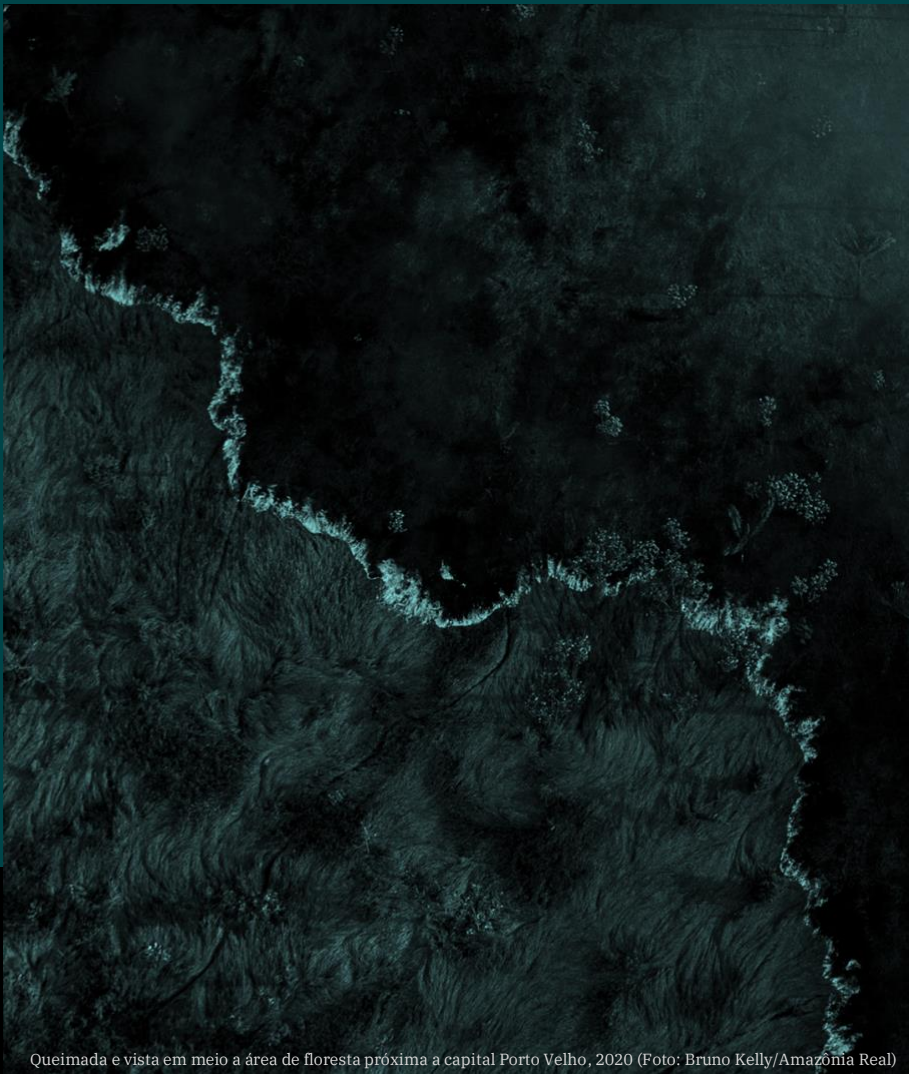


Chapter 6 In Brief

Biogeochemical cycles in the Amazon



Queimada e vista em meio a área de floresta próxima a capital Porto Velho, 2020 (Foto: Bruno Kelly/Amazônia Real)



THE AMAZON WE WANT
Science Panel for the Amazon

Biogeochemical cycles in the Amazon

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Key Messages & Recommendations

- 1) The Amazon basin contributes around 16% of global terrestrial photosynthetic productivity in natural systems. Interannual variability in the Amazon is a major contributor to interannual variability in the global carbon (C) cycle.
- 2) The Amazonian rainforest stores large amounts of carbon, which should not be released into the atmosphere. In recent decades, the intact Amazon has been a major carbon sink, reducing climate change. This carbon sink is weakening over time, possibly because of increased frequency of drought and rising temperatures.
- 3) Amazonian methane (CH₄) emissions mainly come from wetlands and are estimated to represent 6-8% of global CH₄ emissions, though large uncertainties in both sources and sinks remain.
- 4) The Amazon has a major influence on aerosol cycling and cloud formation, and hence on atmospheric circulation and albedo. The amount of reactive volatile organic compounds (VOC), their emission pathways, and the resulting oxidative reactivity in the atmosphere, including the impact on secondary organic aerosols (SOA) production, evapotranspiration, water condensation, and rainfall, is still poorly understood.

Abstract This chapter summarizes the cycles of three key biogeochemical elements, carbon, nitrogen, and phosphorus, with a focus on carbon, spanning both terrestrial and aquatic ecosystems in the Amazon. The chapter also examines the emissions of two key trace gases which make substantial contributions to radiative warming, methane and dinitrogen oxide (N₂O), and summarizes trace gas and aerosol emissions from the Amazon and their impact on atmospheric pollution, cloud properties, and water cycling.

The Amazon's carbon cycle over the last 1 million years The last 1 million years have been dominated by a roughly 100,000 year climate cycle, 90% of which is largely a cool climate with low atmospheric CO₂ (~180 ppm) and extreme climate variability, broken by short (~10,000 year periods) of warmer and wetter conditions, higher CO₂ (~280 ppm) and a more stable climate (the Holocene being a prime example). The low CO₂ concentrations of glacial periods (180 ppm) may be close to the threshold of viability of photosynthesis, and would have greatly reduced ecosystem productivity.

There has been much speculation as to how Amazonian forests varied during glacial-interglacial cycles. Haffer (1969)¹ famously suggested that during glacial maxima the forest biome retreated into refugia separated by cerrado. This scenario has

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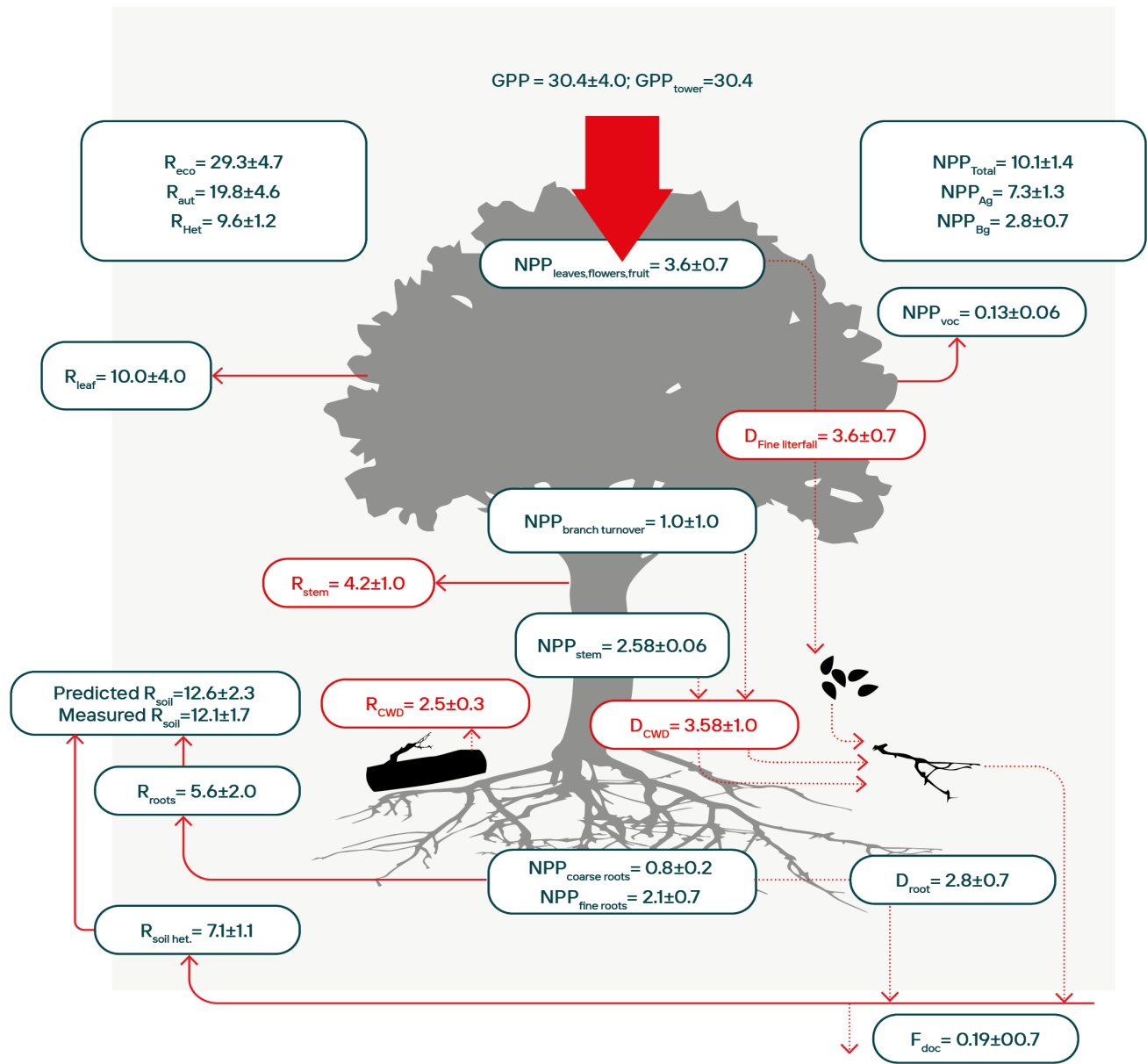


Figure 6.1 The carbon cycle of a typical Amazonian forest (near Manaus, central Amazon). Adapted from data in Malhi et al. (2009)⁶. GPP = Gross Primary Productivity (predicted as sum of NPP and autotrophic respiration, and directly estimated from flux tower measurements (NEE + R_{eco}); NEE - net carbon flux or net ecosystem exchange, R_{eco} - combination of autotrophic and heterotrophic respiration, NPP - Net Primary Productivity, in total, and above ground (AG) and belowground (BG) components, and its components as (i) canopy production (leaves, flower, fruit, twigs); (ii) branch turnover; (iii) volatile organic carbon emissions (VOC); (iv) above-ground woody tissue production (stem); (v) coarse root production; (vi) fine root production; R - Respiration, in total and autotrophic (aut) and heterotrophic (het) components, and its components as (vii) leaf respiration; (viii) wood tissue respiration; (ix) root respiration; (x) soil heterotrophic respiration; (xi) total soil respiration, either directly measured or predicted as sum of inputs assuming no net change in soil carbon stocks; D - detritus fluxes, as (xii) fine litterfall; (xiii) coarse woody debris production; (xiv) root detritus production; (xv) F_{doc} - carbon export in the form of dissolved organic carbon. Units are Mg C ha⁻¹ y⁻¹.

not stood the test of time; the broad consensus today is that there was only modest retreat in forest extent during glacial periods. Paleoecological and speleotherm¹ data suggest that the climate was undoubtedly drier, but that the lower temperatures reduced evapotranspiration rates and enabled the forest to persist²⁻⁴. However, substantial areas of forest may have been dry forests interweaved between moist rainforests. The variability of the climate may have enabled an occasional corridor of savanna to open in eastern Amazonia. Overall, Amazonian carbon stocks are likely to have been only slightly reduced from present-day values, but productivity would have been substantially reduced and the rate of carbon cycling slower².

In the latest interglacial period, the Holocene (11.7 thousand years ago to the present), rainforest productivity and carbon stocks initially increased with warmer, wetter, and higher CO₂ conditions. However, over the Early-Mid-Holocene (ca. 8500–3600 years before the present), reduced precipitation and increased fire frequency affected much of the south of the region, resulting in forest retreat and savanna and dry forest expansion². In the Late Holocene, the rain belt and forest gradually expanded southwards, resulting in a probable overall increase in Amazonian forest biomass to its peak values in the last thousand years².

Carbon cycle processes in the terrestrial Amazon

The net carbon balance of terrestrial Amazonian systems is the result of large fluxes in carbon uptake and release. With their year-long growing season, Amazonian tropical forests are among the most productive natural ecosystems on Earth. Typically, about one-third of the input of carbon to the forest through photosynthesis, termed Gross Primary Productivity (GPP), is used for biomass production of wood, fine roots, leaves, and reproductive tissues (Net Primary Productivity or NPP), and two-thirds is used by plant metabolism, resulting in the release of carbon dioxide (CO₂) by the vegetation (autotrophic respiration)⁶ (Figure 6.1) Aboveground woody biomass growth, the most commonly measured

aspect of carbon uptake by vegetation, accounts for only 8-13% of the photosynthetic carbon uptake⁵ but contributes most of the long-lived biomass carbon store. Canopy and fine root productivity account for similar amounts of carbon use, but because fine root tissues are short-lived they have a negligible effect on total biomass stocks⁶. Dead biomass is fragmented and metabolized by fungi, bacteria, and soil macro-fauna, releasing CO₂ to the atmosphere (heterotrophic respiration). Smaller fluxes include volatile organic compounds, methane, and outflow of dissolved organic carbon in streams. The net carbon balance of a mature upland Amazonian forest could be expected to average about zero, as uptake of carbon through photosynthesis is compensated by release of carbon through heterotrophic and autotrophic respiration. However, long-term inventories suggest a net rate of increase of vegetation biomass of 0.6 Mg C ha⁻¹ y⁻¹ (where Mg is 10³ grams) or about 2% of photosynthesis⁷, that may result from (i) episodic disturbance and recovery; (ii) some large long-lived trees continuing to accumulate biomass for many centuries; (iii) rising CO₂ concentration, or changes in temperature or rainfall leading to long-term trends in productivity and/or respiration. Evidence suggests this accumulation stops (and even reverses) in drought years⁸ and is declining in the long-term⁷. Longer dry seasons may lead to intact forests becoming net carbon sources in the near future, aggravating climate change.

Broadly, the magnitude of GPP is determined more by seasonality in rainfall than soil nutrient status, with the highest values found in the forests of the northwestern Amazon where rainfall is high throughout the year, and the lowest values in regions with a long dry season. The highest productivities reported for the Amazon are in the aseasonal and relatively fertile forests near Iquitos in Peru⁵. Sandy soils, such as those found in the upper Negro basin, support lower productivity. However, rates of NPP and woody biomass production do not follow the same regional pattern, as the fraction of photosynthesis allocated to

¹Geological formations in caves where mineral deposits accumulate over millennia.

biomass production appears higher in drier regions. A gradient in tree turnover occurs across the Amazon, with trees in the western and southern Amazon tending to grow faster and die younger, and trees in the eastern Amazon biome (especially the Guiana shield) being slow-growing and long-lived⁹. This change in dynamics affects the patterns of biomass, with the highest biomass Amazonian forests found in the north-eastern Amazon¹⁰. Hence, in mature forests, rates of tree growth are negatively correlated with forest biomass, and tree mortality and turnover influence biomass more strongly than productivity and growth rates. In montane systems in the Andes, the productivity of forests declines with elevation, halving by about 3,000 m elevation¹¹. Forest turnover is not correlated with elevation; forest biomass in the mountains declines in proportion to declining productivity. Both the magnitude and nature of soil carbon stocks are highly variable across the Amazon. Soil types range from highly weathered ferralsols dominating the eastern parts of the basin, through younger soils in the western basin and on lower montane slopes, occasional patches of sandy soils, and carbon-rich organic soils dominating in wetland regions such as northern Peru and in montane cloud forests¹².

Disturbances as modifiers of the Amazonian carbon cycle The Amazonian carbon cycle can be disrupted abruptly, with long-lasting effects, by forest disturbances associated with intensification of seasonal cycles^{13,14}, which can be exacerbated by deforestation¹⁵ (see Chapters 22-24).

Blowdowns Weather and wind systems can result in large patches of tree mortality by uprooting or breaking tree trunks^{16,17}. These events can cause significant losses of carbon from the aboveground biomass, accounting for $\sim 1.28 \text{ Gt C y}^{-1}$ of losses over the entire Amazon region¹⁶ (where Gt is 10^{15} grams). Despite the magnitude of impacts on C stocks, recovery of disturbed patches promotes net biomass accumulation that approximately balances the observed losses in the long-term.

Drought-induced stress Water limitation in upland forests can reduce the capacity of the forest to take

up atmospheric CO_2 and increases tree mortality^{18,19}. Drought can directly reduce the photosynthetic capacity of forests²⁰⁻²³ and can contribute to mortality. In seasonally flooded forests, in contrast to upland forests, droughts may relieve forest stress, increasing growth and NPP²⁴.

Fire occurrence Human-induced land-use and cover change is a key cause of fire, as they are directly related to ignition sources. One of the most uncertain components of Amazonian forest fire impacts is their potential implications for CO_2 levels in the atmosphere and consequent global warming. Amazonian forest fires are estimated to contribute mean annual emissions of $4.2 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ y}^{-1}$, and cumulative emissions of $\sim 126 \text{ Mg CO}_2 \text{ ha}^{-1}$ for 30 years after a fire. Cumulative CO_2 uptake offsets 35% of these emissions ($45 \text{ Mg CO}_2 \text{ ha}^{-1}$) within the same timeframe. Approximately 4.5% of the region has burned at least once in the last 12 years. During this period, ca. $60,000 \text{ km}^2$ of burned area occurred in areas already deforested and in areas mapped as primary forests in the year 2000²⁵. The majority of forest fires result from leakage of fires from deforested areas to adjacent forest. Apart from at the driest fringes, most of the Amazon region is not naturally fire susceptible and its ecosystems are not resilient to fires.

Carbon cycle processes in aquatic Amazonian ecosystems The uptake, release, and transport of carbon by aquatic ecosystems is a significant component of the regional carbon cycle. High rates of primary production by plants and algae in aquatic environments, considerable sedimentation in lakes and reservoirs, and large amounts of CO_2 and CH_4 emitted from rivers, lakes, and wetlands all lead to disproportionately large fluxes relative to the area of aquatic systems^{26,27}. Exchanges of carbon dioxide and methane between surface water and the atmosphere depends on the concentration gradient between the air and water and on physical processes at the interface. Methane can also exit via bubbles and pass through the tissues of aquatic plants, both herbaceous and woody. Water to atmosphere fluxes of CO_2 from all aquatic environments in the Amazon and Tocantins River systems, covering

approximately 970,500 km², are estimated to be 722 Tg C y⁻¹ (where Tg is 10¹² grams). Fluxes from hydroelectric reservoirs add 8.85 Tg C y⁻¹. Of the total, excluding hydroelectric reservoirs, fluxes from river channels represent about 19%, streams about 14%, floodable forests 36%, and other wetlands plus a small contribution from the open water of lakes and reservoirs about 30%. While terrestrial sources of dissolved organic carbon (DOC) and particulate organic carbon (POC) contribute to these fluxes, the majority of the carbon evaded to the atmosphere is likely derived from organic matter in aquatic plants photosynthesizing with atmospheric CO₂²⁸. Hence, most of these fluxes represent respiration within aquatic habitats, not carbon transported from uplands. The total NPP attributed to flooded forests (excluding wood increments), aquatic macrophytes, phytoplankton, and periphyton for the central Amazon region is about 300 Tg C y⁻¹²⁶. Flooded forests account for 62% of the total, aquatic macrophytes for 34%, and the remaining 4% is associated with periphyton and phytoplankton. Approximately 10% of the total value equals the export of organic carbon by the Amazon River²⁹, CH₄ emission is about 2.5%³⁰, and a similar percent is likely to be buried in sediments. The remaining portion is close to being sufficient to fuel the respiration that results in the degassing of 210 +/- 60 Tg C y⁻¹ as carbon dioxide from the rivers and floodplains for the central region³¹.

Nutrient cycling in the Amazon basin Tropical forests are responsible for about 25% of global terrestrial NPP, which, in turn, is modulated by the environmental availability of water, energy, and nutrients. Interactions among biogeochemical cycles can affect the Amazon carbon cycle, as limitation by nitrogen (N) and phosphorus (P) can be a constraint to plant productivity.

Nitrogen Inputs of nitrogen to Amazon ecosystems are derived largely from biological N fixation, a process mediated by microorganisms in symbiotic association with specific families of plants and as free-living microorganisms. Inputs derived from atmospheric deposition also contribute. Some calculations suggest N₂ fixation on the order of 15-

25 kg N ha⁻¹ y⁻¹ depending on soil type³². However, Nardoto *et al.* (2014)³³ suggested a maximum symbiotic fixation rate of 3 kg N ha⁻¹ y⁻¹. Reis *et al.* (2020)³⁴ suggest rates in South American moist forests on the order of 10 ± 1 kg N ha⁻¹ y⁻¹, where 60% is from free-living N-fixing organisms, and 40% from symbiotic association with legumes. Internal N cycling in the Amazon, which depends on precipitation, soil water availability, and soil nutrients, is also important³⁵. In regions under anthropogenic pressure, as in Paragominas (Pará, Brazil), the rate of nitrogen deposition can be significant, with N input of 4 kg⁻¹ha⁻¹y⁻¹ from precipitation. Polluted air from biomass burning leads to high atmospheric nitrogen oxide (NOx) concentrations.

Phosphorus On old, weathered soils, found in much of the Amazon, phosphorus is often a more limited macronutrient than nitrogen. Soluble forms of P occur in low concentrations^{36,37} and gaseous forms are almost non-existent. The effect of low P availability is further exacerbated because many tropical soils can occlude soil P and render it unavailable to plants. The main inputs of P into Amazonian ecosystems are from weathering, either from local soils or from Andean material transported in rivers and deposited on floodplains, and deposition in the form of dust or ash. Total atmospheric deposition of P is estimated to be 16–30 kg P km⁻² y⁻¹³⁸, of which Saharan dust inputs are estimated to be no more than 13%, and the bulk is from biogenic aerosols and biomass burning³⁹. Vitousek and Sanford (1986)³⁸ estimated that the recycling of phosphorus through litterfall is 140–410 kg P km⁻² y⁻¹, an order of magnitude greater than atmospheric inputs. Fluvial export of P, based on discharge at Óbidos, is 1.46 Tg P y⁻¹, or about half of the inputs to the basin⁴⁰. Strong gradients in P availability occur across the basin, with the lowest availability on the old, weathered oxisols of the eastern Amazon, and higher concentrations on younger soils in the western Amazon⁴¹. The high productivity of the Amazon forest despite low P availability is facilitated by tight recycling of P within the forest, where around half of leaf P is resorbed prior to leaf senescence, and most of the

rest captured by fungal hyphae soon after litter fall or plant death^{36,42}.

Other major greenhouse gases (GHG)

Methane (CH_4) Well-drained soils of the upland forest are often a net CH_4 sink, estimated to be 1-3 Tg CH_4 y^{-1} ^{43,44}. However, poor drainage and soil properties can create localized anoxic microsites that can facilitate methane production, causing forests to switch from sinks to small sources⁴⁵. Methane can be produced by a variety of fungi and archaea within tree stems⁴⁶, present in living trees with no visual decay⁴⁷. Methane sources have been detected within forest canopies⁴⁸. Tank bromeliads⁴⁹ and termites⁵⁰

are known to produce methane and also harbor methanogens (i.e., microorganisms that produce CH_4). A recent study indicated high emissions from termite mounds, suggesting the likely underestimation of the role of termites at an ecosystem scale⁵¹.

In aquatic environments, methane emissions are on average 0.7 Tg CH_4 y^{-1} from rivers, 0.4 Tg CH_4 y^{-1} from streams, 0.7 Tg CH_4 y^{-1} from lakes, and ~38.7 Tg CH_4 y^{-1} from flooded forests (see Chapter 6). Trees in inundated areas are a recently identified, large source of methane⁵². Other wetland emissions, such as those from interfluvial wetlands in the Rio Negro basin; savanna floodplains in Roraima, Moxos, and

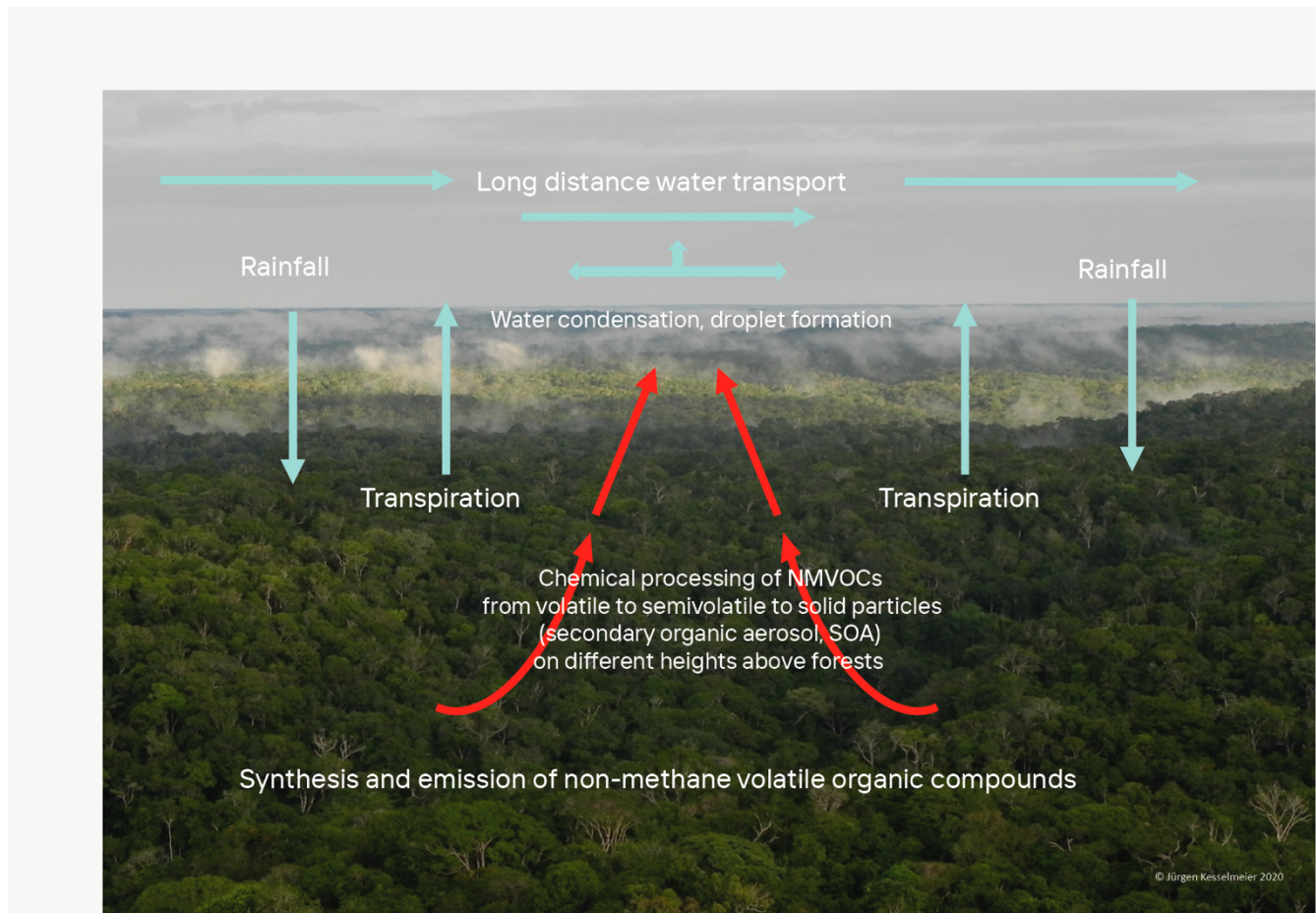


Figure 6.2 Non-Methane Volatile Organic Compound (NMVOC) emissions act as an organic water-catching and water-transporting system through the chemical and physical processing of biogenic trace gases to secondary organic aerosols which serve as condensation nuclei for water vapor.

Bananal; and others in the Tocantins basin account for 9.6 Tg CH₄ y⁻¹. Methane emissions from hydroelectric reservoirs within the Amazon basin are estimated to be approximately 0.58 Tg CH₄ y⁻¹.

The overall CH₄ budget includes multiple sources and sinks whose contributions are sensitive to feedback from drought conditions, and significant gaps remain in understanding how these droughts will affect methane budgets⁵³. Top-down estimates of emissions indicate that the Amazon is a globally-important source of methane.

Nitrous oxide (N₂O) N₂O emissions, predominately from denitrification, are related to biological and physical-chemical characteristics of the soil. Rapid nutrient cycling related to high temperatures, water availability, and high N:P ratios result in tropical forests emitting high rates of N₂O to the atmosphere. Tropical regions account for 71% of global natural ecosystem emissions⁵⁴, and tropical South America, particularly the Amazon region, accounts for 20% of global emissions⁵⁵. Most N₂O emissions from freshwater systems occur in wetlands. Figueiredo *et al.* (2019)⁵⁶ and Galford *et al.* (2010)⁵⁷ suggest that Amazon mature forests (including upland and periodically flooded forests) are responsible for ca. 6.5% of the global N₂O emissions from natural systems (Figure 6.2).

Aerosols and trace gases

Biogenic Non-Methane Volatile Organic Compounds (NMVOCs) The Amazonian ecosystem is regarded as the largest source of biogenic NMVOCs, but the emission of biogenic volatile organic compounds (BVOCs) makes a minor contribution to the carbon cycle of the Amazon basin⁵⁸. Anthropogenic activities as well as climate changes have large effects on NMVOC emission rates^{59,60} and affect particle production, with consequences for water condensation, droplet formation, cloud production, and the water cycle (Figure 6.2). Of particular significance is the heterogeneity of VOC emissions from vegetation and the dynamics of seasonal or developmental changes in the Amazon^{61,62}. Biogenic production and release of VOCs are closely related to

plant diversity and, consequently, the number of biogenic volatiles is numerous^{63,64}.

Physics and chemistry of aerosols and cloud condensation nuclei (CCN) Aerosols affect radiation directly by scattering and absorbing light and indirectly by cloud condensation. Under natural conditions, the Amazon forest is one of the few continental regions where aerosol concentrations resemble those of the pre-industrial era, in the range of 300- 500 particles per cm³ and 9-12 μg m⁻³ ^{65,66}.

Aerosols constitute an essential ingredient for cloud formation and development, since they can act as CCN, over which the water vapor condenses producing cloud droplets. Some particles, known as ice nuclei (IN), can initiate the formation of ice crystals inside clouds, providing a faster growth to precipitable droplet sizes compared to CCN, and thus influencing precipitation⁶⁷. Measurements and modelling indicate that biogenic secondary organic aerosols act as CCN in the Amazon forest, while ice nuclei consist of primary biological aerosols and mineral dust particles transported from Africa. These aerosols can act as large CCN, generating large droplets and inducing rain in warm clouds⁶⁸⁻⁷¹. While aerosols provide nuclei for cloud formation, convective clouds may stimulate the formation of secondary organic aerosols through in-cloud processing of biogenic emissions (Figure 6.3).

Observations demonstrate biosphere-atmosphere integration in the Amazon, where biogenic emissions, clouds, and precipitation interact; in this sense, the forest can be viewed as a biogeochemical reactor. The biosphere emits BVOCs and aerosols, which are processed by photochemistry, providing nuclei for the coalescence of water and the formation of warm and cold clouds, which result in precipitation, sustaining the hydrological cycle^{70,72}.

Ozone and photochemistry O₃ is a highly reactive trace gas, with large, globally varying atmospheric concentrations. With no significant direct source of tropospheric O₃, its concentration depends on precursors like NO_x, carbon monoxide (CO), VOCs^{61,73,74}, and on exchanges between the stratosphere and

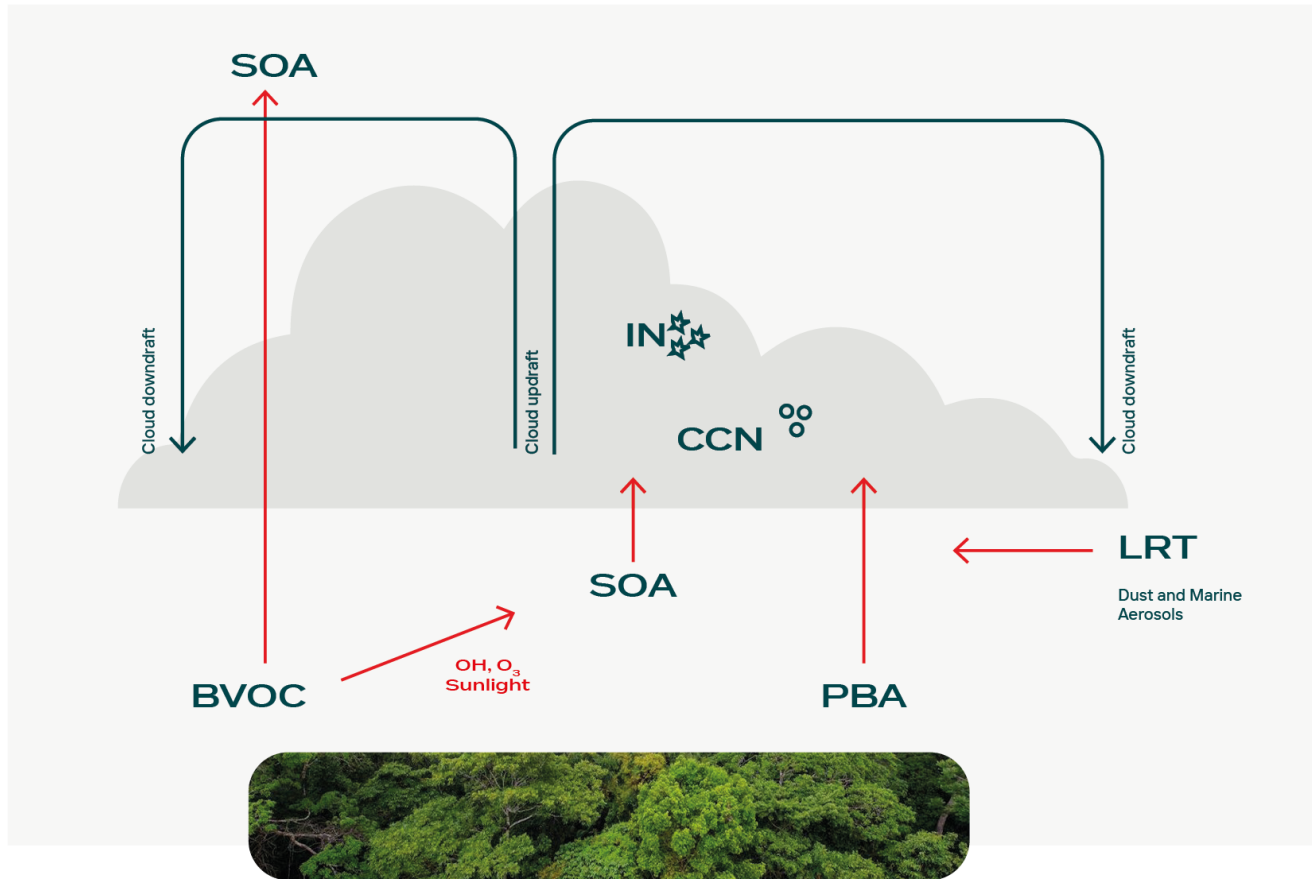


Figure 6.3 Interactions between BVOC emissions, long range transport (LRT) of aerosols (SOA), and clouds (CCN) in the Amazon. PBA = coarse mode primary biological aerosols.

troposphere^{75,76}. The remote Amazon rainforest has low O₃, though this is drastically changed by biomass burning and deforestation, which leads to enhanced NO_x and O₃ concentrations over most parts of the Amazon basin, especially during the dry season. Mixing ratios of O₃ above 40 parts per billion, which also occur in the remote Amazon due to biomass burning, are known to cause damages on leaves^{77,78}; hence, even remote areas far away from biomass burning can be affected by the air pollution, transported over several hundreds of kilometers across the Amazon basin.

Conclusions The Amazon is a key feature of the planet's biosphere; its biogeochemical cycles are major factors for the environment and climate and form the largest single-biome or single-basin

contribution to many key planetary biogeochemical processes. Geologic and climatic variability across the Amazon play an important role in shaping the features of the region's biogeochemistry and ecosystem function. The exchange of trace gases, such as GHG and reactive gases, and secondary and primary particles, contribute directly and/or indirectly to the greenhouse effect and affect atmospheric chemistry and physics. Emission (production) and deposition (uptake) processes affect the current concentration of GHGs such as CH₄, CO₂, O₃ and N₂O. Continued degradation of the Amazonian rainforest and the passing of potential tipping points would result in a weakening and possible collapse of the biogeochemical network, with severe consequences for Amazonian

ecosystems and for the communities that rely on them.

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