birth (Barthem *et al.* 2017). Low water levels during extreme drought events can lead to temporal river fragmentation, blockage of fish migrations, and local extinctions (Freitas *et al.* 2012). However, studies assessing the magnitude of climate change disruptions to migrations are needed.

Tectonics and climate change are clear marks in the evolution of the Amazon biota. Amazonian fish have experienced speciation booms during critical periods of oxygen availability, high temperatures, and extreme carbon dioxide levels (Albert *et al.* 2018). Environmental pressures in these geological periods shaped the biology of thousands of fish species in the Amazon, including the appearance of peculiar physiological, biochemical, and reproduction features in these species (Val and Almeida-Val 1995). Three water quality aspects deserve to be highlighted here, given their connections with the conservation of the Amazon biome in light of the new scenarios imposed by the current climate changes and foreseen for the near future. These aspects are oxygen availability in the aquatic environment, water acidity owing to the dissolution of CO_2, and temperature increase.

The availability of oxygen has always been a significant environmental challenge for fish in the Amazon; fish have developed a wide range of adaptations to transfer oxygen from the environment to the different organs (Val and Almeida-Val 1995; Val *et al.* 1998). Some of these adaptations, such as aerial breathing as in Pirarucu (*Arapaima gigas)* (Brauner and Val 1996) and the expansion of the lower lips of Tambaqui (*Colossoma macropomum)* (Saint-Paul 1984) for breathing on the surface of the water column, among others, place these animals in contact with a modified atmosphere. The increase in temperature contributes to increased ventilation and, therefore, increased contact of the gills and respiratory organs with water and air with modified properties (Almeida-Val and Hochachka 1995).

As the water warms, it loses its ability to hold oxygen, but at the same time, triggers a greater oxygen demand in cold-blooded animals such as fish. Andean Amazon fish species, particularly those that inhabit high elevations and prefer cold water, are highly susceptible to contractions in their distribution range and eventually to extinction as they move upstream, searching for cooler water (Herrera *et al.* 2020). Increases in the metabolism of warm-water species in lowland habitats can trigger greater food intake and cause unforeseen consequences in local food webs. Tambaqui exposed to experimental conditions that mimic elevated air temperature and CO_2 predicted by climate change scenarios increased their food intake, but their growth decreased under the most extreme warming scenarios (Oliveira and Val 2017). Such physiological responses of large and long-living fish such as the Tambaqui can increase competition with other fish species and reduce the carrying capacity of aquatic ecosystems.

Many fish species in the Amazon are susceptible to small temperature increases (Campos *et al.* 2018). The maximum critical temperature of some fish groups is already very close to the current average maximum temperatures. Small temperature increases affect multiple physiological processes. Studies with Tambaqui demonstrated that the most basic reproductive processes, such as fertilization, are sensitive to environmental conditions, including temperature and pH (Castro *et al.* 2020). Moreover, changes in metabolic processes that provide the energy necessary for fish survival under different situations may be an example of the increased environmental variability in Amazonian environments.

Acidic waters are common in the Amazon (see Chapter 4). The black waters of the Negro River, for example, are typically acidic, and some of its marginal lakes may have waters with pH values as low as 3.5. Even so, hundreds of different fish species inhabit these waters, including hundreds of ornamental fish species that support a significant economy of some Amazonian villages (see Chapter 30). We are far from knowing the resilience of Amazonian fish to pH variations. However, we know that they use different strategies to maintain ionic homeostasis in the face of challenging situations imposed by the acidity of the Negro River (Gonzalez *et al.* 2002). We also know that Tambaqui is remarkably resilient to acidic water exposure (Wood *et al.* 1998). Thus, at least for the species studied so far, except for fertilization, the acidic pH does not represent an expressive limiting factor. However, further studies involving other fish species are necessary.

We are far from understanding the effects of climate change on fish in the Amazon. However, according to IPCC models, we already know that fish are significantly affected when exposed to simulated environmental scenarios for temperature, CO_2, and humidity for the year 2100. In the case of Tambaqui, an important commercial species for the entire Amazon, transcriptional readjustments (Prado-Lima and Val. 2016), intense vertebral disorders with increased levels of lordosis, kyphosis, and scoliosis (Lopes *et al.* 2018), and reduced feed conversion, with animals eating more and growing less in the most drastic climatic scenarios (Oliveira and Val 2017), were observed. The disturbances also occur with ornamental fish species of Rio Negro (Fé-Gonçalves *et al.* 2018). Undoubtedly, fishing and fish farming will need to incorporate new technologies in the face of new climate scenarios to maintain protein production and ensure food security.

23.1.2 Forest dynamics in a changing climate

Forest dynamics are characterized by interactions between disturbances and demographic processes (e.g., recruitment, growth, and mortality), which together shape much of the structure, carbon content, and species composition of Amazonian forests. Despite their high resilience, anthropogenic climate change is severely altering forest dynamics across the entire Basin. This includes old-growth, degraded, and secondary forests. Climate change exacerbates chronic drivers of forest change (e.g., rising temperature and CO_2) and the extent, frequency, and intensity of single and compounding disturbance events—including wildfire, drought, windthrow, and biotic attack. An outstanding question is whether such interactions between stressors and disturbances will be large enough to surpass the capacity of tropical forests to resist and respond to such changes, especially as they interact with land-use change (see Chapter 24).

Global carbon emissions have impacted Amazon's most remote forests by changing the atmospheric composition and air temperature. The accumulation of atmospheric CO_2 has contributed to the increased growth of primary forests and mortality rates in the mid-2000s (Brienen *et al.* 2015). Although this likely CO_2 effect has ultimately promoted forest carbon (C) gains, especially during the 1990s, carbon accumulation rates are now slowing down. One possible explanation for this change is that forest mortality losses are outpacing potential gains from forest-enhanced growth. Another contributing factor to increasing mortality—other than CO_2—is the increase in air temperature in the region. Many Amazonian trees operate close to their bioclimatic limit. Thus, when air temperatures rise, autotrophic respiration increases the carbon-related costs for tree growth, partially explaining why carbon accumulation in Amazonian forests decreases nearly 9 MgC ha per degree Celsius increase in air temperature (Hubau *et al.* 2020). Extreme daytime temperatures are critical in depressing tree growth rates.

Another characteristic of intact lowland forests that are changing is their floristic and functional composition, with an ongoing shift in tree species composition in the Amazon towards a more dry-affiliated community (Esquivel-Muelbert *et al.* 2019). These changes have been linked to climate-change drivers altering forest recruitment and mortality, with atmospheric CO_2 playing important roles. Overall, these ongoing changes in primary forest dynamics have been subtle, with their detection concentrated in field plots located in primary forests.

Although forests have evolved being exposed to some small level of disturbance, increased disturbance regimes can cause severe and prolonged forest degradation. This can sharply reduce forest species richness, reduce carbon storage capacity, and cause significant shifts in species composition (towards a more generalist, less diverse community of plants). The forests most susceptible to these disturbances grow along the driest southern and eastern margins of the Amazon, where drought, wildfires, and fragmentation already interact synergistically (Morton *et al.* 2013; Alencar *et al.* 2015). Lowland forests (e.g., *igapos*) are also particularly vulnerable to some of these disturbances, including fire and drought interactions (Flores *et al.* 2017). Despite the extensive degradation caused by drought-fire interactions in the Amazon, it is still unclear how much is caused by climate change itself, given complex interactions involving land-use change.

Although forests disturbed by compounding extreme events may eventually recover, it is still unclear how long it will take. A single disturbance event such as drought may kill the most susceptible species and select more drought-resistant trees, which can potentially reduce tree mortality in successive events. Furthermore, previous studies suggest that even severely disturbed forests can recover some pre-disturbance characteristics (e.g., fluxes of H_2O) within decades (Chazdon *et al.* 2016). However, climate change is expected to increase the risks of new disturbances impacting the area, perhaps before recovery occurs. Although higher levels of atmospheric CO_2 may facilitate forest recovery, more frequent disturbances would result in chronic impoverishment of biomass and biodiversity, especially in landscapes becoming more fragmented by deforestation (see Chapter 24). In fact, as the regional climate changes, forest resilience is expected to decrease (Schwalm *et al.* 2017).

Modeling studies indicate that climate changes will have potentially significant effects on forests in the near future. Considering only primary forests, increased atmospheric CO_2 concentration could theoretically offset losses in carbon stocks from increased temperature. However, recent studies suggest that the CO_2 fertilization effect is limited mainly by the availability of other nutrients and the diversity of functional strategies across species (Fleischer *et al.* 2019). Most predictive vegetation models or Earth System Models (ESM) used to project potential trajectories of Amazonian forests are too sensitive to CO_2 fertilization, lack adequate nutrient limitations, are not very sensitive to variability in precipitation, and lack disturbances such as drought-induced tree mortality and logging wildfire, and edge effects. Another priority for dynamic vegetation models is the representation of plant hydrodynamics, distribution of water and nutrients below ground, and partitioning of solar radiation between competing plant canopies (Fisher *et al.* 2018).

Improving our understanding of the potential impacts of climate change on forests in the near future requires long-term monitoring, from individual trees to the entire continent. It also entails improving the current climate-global dynamic vegetation models, which are the primary tool used to forecast tropical forests' potential trajectories. ESM predict the Amazon to be dryer than today, with an additional exacerbated sensitivity of vegetation models on the CO_2 fertilization effect (Ahlström *et al.* 2017). Although these models have rapidly advanced, this extraordinarily complex system with more than 15,000 tree species remains to be fully understood. The potential legacies of increased forest degradation by compounding disturbances can persist for long periods. This necessitates urgency in identifying potentially catastrophic thresholds of forest health declines associated with rising temperatures and changes in precipitation patterns (see Chapter 22).

23.1.3 Carbon cycling and storage

The long-term balance between carbon uptake during photosynthesis and carbon losses during respiration and tree mortality dictates how much carbon Amazonian forests can store. The mature Amazonian ecosystem stores large amounts of carbon above and below ground (~150–200 Gt C; see Chapter 6). Production of woody biomass (longest-lived plant tissue and an important C stock) accounts for approximately 8–13% of the photosynthetic carbon uptake. Most of the remainder is respired back to the atmosphere. Simultaneously, a smaller fraction is stored as sugars and starch, allocated for growth or to maintain physiological processes. The total gross primary productivity (GPP) allocated for growth (net primary productivity; NPP) ranges from 30 to 45%, with more of the NPP being used for wood increment (39%) than for leaf (34%) and fine root (27%) production (Malhi *et al.* 2011). There are relatively few direct measurements of NPP and GPP across Amazon. The magnitude of GPP varies significantly with rainfall and soil nutrient status, with the highest values found in the wet forests of northwestern Amazon and lower values found in regions with a long dry season (Malhi *et al.* 2015). However, few studies have quantified all these NPP components and their distribution between forest components.

The spatial variability of C uptake and productivity of Amazonian forests strongly relates to climatic gradients across the basin. Overall, photosynthesis is lower in regions with an average total annual precipitation < 2,000 mm and dry seasons longer >3.5 months (Guan *et al.* 2015). Extreme wet areas can constrain GPP owing to high cloud cover and low light availability (Lee *et al.* 2013). Despite variability in GPP across the Amazon, most high-elevation primary forests average between 20 and 40 megagrams of carbon (MgC or 106 g)/ha per year (Malhi *et al.* 2011). NPP can follow similar spatial patterns to GPP, although differences are common because of the influence of autotrophic respiration on NPP (Brando *et al.* 2019a).

Recent studies have shown that forest carbon cycling in the region is changing, with important implications for this large global carbon reservoir. A few decades ago, primary forests of the Amazon were removing carbon from the atmosphere at a rate of approximately 0.5 tons per hectare per year (Ometto *et al.* 2005; Araujo *et al.* 2002; Chambers *et al.* 2001; Artaxo *et al*. 2021). However, the rate of carbon accumulation has sharply declined over the past two decades. One important reason for this reduction is significant droughts causing widespread reductions in tree growth and increases in tree mortality, especially the larger, carbon-rich ones, as shown in Figure 23.2 (Brienen *et al.* 2015; Brando *et al.* 2019a). Another potential cause for the reduction is the increase in atmospheric CO_2, promoting higher forest turnover rates (McDowell *et al.* 2018). As a combined result of these changes, the carbon accumulation capacity of undisturbed forests is getting weaker for both the Amazon and tropical Africa, with the possibility of forests becoming global carbon sources (Hubau *et al.* 2020; Brienen *et al.* 2015; Gatti *et al.* 2021).

Given the significant impact of climate (precipitation, temperature, cloud cover) on the geography of carbon stocks and productivity of Amazon forests, ongoing climatic changes are expected to cause significant shifts in the forest carbon cycling. Future temperature and precipitation changes, in addition to increases in climate extremes, will bring additional stress (Lovejoy and Nobre 2018, 2019; Nobre *et al.* 2019; Aguiar *et al.* 2016). Although intact tropical forests are estimated to be Earth's largest carbon sink (Pan *et al.* 2011; Phillips *et al.*

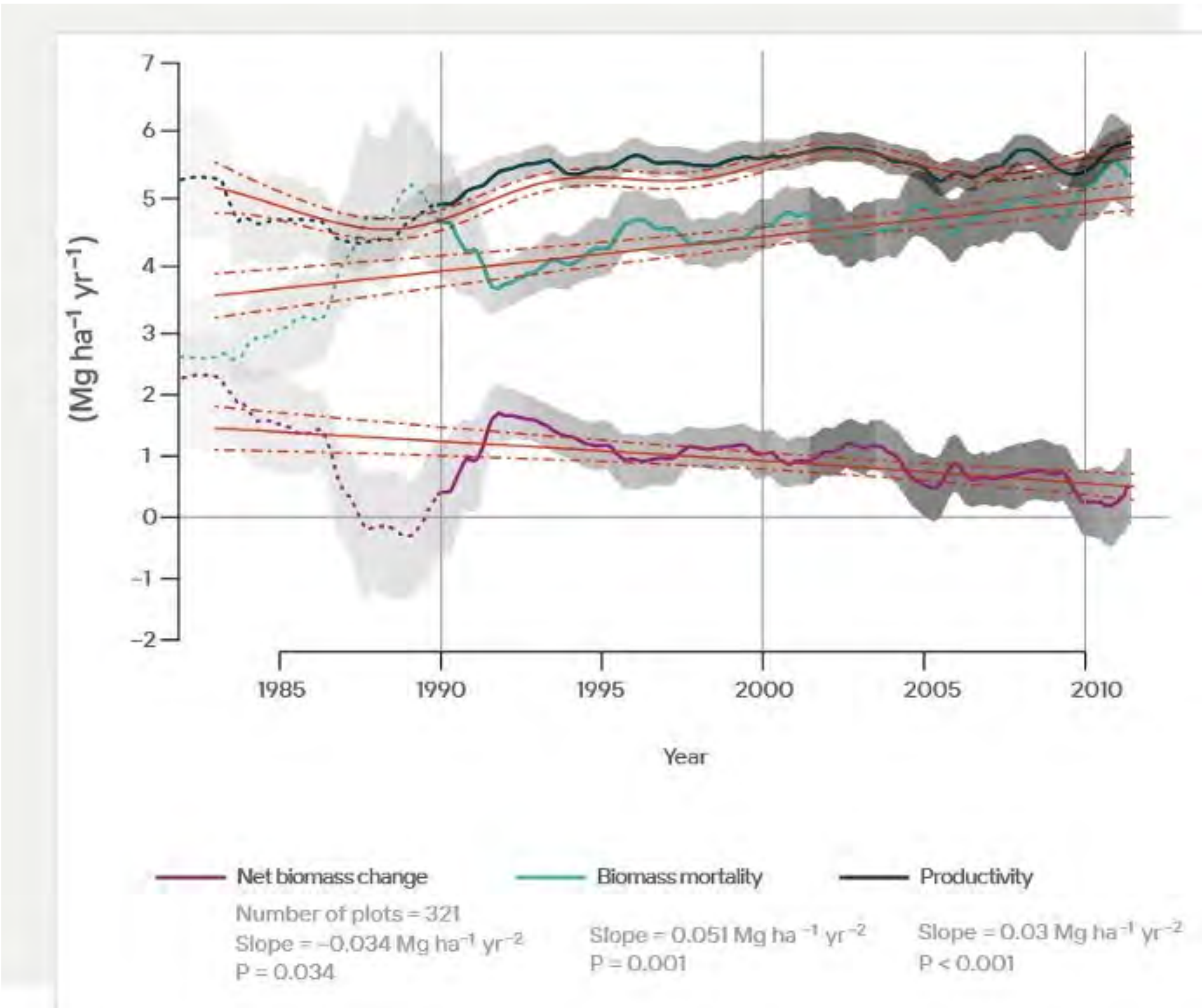

Figure 23.2. Long-term net above-ground biomass changes of old-growth tropical forests in the Amazon. Trends in productivity and mortality across all sites from 1985 to 2010. a) Net biomass change, b) biomass mortality, and c) forest productivity. It is possible to observe a decrease in net biomass change owing to an increase in biomass mortality. Adapted from Brienen et al. 2015.

2009; Ometto *et al.* 2005), the stability of this sink is susceptible to a warming climate and disturbance processes (Lenton *et al.* 2008). A change in drought regimes is expected to reduce the carbon storage capacity of tropical forests, especially those located in the southeast portion of the Basin. Such changes in climate–forest interactions will most likely change the emissions and atmospheric processes that have been discussed in previous sections, especially if global climate change is aggravated regionally by deforestation (Hoffmann *et al.* 2003). Burned forests in the Amazon have 25% lower than expected carbon stocks 30 years after the fires, with no further recovery in growth and mortality dynamics (Silva *et al.* 2018, see also Chapter 19).

The Amazon is currently subjected to pressures that go well beyond climate change (see Chapters 14–21). A wide range of severe disturbances, either natural or human-made, have directly or indirectly threatened the ecosystems' health, functions, and services in the Amazon, affecting biodiversity and carbon storage functions (Trumbore *et al.* 2015). A significant issue is that these disturbances interact with global climate change, having potentially compounding effects on forest carbon stocks (see also Chapter 19). In southeast Amazon, forests become much more vulnerable to fire along their edges with agricultural fields, during droughts and heatwaves, and where logging removes canopy cover. Once forests burn, they tend to be more severely disturbed by windstorms than primary forests, explaining why forest carbon stocks can reduce by 90% when impacted by these disturbances (Brando *et al.* 2019b).

Unfortunately, the carbon stocks of Amazon forests are not threatened only by interactions between forest disturbances and climate change. Deforestation has also been an essential driver of carbon storage reductions. Over the last three decades, the Brazilian Amazon forest has lost 741,759 km^2 of forests (MapBiomas 2020), representing 19% of the Brazilian Amazonian forested area. The annual rate of Amazonian deforestation was strongly reduced from 27,772 Km^2 to 4,571 Km^2 per year from 2004 to 2012, showing that it is possible and feasible to reduce tropical deforestation (Figure 23.3; see also Chapter 17). Unfortunately, from 2012 to 2020, deforestation has significantly increased, and the annual rate of deforestation in 2020 was 10,851 km^2 because of changes in Brazilian national policies for the Amazon region. The 2019 deforestation in the Brazilian Amazon released approximately 559 $MtCO_2$, according to estimates from Brazilian National Institute for Space Research (INPE 2021), and the deforestation pressure is increasing carbon emissions. The remaining forest edges have become much more flammable and prone to burning (Brando *et al.* 2020). These emissions go against Brazilian Nationally Determined Contributions (NDCs) to the Paris Agreement, whose commitment is to eliminate illegal deforestation by 2030.

There is an ongoing debate about the net carbon flux between Amazonian forests and the atmosphere when the entire Basin is considered (see SPA's Cross-Box on Carbon Budget). Some studies indicate that the carbon accumulation of standing forests is large enough to offset carbon losses from disturbances and deforestation, while others point to Amazonian forests acting as carbon sources (e.g., Pan *et al.* 2011; Gloor *et al.* 2012; Baccini *et al.* 2017; Schimel *et al.* 2015; Brienen *et al.* 2015). This apparent disagreement is mainly because the net carbon flux is the difference between two large gross fluxes. The carbon emissions primarily result from deforestation, and the carbon uptake is due to forest growth, likely supported by the increasing CO_2 concentration in the atmosphere.

Consequently, any change in the processes that affect atmosphere–biosphere interactions can significantly change the net carbon transfer between the tropical forests and the atmosphere, with substantial repercussions for atmospheric CO_2 levels and global climate (Lewis 2006; Chambers and Silver 2004). In other words, if deforestation, forest degradation, wildfires, edge effects were to be avoided, the net carbon uptake of Amazonian forests would contribute much more effectively to carbon removal from the atmosphere (Houghton *et al.* 2018).

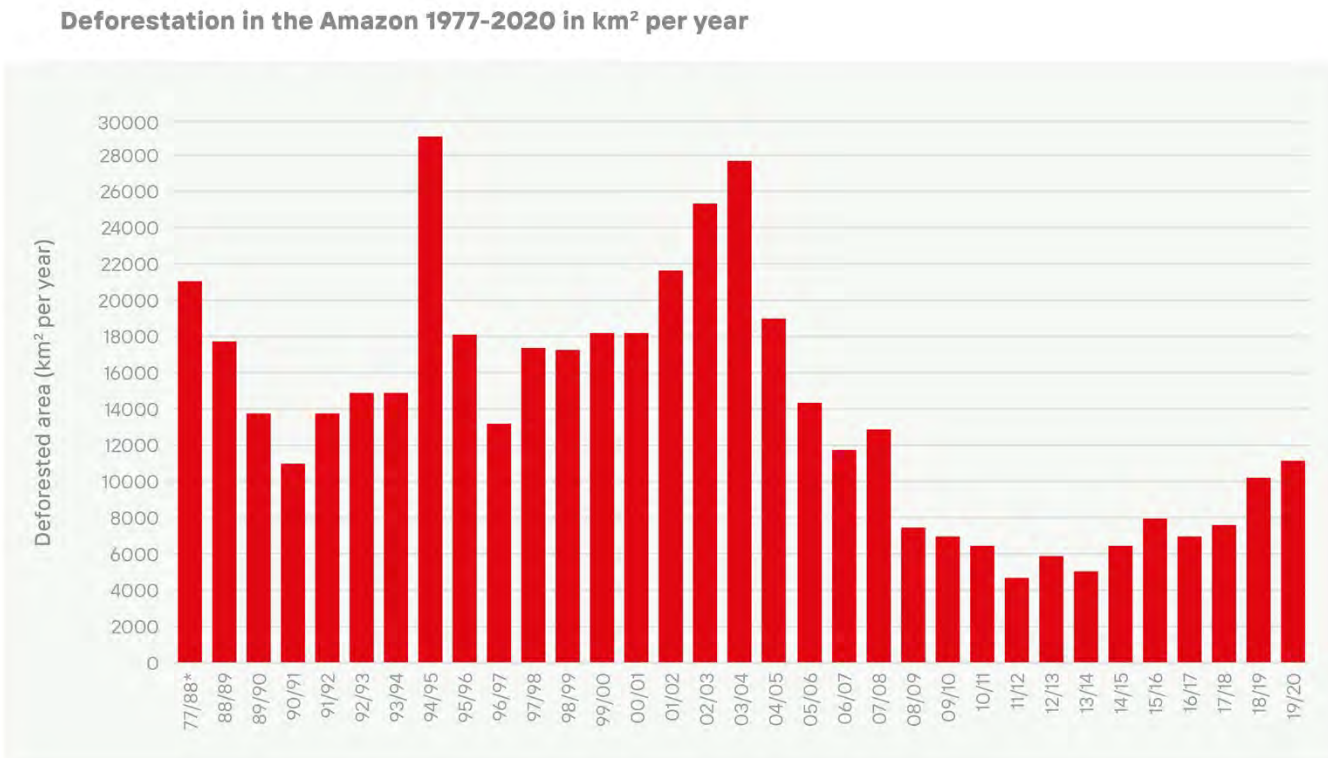

Figure 23.3 Time series of annual deforested area in the Brazilian Amazon, from 1977 to 2020. Data from the INPE PRODES program.

23.1.4 Freshwater impacts

Amazon freshwater ecosystems have been impacted by changes in landscape during their formation and evolution (see Chapters 1 and 2). Although natural, these changes leave a signature that will be part of several ecosystems, and all aquatic organisms are adapted to them. The highest evolutionary impact on recent freshwater evolution is river capture owing to geological changes (Val *et al.* 2014). River capture is a geomorphic mechanism of network reorganization by which a basin captures large portions of the network of an adjacent basin, thus creating a barrier for species dispersal. Landscape changes in the Amazon water bodies, such as drainage network reorganization, influence the distribution range and connectivity of aquatic biota and, therefore, their evolution (Albert *et al.* 2018). Such natural changes have occurred in the Amazon since the Andean uplift, resulting in a change in the landscape and causing habitat loss (Wittmann and Householder 2016). Loss of habitat is the primary driver of both the appearance and extinction of new species, the latter being the most substantial impact in freshwater systems. Ongoing impacts, though, do not give sufficient time for fish assemblages, species, or populations to recover or adapt to the new conditions, threatening the persistence of species in those ecosystems.

Recent human activities have caused several habitat losses and the extinction of many species in the current evolutionary time. These changes are happening so fast that it is currently known as the 6th mass extinction (Ceballos et al. 2017). On top of the current extinction rates, the impacts of mining, hydroelectric power plants, overfishing, and the release of industrial, urban, and medical pollutants result in synergic effects over the aquatic biota in the Amazon Basin landscape (see Chapter 20). Fish of the Amazon are, as already mentioned, adapted to extreme conditions such as low pH, variable dissolved oxygen (both spatial and day/night changes), and also periodic lack of oxygen and variable types of water that have different amounts of dissolved organic carbon (DOC). Most anthropic actions induce changes in these water quality characteristics, resulting in temperature increases, hypoxia, and acidification. Synergic effects of the release of herbicides cause tissue, cellular, and DNA damages that are acute and even worse when fish face hypoxia and higher temperatures (Silva *et al.* 2019; Souza *et al.* 2019).

The exposure of some species, particularly the Tambaqui (a model species), to climate rooms built to mimic the future scenario forecast by IPCC for the year 2050 revealed many damages and some degree of mortality to fish subjected to warmer temperatures. The whole transcriptome gene expression showed that differentially expressed genes act to readjust or adapt protein expression and respond to changes in their metabolism (Fé-Gonçalves *et al.* 2020). Either they adjust their metabolism or die. These are few studies considering the effects of climate change on the dimension of aquatic biota in the Amazon. We are far from understanding how the complex network of impacts caused by humans in the recent past will modify the aquatic biota at several ecological and biological levels.

23.1.5 Climate change and hydrology

Several climate drivers perturb the hydrologic cycle of the Amazon Basin. Rainfall in the Amazon is sensitive to seasonal and interannual variations in sea surface temperature (SST) in the tropical oceans (Fu *et al.* 2001; Liebmann and Marengo 2001; Marengo *et al*. 2008a,b; see also Chapters 5 and 22). The warming of the tropical east Pacific during El Niño events suppresses wet season rainfall by modifying the (East–West) Walker Circulation. Large-scale teleconnections lead to simultaneous changes in the northern hemisphere extratropics, altering moisture flow into the Amazon, inducing drought events (Williams *et al.* 2005; Ronchail *et al.* 2002). Moreover, variations in Amazonian precipitation are also linked to SST in the tropical Atlantic (Liebmann and Marengo 2001). A warming of the tropical North Atlantic relative to the south leads to a northwestward shift in the Intertropical Convergence Zone (ITCZ) and compensating atmospheric dry air mass descent over the Amazon, sometimes producing intense droughts such as those in 1963 and 2005 (Marengo *et al.* 2008a,b). Gloor *et al.* (2013) showed that the Amazon river discharge at Óbidos is significantly increasing during dry and wet seasons. This could be caused by an increase in the input of water vapor from the tropical Atlantic owing to the substantial sea surface temperature increase since the 1980s. A time series of the Amazon river discharge at Óbidos is shown in Figure 23.4.

Observations and models suggest large-scale deforestation could cause a warmer and somewhat drier climate by altering the regional hydrologic cycle (see also Chapter 22). Model results (Sampaio *et al.* 2007; Sampaio 2008) suggest that if more than 40% of the original extent of the Amazon forest is lost, rainfall will significantly decrease across the eastern Amazon. Complete deforestation could cause the eastern Amazon to warm by more than 4°C, and precipitation from July to November could decrease by 40%. Crucially, these changes would be in addition to any change resulting from increased greenhouse gas (GHG) emissions; reducing deforestation can offset the impacts of GHG. It has been suggested that 20–25% of basin-wide deforestation may be a tipping point beyond which forest loss causes climate impacts that cause further forest loss (see Chapter 24; Sampaio *et al.* 2007).

A key question is whether a general long-term trend exists during recent decades toward drought conditions and, if so, to what degree it is associated with GHG emissions and deforestation. Li *et al.* (2008) show that the Standard Precipitation Index (SPI), a measure of changes in precipitation normalized by the standard deviation, does indeed suggest a more pervasive drying trend over the southern Amazon between 1970–1999. Previously, tendencies studied by Marengo (2009) for the period 1929–1998 suggested that no unidirectional

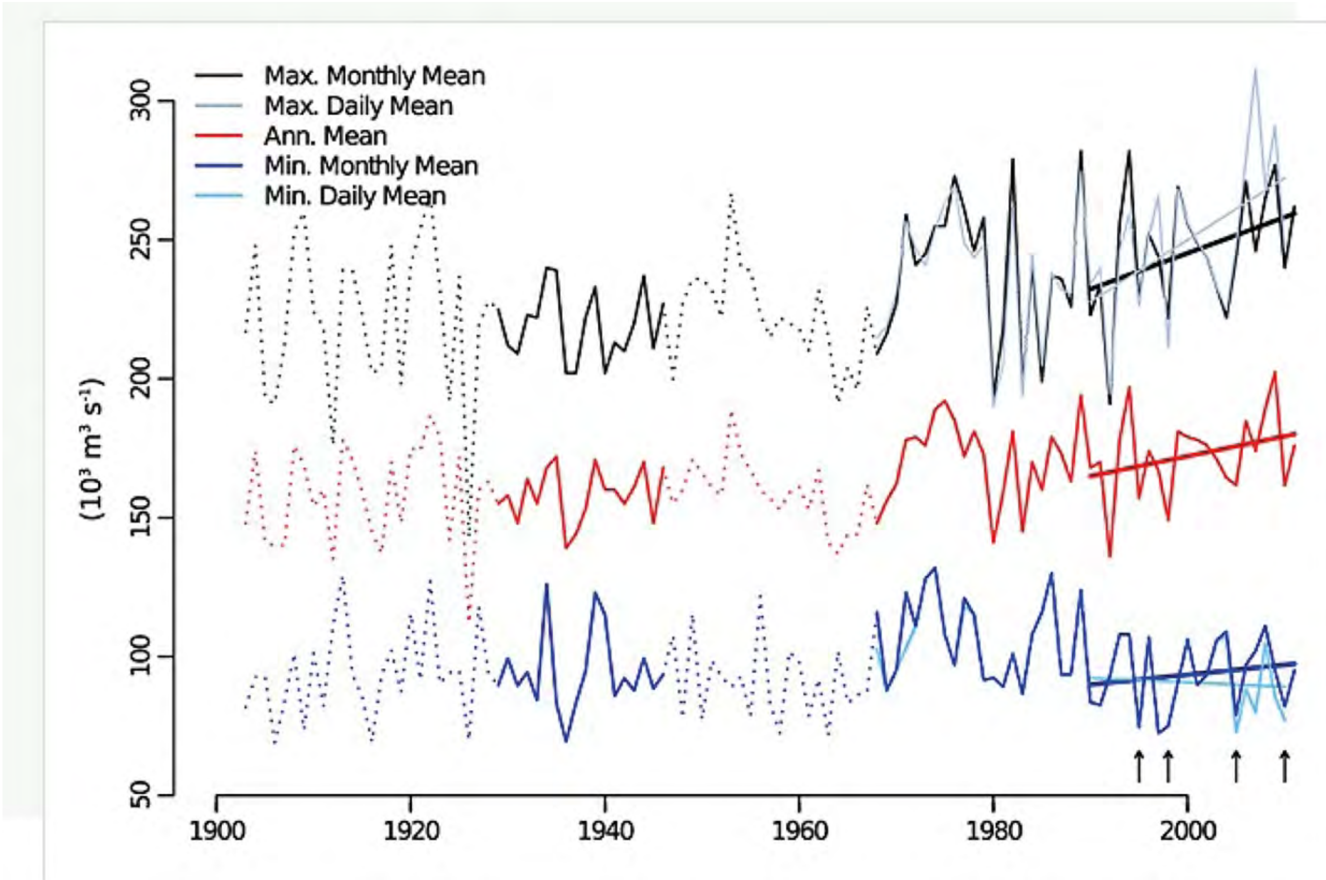

Figure 23.4. Long-term time series of the Amazon river discharge at Óbidos during the dry season (blue), wet season (green), and whole year (red). Source: Gloor et al. (2013).

rainfall trend existed in the entire Amazon region. However, a slight negative/positive trend was identified in the northern/southern Amazon. To understand the discrepancies between these studies, it is necessary to evaluate the timescales over which the data were analyzed. Perhaps, the most critical aspect of natural Amazonian precipitation change is interannual and interdecadal variability in rainfall. Studies have identified a negative trend for southern Amazon during 1970–1999 coincided with the mid-1970s–1998 downward rainfall trend of the interdecadal rainfall variability in northern Amazon (Marengo 2009). This decadal variability seems to be linked to interdecadal variations in the SST in the tropical Atlantic (see Chapter 22).

Despite some progress in reducing deforestation rates from 2002 to 2011, after 2005, some parts of the Amazon Basin, such as the eastern Amazon region, a transition zone between rainforest and savanna environments, remain particularly vulnerable to feedbacks from ongoing land-use conversion to agriculture (Coe *et al.* 2013). The expansion and intensification of agriculture (see Chapter 15) shift how incoming precipitation and radiation are partitioned among sensible and latent heat fluxes and runoff (Bonan 2008; Coe *et al.* 2013; Foley *et al.* 2005; Neill *et al.* 2013). Relative to the forests they replace, crops and pasture grasses have reduced root density and depth and lower leaf area index (LAI). This decreases water demand and evapotranspiration (ET) (Coe *et al.* 2009, 2013; Costa *et al.* 2003; D'Almeida *et al.* 2007; Moraes *et al.* 2006; Lathuillière *et al.* 2012; Nepstad *et al.* 1994; Pongratz *et al.* 2006; Scanlon *et al.* 2007). At local and regional scales (i.e., watersheds of 10-100,000 km^2), such reductions in evapotranspiration lead to increased soil moisture and runoff (Coe *et al.* 2011, 2009; Hayhoe *et al.* 2011; Neill *et al.* 2006). At continental scales (i.e., Amazon Basin), these land cover changes may reduce rainfall and decrease runoff (D'Almeida *et al.* 2007; Davidson *et al.* 2012; Stickler *et al.* 2013).

23.2 Impacts of climate change on ecosystem services

23.2.1 Pollination and seed dispersal

Nature in the Amazon has a wealth of ecosystems and biodiversity, which are indispensable to delivering ecosystem services across scales (Díaz *et al.* 2019). At landscape to regional scales, Amazon's forests regulate hydrological cycles (Salazar *et al.* 2018), water quality, and nutrient cycling, which supports freshwater and forest biodiversity (Menton *et al.* 2009). Ecosystem services result from the interactions between several biotic and abiotic components, with biodiversity supporting ecosystem functions that affect life on the planet (Mace *et al.* 2012). Anthropogenic climate change is one of the main current threats to biodiversity linked to species decline (Díaz *et al.* 2019). Among biotic interactions, pollination and seed dispersal play an essential role in determining plant diversity and distribution in natural ecosystems (Wang and Smith 2002) and agricultural production. In this context, bees, birds, and bats that act as pollinators, seed dispersers, and pest controllers are crucial (Kremen *et al.* 2007). These groups are susceptible to spatially operating ecological factors, which makes their services highly contextual (Kremen 2005; Mitchell *et al.* 2015).

Birds are good biological indicators of climate change impacts on ecosystem services. Their occupancy of all terrestrial habitats and the consumption of virtually all types of resources provide critical ecosystem functions and services such as pollination, seed and nutrient dispersion, predation, and scavenging. Miranda *et al.* (2019) compiled extensive species occurrence data representative of southeastern Amazon to assess the potential climate change impact on avian assemblages. Using Species Distribution Modeling (SDM), they analyzed how different climate change scenarios could affect the pattern of species distributions and assemblage compositions. They grouped species based on their primary diet (frugivores, insectivores, nectarivores, and others) as a proxy to ecosystem services (seed dispersion, pest control, and pollination). They estimated that between 4–19% of the species would find no suitable habitat considering the entire study area. Inside the currently established protected areas, species loss could be over 70%. The results suggested that frugivores would be the most sensitive guild, bringing consequences on seed dispersal functions and natural regeneration. Moreover, they identified the western and northern parts of the study area as climatically stable. At the same time, climate change will potentially affect avian assemblages in southeastern Amazon with negative consequences to their ecosystem functions (Miranda *et al.* 2019).

Bats have also been associated with hundreds of plant species (Kunz *et al.* 2011; Ghanem and Voigt 2012). They occupy different trophic niches and perform various functions in nature, acting as flower pollinators (nectarivores), seed dispersers (frugivores), and pest controllers (insectivores). Frugivorous bats work in a complementary way with birds with the same trophic habits, acting together to diversify the microhabitat where they deposit seeds, thus contributing a significant service when considering the quantity and quality of dispersion (Jacomassa and Pizo 2010; Sarmento *et al.* 2014).

The effects of climate change on the distribution of bat species occurring in the Carajás National Forest (eastern Amazon, southeastern Pará state, Brazil) was examined by modeling species distributions (Costa *et al.* 2018). The authors evaluated 83 species of bats to identify the species potentially more sensitive to climate changes and if they would be able to find suitable areas in the Carajás area in the future. Besides, they assessed the priority areas that protect the most significant number of species from climate change. A considerable fraction (57%) of the analyzed species would not find suitable locations in Carajás under the climate change scenarios. Pollinators, seed dispersers, and more generalist (omnivorous) bats would potentially be the most affected, suffering a 28–36% decrease in suitable areas under the 2070 scenario, affecting the plants that interact with bats. According to the scenarios, current protected areas in the Brazilian state of Pará would not protect most species in the future.

Both studies (Miranda *et al.* 2019 and Costa *et al.* 2018) emphasize that the possible effect of climate change and protected areas' location needs to be considered for conservation strategies of pollination and seed dispersal services in the case of future climate change.

Besides bats and birds, projections indicate the impacts of climate change on the distribution of bees in the Amazon, impacting crop pollination (Giannini *et al.* 2020). Using two different algorithms and geographically explicit data, the analyses and projections of the distribution of 216 species occurring at the Carajás National Forest showed that 95% of bee species would face a decline in their total occurrence area. Only 4–15% would find climatically suitable habitats in Carajás. Bees with medium and restricted geographic distributions and vital crop pollinators would experience significantly higher losses in occurrence areas while wide-range habitat generalists would remain. The decline in crop-pollinator species will probably pose negative impacts on pollination services.

Climate change will promote the redistribution of biodiversity, and species-specific differences in response to the changes can decouple the interacting species' distribution. Such pervasive and indirect effects of climate change may have spillover effects upon economies and human well-being. The extraction of Brazil nuts, açai, guarana, cocoa, and others can be critical socio-economic activities associated with non-timber products in the Amazon (Peres and Lake 2003; Zuidema and Boot 2002; see also Chapter 30). The potential effects of future distribution mismatch of seed dispersal and pollination of Brazil nuts were studied by Sales *et al.* (2021). The projections indicated that Brazil nuts' pollinators would lose nearly 50% of their suitable distribution in the future, leading to an almost 80% reduction in co-occurrence potential. Local pollinator richness was predicted to diminish by 20%, potentially decreasing pollination redundancy and resilience to environmental changes. Another study pointed out the magnitude of the loss of seed dispersal services by primates as a function of the future redistribution of species. Primates are remarkable seed dispersers, comprising up to 40% frugivore biomass in tropical forests (Chapman 1995). The projections indicate average contractions of 56% (23 to 100% reduction) on the studied primates' suitable areas (Sales *et al.* 2021).

23.2.2 Aquatic ecosystems

Climate change is predicted to affect ecosystem services provided by freshwater ecosystems, including access to drinking water, electricity derived from hydropower, navigation, and, most importantly, fisheries (Castello and Macedo 2016), the primary source of animal protein and major economic driver in the Amazon region. The monetary value of Amazonian fisheries is estimated at more than USD 400 million annually, and just in the Brazilian Amazon, it involves more than 200,000 fishers (Barthem *et al.* 1997; Barthem and Goulding 2007; Duponchelle *et al.* 2021). These figures, however, likely underestimate the actual value of Amazonian fisheries, given that fish used for consumption at fisher households are not included in fisheries landing statistics and because small-scale fisheries are highly heterogeneous at natural, social, and economic scales (Castello *et al.* 2013).

Fisheries' yields are being impacted by climate change in unpredictable ways. For example, over ten years (1994–2004), the body length of fish harvested in the central Amazon (Solimões), Madeira, and Purus rivers have declined in response to the intensification in drought. This change in fish yields reflects a decrease in the abundance of large predatory fish, which is compensated for by increasing the number of smaller fish that feed lower in the food chain (Fabré *et al.* 2017). Over the same period, fisheries' yields in the lower Amazon River (Óbidos, Santarém, and Monte Alegre) declined by 50% relative to those from adjacent floodplain lakes. Moreover, target fish species responded differently to local environmental stressors related to climate change, such as reduced discharge, elevated water temperature, and wind, but also to global-scale stressors such as sea surface temperature and climatic indices related to El Niño-Southern Oscillation events (Pinaya *et al.* 2016). Calculating the economic losses owing to reductions in fisheries yields induced by climate change is challenging because of the sparse knowledge on fisheries yields per habitat type (e.g., floodplain lakes, flooded forests, flooded savannahs; Barros *et al.* 2020; Castello *et al.* 2018; Goulding *et al.* 2019) and the lack of reliable long-term fisheries statistics to assess trends across the Basin.

Although aquatic ecosystems provide many more services to human populations beyond fisheries, the lack of quantification of many of those services hinders our ability to estimate losses. Extreme droughts will likely reduce access to fresh water for drinking and bathing, alter natural flow regimes, which in turn will affect riverine navigation and access to off-channel fishing, hunting, and farming grounds, and affect cultural services, including recreation and the persistence of sacred places, usually linked to river-rapids. Lastly, spatial gradients in the effects of climate change on ecosystem services are expected, given the differences in flow regimes and precipitation patterns across the Basin as one moves from north to south and west to east (see Chapter 22).

Aquaculture activities may be considered an environmental service when done in natural ponds or cages on the rivers. It is among the services that aim to protect wild fish populations and increase protein availability to humankind. However, this activity has some adverse effects on the natural water systems if not monitored by specialists. Household-based aquaculture facilities lack control and regulation and can use and release many toxic substances to the natural environment. Although this activity is considered essential to avoid overfishing and provides protein to local people, it is still considered a threat to the environment (Silva *et al.* 2019).

23.3 Climate feedbacks of vegetation and land-use changes

The Amazon ecosystem is directly affected by climate and land-use changes in many ways, but there is also feedback between these two processes that may amplify the negative impacts (Betts and Silva Dias 2010). Deforestation for the expansion of agricultural lands affects climate through changes in the energy and water balance and the carbon cycle. For example, pasture and crops that typically replace forests have a lower capacity to cycle water through evapotranspiration, and the extra water tends to increase the runoff. A large amount of carbon emissions from Amazon deforestation contribute to increases in the atmospheric GHG and temperature globally, which are also expected to increase forest water use efficiency through CO_2 fertilization and reduce the amount of water vapor recycled to the atmosphere. Recent studies have shown an increased vapor deficit throughout the Amazon, but it is still unknown if this is a transient or permanent trend nor how this can affect the forest and drive feedback over the long term. The reduced ET can impact precipitation, but changes in response to deforestation depend on how large and where deforestation occurs. Therefore, the impact of deforestation and climate change on hydrology in any location will be a complex function of those competing impacts (Coe *et al.* 2009).

Forest conversion and degradation impact climate through two pathways. The first is through the carbon cycle. Globally, photosynthesis removes almost 30% of all global anthropogenic CO_2 emissions each year. Tropical forests are the most significant fraction of that carbon sequestration. With an area of 7.3 million km², the carbon stored in the Amazon's forests (~150-200 billion tons of carbon stores in soils and vegetation) is equivalent to more than ten years of current global carbon fossil-fuel emissions. More than half of all CO_2 emissions from Amazon nations result from deforestation and degradation, and the total contribution to global atmospheric CO_2 content has been significant (Global Carbon Project 2019). The net emissions from 2003 to 2016 alone were estimated at 4.7 Gt CO_2 (Walker *et al.* 2020).

The second mechanism by which deforestation and degradation affect climate is through the energy and water balance. Tropical forests have a low albedo, high evapotranspiration, and high roughness compared with croplands and pastures that often replace them (see Chapter 7). Those characteristics firmly control the local and, less strongly, global climate. The low albedo results in the absorption of a significant fraction of incoming solar radiation and the production of high net energy in the forest system. Much of that energy is used in the cooling process of evapotranspiration, which is generally high throughout the year because of relatively abundant sunshine and rainfall or stored soil moisture. The relatively high surface roughness and aerodynamic conductance increase the atmospheric mixing of ET and energy into the troposphere (Panwar *et al.* 2020). Deforestation and degradation reduce evapotranspiration, increase the surface temperature (e.g., Silvério *et al.* 2015), and if large enough, reduce rainfall regionally (e.g., Butt *et al.* 2011; Spracklen and Garcia-Carreras 2015; Leite-Filho *et al.* 2019). The type of land use that follows from deforestation has a lesser but still important impact, with crops having a relatively more significant impact than pasture (Silvério *et al.* 2015).

The high deforestation and forest degradation rates have impacted biodiversity, forest resilience, and climate over the past few decades (Davidson *et al.* 2012). In addition to large-scale deforestation, the Amazon has experienced large amounts of forest degradation, calculated as 1,036,080 km² over the last 30 years (Mapbiomas 2020). By 2018, 870,000 km² of forests have been lost in the Pan Amazon (Mapbiomas 2020). However, there is strong evidence to suggest that it occurs at the same or more significant scale than deforestation (Walker *et al.* 2020).

23.3.1 Surface albedo and radiation balance

Deforestation to expand agriculture results in permanent changes to the surface radiation balance, impacting climate at local and regional scales. Crops and pastures that typically replace forests have shallow roots systems and a seasonal growing season, which tend to decrease the net surface radiation (Rnet), which is the sum of solar shortwave and net longwave radiation fluxes absorbed by the land surface (Coe *et al.* 2016). Rnet reduction is linked to increases in the surface albedo and the outcoming flux of longwave radiation, limiting the system's capacity to cycle water through evapotranspiration. These local changes in the Rnet and water balance alter circulation and shorten the rainy season (Butt *et al.* 2011; Knox *et al.* 2011), affecting crop productivity over the agricultural frontier over the Amazon and Cerrado regions.

Surface albedo is the ratio of reflected radiation to the incident total solar in the short wavelength spectrum. It is the main factor affecting the land radiation balance and has frequently been considered in global and regional climate studies. The primary identified sources of variation of land surface albedo are land cover, solar elevation angle, canopy wetness, and cloud cover (Pinker *et al.* 1980; Bastable *et al.* 1993; Culf *et al.* 1995).

The albedo of different tropical land covers has been studied for over 40 years. The first measurements in the Amazon during Amazon Region Micrometeorological Experiment (ARME) indicated an average albedo of 12.3±0.2% for a tropical forest near Manaus, Brazil (Shuttleworth 1984). Later, during Anglo Brazilian Amazonian Climate Observation Study (ABRACOS), Bastable *et al.* (1993) verified an average albedo of 13.1% for the same site and 16.3% for a nearby pasture, a difference of 3.2%. Synthesizing the measurements at three Amazonian forest sites and three pasture sites, Culf *et al.* (1996) found average albedos of 13.4% and 18%, respectively (4.6% difference).

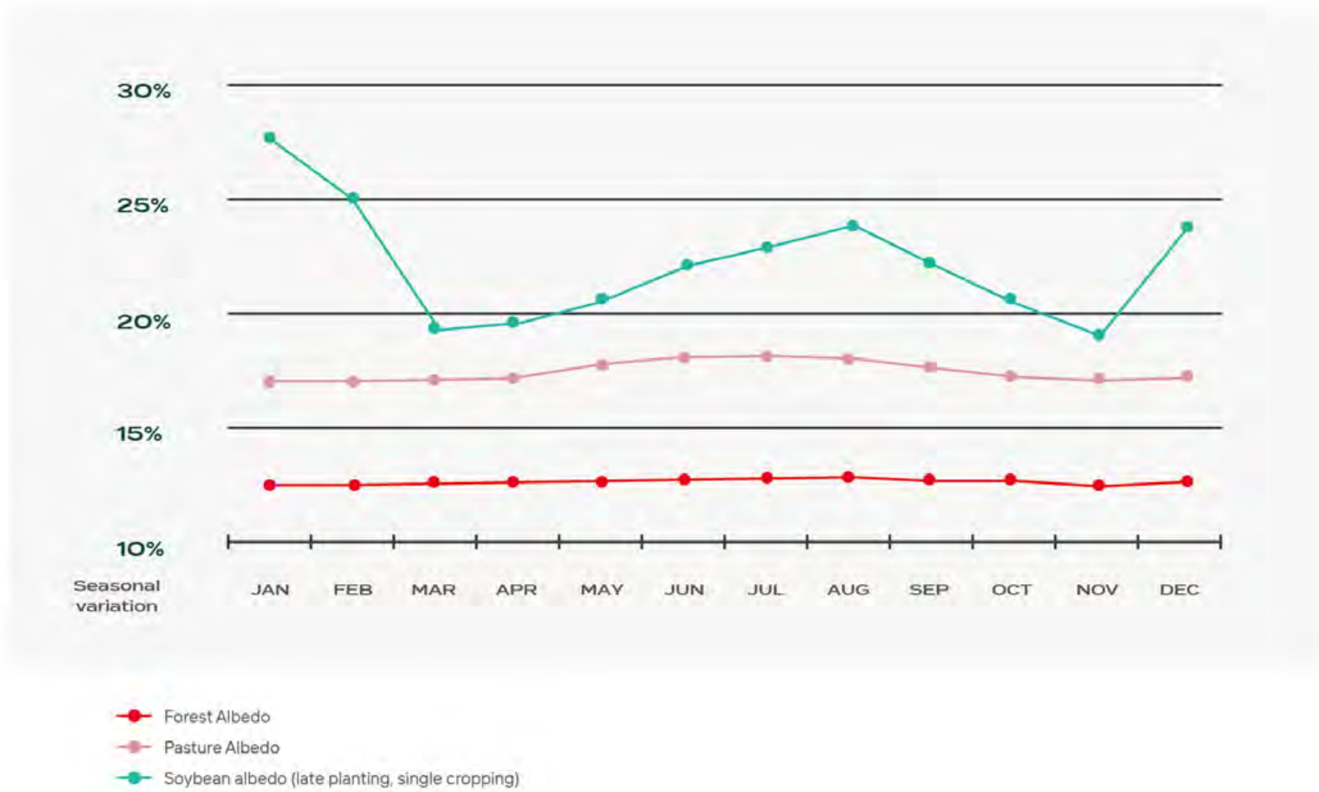

Figure 23.5. Seasonal variation of the forest, pasture, and soybean albedo. A single soybean growing season is represented. A strong increase in surface albedo can be observed when the forest is changed to pasture or soybean. Figure adapted from Costa et al. (2007).

Seasonal albedo for the rainforest, pastures, and soybean cropping systems typical of the Amazon are shown in Figure 23.5. Rainforest and pasture albedo are from Culf *et al.* (1996). Although the forest albedo is more stable throughout the year, presenting low variability according to the elevation of the sun and the moisture of leaves and soil, the pasture albedo is more sensitive to these factors, showing large variability during the year. Canopy height, vegetation density, the proportion of the exposed bare soil, or the predominantly vertical inclination of the leaves probably explain the wider variability of the pasture albedo. It is important to observe the significant difference between the forest albedo (approximately 13%) to pasture albedo (17%), whereas soybean shows much higher overall and seasonally variable albedo.

The seasonal variability of crop albedo depends on several factors, including the cropping system adopted (single cropping or double cropping), the crop itself (soybean, maize), and the planting date. Other factors are crop residues on the field after harvest, the albedo of the soil itself, and whether or not the field is plowed before planting. Here we present soybean albedo data from Costa *et al.* (2007), adjusted for a late planting date (November). The soybean albedo (for the growing season only) indicates an increased albedo as the crop grows and decreasing albedo as the crop drops leaves and dries out. For the period between growing seasons, the albedo rises again due to crop residues (straw) on the ground, decreasing as straw decomposes and the field is prepared for planting. Although many details of this seasonal curve will vary according to the factors listed above, crop albedo is typically much higher than pasture albedo and forest albedo.

Sena *et al.* (2013) analyzed surface albedo changes from land-use change radiative forcing over Rondonia from 2000 to 2009. The top of the atmosphere (TOA) flux for aerosol optical depth (AOD)=0 (no aerosol particles) for forest areas was 147 W/m², and over deforested areas, this value was 160 W/m². The difference of 13 W/m² is the radiative forcing due to a change in surface reflectance from forest to deforested regions of Rondonia. Evapotranspiration has also changed significantly, from forest areas to pasture with 0.35 cm column water vapor smaller at the pasture. This is approximately 10% of the total column water vapor, a very significant change.

23.3.2 Changes in soil moisture and evapotranspiration

More than half of the precipitation in the Amazon is transferred back to the atmosphere through evapotranspiration, consuming a lot of the energy and cooling the surface (see Chapter 5). However, land-use transitions can disrupt this system by dramatically reducing evapotranspiration. Therefore, changes in evapotranspiration and soil moisture associated with land use and land cover change, including deforestation and degradation, are crucial to understanding the possible trajectories of Amazon forests health in the coming years. Pasture and cropland that typically replace forests have smaller roots and do not access deep soil moisture or groundwater and have a much shorter growing season than the forests they replace (Coe *et al.* 2016; Costa *et al.* 2007; Negrón Juárez *et al.* 2007; Pongratz *et al.* 2006). For example, crops and pastures in the southern Amazon evapotranspire at rates equivalent to forests but only for 2–3 months per year at the peak of the growing season (von Randow *et al.* 2012). At the same time, forests evapotranspire at near-peak rates (>100 mm/month) for up to 10 months per year because of their access to the ample stored soil moisture in the top 10 m of the soil column.

These differences have a profound impact on the seasonal distribution of evapotranspiration and the annual total. This has been extensively studied at large and small spatial scales throughout the Amazon and Cerrado environments. Conversion of the native vegetation results in a decrease in the mean annual ET of approximately 30%, and during the dry season, this decrease is much larger (Arantes *et al.* 2016; Lathuillière *et al.* 2012; Panday *et al.* 2015; Spera *et al.* 2016). The changes to ET directly impact other variables that influence the surface water balance, soil moisture, and groundwater storage increase by as much as 30% locally and streamflow by 3-4-fold in small headwater streams and as much as 20% in very large rivers such as the Tocantins/Araguaia (Coe *et al.* 2011; Hayhoe *et al.* 2011; Heerspink *et al.* 2020; Levy *et al.* 2018; Neill *et al.* 2013).

Much of the precipitation in the Amazon is a result of moisture recycled by the forest (Salati and Vose 1984; Maeda *et al.* 2017). Therefore, the decrease in ET resulting from deforestation directly impacts the amount, location, and timing of rainfall. Numerous observational and numerical modeling studies have shown a clear link between deforestation and delayed onset and an earlier end to the rainy season (Butt *et al.* 2011; Debortoli *et al.* 2015; Fu *et al.* 2013). In numerical modeling studies, Li and Fu (2004) and Wright *et al.* (2017) showed that evapotranspiration, by increasing humidity throughout the atmosphere during the late dry season, is a crucial factor needed to initiate rainfall, with initiation being hastened by 2–3 months compared with simulations without forest ET. Evidence indicates that dry season humidity in the Amazon decreases, making the dry season more severe (Barkhordarian *et al*. 2019). Using detailed analysis of rain gauge data in the southern Amazon, Leite-Filho *et al.* (2019) estimate that for every 10% increase in deforestation, the onset of the rainy season is delayed by approximately 4 days (see also Chapter 22), which has amounted to an 11–18-day average delay in the rainy season onset in Rondônia, Brazil (Butt *et al.* 2011).

GHG emissions and deforestation have opposite effects on evapotranspiration. Increased emissions (and associated increased atmospheric temperatures) tend to increase ET, whereas deforestation (and associated land conversion to agriculture) decreases ET. It has been suggested that an overall reduction in the area of Amazonian forest will push much of the Amazon into a permanently drier climate regime (Malhi *et al.* 2008). At an annual scale, deforestation-reduced ET only partly offsets the positive effect of GHG emissions on ET, resulting in a net increase of runoff by the end of this century. In southeastern Amazon, model simulations with 50% forest area loss combined with climate change led to a consistent ET decrease, which offsets positive ET changes owing to climate change alone. For instance, model projections of the water budget in the Xingu basin (Guimberteau *et al.* 2017) are consistent with Panday *et al.* (2015), who found opposite effects of deforestation and GHG impacts during the past 40 years using a combination of long-term observations of rainfall and runoff/discharge.

Generally, the resulting increase of runoff owing to deforestation (i.e., ET decreases are associated with runoff increases) is consistent with other studies at local and regional scales (e.g., Sterling *et al.* 2013; Rothacher 1970; Hornbeck *et al.* 2014). For instance, the increase of annual runoff in the Xingu catchment (+8%; Guimberteau *et al.* 2017) owing to deforestation is of the same order as the results of Stickler *et al.* (2013), who found a 10–12% runoff increase given 40% deforestation in this catchment. From August to October, in the southeastern catchments, deforestation amplifies the effect of climate change in reducing ET, particularly in the south of the Tapajós catchment and in the north of the Madeira and Xingu catchments where deforested areas are the largest. Therefore, deforestation contributes to the increase in runoff (+27 % in the Tapajós).

In summary, the initial significant decrease in ET initiated by deforestation has already impacted much of the Amazon, particularly the south of the basin, and has large-scale feedback to precipitation. The changes in hydrology in response to deforestation depend on where and how large deforestation is (Coe *et al.* 2009; Heerspink *et al.* 2020). However, evidence suggests that the climate changes can be expected to be of the same scale as changes associated with increasing greenhouse gases and the same direction—significantly increased temperatures, decreased rainfall, and reduced length of the rainy season.

23.4 Biogenic and fire aerosol emissions and impact in and outside the region

The Amazonian atmosphere is dominated by two clear seasons. In the wet season, the atmosphere is dominated by natural primary biogenic aerosol particles emitted directly by the vegetation (Prass *et al.* 2021; Whitehead *et al.* 2016; Pöschl *et al.* 2010). In the dry season, biomass burning emissions have strong impacts on the Amazonian ecosystems and atmospheric properties (Davidson *et al.* 2012; Andreae *et al.* 2004; Andreae *et al.* 2012; Andreae 2019). Significant emissions of carbon monoxide, ozone precursors, nitrogen oxides, aerosol particles, and other compounds significantly alter the atmospheric composition over large areas of South America, and they can travel for thousands of kilometers (Andreae *et al.* 2001; Freitas *et al.* 2005; Reddington *et al.* 2016). Critical ingredients of forest emissions, such as biogenic volatile organic compounds (VOCs), are changing, possibly associated with higher temperatures (Yáñez-Serrano *et al.* 2020). These emissions have significant impacts on the ecosystem, including the radiation balance, atmospheric chemistry, and human health (Forster *et al.* 2007; Artaxo *et al.* 2013; Bela *et al.* 2015; Butt *et al.* 2020). Fire emissions are calculated with fire burned area derived from remote sensing data and emission factors measured in field experiments (van Marle *et al.* 2017; Randerson *et al.* 2012). Future climate variability is expected to increase the risk and severity of fires in tropical rainforests. In the Amazon, most fires are human-driven. A way to assess the aerosol column in the atmosphere is by looking at the so-called aerosol optical depth, which expresses the total amount of particles in the whole aerosol column. AOD can be measured using a moderate-resolution imaging spectroradiometer (MODIS) sensor or sun photometers from the NASA AERONET network.

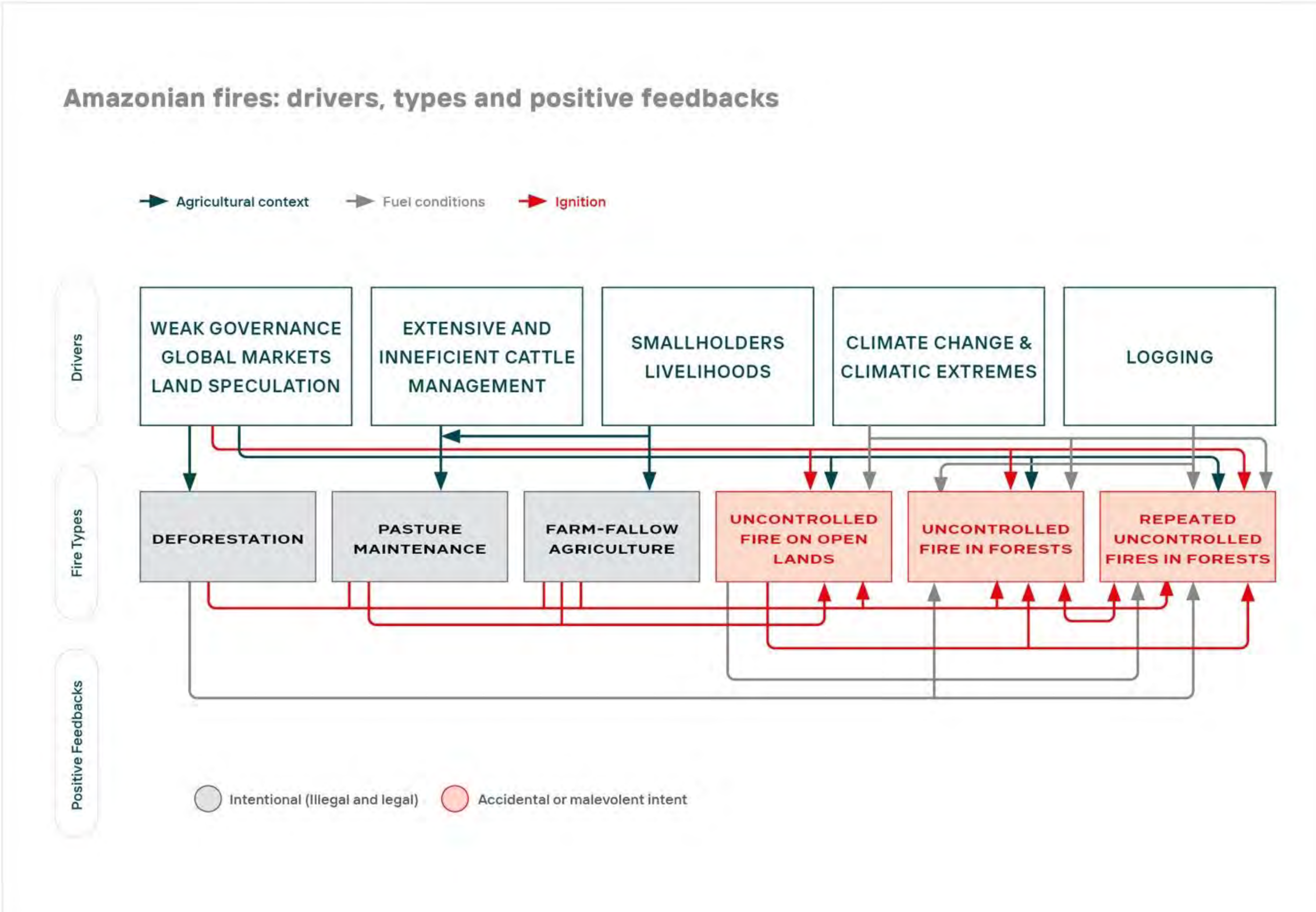

Figure 23.6. Schematic diagram of the complex relationship between the main fire drivers in the Amazon. Figure adapted from Barlow et al. 2020.

The drivers of Amazonian fires are complex and very diverse (see Chapter 19). A schematic view of the complex relationship between the main fire drivers is shown in Figure 23.6. The impacts are also various, and fire emissions influence the regional carbon and water cycle, human health, and ecosystem health, besides being a significant contributor to global warming. Global deforestation is responsible for 13% of greenhouse gas emissions (Global Carbon Project 2020).

23.4.1 Impacts of biomass burning emissions on the radiation balance

The high loading of aerosols from biomass burning impacts direct radiative forcing (DRF) over large areas in tropical forests (Procópio *et al.* 2003; Eck *et al.* 2003). The geographical distribution of DRF follows the sources and transport of biomass burning aerosols and impacts in areas outside the Amazon region, such as central and southern Brazil, north of Argentina, Pantanal, and other regions. As most biomass-burning aerosols scatter sunlight, the impact on the temperature is to cool down the surface. Black carbon (an absorbing aerosol component) emissions from Amazonian biomass burning changes the snow and ice albedo in the tropical glaciers, impacting the melting of Andean glaciers (Aliaga *et al.* 2021; Bianchi *et al.* 2021). The black carbon component absorbs solar radiation and has a heating effect on the top of the boundary layer. The average surface radiative forcing can be as high as -36 W/m^2 (Sena and Artaxo 2015; Reddington *et al.* 2016). Just for comparison, the global anthropogenic forcing that drives climate change is +2.3 W/m² (Boucher *et al.* 2013).

A long time series (2000–2021) of aerosol optical depth over five sites in the Brazilian Amazon is shown in Figure 23.7. In the wet season, very low atmospheric aerosol loading is observed, with a very clean atmosphere. AOD is among the highest values observed everywhere in the world during the dry season, with significant year-to-year variability. This high year-to-year variability is partially driven by climate and also by policies affecting deforestation and biomass burning (Morgan *et al.* 2019).

Clouds and aerosols influence the flux of photosynthetic active radiation (PAR) critical for carbon assimilation (Net Ecosystem Exchange - NEE) by the forests. Also, the ratio of diffuse to direct radiation is controlled by clouds, and aerosols and plants do photosynthesis more efficiently with diffuse radiation because of the more extensive penetration of radiation into the forest canopy (Rap *et al.* 2015; Procópio *et al.* 2004). Analysis of the change in NEE from the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) tower data from 1999 to 2002 in Rondônia shows a 29% increase in NEE when the AOD increased from 0.10 to 1.5 at 550 nm. In Manaus (ZF2 tower), the aerosol effect on NEE accounted for a 20% increase in NEE. High aerosol loading (AOD above 3 at 550 nm) or high cloud cover leads to reductions in total solar flux and a substantial decrease in photosynthesis up to the point where NEE approaches zero (Cirino *et al.* 2014). Large-scale modeling studies show similar results in terms of strong aerosol effects on carbon uptake for the Amazon. Model simulations with three times the biomass burning emissions of 2012 show significant increases of 20 to 40% in surface diffuse radiation, GPP, and NPP, especially in August at the peak of the biomass burning season (Rap *et al.* 2015).

23.4.2 Impacts of ozone from biomass burning precursors on the ecosystem

The Amazon in the wet season shows very low background ozone (O_3) concentrations (<20 ppbv), and the ecosystem is adjusted to this low O_3 concentration. However, in the dry season, high values of 40 to 80 ppbv were observed downwind of biomass burning plumes (Bela *et al.* 2015), and at this

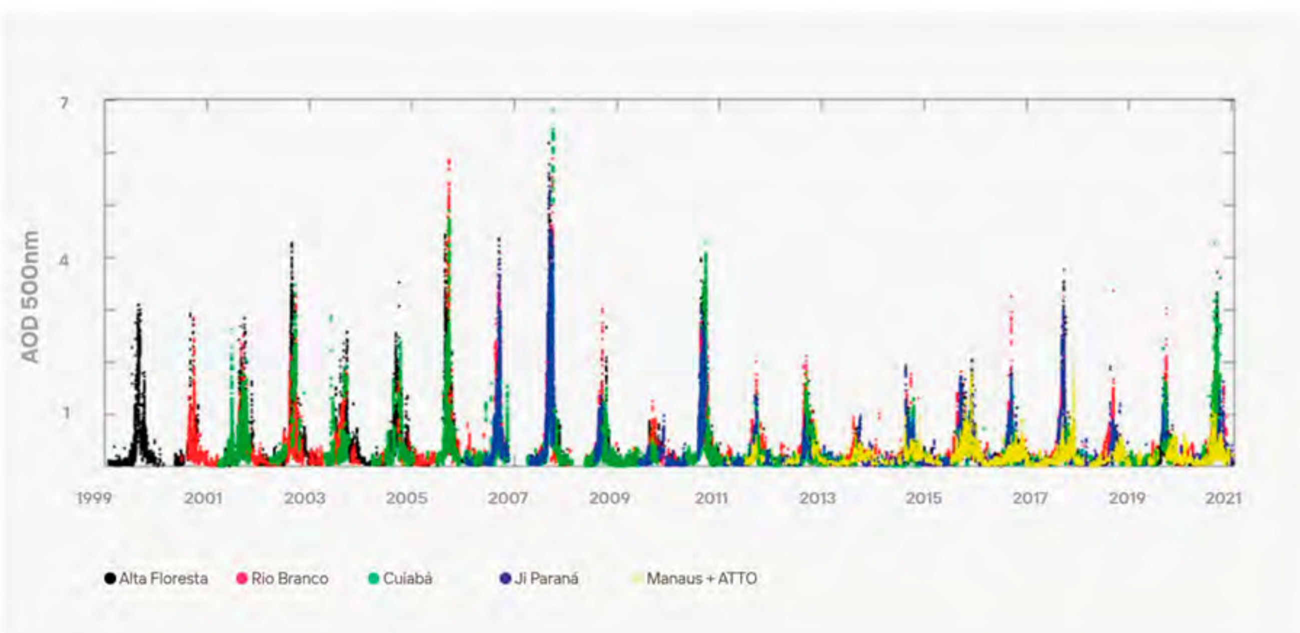

Figure 23.7. Long time series (2000–2021) of aerosol optical depth (AOD) over 5 sites in the Brazilian Amazon. Significant year-to-year variability is driven by climate and public policies toward reducing deforestation and biomass burning emissions.

level of ozone, damage to vegetation occurs. Biomass burning emits significant amounts of ozone precursors, nitrogen oxides (NOx), and VOCs that lead to surface ozone formation downwind of the plumes (Bela *et al.* 2015; Artaxo *et al.* 2013). Tropospheric ozone is an important air pollutant, which causes adverse effects on human health, crops, and natural vegetation (Jacobson *et al.* 2014; Reddington *et al.* 2015; Pacifico *et al.* 2015). Simulations with a global chemistry transport model show that NO_2 increased in concentration by 1 ppbv per decade and ozone by 10 ppbv per decade, a substantial increase (Pope *et al.* 2020). Pacifico *et al.* (2015) used the UK HadGEM2 earth system climate model to assess the impact of biomass burning on surface ozone and its effect on vegetation. The impact of ozone damage from present-day biomass burning on vegetation productivity is approximately 230 TgC yr−1. This ozone damage impact over the Amazon forest is of the same order of magnitude as the release of carbon dioxide due to fire in South America, showing that the effect is significant. The increase in ozone will further damage natural vegetation and reduce photosynthesis (Pacifico *et al.* 2015; Sitch *et al.* 2007), leading to reductions in crop yields downwind of forest fires, including in Mato Grosso and Goiás (Brazil), with large agribusiness areas. These effects combined could substantially impact natural vegetation, agriculture, and public health, with potential degradation in ecosystem services and economic losses. Ozone is also an important greenhouse gas, so biomass burning emissions also contribute to the global temperature increase and radiative forcing.

23.4.3 Impacts of biomass burning emissions on clouds and precipitation

Clouds are formed from three main ingredients: water vapor, aerosol particles that act as cloud condensation nuclei (CCN), and atmospheric thermodynamic conditions (Boucher *et al.* 2013). The complex physical-chemical interaction seen in the Amazon basin includes the processes of rainfall formation, diurnal, seasonal, inter-annual cycles, cloud spatial organization, the mechanisms controlling CCN, the interaction between vegetation, boundary layer, clouds, and upper troposphere (Liu *et al.* 2020). These processes were all in perfect combination, defining a stable climate that produces rainfall equivalent to 2.3 meters over the area of the Amazon Basin, equivalent to $14{\times}10^6$ km^3 of rain each year on average. However, these unique nonlinear complex mechanisms have been modified by human activities (Silva Dias *et al.* 2002; Pöschl *et al.* 2010). Biomass burning with significant aerosol particle emissions alters the CCN concentrations, changing cloud microphysics, cloud lifetime, and precipitation (Andreae *et al.* 2004). With plenty of water vapor, these extra CCN enhance the number of droplets with a reduced size. These smaller initial droplets reduce the efficiency of droplets to grow to precipitable size, increasing cloud lifetime and reducing precipitation. The effect of deep convective clouds is difficult to predict because of insufficient knowledge available on mixed-phase and ice cloud microphysics (Artaxo *et al.* 2021; Machado *et al.* 2018). The primary biogenic aerosol particles are quite efficient ice nuclei (IN) particles necessary to produce deep ice clouds (Prenni *et al.* 2009; Schrod *et al.* 2020; Patade *et al.* 2021). There are significant differences among cloud droplets from pristine and biomass-burning polluted environments, as was observed in the GoAmazon2014/15 experiment (Martin *et al.* 2010; Nascimento *et al.* 2021), including differences in the vertical distribution of the cloud droplet number concentrations, especially in convective clouds (Wendisch *et al.* 2016).

Evapotranspiration provides a significant proportion of the atmospheric moisture over the Amazon, becoming increasingly critical towards the western part of the Basin (Spracklen *et al.* 2012; Molina *et al.* 2019). Deforestation and increasing atmospheric CO_2 reduce evapotranspiration, the amount of water available for rainfall in the western Amazon Basin, and adversely impact rainforest resilience (Zemp *et al.* 2017). This effect extends beyond the Amazon Basin into the Rio de la Plata region, for which Amazonian evapotranspiration is a vital moisture source (Camponogara *et al.* 2014, 2018; Zemp *et al.* 2014).

In terms of biomass burning, aerosol impacts precipitation and monsoon circulation, where many confounding factors make it difficult to establish causality from purely observational studies (Zhang *et al.* 2009). Changes in surface properties, evapotranspiration, albedo, thermodynamic conditions, and other parameters make predicting the effects of aerosols on precipitation very difficult (Artaxo *et al.* 2020). One of the few observational studies of the impacts of biomass burning on rainfall was by Camponogara *et al.* (2014). Combining Reanalysis, data from the Tropical Rainfall Measuring Mission (TRMM), and AERONET data from 1999 to 2012 during September–December, a clear relationship between aerosols and precipitation was derived. Results show that high aerosol concentrations tend to suppress precipitation. A significant reduction in rainfall at the La Plata basin was observed with increasing biomass burning aerosols in the Amazon.

The lack of a significant meteorological observation network in the Amazon makes assessing changes in precipitation quite tricky and inaccurate. The same is true for an extended aerosol and trace gases observation network.

23.5 Conclusions

There is no question that the impacts from climate change and deforestation in the Amazon are strong, diverse, and well documented. From biodiversity, carbon cycling, hydrological cycles, biomass burning, wherever we look, climate change, and anthropogenic land-use change are already impacting the Amazonian ecosystems. And the reverse is also true, especially in terms of carbon emissions owing to deforestation. Tropical deforestation is responsible for 13% of global CO_2 emissions (Global Carbon Project 2020), and Brazil, Colombia, Bolivia, and Peru are among the top 10 tropical deforestation countries. Reducing tropical deforestation is the fastest and cheapest way to mitigate greenhouse gas emissions, with many co-benefits. Tropical forests suffer from significant stress from climate change, particularly an increase in temperature, altered hydrological cycle, and an increase in climate extremes. Reducing biomass burning is essential to minimize several negative aspects associated with high concentrations of aerosols, ozone, carbon monoxide, and nitrogen oxides over large areas of South America. Three main effects of climate changes in aquatic systems (both marine and freshwater) are ocean and hydrographic basins warming, acidification, and oxygen loss. If we consider only these effects, we can expect habitat loss, changes in fish migration, disturbances in fish assemblages, and changes in spatial fish species distribution. These are the main impacts climate change will cause for aquatic systems biota. However, other effects may be an important driver for biodiversity loss but occur either in continental or marine water systems. The loss of biodiversity is expected not only from direct deforestation but also from different sensitivities of plant species to increased temperature and reduced precipitation. It is important to emphasize that in addition to reducing tropical deforestation, it is also essential to reduce fossil fuel use to reduce the rate of climate change.

23.6 Recommendations

- A comprehensive network of Amazonian environmental observatories and a system for sharing comparable data is needed to detect changes in ongoing terrestrial, freshwater, and estuarine ecosystems.
- More integrated studies on biodiversity loss and climate change, such as species resilience, are needed.
- The possible effect of climate change and protected areas location needs to be considered for conservation strategies, taking into account pollination and seed dispersal services.
- More studies on the feedbacks between climate change and Amazonian ecosystem functioning are vital and must be better known and quantified, especially for carbon and water vapor feedbacks.
- It is necessary to perform studies on the basin-wide water balance considering evapotranspiration, aerial rivers, and all water balance components in the Amazon.

- Studies on the ecosystem and species resilience to increased temperatures and reduced water supply are needed.
- In addition to reducing deforestation, it is also essential to reduce fossil fuel burning, which is the leading cause of climate change.
- Paleoclimate studies are needed to investigate past climate variations to help understand natural climate variability and better understand the historical role of humans shaping the landscape over several timescales.

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Amazon Assessment Report 2021

Chapter 24

Resilience of the Amazon forest to global changes: Assessing the risk of tipping points

Região Metropolitana de Manaus, estiagem incomum (Foto: Alberto Cesar Araujo/Amazônia Real)

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Graphical Abstract

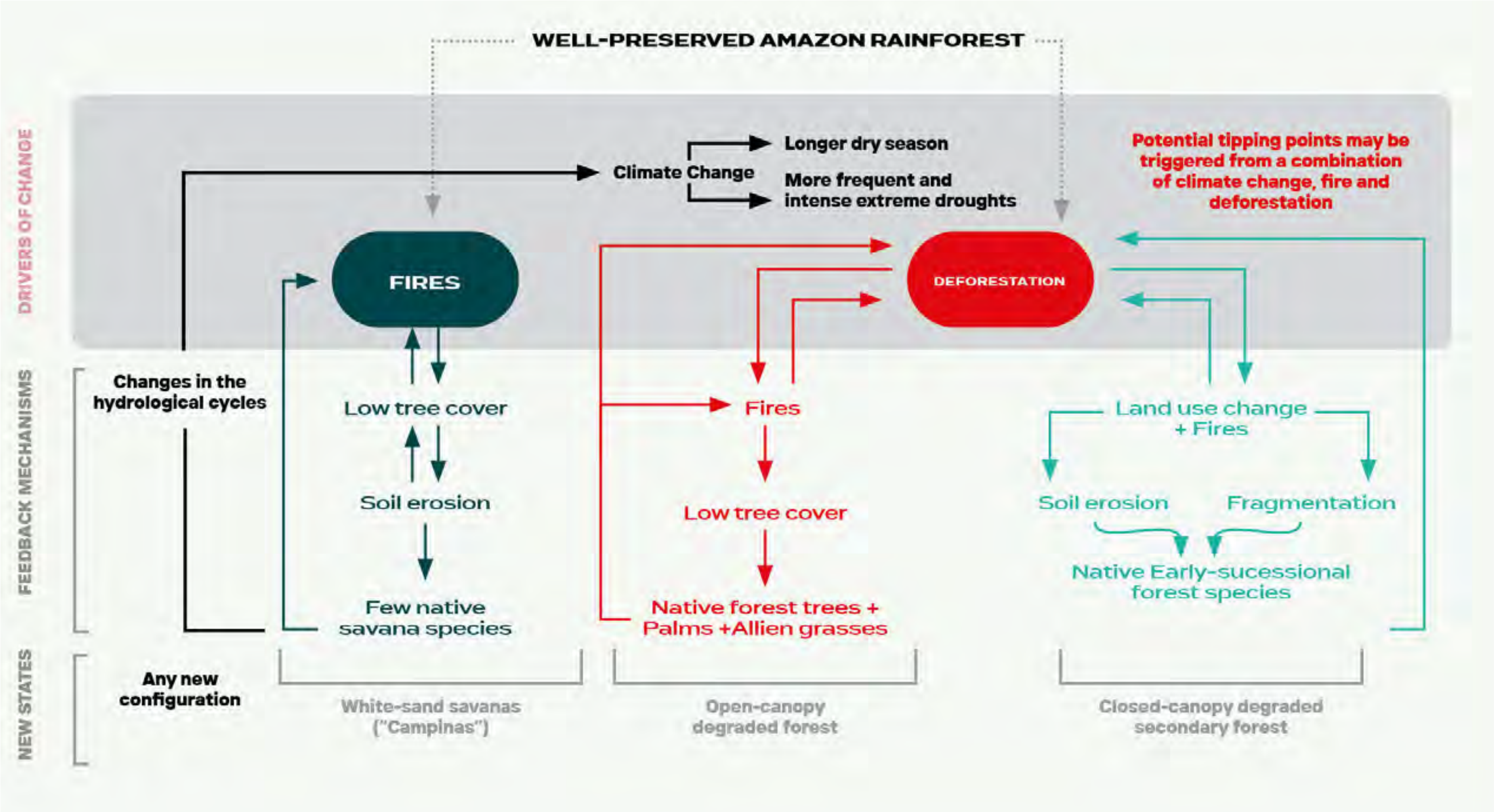


Figure 24.A Simplified diagram illustrating the drivers of change that can lead to tipping points in Amazonian rainforests. Drivers of change refer to direct (i.e., higher global temperatures) and indirect (i.e., longer dry season and more frequent and intense extreme drought events) large-scale climate change effects, followed by regional to local scale wildfires and deforestation. If tipping points are crossed in current drivers of change, either individually or in a compound way, the depicted cascading chains of impacts resembling a domino effect, called feedback mechanisms, are key to trap rainforests into three different potential states already registered and documented within Amazonian rainforest: white-sand savanna (or "Amazonian *campinas*"), open-canopy degraded forest or closed-canopy degraded secondary forest.

Resilience of the Amazon Forest to Global Changes: Assessing the Risk of Tipping Points

Marina Hirota[a], Bernardo M. Flores[a*], Richard Betts[b], Laura S. Borma[c], Adriane Esquível-Muelbert[d], Catarina Jakovac[e], David M. Lapola[f], Encarni Montoya[g], Rafael S. Oliveira[h], Boris Sakschewski[i]*

Key Messages

- Five tipping points described in the literature comprise disturbances triggered by changes in climatic conditions and human activities, and associated large-scale feedback mechanisms. Nevertheless, the heterogeneity in forest responses throughout the Amazon basin (i.e., how resistant and recoverable different forests are) seem to be key in determining the systemic resilience of the entire Amazon system, and should be a research priority.
- Based on empirical evidence, there are four potential ecosystem configurations that Amazonian forests could shift to: (i) a closed-canopy seasonally dry tropical forest state; (ii) a native savanna state; (iii) an open-canopy degraded state; and (iv) a closed-canopy secondary forest state. Due to the existence of novel feedbacks associated with invasive plants and human-modified landscapes, we consider the open-canopy degraded state and the closed-canopy secondary forest state as more likely to occur over broad areas, particularly across the 'arc of deforestation'.
- Further studies are needed to understand how past underlying conditions (e.g., soil fertility and rainfall regimes) affect resilience and how different species cope with the same amount of disturbance. This is key to unveiling how response heterogeneity may either increase or dampen the systemic resilience of Amazonian ecosystems.
- The likelihood of crossing tipping points within Amazonian ecosystems has been best studied so far with the use of models. Despite continuous model improvements and reductions in uncertainty, there is a lack of observational (field and remote sensing) and experimental evidence to improve these models and evaluate their results. As such, there is no reasonable/strong scientific agreement, from a modeling perspective, on the likelihood of crossing an Amazonian tipping point in the future. However, the likelihood can be expected to increase with higher levels of climate change and/or direct deforestation/degradation. Priority areas for model-data integration are understanding the CO_2 fertilization effect, soil nutrient limitations, recruitment/mortality dynamics, plant functional diversity, and reducing uncertainty in Amazonian rainfall projections.

Abstract

Here we review and discuss existing evidence of ongoing changes in the Amazon forest system that may lead to resilience loss and the crossing of tipping points beyond which the ecosystem may shift persistently to an alternative state. Grounded on the theory of complex dynamical systems, we analyze the state

[a] Federal University of Santa Catarina, Campus Universitário Reitor João David Ferreira Lima, s/n. Trindade. 88040-900. Florianópolis, Brazil, marinahirota@gmail.com, mflores.bernardo@gmail.com
[b] MetOffice, FitzRoy Road, Exeter, Devon EX1 3PB, United Kingdom,
[c] INPE/DIIAV, Av. dos Astronautas 1758, São José dos Campos, Brazil
[d] University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom
[e] Forest Ecology and Management Group, Wageningen University & Research, Wageningen, 6700 AA, The Netherlands
[f] University of Campinas, Av. André Tosello 209. 13083-886, Campinas, Brazil
[g] Department of Geography and Planning, School of Environmental Sciences, University of Liverpool, Roxby Building, L69 7ZT, UK
[h] University of Campinas, Rua Monteiro Lobato 255, 13083-862, Campinas, Brazil
[i] Potsdam Institute for Climate Impact Research, Telegrafenberg A62, 14412 Potsdam, Germany

of the Amazon forest and its potential trajectories in the 21st-century, aiming to provide support for a science-based management scheme for enhancing systemic resilience. This review is based on five systemic tipping points for which there is evidence; four climate-related: (1) annual rainfall value below 1,000-1,500 mm/yr, (2) dry season length above seven months, (3) for Amazon lowlands, a maximum cumulative water deficit above 200 mm/yr, (4) a global increase of 2°C on the equilibrium temperature of the Earth; and one associated with human-induced changes: (5) 20-25% accumulated deforestation of the whole basin. Evidence suggests that, depending on varying combinations of stressing conditions, disturbances, and feedback mechanisms, current forest configurations could be replaced at local scales by: (i) a closed-canopy seasonally dry tropical forest; (ii) a native tropical savanna state; (iii) an open-canopy degraded state; and (iv) a closed-canopy secondary forest. Local-scale forest collapses could trigger cascading effects on rainfall recycling, intensifying dry seasons and wildfire occurrence, and leading to massive forest loss at continental scales, particularly in the southwest of the basin. The probability of crossing such tipping points depends largely on heterogeneities across the system, including geological, physical, chemical, and cultural processes that influence connectivity and the likelihood of contagious disturbances. Biodiversity patterns were historically shaped over the past 60 million years by these processes and still today influence forest adaptive capacity and resilience. Thus, maintaining biodiversity is critical for enhancing resilience and reducing the risk of systemic forest collapse in the near future.

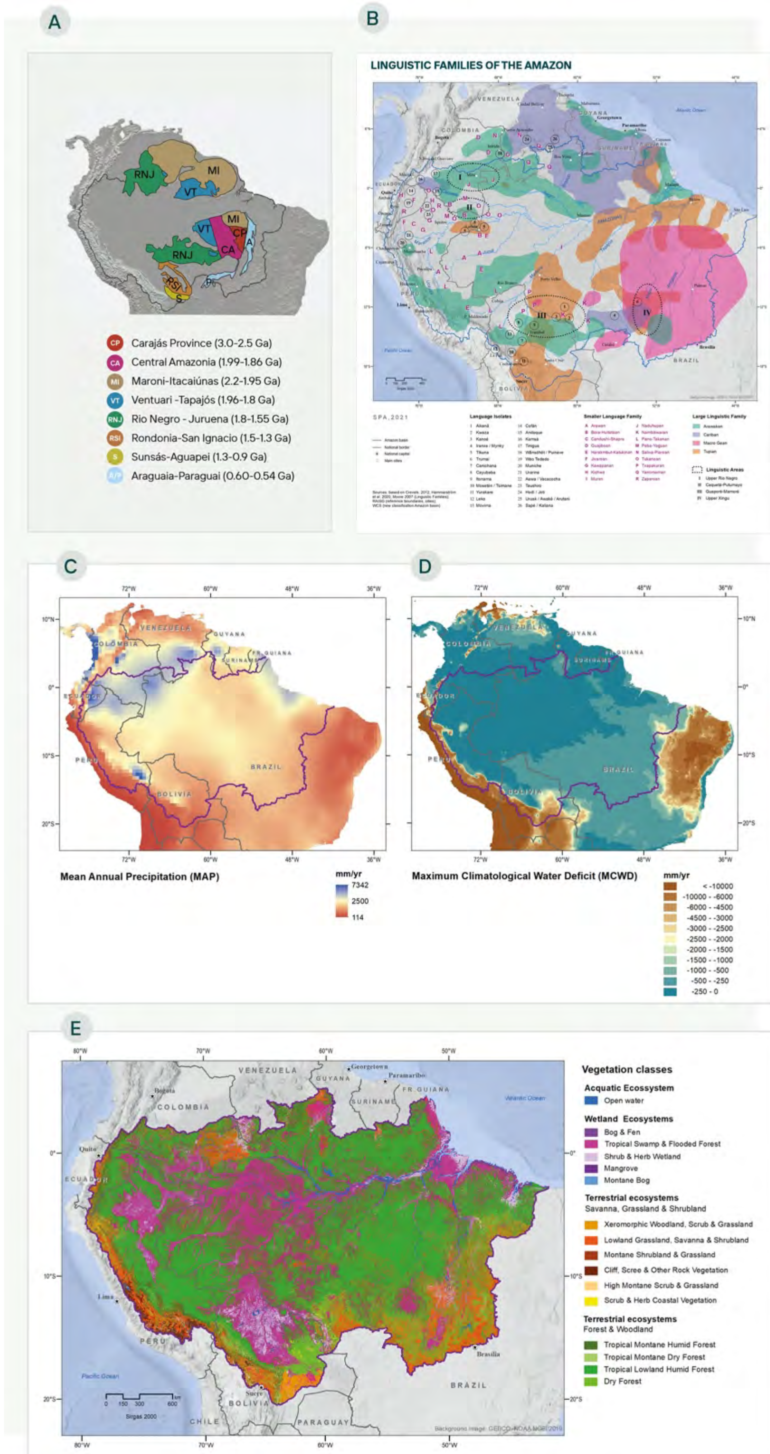
Keywords: tipping points, resilience, biodiversity, heterogeneity, connectivity, climate change, land-use change.

24.1 Introduction

The Amazon is a complex dynamical system that has been constantly changing for at least 60 million years ago (Ma), with geological, hydrological, and evolutionary processes shaping the system that we know today (Hoorn *et al.*, 2010; Chapters 1-7; Figure 24.1). While the Amazon River was formed around 10 – 4.5 Ma (see Chapters 1 and 2), forests expanded over non-forest habitats, and during the same time, massive wetlands retreated at the western parts of the basin. This process altered the courses of most rivers, causing new geographical barriers to emerge, altering the distribution of species, and creating the conditions for diversification and speciation (Hoorn *et al.* 2010, see also Chapters 1 and 2). More recently, around 12,000 years ago, humans arrived in the Amazon (Potsch *et al*. 2018, see also Chapter 8) and began to contribute to further changes in the landscapes and alter plant species distributions (Levis *et al.* 2017, see also Chapters 8 and 10).

As a result of the interplay between these processes (both natural and anthropogenic) operating at different spatial and temporal scales, the Amazon is currently an extremely heterogeneous and biodiverse system (see Chapters 3 and 4, and Figure 24.1b). Forest tree communities across the basin are formed by different sets of species with contrasting functional traits selected by continental to local environmental conditions, the main drivers of this heterogeneity including soil (Quesada *et al.* 2012), climate (Davidson *et al.* 2012; ter Steege *et al.* 2013; Esquivel-Muelbert *et al.* 2017), topography (Oliveira *et al.* 2019), and microclimate (Barros *et al.* 2019). Savannas also occur along the fringes of the Amazon basin and as "islands" within the dominant forest habitat (Prance 1996). The varying types of forest and non-forest habitats that exist are connected through a rich web of ecological interactions, which have contributed to maintaining the whole system for the past 45 ka. Such resilience has been observed even under the extremely dry conditions of the Last Glacial Maximum (LGM) around 20 ka (Wang *et al.* 2017).

In the last century, however, the Amazon system began to change faster, mostly due to local, regional, and global human activities that intensified particularly since the 1970s (See Chapters 14-21, and Figs. 24.2c-e). Within the last two decades, extreme droughts have become more frequent, and extremes in precipitation during the wet and dry



24.1 Heterogeneity in abiotic and biotic conditions throughout the Amazon system, which shaped a range of plant community assemblages within different time and spatial scales. (a) geochronological map of South America with the main provinces of the Amazon Craton (see Chapter 1); (b) past cultural diversity (to be defined either early ceramics complexes or Holocene ceramic complexes - still to be built by the map team) (see Chapter 8); (c) current climatological mean annual precipitation (MAP, mm/yr, mean value for the period from 1981 to 2010) from CHIRPS dataset (Funk *et al.* 2015); (d) current maximum climatological water deficit (MCWD, mm/yr, mean value for the period from 1981 to 2010) from CHIRPS dataset (Funk *et al.* 2015); (e) wetland and terrestrial ecosystems of the Amazon to show the tremendous biodiversity embedded within the system (See Chapter 4).

seasons have intensified (see Chapter 22; Marengo *et al.* 2011; Gloor *et al.* 2013; Jiménez-Muñoz *et al.* 2016). Mean, maximum, and minimum temperatures have also risen (see Chapter 22; Jiménez-Muñoz *et al.* 2013), particularly on fragmented landscapes due to deforestation (Zeppetello *et al.* 2020). As a result, mature Amazonian forests are now losing drought-sensitive species and becoming more dominated by drought-tolerant species (Esquivel-Muelbert *et al.* 2016, 2019; see also Chapter 23), with higher mortality rates for drought-sensitive species taking place particularly along the southern fringes of the Amazon (Esquivel-Muelbert *et al.* 2020). In the central Amazon, interactions between extremely wet and dry periods are increasing tree mortality rates and reducing growth (Aleixo *et al.* 2019; Esteban *et al.* 2021).

Moreover, human-induced wildfires are intensifying (Alencar *et al.* 2015, see also Chapter 22), causing unprecedented levels of tree mortality (Brando *et al.* 2014). The expansion of cattle production has introduced invasive alien grasses, increasing the flammability of degraded and regenerating forests (Cochrane 2003). Moreover, deforestation disrupts forest-rainfall interactions across the Amazon by interrupting the moisture recycling by forest trees (see Chapter 7), and consequently the east-west moisture flow; a process that may accelerate forest loss (Zemp *et al.* 2017; Staal *et al.* 2020). Wildfires and deforestation also threaten species located along the southern edge of the system (Steege *et al.* 2015), particularly where forests are likely to be more resilient to climate change (Ciemer *et al.* 2019). On the other hand, changes in wildfire regimes may affect areas away from the southern edges, given that species may have fewer adaptations to thrive under more frequent and intense wildfire events (Staver *et al.* 2020). In the case of Brazil, the Amazonian country that holds the largest deforestation rates (see Chapter 19), rates had been slowing down but began to rise again starting in 2012, due to political changes that led to the weakening of Brazilian environmental governance (Levis *et al.* 2020; Rajão *et al.* 2020, see Chapters 14 and 17). All these changes imply that the Amazon now has to deal with unprecedented levels of stressing conditions and disturbance regimes.

A topic that has raised concern is the potential existence of an ecological tipping point that could affect the stability of the Amazon, causing large-scale forest dieback or collapse (Box 24.1). Despite increasing evidence of tree mortality caused by extreme rainfall events (both dry and wet), fire, deforestation, and the potential of their combined effects (Cochrane *et al.* 1999; Aragão *et al.* 2007, 2008; Phillips *et al.* 2009; Brando *et al.* 2014; Nobre *et al.* 2016; Esquivel-Muelbert *et al.* 2020; Staal *et al.* 2020; Esteban *et al.* 2021), the actual behavior of the Amazon system remains uncertain. For instance, with increasing water-deficit levels and aridity, the Amazon forest may not necessarily shift abruptly across the whole basin, but instead shift gradually with the least-resilient forests affected first, followed by the more resilient ones (Levine *et al.* 2016; Figure 24.1). On the other hand, human-induced changes are likely to occur faster than the time forest communities would need to recover. Moreover, a long-lasting hypothesis is that the Amazon forests that collapse may undergo a "savannization" process, i.e., forests would be replaced by savanna-like vegetation (Nobre *et al.* 1991). Nevertheless, evidence suggests that native savannas are unlikely to replace all portions of the Amazon forest, since most stressors are associated with human activities that would introduce invasive alien grasses instead of native savanna species (Veldman and Putz 2011), trapping forests in a degraded and early successional stage (Barlow and Peres 2008).

Grounded on the theory of complex dynamical systems, we review and discuss existing evidence of ongoing changes that may reduce forest resilience and potentially lead to tipping points (Box 24.1), in which the Amazon forest may shift into other configurations. By analyzing the state of the Amazon forest and its potential trajectories in the 21st-century, we expect to provide critical information that will support a science-based management scheme for enhancing the resilience of this iconic system.

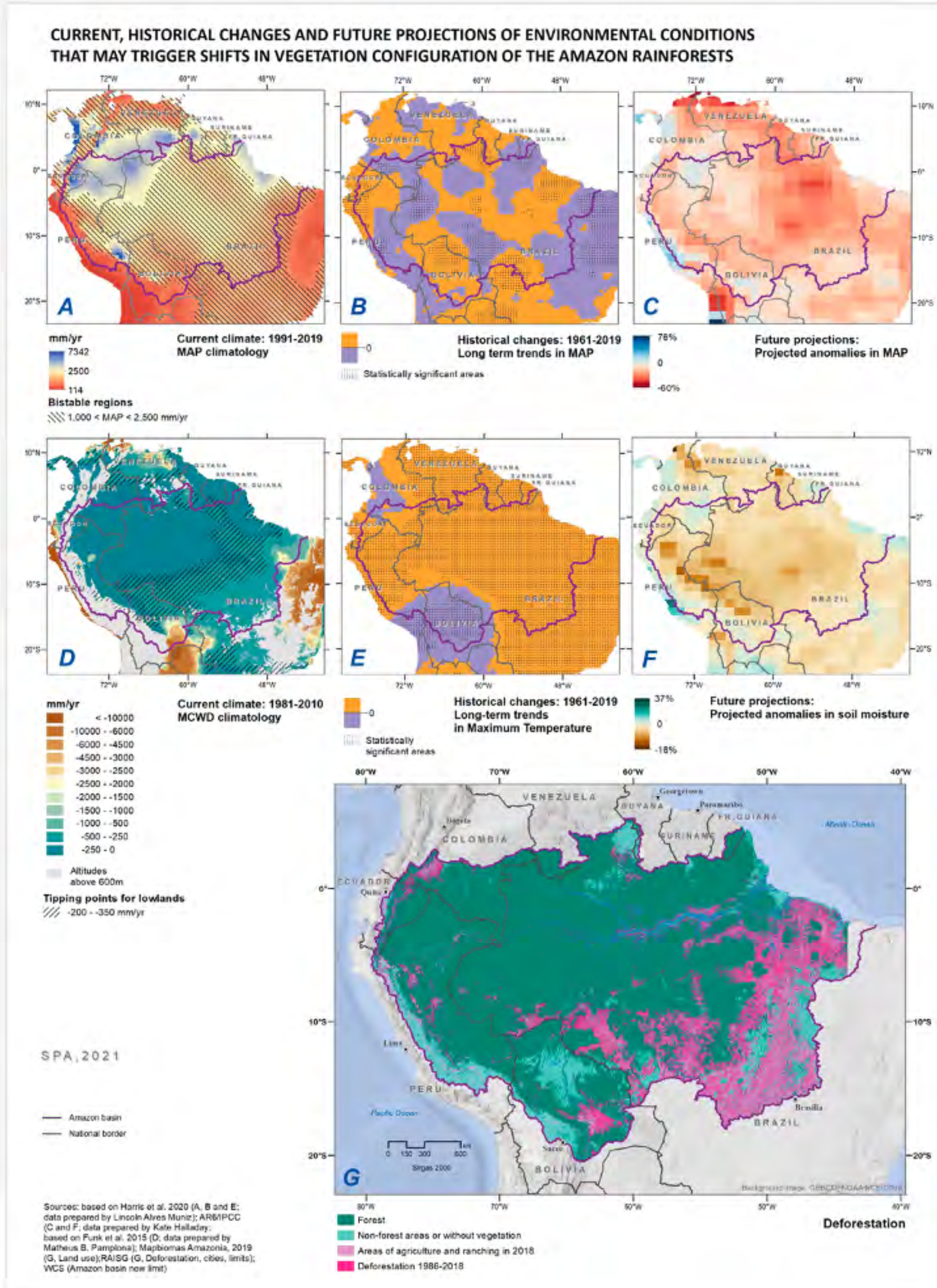


Figure 24.2 Tipping points (section 2) and disturbances/perturbations which may affect the resilience of the Amazon. (A) 1991 - 2019 climatology of mean annual precipitation (MAP, mm/yr) showing bistable areas for tipping point range (tipping point 1) using CRU 4.04 dataset (Harris *et al.* 2020); (B) historical changes from 1961 to 2019 in MAP (hatched areas are statistically significant) using CRU 4.04 (Harris *et al.* 2020); increases in MAP (larger than 0) shown in orange, and decreases in MAP (lower than 0) shown in purple; (C) projected relative changes in MAP at 4°C global warming with the UKESM1 climate model (Sellar *et al.* 2019) for the period 2070-2100; future increases in MAP shown in blue and future decreases in red; (D) 1981-2010 MCWD climatology showing tipping points (-200 and -350 mm/yr for lowlands) (tipping point 3); (E) historical changes from 1961 to 2019 in maximum temperatures (hatched areas are statistically significant) using CRU 4.04 dataset (Harris *et al.*, 2020); increases in T_{max} (larger than 0) shown in orange, and decreases (lower than 0) in T_{max} in purple; (F) projected relative changes in soil moisture at an extreme 4°C global warming with the UKESM1 climate model (Sellar *et al.* 2019) for the period 2070-2100; future increases in soil moisture shown in green and future decreases in brown; (G) deforestation according to MapBiomas.

24.2 Potential Tipping Points and New Configurations

The tipping points that have been proposed for the Amazon rainforests so far are: (1) annual rainfall totals below 1,000 mm/yr, inferred from satellite observations of tree cover distributions (Hirota *et al.* 2011; Staver *et al.* 2011; Figs. 24.2a-d) or 1,500 mm/yr inferred from global climate models (Malhi *et al.* 2009), (2) dry season length longer than seven months, inferred from satellite observations of tree cover distributions (Staver *et al.* 2011), (3) for the Amazon lowlands, maximum cumulative water deficit values larger than 200 mm/yr or 350 mm/yr, inferred from different analyses with global climate models (respectively, from Malhi *et al.* 2009; Zelazowski *et al.* 2011; Figure 24.2e); (4) an increase of 2°C on the equilibrium temperature of the Earth, inferred from a coupled climate–vegetation model (Jones *et al.* 2009; for instance, with consequences shown in Figs. 24.2d,g), and (5) surpass 20-25% accumulated deforestation, inferred from a combination of environmental changes (i.e., increases in dry season length, see Chapter 22), climate projections for the most pessimistic pathway of the Intergovernmental Panel on Climate Change (IPCC; Figs. 24.2d,g), and human-induced degradation via deforestation (Figure 24.2h) (Nobre *et al.* 2016; Lovejoy and Nobre 2019). The main concern is that beyond these possible tipping points, the system would enter a loop of rainfall reduction, fire, and forest mortality.

Given the challenges in acquiring sufficiently long time series to effectively and directly account for temporal changes, their impacts on vegetation cover, and consequent tipping points (Box 24.1), the ones mentioned above have been inferred and proposed by different types of modeling and observational approaches. The first two use a space-for-time substitution method, which replaces temporal information on changing conditions and

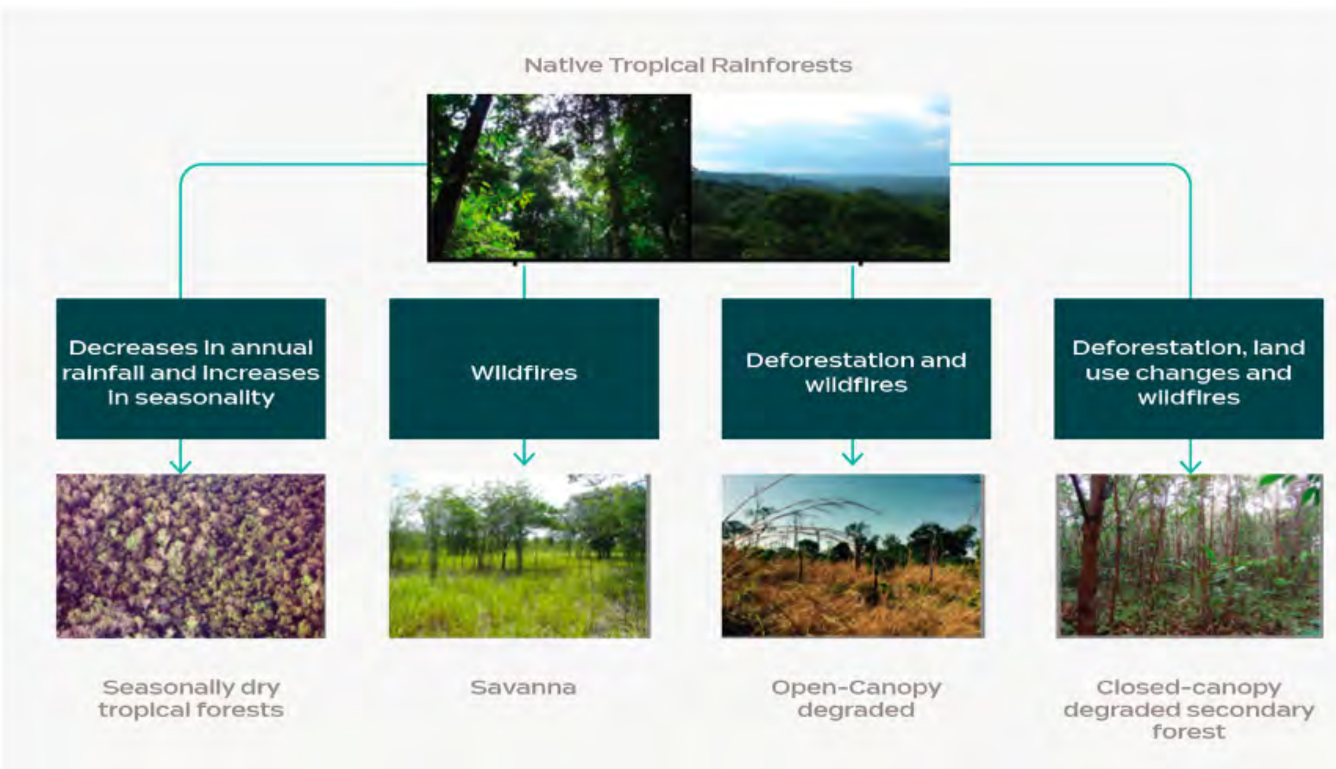


Figure 24.3 Potential alternative configurations and drivers. Photo credits: Native tropical rainforests at ZF2 Station (AM, Brazil) by Marina Hirota; seasonally dry tropical forests at Maracá Island (RR, Brazil) by Marcelo Trindade Nascimento; savanna at Barcelos (AM, Brazil) by Bernardo M. Flores; open-canopy degraded at Fazenda Tanguro (MT, Brazil) by Paulo Brando; closed-canopy degraded secondary forest at Tefé (AM, Brazil) by Catarina Jakovac.

their impacts (e.g., changes in precipitation intensity leading to changes in vegetation cover) by observational data of vegetation status (canopy closure using tree cover values) along a gradient of precipitation (e.g., 1,000 to 2,500 mm/yr) at a single snapshot in time. Tipping points (3) to (5) are based on coupled climate-vegetation models, which are able to simulate long time series with their integrative structure, but depend on a set of parameterizations that may fail to adequately represent soil-plant-atmosphere interactions. Thus, even having a glimpse of thresholds that may trigger irreversible changes, the trajectories leading to stable and transient configurations of the Amazon basin need to be further explored and studied by a combination of experimental and modeling studies. For instance, a recent study has shown that, given the large uncertainty and variability inv olved in projecting future climate conditions, after correcting for models' biases identified using observational data, a basin-wide Amazon dieback is unlikely to occur, even under the most pessimist IPCC pathway (Chai *et al.* 2021).

Based on existing evidence, we identify four main configurations Amazonian forests may shift to and persist in due to self-reinforcing feedbacks (Figure 24.3): (i) a closed-canopy seasonally dry tropical forest, with increasing abundance of deciduous tree species; (ii) a tropical savanna state, dominated by native grass and tree species; (iii) an open-canopy degraded state, dominated by invasive alien grasses and native fire-tolerant tree species; and (iv) a closed-canopy secondary forest, dominated by native early successional tree and other plants species. In the following subsections, we explain how current environmental changes in the Amazon system (see Chapters 14-22 and Figure 24.2) may alter forest dynamics, as well as feedback mechanisms (Box 24.1) that could arrest Amazonian ecosystems in the configurations (i) to (iv), and illustrate these trajectories with evidence on past and current changes.

24.2.1 Forest shift to a closed-canopy, seasonally dry tropical forest

Considering the observed trends towards a drier climate in some parts of the Amazon (see Chapter 22), there is a possibility that forests over nutrient-richer soils may shift into a closed-canopy state that resembles, in terms of structure and functioning, a seasonally dry tropical forest (SDTF) (Malhi *et al.* 2009; Dexter *et al.* 2018), dominated by fast-growing deciduous trees, with high tolerance to drought conditions, and a higher demand for nutrients. This type of semi-deciduous forest (i.e., with varying abundances of deciduous species) is very common in the transitional zones along the Amazon's boundaries, and under drier climatic conditions (Silva de Miranda *et al.* 2018) could expand over wet Amazonian forests (Dexter *et al.* 2018). For instance, drought-tolerant species are widely distributed across the Amazon region (Esquivel-Muelbert *et al.* 2017), and a shift in the climate regime would allow them to dominate (Esquivel-Muelbert *et al.* 2019). However, drought-tolerance is not only expressed in terms of deciduousness, and alternative phenotypes may include trees with more resistant water-transporting systems (Barros *et al.* 2019) and/or deeper-rooted species. Nonetheless, a shift to a semi-deciduous forest would probably not follow catastrophic non-linear dynamics, with associated tipping points (Box 24.1, Figure 24.B1) because rainforests and STDFs occupy separate climatic niches (Silva de Miranda *et al.* 2018), implying that tree species may have to migrate long geographical distances. Hence, such changes might occur smoothly and more gradually with increasing aridity and seasonality (Oliveira *et al.* 2021.).

24.2.2 Forest shift to a native savanna state

The Amazon forest is often assumed to shift into a savanna-like state, once it passes tipping points such as the ones described above (Cox *et al.* 2004; Jones *et al.* 2009; Hirota *et al.* 2011; Staver *et al.* 2011; Lovejoy and Nobre 2019). However, evidence

Box 24.1 Main concepts and definitions based on the theory of dynamical systems

The theory of dynamical systems suits as a model to any type of system that evolves in time. The dynamics of such systems may have linear, nonlinear, chaotic, and complex behaviors, depending on the underlying conditions or the control/explanatory variables, and the response or state variable (Strogatz 2015). For ecosystems such as the Amazon, conditions would be, for instance, the total amount of precipitation or nutrient availability; the state variable would represent the status of vegetation cover, e.g., tree cover percentage or productivity. When the system presents nonlinear dynamics, we can have a steep but still gradual shift from one ecosystem state to another (Figure 24.B1, left panel b), meaning that for each condition there is one and only one ecosystem state associated; and a more abrupt or catastrophic shift (Figure 24.B1, left panel c), when two (or more) ecosystem states can exist under the same set of conditions (the reason why the sigmoid from panel b turns into an s-shaped curve in panel c). The two possible configurations (continuous red line on left panel c) represent stability and are called alternative stable states or attractors; and the dashed red line in the middle represents the transient behavior of the system and is called the unstable states or repellors (from there the system could move either upwards to the higher stable state or downwards to the lower state - see green arrows pointing up and downwards).

The two black open circles (F1 and F2) are named bifurcation points, tipping points, or critical thresholds. In this sense, such tipping points exist only when two or more alternative stable states occur (Scheffer et al. 2001). Tipping points can be reached if either disturbances (changes in conditions), or perturbations (changes in the state), or both occur (Fig. 24.B1, right panels) (Van-Nes et al. 2016). First, if conditions change and F2 is crossed (Fig. 24.B1, right panel a), a sudden drop (downwards) can occur towards a different state. Interestingly, to return to the original state, the system would need to undergo a much stronger change in conditions, in this case, to reach the other bifurcation point F1, which could lead the system upwards again. This path-dependence behavior is called hysteresis. Such a feature defines the likelihood of irreversibility after crossing a tipping point. Eventually, it is so challenging to return conditions to F1 levels, and thus return to the original state, that reaching a tipping point can indeed cause irreversible changes. In the case of Amazon rainforests, climate change translated into extreme drought events or increases in dry season length could represent changes in one of the underlying conditions that maintain Amazonian ecosystems in the current configuration. Secondly, if changes occur in the ecosystem state, e.g., decreases in tree cover after deforestation and/or wildfire events, the system could reach the instability region (red dashed line), causing either a return to the original state or a (irreversible) change in the system configuration.

In either case what drives the accelerated shift to a new state are **positive** *feedback mechanisms* (DeAngelis *et al.* 1986), determined by the internal dynamics of the system in a closed loop, i.e., the initial perturbation is self-reinforced and amplified. For instance, deforestation leads to less tree cover, which, in turn, leads to less evapotranspiration, less precipitation, and thus less tree cover; i.e., in this case, the initial perturbation is reinforced and amplified. On the other hand, (**negative**) **stabilizing** *feedback mechanisms* occur when they dampen the initial disturbance/perturbation (DeAngelis *et al.* 1986). Therefore, in broader context, *tipping points* can refer "to any situation where accelerating change caused by a positive feedback drives the system to a new state" (Van-Nes *et al.* 2016).

The connection between *tipping points* and *resilience* is more easily observed when building *stability landscapes* (or ball-in-a-cup diagram) using the concept of *basins of attraction* (Fig. 24.B2a, b) (Scheffer *et al.* 2001; Strogatz 2015). In this sense, theoretically *resilience* can be qualitatively understood as the size of the *basin of attraction* (valleys on Fig. 24.B2a). Each cross-section of the ecosystem state *vs.* conditions

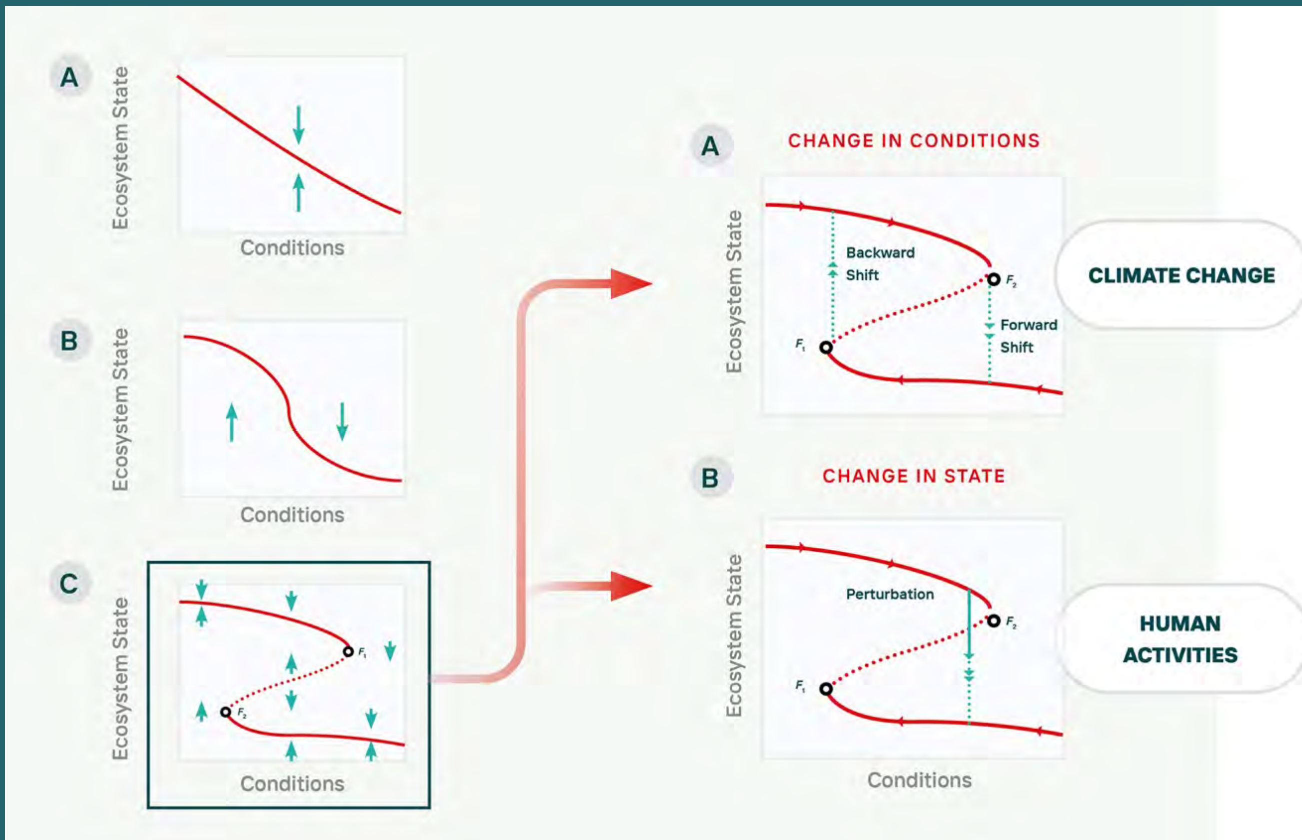


Figure 24.B1 (Left panels) Linear and nonlinear responses of ecosystem state (y-axis) depending on underlying conditions (x-axis). (Right panels) Illustration of how catastrophic shifts can occur under changes in conditions (e.g., climate changes) and in the state variable (e.g., human activities). Modified from Scheffer *et al.* (2001).

graph corresponds to a different *stability landscape*, showing potential *alternative stable states* and the **size** of the *basin of attraction* separating them. Particularly, for tropical forests, Fig. 24.B2b shows five condition cross-sections (for increasing precipitation): 1) only a treeless state, i.e., only one *basin of attraction* representing one state possible; 2) two *alternative stable states*, namely treeless and savanna, with a higher resilience (deeper valley) associated with the treeless state; 3) and 4) forests and savannas as *alternative states* with higher forest resilience related to higher levels of precipitation; 5) only forests as a stable state with the highest levels of precipitation. Note that this diagram shows only precipitation as a driving condition. We can go further and think about changes in the conditions or in the ecosystem state (Fig. 24.B1) using this type of diagram (Figs. 24.B2c-e).

For instance, increases in the frequency of extreme droughts and/or in dry season length could **erode** the *basin of attraction* of the forest state, i.e., forests lose resilience up to a point that a relatively lower-intensity drought could trigger a shift towards another *basin of attraction* easier than if climate change impacts would not occur (Fig. 24.B2d). Human-induced changes affecting the ecosystem state directly (e.g., wildfires or deforestation) would provoke a state flip independently on whether forests had lost resilience or not (Fig. 24.B2e).

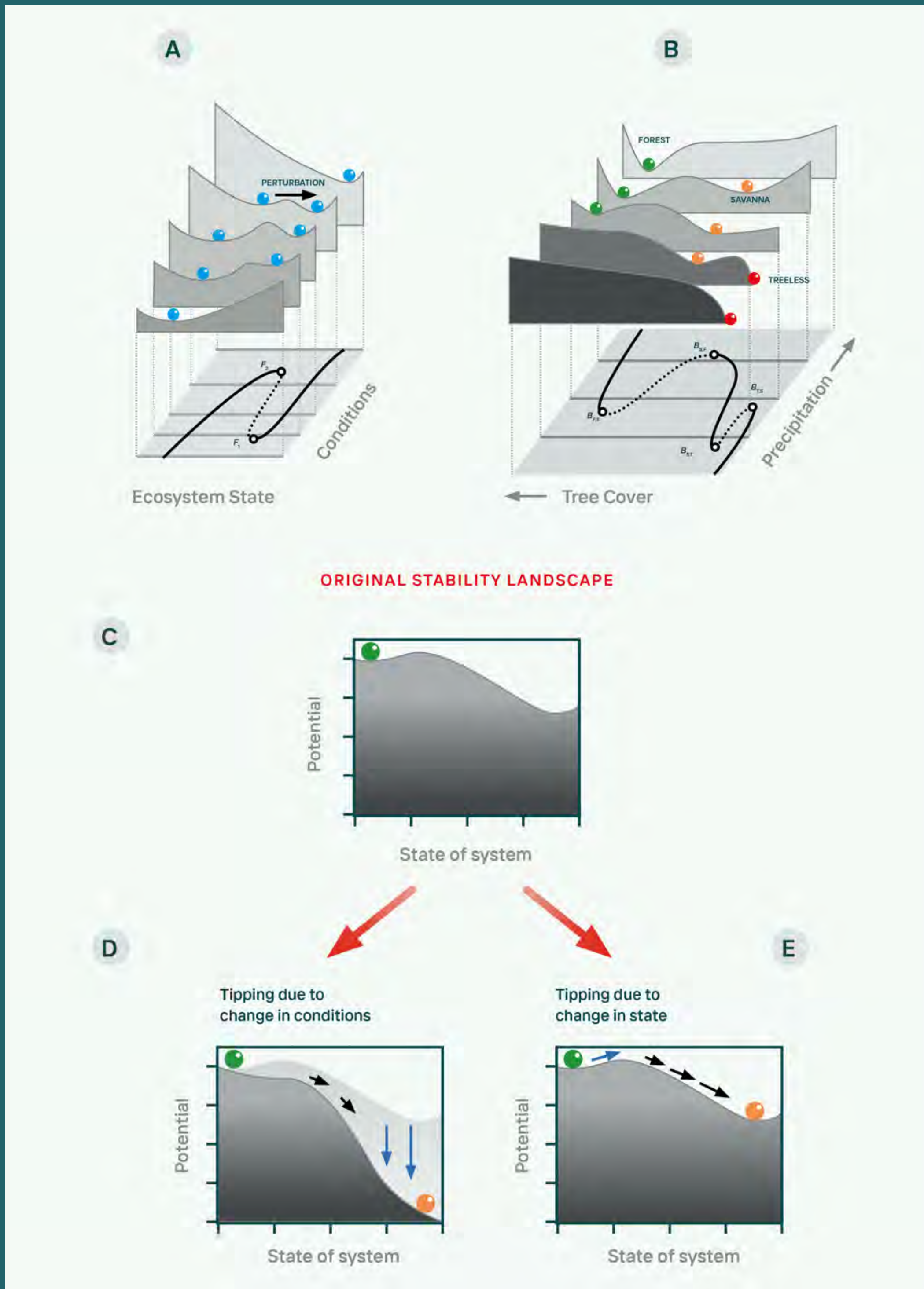


Figure 24.B2 The connection between *tipping points* and *resilience* using *stability landscapes*. Modified from Scheffer *et al.* (2001); Hirota *et al.* (2011); van Nes *et al.* (2016).

Based on the ball-in-a-cup diagram, we use the qualitative definition of resilience as the capacity of the Amazon region to persist as a tropical rainforest, maintaining similar interactions and functioning, despite being constantly pushed away from its stable states by disturbances and perturbations (Holling 1973).

for such shifts at the local scale is lacking, mostly because disturbed forests are commonly invaded by alien grasses (see section 22.2.3) instead of native grass species from South American savannas (Veldman 2016). This happens particularly in landscapes where forest is converted into pastures; invasive grasses escape and become dominant in disturbed forests. Nonetheless, far from the agricultural frontier ("arc of deforestation"), and far from small-scale pastures at the core of the Amazon forest system, black water floodplain forests disturbed by wildfires are being replaced by native savanna vegetation (Flores and Holmgren 2021) (Figure 24.3). In floodplain landscapes of the Rio Negro, fires are highly destructive, killing practically all trees, and allowing the ecosystem to shift to a savanna state within only 40 years. After the first wildfire, soils start to change from clayey to sandy, while tree composition shifts from forest to white-sand savanna species, and the herbaceous community remains dominated by native opportunistic plants (Flores and Holmgren 2021). This local abrupt shift from forest to white-sand savanna seems to be driven by repeated wildfires and a strong flood erosion mechanism that alters plant-soil interactions, favoring savanna species. Previous analyses at the basin scale have shown that these floodplain forests are less resilient than upland forests (Flores *et al*. 2017), including in the watersheds of large white-water rivers, such as the Madeira and Solimões. Hence, as in other forest-savanna transition zones, evidence suggests that savannas of the Amazon system may expand and persist due to feedback mechanisms involving repeated wildfires and soil erosion processes (Flores *et al*. 2020; Flores and Holmgren 2021).

24.2.3 Forest shift to an open-canopy, degraded state

When forests are repeatedly disturbed and native savanna species are not able to colonize, the ecosystem often becomes trapped in an open-vegetation state, dominated by fire-tolerant tree and palm species that usually occur in the forest, together with invasive alien grasses and opportunistic herbaceous plants (Perz and Skole 2003; Veldman and Putz 2011), as well as vines and lianas (Tymen *et al*. 2016; Maia *et al*. 2021; Medina-Vega *et al*. 2021) (Figure 24.3). Below, we describe the feedback mechanisms that have been proposed to explain how the ecosystem can be trapped in this state.

Numerous disturbances that open the forest structure immediately increase light availability at ground level, allowing herbaceous plants to invade (Cochrane and Schulze 1999; Silvério *et al*. 2013; Longo *et al*. 2020). Satellite observations of fire occurrences from across the global tropics reveal that when tree cover is reduced below 50%, ecosystem flammability rises steeply (van Nes *et al*. 2018). Because most trees in the Amazon forest are fire-sensitive, repeated fires often kill most of the tree community (Cochrane and Schulze 1999; Barlow and Peres 2008; Balch *et al*. 2011; Brando *et al*. 2012; Staver *et al*. 2020), particularly the younger individuals, reducing tree recruitment (Balch *et al*. 2011). As a result, disturbances that reduce forest cover below this threshold may cause the ecosystem to be trapped in an open-canopy state by repeated wildfires. Such consequences have been reported in multiple studies in the Amazon, showing that shifts to an open-canopy degraded state are already occurring (Barlow and Peres 2008; Brando *et al*. 2012; Flores 2016).

Other feedback mechanisms are also known to contribute to this ecosystem shift at the landscape scale. For instance, the expansion of invasive alien grasses may also directly reduce tree recruitment due to light competition with young seedlings (Hoffmann *et al*. 2004), which maintains low tree cover and grass dominance. Forest loss, degradation, and fragmentation inhibit the movement of many mobile animal species, particularly the ones that are sensitive to open habitats (Laurance *et al*. 2004), causing many species to disappear from the system (Barlow *et al*. 2016). In the case of frugivore species, by avoiding the use of open disturbed habitats, tree seed dispersal in those sites may become limited, reducing tree recruitment and forest regrowth. This dispersal limitation feedback is expected to be stronger where disturbances are most severe (Turner *et al.* 1998). Evidence from the tropical Atlantic Forest suggests that 30% tree cover could be a threshold in which many forest adapted animal species disappear, and are replaced by disturbance-adapted species (Banks-Leite *et al.* 2014), potentially disrupting plant-animal interactions that are critical for forest recovery.

The current expansion of open-canopy degraded ecosystems across vast portions of the southeastern Amazon forest is triggering other types of feedback mechanisms at the regional and global scales. Forests play a major role in maintaining the rainfall regime of the Amazon by allowing moisture that originates in the Atlantic Ocean to be transported across the basin; a process that may involve up to seven cycles of rainfall and re-evapotranspiration (Spracklen *et al.* 2012; Zemp *et al.* 2017; Staal *et al.* 2018; see also Chapter 7). Hence, by interrupting this process, deforestation and forest degradation will likely reduce rainfall at the central and western Amazon, with stronger potential impacts, particularly during the dry season. This process also involves a feedback between drought and deforestation that is already strengthening with accumulated deforestation, in which the more forest area is lost, the stronger the dry seasons will be, further increasing deforestation rates (Staal *et al.* 2020) and forest fires (Xu *et al.* 2020). In addition to its effects on precipitation, deforestation also affects regional temperatures, with fragmented landscapes being considerably hotter than non-fragmented ones (Zeppetello *et al.* 2020). Due to this large-scale feedback, a tipping point (5) has been proposed to cause major forest dieback within the Amazon basin (Nobre *et al.* 2016; Lovejoy and Nobre 2019). A previous model study had estimated this deforestation tipping point at 40% (Sampaio *et al.* 2007), yet, recent evidence based on a climate-vegetation model that accounts for the combined effects of climate change, deforestation and wildfires (Nobre *et al.* 2016; Lovejoy and Nobre 2019), suggests that this threshold might indeed be closer to 20-25%. In sum, considering these broad-scale interactions, the more Amazonian forests become trapped in an open-canopy degraded state, the more likely that a 20-25% threshold is sufficient to accelerate a critical systemic transition.

24.2.4 Forest shift to a closed-canopy, secondary forest state

Different from the previous cases, in which the forest is trapped in a contrasting open-canopy state, here, disturbed forests recover their closed-canopies but do not progress towards a mature forest state. Instead, they persist in an early successional stage, trapped by different feedback mechanisms (Figure 24.3). Such secondary forests may not be identified through satellite monitoring of canopy conditions, as high levels of greenness and leaf area index may be interpreted as if the ecosystem has recovered its original forest state; however, aspects such as biodiversity and carbon storage would remain at much lower values (Poorter *et al.* 2016; Rozendaal *et al.* 2019). In the Brazilian Amazon, for example, around 23% of previously deforested land is currently covered by secondary forests (INPE and EMBRAPA 2016), but the ecological state of regrown vegetation is unknown.

Under optimal conditions, during regrowth, environmental conditions in the understory gradually change along with species taxonomic and functional composition, in a transition from an open-canopy state with light-demanding species towards a closed-canopy state with mature-forest species. With time, species diversity increases and plant-animal interactions recover complexity and biomass (Poorter *et al.* 2016; Rozendaal *et al.* 2019). Nonetheless, secondary forests are almost two times more likely to be cleared for land use than mature forests, possibly due to lower governmental restrictions and higher accessibility (Wang *et al.* 2020). As a result, most secondary forests are cleared again before 20 years of regrowth (Chazdon *et al.* 2016; Jakovac *et al.* 2017; Schwartz *et al.* 2020). Such feedback causes secondary forests to persist in the landscape only at an early-successional state (Barlow and Peres 2008).

A combination of socio-economic and biophysical factors defines where and when forests recover their previous state in terms of structure and composition. Within the traditional shifting cultivation systems that dominate riverine landscapes of the Amazon, forest regrowth constitutes the fallow period that supports repeated crop yields, being an essential element of the rotational system. In contrast, throughout the extensive pasturelands that dominate Amazonian landscapes in the "arc of deforestation", forest regrowth constitutes an obstacle to pasture productivity and is often managed with prescribed burning. Eventually, regrowth may occur in abandoned areas when landowners do not have the means to continue managing the land or when land productivity is reduced by soil degradation (Vieira *et al.* 2014; Nanni *et al.* 2019). Therefore, feedback mechanisms between social and ecological elements partly determine whether the ecosystem will become arrested in a closed-canopy secondary forest state.

The capacity of secondary forests to fully recover depends on the management practices applied prior to the abandonment and on the landscape context where it occurs (Jakovac *et al.* 2021). Repeated fire use to clean pastures and fertilize cropping fields reduces soil fertility and consequently the rates of forest recovery, particularly when return-intervals between slash-and-burn events are shortened (Zarin *et al.* 2005; Jakovac *et al.* 2015; Heinrich *et al.* 2020). Under a high disturbance regime, survival strategies are favored over growth strategies and a plant community with conservative traits is more likely to thrive. Survival traits include high sprouting ability and low nutrient demand (Jakovac *et al.* 2015), high wood density and high leaf toughness (Fernandes Neto *et al.* 2019), all of which are traits associated with resistance to disturbance and often with slow growth rates (Poorter *et al.* 2010). Lianas and grasses are also favored by disturbances (Roeder *et al.* 2010; Veldman and Putz 2011), contributing to arrest succession by competing with trees and leading to reduced growth rates and higher tree mortality (Schnitzer and Bongers 2002). Combined, these feedbacks impede forest succession, maintaining lower basal area, biomass, canopy height, and species diversity, as well as higher density of stems, lianas in the canopy, and grass cover in the understory (see also Chapter 19).

Furthermore, forest fragmentation associated with deforestation limits tree seed dispersal, reducing tree recruitment (Arroyo-Rodríguez *et al.* 2015), representing another amplifying feedback that can hinder secondary forest succession. The seed rain in such landscapes is mainly composed of early successional pioneers dispersed by wind or by generalist seed dispersers such as bats and birds that are able to cross large extents of pasture or cropping fields (Cubiña and Aide 2001; Wieland *et al.* 2011). Overhunting in degraded forests embedded within human-modified landscapes further contributes to reduce the availability of animal dispersers and increase dispersal limitation (Bagchi *et al.* 2018). The slow inputs of seeds from mature forests results in consistently slow species accumulation over time and therefore a slow species turnover during regrowth (Mesquita *et al.* 2015).

In sum, different combinations of drivers and feedback mechanisms can cause Amazonian forests to be trapped in different configurations, some of which are alternative states (Box 24.1). Shifts to the abovementioned alternative configurations may occur locally, but depending on the scale of the feedbacks, they may become contagious and spread disturbances across large parts of the basin, increasing the probability of a systemic forest dieback. Moreover, other types of configurations are possible, such as the bamboo-dominated (*Guadua sarcocarpa*) forests of the southwestern Amazon that self-perpetuate facilitated by fire feedback; however, we have focused on four general types that are more likely to expand in the coming future.

24.3 Past Evidence of the Dynamics of Amazonian Ecosystems Since the Last Glacial Maximum (20 Ka)

Studies focusing on past vegetation changes have documented several of the forest change scenarios outlined in section 22.2 (see also Chapters 1 and 2). For instance, an expansion of savannas in the northeastern portions of the basin during a climatically unstable period with increasing temperatures was registered at the beginning of the Holocene, i.e., approximately 11 ka (Rull *et al.* 2015). However, the changes observed in sedimentary archives have not always shown a change towards savannization, but depended on the nature of the environmental driver. For instance, pollen analysis revealed a rainforest expansion during the last 3,000 years in forest-savanna boundaries of the southern Amazon, driven by wetter conditions related to changes in the location of the intertropical convergence zone (Mayle *et al.* 2000). Hence, under wetter conditions, these forests have likely reached their maximum potential southern limit for the past 50 ka (Mayle *et al.* 2000), with a 22% increase in the CO_2 storage budget since the mid-Holocene (6 ka) (Mayle and Beerling 2004). Given the historical observations registered during the last decades (see Chapter 22), the climate projections forecasted for this region towards drier conditions (Magrin *et al.* 2014), and the current levels of human impacts, it is unlikely that this forest expansion and consequent increased carbon sequestration will continue. Instead, combined evidence suggests that these forests are more likely to recede, being replaced by open vegetation types.

Empirical data of long-term forest dynamics have shown the differential sensitivity to past climate change across the Amazon basin. Regions like the southern and southeastern Amazon have shifted between forest and open savanna vegetation in relatively recent periods of colder and drier LGM climate (Absy and Hammen 1976), whereas the Andean flank in the western (van der Hammen and Absy 1994) and eastern portions of the Amazon (Wang *et al.* 2017) seem to have persisted as forest. Long-term ecological data from pollen analysis have shown the prevalence of various types of rainforests, both in the southwestern cloud forests and northwestern pre-montane forests of the Amazonian highlands, showing the importance of cloud cover in buffering forests when facing climate change (Urrego *et al.* 2010; Montoya *et al.* 2018). The presence of forests with distinct composition during the LGM has also been observed in the northwestern Brazilian Amazon (Bush *et al.* 2004; D'Apolito *et al.* 2013). This regional evidence of a persistently forested Amazon are consistent with large-scale speleothem analyses showing a remarkable stability of the Amazon rainforest for the past 45 ka, even under a 60% decrease in precipitation totals (Wang *et al.* 2017).

The Mid-Holocene Dry Event (MHDE; 9-4 ka) has been proposed as a potential past analog of current and future trends of decreased precipitation, yet there is still limited evidence covering the entire duration of MHDE throughout the basin. Currently available paleo-records, however, suggest a higher vulnerability of tropical forests to extended droughts in peripheral transitional zones (Mayle and Power 2008; Smith and Mayle 2018). In addition, changes in plant functional traits spanning the termination of the MHDE (i.e., a period of increasing rainfall amount) suggest that rainfall increases led to a replacement of slow-growing, drought-tolerant taxa by fast-growing, drought-vulnerable taxa (van der Sande *et al.* 2019). Indeed, secondary forest species usually differ in their ecological strategies from mature forest species, changing the forest functioning and stability. In southeastern Venezuela, for instance, rainforest taxa were replaced by secondary dry forests around 2.7 ka, a shift that persisted for more than 1,000 years. These secondary forests were finally replaced 1.4 ka under a period of high fire occurrence by the current vegetation consisting of open savanna (Montoya *et al.* 2011).

When a forest is disturbed, the rates of ecosystem change observed in sedimentary archives depend on the ecological scale, being abrupt (decadal) at the species level, but gradual (centennial) at the community level (Montoya *et al.* 2018, 2019). In a tropical meta-data analysis of forest recovery rates after disturbances based on pollen records, Cole *et al.* (2014) observed that South American forests required an average of 325 years to recover from disturbances (natural and human-induced). The recovery rate was calculated in terms of attaining a forest cover (expressed in % of tree pollen) similar to that prior to the disturbance, without differentiating changes in the forest composition, structure, or function. Forests exposed to natural, large, infrequent disturbances (i.e., hurricanes or volcanic eruptions) recovered faster compared to those affected by post-climatic and human impacts. However, forests exposed to more frequent disturbances usually recovered faster, suggesting that repeated disturbances may increase forest adaptive capacity and resilience, yet over multi-centennial time scales (Cole *et al*. 2014). In the Andean Amazon region, Loughlin *et al*. (2018) studied lands that were managed by Indigenous populations, but following European conquest, forests recovered structurally (not compositionally) in only 130 years, possibly because the higher soil productivity of this region boosted tree growth. Despite differences in these estimates, both studies manifest that the temporal range required for forests to potentially recover is multi-centennial (Cole *et al*. 2014; Loughlin *et al*. 2018).

In summary, paleoecological evidence hints at two main directions. Firstly, the Amazon forests have undergone local to regional shifts to dry secondary forests or savannas depending on the disturbances at play (climate- or human-induced changes), but not a basin-wide abrupt dieback, even during intense drier and warmer periods that could well represent analogs of the hypothesized climate-related tipping points (1) – (4). Secondly, the recovery ability of Amazonian forest ecosystems depends on their disturbance histories; the more disturbance-adapted, the faster the recovery rates. Nevertheless, long-term ecological data are still limited in the basin and concentrate primarily along the Amazon's margins; more work is still needed to unravel the dynamics of such heterogeneous ecosystems (Lombardo *et al*. 2018). In addition, some important caveats need to be addressed when using paleo-data as reference for future dynamics: (1) the rates and magnitudes of the changes projected for the near future, with combined disturbance events (climatic and human-induced) acting synchronously, are unprecedented and may hamper forest recovery due to novel mechanisms; and (2) the baseline conditions we have shown are no analog of ecophysiological drivers such as the enhanced atmospheric CO_2 concentrations of the 21st century (section 22.5.3).

24.4 Drivers of Amazon Forest Resilience

Across the Amazon forest system, biotic diversity and abiotic heterogeneity promote a huge variety of responses to disturbances such as extreme droughts and wildfires (Feldpausch *et al.* 2016; Longo *et al.* 2018). This spectrum of responses affects the balance between plant growth, survival, and mortality, and therefore, the resilience of ecosystems. Below, we discuss the main environmental factors that affect plant growth and mortality at different spatial and temporal scales.

The resilience of the Amazon forest is directly linked to the functional characteristics of individual trees and their capacity to resist adverse conditions and disturbances. Thus, processes that exert pressure on the capacity of trees to maintain their functioning and survival are critical. Water deficit associated with increasing length of the dry season or extreme droughts (i.e., related to *tipping points* (2) and (3), section 22.2), is likely to be the major climatic threat to Amazonian trees, as suggested by observational and experimental studies, showing that droughts increase tree mortality rates of individual trees (Nepstad *et al.* 2007; DaCosta *et al.* 2010; Phillips *et al.* 2010; Rowland *et al.* 2015; Zuleta *et al.* 2017; Aleixo *et al.* 2019; Janssen *et al.* 2020b). At least 50% of the Amazon forest is exposed to seasonal droughts of three months or more (Nepstad *et al.* 1994), and contrasting rainfall regimes have selected species with different drought resistance mechanisms (Oliveira *et al.* 2021; Barros *et al.* 2019; Brum *et al.* 2019). In many cases, extreme drought events may not necessarily cause the death of trees, but reduce their growth and capacity to maintain transpiration rates. However, a recent meta-analysis of field observations reveals that highly diverse Amazonian tree communities seem to buffer this effect, conferring higher ecosystem resistance in terms of evapotranspiration rates (Janssen *et al.* 2020a).

Examples of functional characteristics of Amazonian trees to cope with seasonal water deficit include: (1) investment in deep roots (Nepstad *et al.* 1994; Brum *et al.* 2019); (2) roots that allow hydraulic redistribution during the dry season (i.e., passive movement of water from deep to shallow soil through roots) (Oliveira *et al.* 2005); (3) high embolism resistance, particularly in shallow-rooted understory trees and trees over plateaus far away from the water table (Oliveira *et al.* 2019; Brum *et al.* 2019); (4) strong stomatal control in the dry season resulting in high water use efficiency (Barros *et al.* 2019; Brum *et al.* 2019); (5) leaf shedding capacity by deciduous species (Wolfe *et al.* 2016). Although these traits do not guarantee survival under the increasingly drier and variable climates of the future, in locations where the dry season has been intensified, changes in forest composition dynamics are already underway through the recruitment of more dry-affiliated species and the mortality of more wet-affiliated species (Esquivel-Muelbert *et al.* 2019). Also, life-history strategies (e.g., fast-slow continuum in growth rates) have been shown to determine species-level mortality, i.e., the faster you grow, the higher is the mortality risk (Esquivel-Muelbert *et al.* 2020).

There is also evidence that temperature changes (see Chapter 22; Figure 2e) could already be changing forest functioning. Warmer temperatures tend to reduce forest productivity rates (Sullivan *et al.* 2020), particularly by intensifying the atmospheric vapor pressure deficit (Smith *et al.* 2020), indicating that rising temperatures may eventually impact forest functioning and persistence (Araújo *et al.* 2021). Additional CO_2 is expected to buffer the effect of water stress by increasing plant water-use efficiency and accelerating tree growth (section 22.5.3). Elevated atmospheric CO_2 may be the cause of the increase in woody biomass and productivity observed across Amazonian forests (Brienen *et al.* 2015), favoring fast-growth species (Esquivel-Muelbert *et al.*, 2019). However, elevated atmospheric CO_2 driven accelerations of tree growth have come at the cost of decreasing tree longevity across the basin, further contributing to increased tree mortality rates (Brienen *et al.* 2015; Hubau *et al.* 2020). The acceleration of the system via CO_2 fertilization may allow trees to reach the canopy earlier and be more vulnerable to death (Brienen *et al*. 2020), and particularly vulnerable to water deficits (Oliveira *et al*. 2021).

Despite the uncertainties regarding forest responses to climate change, current findings suggest that, in the absence of fire, Amazonian forests may change both compositionally and functionally in response to climatic changes, but still remain as closed-canopy forests. Furthermore, if climate-related *tipping points* (2) – (4) (section 22.2) are crossed, shifts are likely to be sparse and local because of the high heterogeneity and diversity of forest types. Increased tree mortality caused by human-induced disturbances (e.g., wildfires and deforestation), however, may contribute to destabilize the Amazon forest (Silva *et al.* 2018), increasing the likelihood that forests will be trapped in an open-canopy degraded state, and that the system as a whole will cross the *tipping point* (5) (section 22.2.3).

24.5 Uncertainties Associated with Tipping Points within the Amazon System

24.5.1 How does forest heterogeneity affect large-scale tipping points?

Amazonian forests are home to more than 15,000 tree species (ter-Steege *et al.* 2020; Chapters 3 and 4). Most of these species are rare, and many remain unknown to science (ter Steege *et al.* 2013), implying that this huge diversity imposes an enormous challenge to the understanding of how the system functions. In particular, dominant species are responsible for most of the ecosystem functions, such as carbon cycling (Fauset *et al.* 2015). Yet, the many non-dominant and rare species that exist in a forest theoretically also play a fundamental role in ecosystem resilience (Walker *et al.* 1999). When stressing conditions and disturbance regimes change, these rare species can offer new possibilities of functioning, thus increasing the capacity of the ecosystem to adapt and persist (Elmqvist *et al.* 2003). For instance, if a tree species is rare in waterlogged forests, but common on drier climatic conditions, due to adaptations such as deep roots, it could emerge as a dominant species if the climate becomes drier. As a general rule, species diversity is therefore expected to increase the resilience of Amazonian ecosystems. First, because diversity has a positive impact on forest productivity (Coelho de Souza *et al.* 2019) and carbon storage (Poorter *et al.* 2015), potentially accelerating regrowth after disturbances. Moreover, as the number of species is related to the number of strategies and potential responses to disturbances, diversity increases stability at the community and ecosystem levels, and the overall forest resilience (Elmqvist *et al.* 2003; Sakschewski *et al.* 2016; Anderegg *et al.* 2018). For instance, disease and herbivore outbreaks have been causing large-scale tree mortality in temperate regions, yet such events have not been observed in the tropics, likely because the high species diversity of tropical ecosystems reduces the spread of contagious diseases. Drought-tolerant species are often distributed across a vast range of precipitation conditions, hence they may occur as rare species in the wet parts of the basin (Esquivel-Muelbert *et al.* 2016). This pattern implies that if climate becomes drier in the more diverse wet forests, drought-affiliated species may already be present and could increase in abundance, maintaining forest cover, while altering forest functioning.

Rainfall variability (intra- and inter-annual fluctuations) may also add more heterogeneity to the system, as forests that experience more variability seem to be more resilient, likely due to a training-effect after experiencing multiple wet and dry periods (Ciemer *et al.* 2019). For instance, tree communities embedded within a more seasonal rainfall regime are more diverse in terms of their tolerance strategies to cope with drought, when compared to communities within a less seasonal rainfall regime (Barros *et al.* 2019). In other words, while higher mean annual precipitation (above 2,500 mm/yr) increases forest resilience (e.g., the northwestern Amazon; Hirota *et al.* 2011; Staver *et al.* 2011), forests exposed to higher seasonality and interannual variability seem to be more resilient to intermediate mean annual precipitation values (between 1,300 and 1,800 mm/yr), compensating the lower resilience (e.g., eastern x northwestern forests). Valley forests may also be less resistant to droughts than plateau forests due to a similar mechanism, due to a training-effect related to water table fluctuations selected for tree communities with contrasting hydraulic traits (Zuleta *et al.* 2017; Cosme *et al.* 2017; Oliveira *et al.* 2019). Nonetheless, *tipping point*s (2) and (3), related to dry season increases in length and intensity, imply that in forests where the climate is already drier, increases in rainfall seasonality could potentially cause forest loss. Also, increases in the frequency of extreme drought events may prevent proper forest recovery (Anderson *et al.* 2018; Longo *et al.* 2018).

Another heterogeneity that may affect the probability of *tipping point* (1) (1,000 mm/yr; section 22.2) is related to seasonal flooding. Amazonian floodplains cover around 14% of the basin and the forests in these ecosystems were shown to be less resilient than the dominant upland forests, with a potential tipping point of forest collapse when annual mean precipitation reaches approximately 1,500 mm/yr (Flores *et al.* 2017). Therefore, exploring the sources of heterogeneities in forest responses to different types of disturbances is key to understanding whether the Amazon could shift gradually or abruptly from local to basin-wide scales (e.g., Higgins and Scheiter 2012; Levine *et al.* 2016).

24.5.2 How does forest connectivity affect large-scale tipping points?

Spatial heterogeneity implies reduced connectivity (fewer interactions) and may have a huge influence on the systemic resilience of the Amazon, altering how the forest responds to changes in climate and human pressures (Levine *et al.* 2016; Longo *et al.* 2018). For instance, the climatic, hydrological, and biogeochemical connections between the Andes and the low-lying Amazon are undeniably key factors in determining the functioning of the entire system, current and future, on the large scale (see Chapters 5, 7 and 22; Builes-Jaramillo and Poveda 2018). Nonetheless, theoretically, connectivity may still be high even in heterogeneous environments, with different processes linking parts of the system (Scheffer *et al.* 2012). Although forests with contrasting geomorphological, climatological, biological, and cultural histories have formed the Amazon (see Chapters 1-13; Figure 24.1), these forests can interact. For instance, biogeochemical cycles involve fluxes that transport water vapor from plateau to valley forests on a landscape scale. At broader scales, large white-water rivers transport huge loads of nutrient-rich sediments from the west to the east of the basin (see Chapters 1, 3 and 4), depositing them along floodplains where forests can grow faster. Eastern Amazonian forests are also connected to western forests through rainfall recycling (Zemp *et al.* 2017, see also Chapter 7); a mechanism that enhances the resilience of western forests but may be losing strength due to deforestation (Staal *et al.* 2020). When a forest is disturbed locally, mobile animals may transport tree seeds and propagules from surrounding forests and accelerate its recovery (Lundberg and Moberg 2003). However, mobile animals may also transport the seeds of alien invasive grasses from open areas to degraded forested landscapes, increasing their flammability. Local human populations of different Amazonian regions may share ancient knowledge of forest management practices (Levis *et al.* 2018, see also Chapters 8 and 10), potentially changing tree species composition and reshaping forest resilience.

In sum, connectivity may theoretically increase systemic forest resilience, because spatial interactions facilitate recovery of disturbed sites, but as conditions change and disturbance regimes intensify, increasing, for instance, landscape fragmentation and wildfires, disturbances may become contagious, resulting in systemic collapse (Scheffer *et al.* 2012). Managing the various processes that connect different parts of the Amazon is therefore critical for enhancing its resilience.

24.5.3 The interplay between the CO_2 fertilization effect and nutrient availability

Two of the most pressing uncertainties regarding the resilience of the Amazon forest to climate change and other anthropogenic disturbances are the potential physiological effect of increased atmospheric CO_2 (also known as the "CO_2 fertilization effect", eCO_2; see also Chapter 23) and the hypothetical limitations to forest productivity and biomass accumulation imposed by soil nutrient constraints, notably phosphorus (P). The current generation of ecosystem models (namely standard Dynamic Global Vegetation and Earth System Models), are constrained in their ability to provide more trustful projections on the impact of climate change on the forest, due mainly to the acute lack of evidence about the existence, magnitude, and duration of a CO_2 fertilization effect and associated limitations imposed by soil nutrients (Lapola 2018).

On the one hand, the CO_2 fertilization effect could, theoretically, increase forest productivity, biomass accumulation rates (Ainsworth and Long 2005), and water use-efficiency (Kauwe *et al.* 2013). On the other hand, the lack of key nutrients for plant metabolism constrains further biomass gains under elevated CO_2 conditions (Norby *et al.* 2010). There are preliminary (i.e., short-term) indications from other phosphorus-limited forests (in sub-tropical Australia), subjected to increased atmospheric CO_2 concentrations, that did not significantly increase biomass (Jiang *et al.* 2020) given that phosphorus is needed especially for making the cell membrane, and also for energetic (ATP) and genetic (DNA and RNA) plant molecules. As such, trees might increase their photosynthetic rates under enhanced CO_2 but do not allocate these extra photosynthates to additional plant biomass, possibly simply increasing biomass turnover rates across the forest ecosystem. Nevertheless, this evidence comes from single-species forests and the response of highly diverse forests such as the Amazon to enhanced CO_2 is yet to be understood. In this sense, observational data along a P availability gradient in Panamanian tropical forests revealed that, although such P limitation exists, it does not affect different species in the same way (Turner *et al.* 2018). This latter finding is of particular relevance for the Amazon forest given that climate change and other anthropogenic disturbances may imply significant alteration of the forest tree community composition and dominance relations, both in taxonomic and functional terms (Norby *et al.* 2016). Alternatively, it is hypothesized that Amazon forest trees could change symbiotic exchanges of carbohydrates and nutrients with mycorrhizae fungi to access currently unavailable soil P pools.

Besides the implications for the Amazonian forest carbon budget and functional diversity, the physiological effects of elevated CO_2 have the potential to interfere in the flux of humidity from trees to the atmosphere, which is especially relevant for the region, where up to 50% of the precipitation that falls within the basin is regionally recycled (Zemp *et al.* 2014). In that sense, free-air concentration enrichment (FACE) experiments in temperate forests in the United States and in an Eucalyptus-dominated woodland in Australia have found a reduction of stomatal conductance and canopy transpiration on the order of -20% (Kauwe *et al.* 2013; Gimeno *et al.* 2016). That is the same magnitude of reduction in transpiration found in recent coupled climate-vegetation modeling studies for the region, which is ultimately related to a basin-wide reduction of 15% to 20% in rainfall (Kooperman *et al.* 2018). Such a rainfall reduction possibly caused by the physiological effect of elevated CO_2 is equivalent to the rainfall reduction in a scenario with complete deforestation of the Amazon (Sampaio *et al.* 2020).

Without an enhancement of productivity and with a reduction of forest canopy transpiration due to increased atmospheric CO_2, the actual Amazon forest and its current community compositions and functional relations are thought to become less resilient to climatic changes, deforestation, degradation, and other anthropogenic disturbances, with pervasive impacts on the regional socio-economy (Lapola 2018). Two ongoing ecosystem-scale experiments - the AmazonFACE experiment and the Amazon Fertilization Experiment (AFEX) - will soon provide valuable information about the CO_2 fertilization effect and the limitation of forest productivity and biomass stocks by soil nutrients in the Amazon forest (Hofhansl *et al.* 2016).

24.6 Modeling the Resilience and Tipping Points of the Amazon Forest

For modelling the impact of global change on vegetation at scales as large as the Amazon basin, Dynamic Global Vegetation Models (DGVMs) and Land Surface Models (LSMs) are the most used tools (Sato *et al.* 2015; Fisher and Koven 2020). Those models are capable of simulating long time series of various pressures on vegetation and are therefore key to project the future of the Amazon system (e.g., White *et al.* 1999; Cox *et al.* 2004). Often DGVMs and LSMs are the vegetation component in Earth System Models (ESMs), and their success in comprehensively representing processes of vegetation growth and interactions with other Earth System components relies on empirically-derived evidence. This means those models need to make use of the information described in section 22.4. Given the extreme complexity involved in soil-plant-atmosphere interactions at different temporal and spatial scales, selecting the most relevant processes and implementing them into models are very challenging tasks (Fisher and Koven 2020), and leads to substantial uncertainties (e.g., Rammig *et al.* 2010).

Model simulations can be performed a) offline, meaning the vegetation model is driven standalone by externally generated climate data or b) coupled, meaning that the vegetation model is part of an ESM in which different compartments of the Earth System (e.g., the vegetation and the atmosphere) can interact. Such a coupling increases the amount of accounted feedback mechanisms (Box 24.1) which are theoretically necessary to identify *classical tipping points*, besides the prerequisite that the DGVM/LSM allows for the existence of two or more alternative vegetation cover configurations under the same underlying conditions (e.g., climatic; Box 24.1). For Amazonian ecosystems, tipping point simulations performed so far rely on both offline and coupled runs (*tipping points* (4) and (5) from section 22.2). Taking the inherent limitations of simulating alternative stable states into account, below we present a summary of what such models can already tell us about dieback, thresholds (Box 24.1), and resilience within the Amazon basin.

About 20 years ago, modeling studies pointed to a potential Amazon dieback under climate change (White *et al.* 1999; Cox *et al.* 2000, 2004; Cramer *et al.* 2001; Oyama and Nobre 2003). Up to now a substantial amount of literature has painted a complex picture with key uncertainties regarding the resilience and potential tipping points of the Amazon under global and regional environmental changes. The results span from the clear identification of crossing tipping points in time, as represented by decreasing levels of tree cover or biomass stock (e.g., Cox *et al.* 2004; Sitch *et al.* 2008), up to an overall increase of biomass and forest cover (Schaphoff *et al.* 2006; Lapola *et al.* 2009; Rammig *et al.* 2010; Huntingford *et al.* 2013). Such a large variety of results can be explained by: 1) whether the DGVM/LSM was coupled (e.g., Cox *et al.* 2004); 2) the existing variety of underlying model assumptions and processes; and 3) general uncertainties on future climate changes in the region. Moreover, DGVMs and LSMs represent vegetation using a limited set of plant functional types (PFTs), which are still not capable of comprising the entire range of plant strategies that confer more or less resilience to Amazonian forests (Oliveira *et al.* 2021). In this sense, a more comprehensive representation of different vegetation ecosystems is needed to improve the simulation of the gradual and abrupt shifts to alternative configurations for the Amazon forests described in section 22.2. Hence, so far, there is a fairly binary possibility simulated by current models: either the current configuration or a complete replacement of forest by another vegetation type.

The main drivers behind this original modeled forest dieback (Cox *et al.* 2004) are acute reduction in regional rainfall, and a prolonged dry period, which affects photosynthetic rates and the accompanying increase in temperature that further increases plant respiration and water demand, resulting therefore in a considerable reduction of plant productivity and growth. The effects on carbon assimilation also impact the flux of water from the surface vegetation to the atmosphere through transpiration, reinforcing the moisture limitation and ultimately leading to a shift of PFTs, from predominantly tropical broadleaf trees to C_4 grasses with about 30% of broadleaf tree cover, resembling savanna vegetation (Betts *et al.* 2004; Cox *et al.* 2004). Even without acknowledging such feedbacks through coupling within ESMs, previous offline simulations support such “savannization” processes (section 22.2.2) under future scenarios of precipitation and temperature changes (Nobre *et al.* 1991; Oyama and Nobre 2003). Importantly, the feedbacks magnify the regional climate and vegetation response, and a long-term commitment to Amazon dieback occurs at 2°C global warming, determining an actual *tipping point* (4) from section 22.2 (Jones *et al.* 2009). Therefore, it is clear that the Amazon dieback is an issue about feedbacks (i.e., interactions within a closed-loop) between the regional climate and the forest vegetation functioning. In this sense, a key component is the regional climate response to global warming and the role of non- or dysfunctional forest states in magnifying this process; in other words, whether the regional climate moves from a configuration supporting the rainforest to another, which it does not. This depends on the availability of soil moisture, which itself depends on precipitation and evaporation, both of which change with global warming (see Figure 24.2 for historical and projected changes in some of these variables). If the regional climate reaches a critical state, the resulting forest dieback magnifies the regional climate change and causes further forest dieback.

However, as in many regions of the world, the projected changes in precipitation in the Amazon due to anthropogenic climate change are highly uncertain (e.g., Jupp *et al.* 2010). While the majority of the current generation of climate models project a decrease in annual mean precipitation with global warming (see Chapter 22), the rate of the Amazon precipitation decrease in relation to global warming varies widely between the models. A family of climate models notable for their projection of severe Amazon drying, HadCM3 (Gordon *et al.* 2000), project annual precipitation in the eastern Amazon

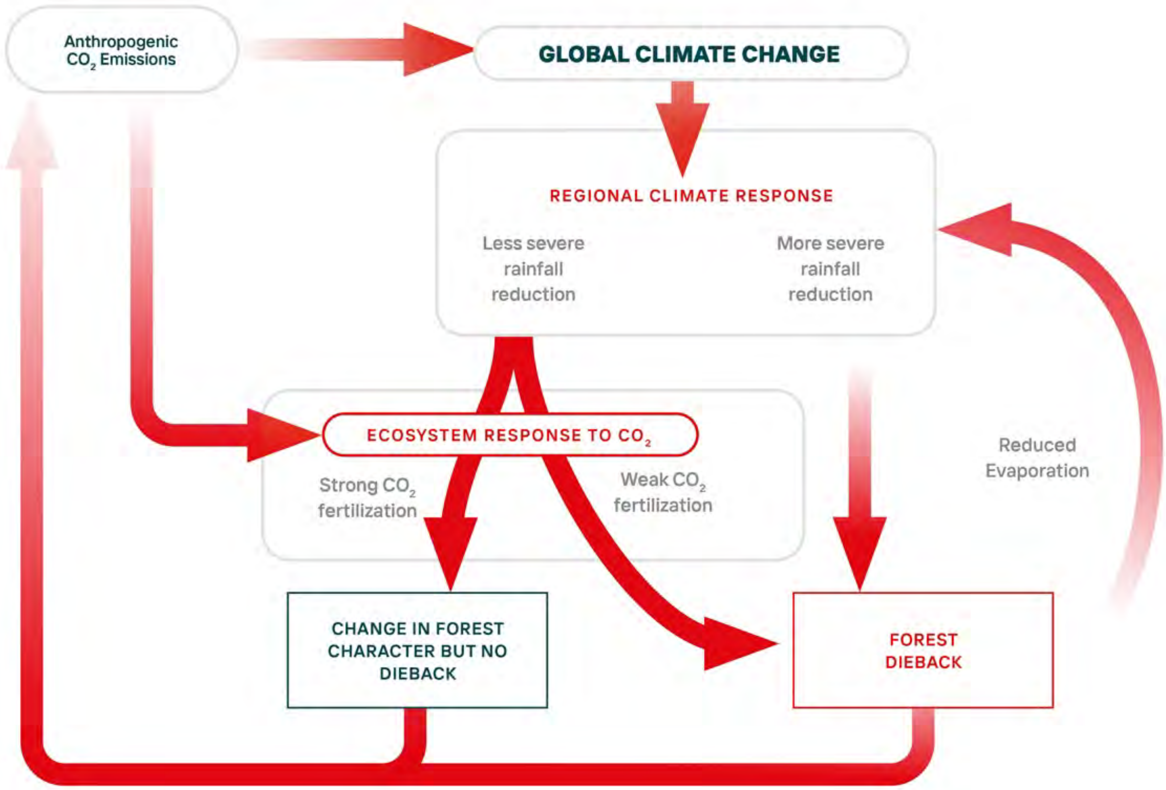


Figure 24.4 Simplified sketch of processes involved in the potential Amazon dieback tipping point due to climate change.

to fall below 1,500 mm/yr at approximately 3°C global warming (Betts *et al.* 2012). This precipitation level has been identified as one of the climatic thresholds critical to the support of rainforests (Malhi *et al.* 2009), with empirical evidence suggesting this seems to be the *tipping point* (1) for floodplain forests (Flores *et al.* 2017). The largest decrease in precipitation in the HadCM3 model family was largely a result of atmospheric circulation changes driven by particular patterns of sea surface temperature (SST) (Harris *et al.* 2008). The variation in precipitation change between the models was found to be related to the strength of the SST changes in the equatorial Atlantic (Good *et al.* 2008, 2013). Most other models also project decreased precipitation, but less severely.

On the one hand, there are three main underlying drivers to the aforementioned climatic changes that can trigger or reinforce a modeled threshold crossed in the region, even under less severe decreases in precipitation: global climatic changes due to higher atmospheric greenhouse gas (GHG) concentration (Cox *et al.* 2004; Schaphoff *et al.* 2006; Lapola *et al.* 2009; Jupp *et al.* 2010; Huntingford *et al.* 2013), deforestation and forest degradation (Sampaio *et al.* 2007; Staal *et al.* 2020), and forest fires (Burton *et al.*; Barlow and Peres 2008; Cochrane and Barber 2009; Nobre *et al.* 2016). The occurrence of the climate tipping point for Amazon forest dieback projected in the models therefore depends partly on the nature of the regional climate response to global warming and the impact of CO_2 fertilization, wildfires, and deforestation (Figure 24.4). If the regional climate response is relatively small, forest dieback does not occur. However, if the regional climate response is large, forest dieback could in principle occur and magnify itself through local and global climate feedbacks.

Regardless of the feedbacks involved, after correcting for biases (found in climatic projections under climate change conditions) identified using observation data, a basin-wide Amazon dieback would be unlikely to occur, even under the most pessimist IPCC pathway (Chai *et al.* 2021). Furthermore, there are some ecological processes that can potentially dampen, offset, or prevent Amazon dieback, namely the CO_2-fertilization effect under enhanced atmospheric CO_2 (section 22.5.3) (Hickler *et al.* 2008; Huntingford *et al.* 2013; Kooperman *et al.* 2018), the acclimation of tree physiology to warmer and drier climates (Kumaranthunge *et al*. 2018), as well as the reorganization of forest communities and/or their functional characteristics such that biomass and other broad characteristics that define crucial ecosystem functions are maintained (Sakschewski *et al.* 2016).

Processes related to functional diversity (e.g., Fyllas *et al.* 2014; Fischer *et al.* 2016; Sakschewski *et al.* 2016), including plant hydraulics (e.g., Christoffersen *et al.* 2016; Xu *et al.* 2016; Eller *et al.* 2020) and rooting depth (Langan *et al.* 2017; Sakschewski *et al.* 2020), have already started to be implemented in current vegetation models to improve the representation of local-scale heterogeneity of the Amazon basin and consequently the ability models have to capture resilience increases due to biotic and abiotic heterogeneity (section 22.5.1) (Levine *et al.* 2016; Sakschewski *et al.* 2016; Longo *et al.* 2018). Furthermore, models demand a high amount of observational, field-based, and/or experimental data, which are still scarce. Kooperman *et al.* (2018), for example, point out that stomatal closure under enhanced CO_2 (as part of the CO_2-fertilization effect) can drive significant modeled rainfall reduction in the Amazon through reduced forest transpiration and moisture recycling (Zemp *et al.* 2017), even though ecosystem-scale evidence on the interplay between enhanced CO_2 and stomatal conductance is very scarce. Adding to that complexity, other studies suggest that stomatal closure under enhanced CO_2 might not turn out to be as strong as anticipated by models, since leaves need to increase transpiration cooling under elevated temperatures (Dong *et al*. 2014). Another example is that modeled phosphorus limitation (existent in about 60% of Amazonian soils, Quesada *et al.* 2012; see Chapter 1) might reduce or even eliminate any gains in primary productivity arising from a supposed CO_2 fertilization effect in the Amazon (Fleischer *et al.* 2019); but, again, there is lack of field data and knowledge on the Amazon phosphorus cycle to corroborate such a result (section 22.5.3).

As such, the way forward for modeling and evaluating the likelihood and mechanisms behind an Amazon tipping point passes first through a closer integration between models, data, and field experiments. Field data show us, for example, that community dynamics – tree recruitment and mortality – play a key role in the impact of climate change and climatic extremes in the Amazon (section 22.4) (Esquivel-Muelbert *et al.* 2019, 2020; Hubau *et al.* 2020). Thus, improving the representation of such recruitment and mortality dynamics and its driving causes is one priority for modeling. Other processes such as the role of plant hydraulics (Eller *et al.* 2018) and increased plant functional diversity (Scheiter *et al.* 2013; Sakschewski *et al.* 2016), as well as large scale heterogeneities related to climate, hydrology, and soil chemistry, for instance, should be explored in more depth by other models. The potential CO_2 fertilization effect on photosynthesis and water use and possible limitation of forest productivity by soil nutrients (section 22.5.3) represent a *quasi*-complete gap in existing models of the Amazon forest vegetation due to the lack of understanding of mechanisms and field data. Last, but not least, narrowing down the uncertainties of rainfall projections for the region would also be very important for better constraining modeling studies on the Amazon tipping point.

24.7 Conclusions

The pressure of intensified anthropogenic activities has promoted the appearance of new stressing factors operating in Amazonian forests, as well as an intensification of some environmental drivers at different spatial and temporal scales. It has been hypothesized that the cumulative effect of disturbances such as deforestation, droughts, and fires may unbalance the natural dynamics of these globally important ecosystems due to the systemic loss of forest resilience. The analysis of the existing literature performed in this chapter has highlighted five different scenarios of tipping points to which Amazonian forests could be sensitive (Figure 24.2), namely: (1) the annual rainfall between 1,000 mm/yr and 1,500 mm/yr inferred from global climate models, (2) the dry season length of seven months, inferred from satellite observations of tree cover distributions, (3) for the Amazon lowlands, the maximum cumulative water deficit values between 200 mm/yr and 350 mm/yr, inferred from global climate models; (4) an increase of 2ºC on the equilibrium temperature of the Earth, inferred from a coupled climate–vegetation model, and (5) the 20-25% accumulated deforestation of the whole basin, inferred from a combination of environmental changes and human-induced degradation via deforestation. Based on empirical evidence, four different ecosystem configurations, some of which could be alternative stable states, have been proposed for Amazonian forests if a tipping point or threshold is crossed, including: (i) a closed-canopy seasonally dry tropical forest state; (ii) a native savanna state; (iii) an open-canopy degraded state; and (iv) a closed-canopy secondary forest state. However, due to the existence of novel feedbacks associated with invasive plants and human-modified landscapes, we consider the open degraded state and the closed-canopy secondary forest state as more likely to occur over broad areas, particularly across the "arc of deforestation". New evidence, however, indicates that in remote parts of the Amazon basin far from the agricultural frontier, the native savanna state could be replacing seasonally inundated forests disturbed by wildfires. Ecological features including differential tree growth, recruitment, and survival among Amazonian species are key to promote forest resistance to, as well recover from, disturbances at local scales. We identify three mechanisms that may affect the risk of a large-scale tipping point due to contagious forest dieback: (a) the environmental heterogeneity and connectivity among forests across the basin; (b) the functional diversity and adaptive capacity of the species present in the different forest types; and (c) the uncertain effect of enhanced CO_2 and nutrient limitation. The lack of this ecological information for many Amazonian species, the uncertainty of the potential feedbacks operating, as well as the need for further improvements in climate change projections hamper the development of robust models for anticipating the potential shifts that Amazonian forests may undergo in the near future. The way forward for modeling and evaluating the likelihood and mechanisms behind an Amazonian tipping point passes first through a closer integration between models, observational data, and/or field experiments. Even with models where a tipping point is not met, and accounting for the uncertainty due to the limited data available, we need to urge the international community within and outside academia to protect, maintain, and sustainably manage the resilience of these complex and dynamic entities that are Amazonian forests.

24.8 Recommendations

- Combining analysis of future environmental change scenarios with past and present dynamics can help improve our understanding of alternative ecosystem configurations.
- A holistic and integrative scientific framework is needed to assess the main heterogeneities, drivers, and ways to manage the resilience of Amazonian forest systems.
- Understanding the heterogeneities of the Amazon is key to assessing the risk of a large-scale tipping point and to design ways to manage the resilience of the system.
- An effective transnational monitoring system is needed to improve our knowledge on the dynamics of different Amazonian ecosystems (embedded in a wider range of environmental conditions), and their potentially heterogeneous response to various types of disturbances (e.g., climatic extremes, wildfires, deforestation).
- Managing Amazonian resilience locally can help reduce the risk of reaching a tipping point. This requires protecting and restoring forest cover, biodiversity, agrobiodiversity, and cultural diversity, as well as controlling the use of fire.

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CONTACT INFORMATION

SPA Technical-Scientific Secretariat New York
475 Riverside Drive, Suite 530
New York NY 10115
USA
+1 (212) 870-3920
spa@unsdsn.org

SPA Technical-Scientific Secretariat South America
Av. Ironman Victor Garrido, 623
São José dos Campos – São Paulo
Brazil
spasouthamerica@unsdsn.org

WEBSITE theamazonwewant.org
INSTAGRAM @theamazonwewant
TWITTER @theamazonwewant