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)

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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Graphical Abstract

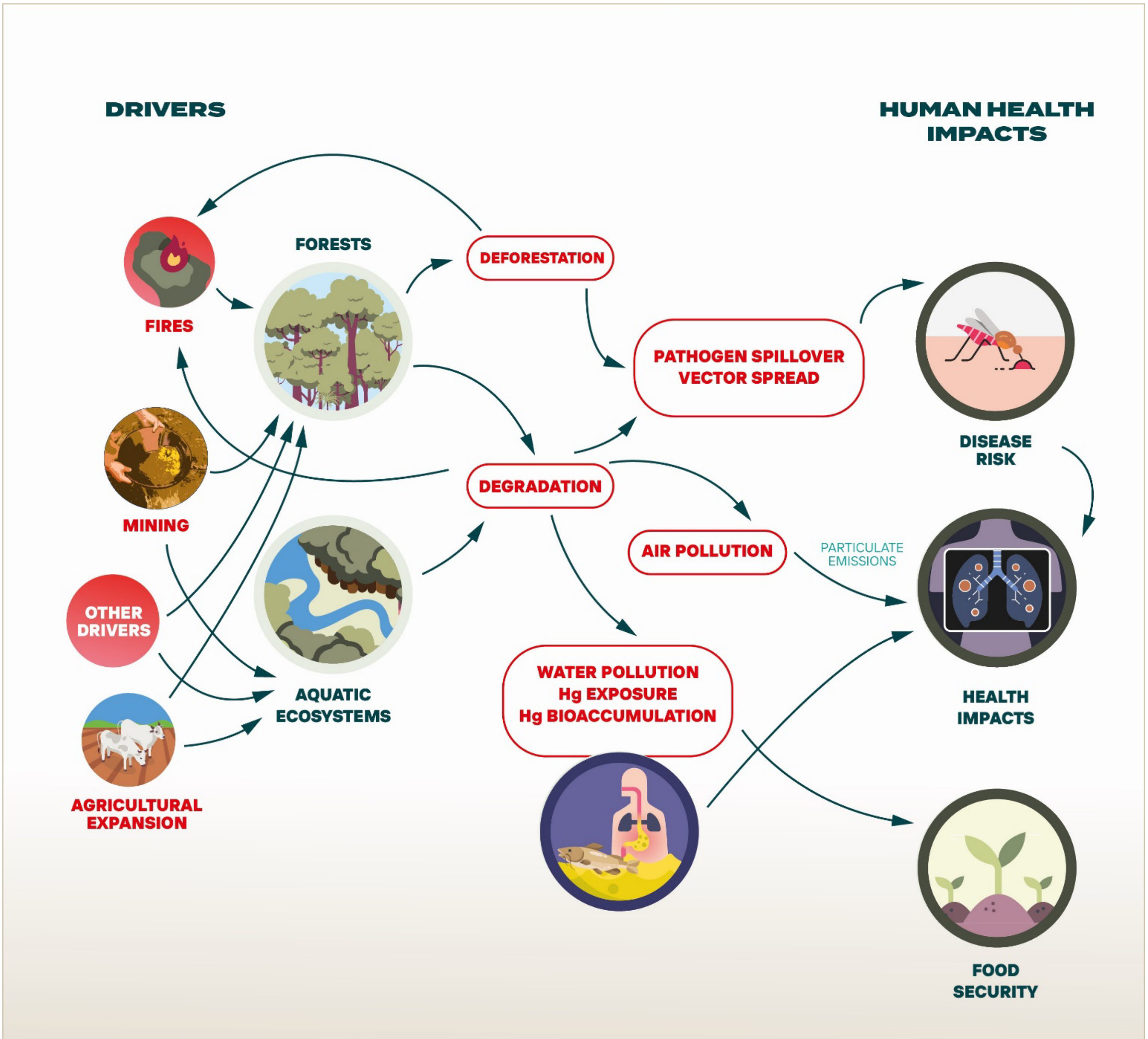

Figure 21.A Graphical Abstract

Human Well-being and Health Impacts of the Degradation of Terrestrial and Aquatic Ecosystems

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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

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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.

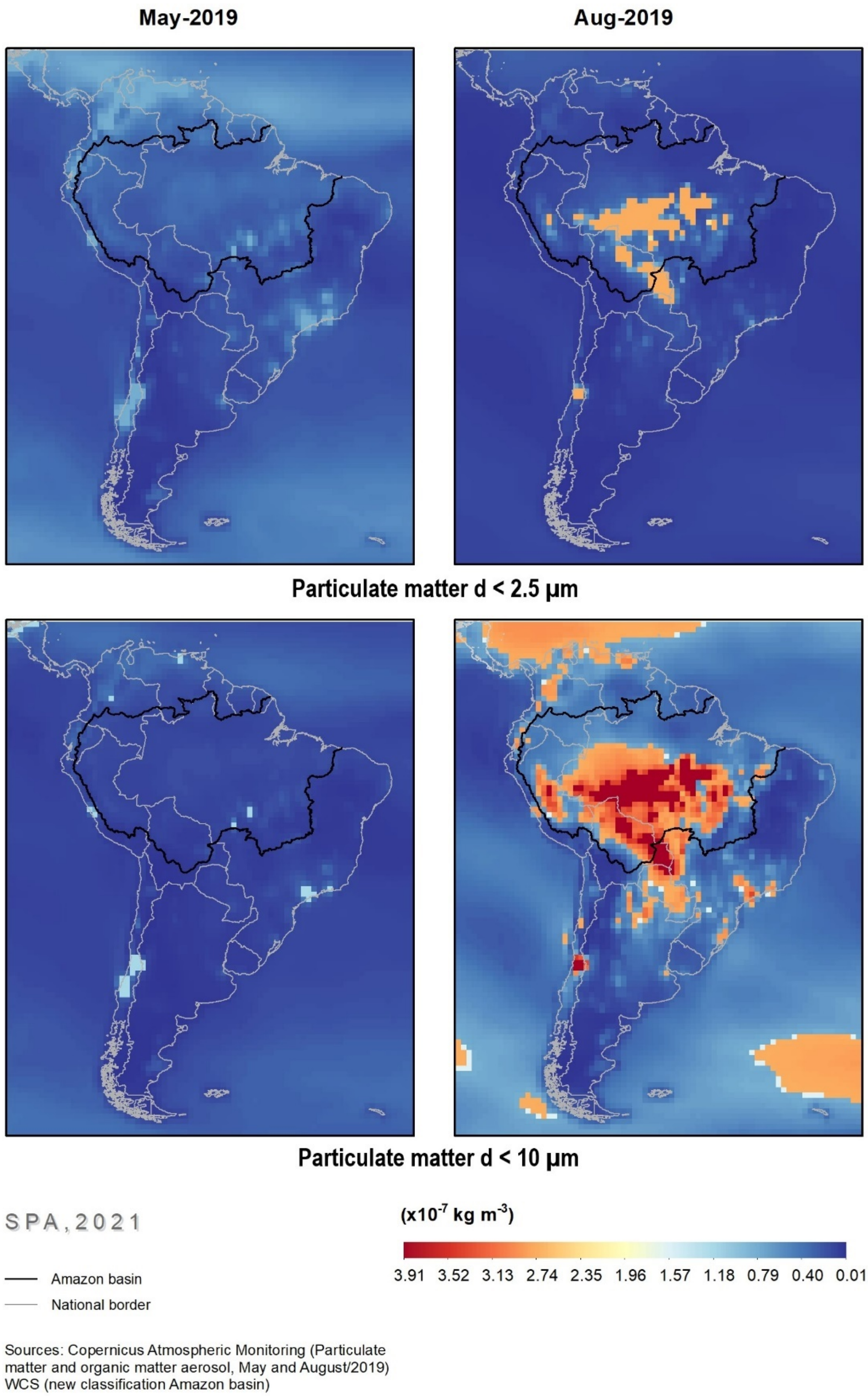

Figure 21.1 Smoke plume and particulate matter circulation (PM2.5, PM10) over South America and Amazonia (black limits - limit adopted by SPA for the Amazon basin) in May 2019 (left panels) and August 2019 (right panels). Sources: Copernicus (2020) and WCS-Venticinque *et al.* (2016).

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.)

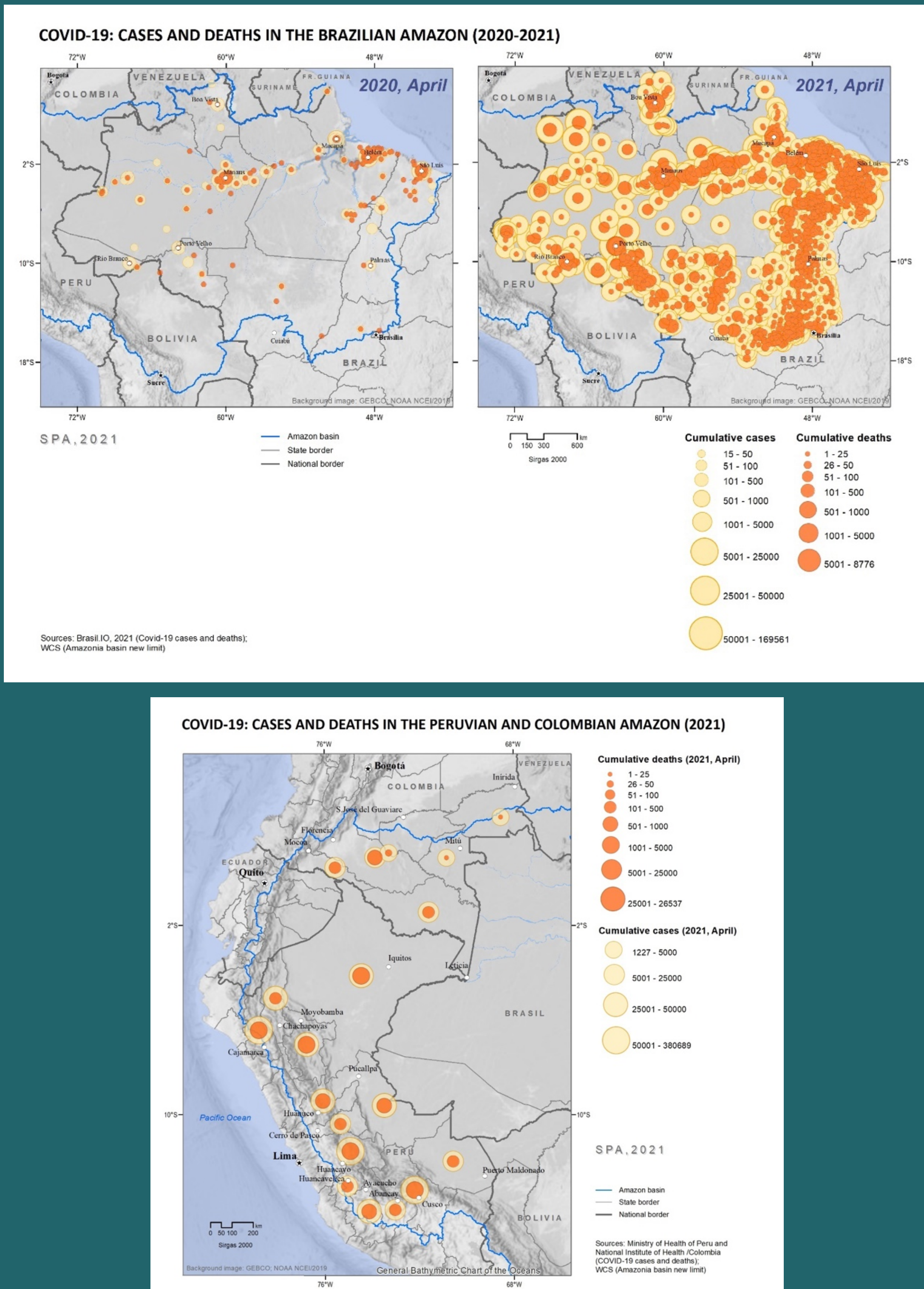

Figure 21.B3.1 COVID-19 cases and deaths in the Brazilian, Colombian and Peruvian Amazon. Sources WCS-Venticinque *et al.* (2016); Brasil.IO.;Ministry of Health of Peru and National Institute of Health Colombia.

Box 21.3 The impact of COVID-19 in the Amazon region (cont.)

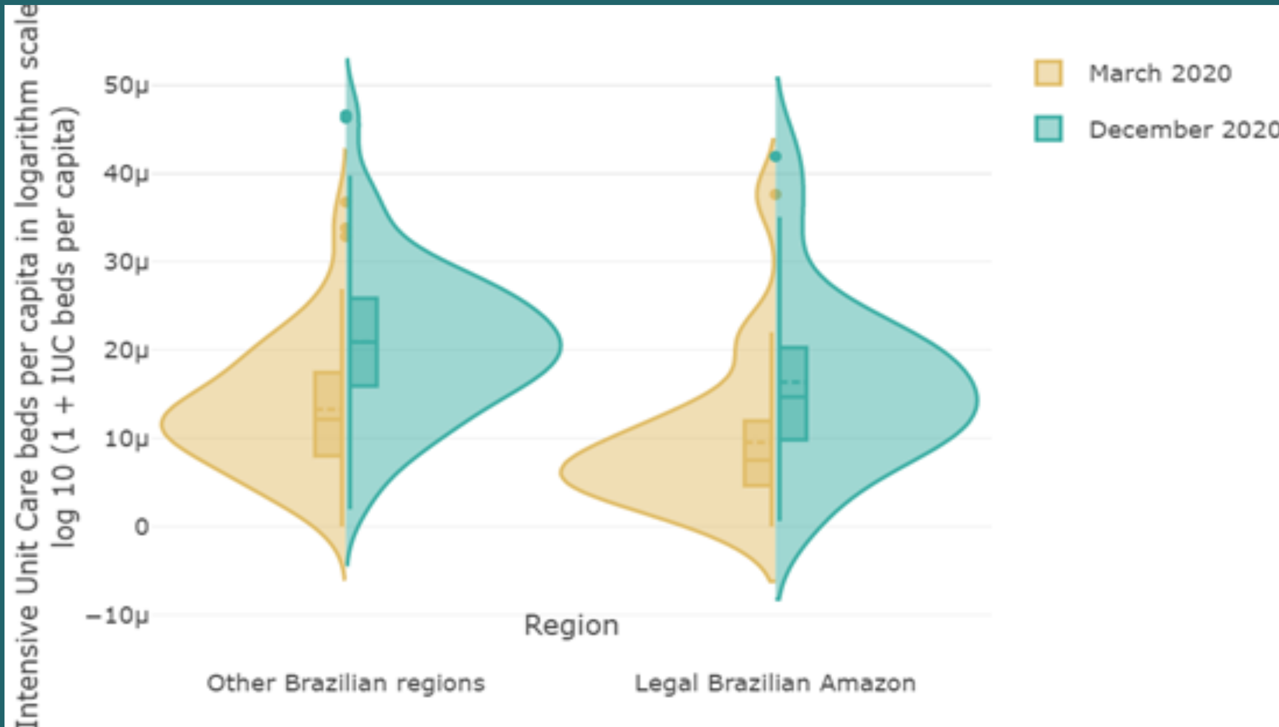

Figure 21.B3.2 Boxplot showing lower Intensive Unit Care for COVID-19 per capita in health macro regions in the Legal Brazilian Amazon compared to other other Brazilian regions, both in early and late 2020. Data Source: Brazilian National Register of Health Establishments (CNES), Ministry of Health.

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).

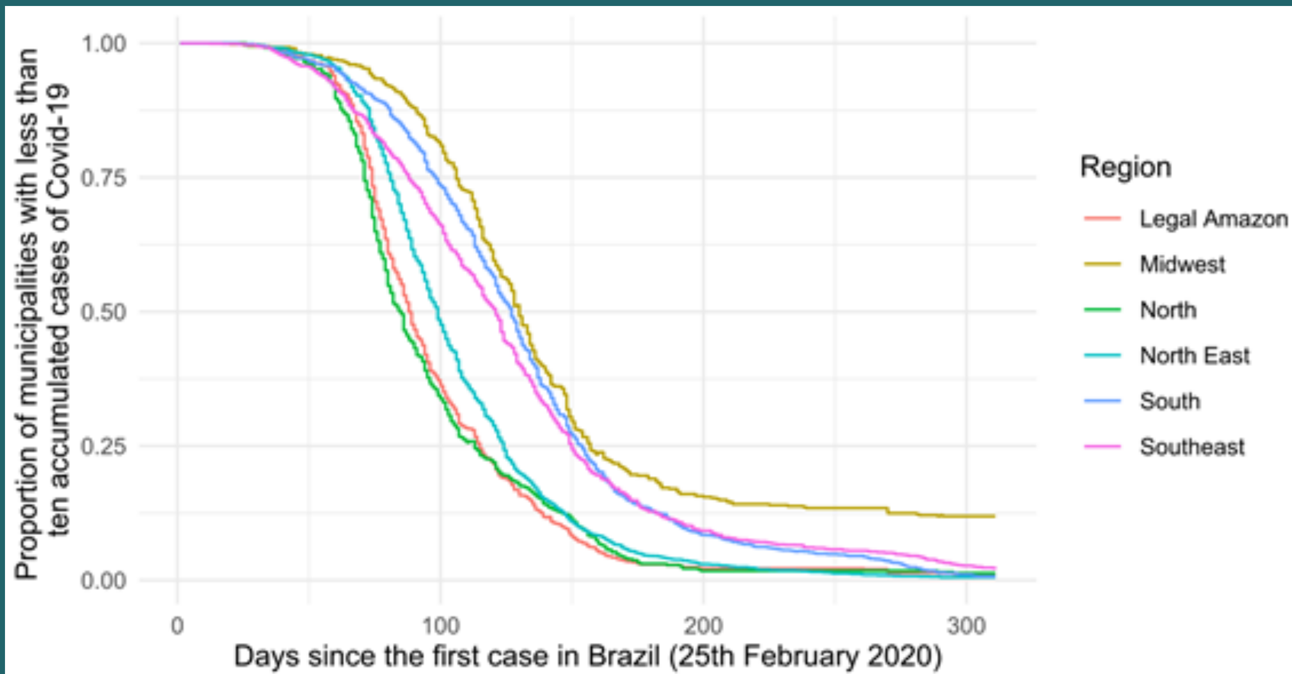

Figure 21.B3.3 Proportion of municipalities with less than ten accumulated cases of COVID-19 among the Legal Brazilian Amazon and geographic regions. The North region (in green - all of which is part of the Amazon) had the fastest rate of spread of covid, with 50% of municipalities being reached in 90 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 Amazonwide and country-level models to estimates for specific locations and issues of individual health and well-being. Similarly, models at different time-scales 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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