3. The ecological impacts of deforestation and problems of climate change

Forests act as a carbon sink because trees absorb CO_2 from the atmosphere through the process of photosynthesis. CO_2 is stored in the rain forest trees' trunks, leaves, and roots. The Amazonian ecosystems store an estimated 150 to 200 billion tons of carbon. From 2003 to 2019, gross carbon loss from Brazilian Amazonia totalled 3.04 billion tons of carbon. A high amount of these CO_2 emissions is attributed to deforestation (56 %), the rest of 44 % due to forest degradation and other human-based activities (Kruid *et al.* 2021; Nobre *et al.* 2016).

Recent scientific studies reveal that parts of the Amazon region now emit more CO_2 into the atmosphere than they absorb (Gatti *et al.* 2021; Harris *et al.* 2021). The Brazilian Amazonia has been transformed from a CO_2 sink to a source for new emissions over the past two decades, whereas the total Amazon biome is still a net carbon sink. It removed about 1.7 billion metric tons of CO_2 equivalent (eq.) more than it emitted. But the Brazilian portion of the Amazonian rain forests, which covers about 60 % of the total Amazonian biome, emitted 3.6 billion metric tons of CO_2 eq. more than it sequestered (Gatti *et al.* 2021; Kruid *et al.* 2021). This means, that Brazilian Amazônia Legal has been transformed by deforestation into a net emitter of carbon dioxide with dangerous implications for regional climate change and global warming.

Protected areas and Indigenous territories are the exception and have been especially effective carbon sinks. They have proved their importance for overall conservation in the Amazon region as a bulwark against climate change (Kruid *et al.* 2021; Hirota *et al.* 2022). Unfortunately, deforestation in Indigenous territories and in conservation units of sustainable use increased in recent years (Santos *et al.*2021).

Cattle ranching is Brazil's largest source of greenhouse gas (GHG) emissions. Cattle methane (CH_4) emissions account for 17 % of all greenhouse gases released in the country (InfoAmazonia, 09.11.2021).

One source of GHG emissions are the numerous reservoirs of hydroelectric power plants in the Amazon region, which are often neglected in the calculation. Hydroelectric plants are often presented as "green energy," which means an energy source without GHG emissions. However, reservoirs emit GHG in various forms by decay of forest biomass. The emissions vary according to the geographical location, and the characteristics of the reservoir, such as flow, water replacement time, area, and water level fluctuations. Methane emissions of hydroelectric reservoirs contribute to global warming. Methane is formed when organic matter decomposes without oxygen present, for example, at the bottom of a reservoir.[435] Furthermore, Amazonian wetlands release 6–8 % of global methane emissions (Nobre *et al*. 2021, Message 4).[436]

Brazil's commitment in Paris 2015 (COP 21[437]) referred to zero "illegal" deforestation by 2030 and to the goal of bringing global warming below the 2°C mark and down to 1.5°C if possible.

However, forest clearing can continue as long as it is "legal". The Rural Environmental Register (CAR) makes it easy to obtain permission for "legal" deforestation up to the limits of Brazil's current Forest Code (20 % in Amazonia). Since many properties still have little clearing, large amounts of "legal" deforestation can continue (Fearnside 2017c).

In 2018, Lovejoy and Nobre (2018; 2019) had already analysed two "tipping points" (deforestation with conversion of the rain forest into drier savannahs and global warming), which will be discussed later.[438] Finer[439] recently emphasised that another "tipping point" is the transformation of Brazilian Amazonia from carbon sink to carbon source of CO_2 emissions (Finer and Mamani 2021). This, of course, concerns Amazônia Legal as a whole, while there is a regional differentiation as mentioned above (Fig. 40) due to the strong spatial differences in deforestation.

For decades, scientists have pointed out the consequences of deforestation in the Amazon region.[440] In recent publications, the alarming situation of climate change has been repeatedly stated, to which deforestation contributes significantly. Trade winds from the Atlantic Ocean with high water temperatures are transporting enormous quantities of water vapour to Amazonia. The humidity falls back onto the forest as rain. The forest returns rainwater to the atmosphere in the form of water vapour. A single tree is capable of sending in the atmosphere up to 1000 liters a day. Antônio Nobre (INPE) has calculated the total amount of water released into the atmosphere every day by the rain forest at around 20 billion tonnes. Air currents at an altitude of approximately 3 km carry the humidity across Amazonia and toward the Andes, which act as a natural barrier with high precipitation rates on the eastern slopes, but redirect the huge vapour masses southwards toward the Midwest, south Brazil and Argentina.

These air currents are popularly known as "flying rivers", i.e. they are "atmospheric waterways" consisting of air masses filled with water vapour. Without "flying rivers,"

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435 Fearnside (1997b; 2002; 2005; 2013a; 2016, among others) has been studying this issue intensively for many years.

436 In 2021, according to ourworldindata.org the share of total Brazilian methane emissions (588.7 million tons; 57 % from agriculture) amounted to 5.7 % on global methane emissions (https://ourworldindata.org/carbon-deforestation-trade; accessed April 22, 2023).

437 COP is the acronym for "Conference of the Parties" to the United Nations Framework Convention on Climate Change (UNFCCC).

438 "A 'tipping point' is the point at which a small change to a stressor or ecosystem state causes the whole ecosystem to shift abruptly to an alternative state, accelerated by amplifying (or self-reinforcing) feedback mechanisms." This may cause systemic collapse (Hirota *et al*. 2022, n. p.).

439 The study was published by the Monitoring of the Andean Amazon Project (MAAP), an initiative of the US-based non-profit Amazon Conservation Association.

440 Among the early publications are: Sioli (1956; 1968; 1973; 1984; 1985); Goodland and Irwin (1975); Nobre *et al*. (1991); Fearnside (1982; 1990; 1997a), among others. In 2021, during COP 26 in Glasgow, renowned scientists launched a new initiative, the *Amazon Assessment Report 2021* (Nobre *et al*. 2021), which emphasised the importance of the Amazon region as a key element of the Earth's climate system and the risk of environmental collapse for the region (Hirota *et al*. 2022).

much of southern Brazil would be a dry zone or even a desert as in comparable latitudes worldwide. Deforestation and expansion of agriculture and cattle farming in the Amazon region will cause loss of ecoservices and negative impacts with reduced rainfall for agribusiness in the South. The hydrological cycle of the Amazon region depends on the transpiration of the forest's biomass and on the evaporation from the surfaces of the rain forest.

> When it rains on the Amazonian forest landscape, at least 75 % of the moisture is returned to the westward-moving air mass. The rainforest recycles the moisture five to six times before it turns southward, feeling the proximity of the high wall of the Andes. Over the whole basin, the air rises, cools, and precipitates out close to 20 % of the world's river water in the Amazon river system (Lovejoy and Nobre 2019, n. p.).[441]

Since more than 50 % of rainwater runs off after deforestation and is no longer available for recycling, this leads to the basic question of how much deforestation rain forests can tolerate, until too little moisture not only threatens their existence but turns large parts of the rain forests into tropical savannahs?

The first model to analyse the "tipping point" for deforestation-generated degradation of the hydrological cycle (Sampaio *et al.* 2007) showed "that at about 40 % deforestation, central, southern and eastern Amazonia would experience diminished rainfall and a lengthier dry season, predicting a shift to savannah vegetation to the east" (Lovejoy and Nobre 2018; 2019, n. p.).

Lovejoy and Nobre "believe that negative synergies between deforestation, climate change and widespread use of fire indicate a tipping point for the Amazon system to flip to non-forest ecosystems in eastern, southern and central Amazonia at 20–25 % deforestation. […] Today, we stand exactly in a moment of destiny: The tipping point is here, it is now" (Lovejoy and Nobre 2018, n.p.).

Since 19.9 % of the original rain forest area in Amazonia has already been cleared by 2021 (Table 18; Fig. 38), this means that – if the research calculations of 20–25 % are taken as a basis – a tipping point ("point of no return") from rain forest to degraded savannah is imminent or at least looms in the next few years. This would have serious negative consequences for climate and biodiversity throughout the region, which would be self-reinforcing and also have global climatic impacts.

Another tipping point is global warming.[442] Climate change has an impact on the hydrological cycle. In the absence of other contributing factors, 4°C of temperature increase in the Amazon region would be the tipping point to degraded savannahs in most of central, southern, and eastern Amazonia (Nobre *et al.* 2016).[443] Exceptional

441 Up to 50 % of the precipitation within the Amazon basin is regionally recycled. The discharge of the Amazon river supplies 16 to 22 % of the world's total river input into the oceans (Nobre *et al.* 2021, Message 3). https://www.environment.co.za/world-environmental-issues-news/a-flying-river-how-the-amazon-forest-produces-the-largest-flying-river-in-the-world.html (accessed May 23, 2024).

442 The Intergovernmental Panel on Climate Change (IPCC) 2022 report "leaves no doubt about the urgency to dramatically cut emissions; to stay on track to limit earth's warming to 1.5°C. GHG emissions need to be cut by 45 % by 2030, compared to 2019 levels" (IPCC 2022).

443 In the last 60 years, warming in the Amazon region was about 1°C. Temperature increase was more pronounced in the last three decades and in deforested areas, such as pastures, during the dry season with up to 1.5°C.

heat waves in Amazonia are becoming more frequent. The number of days with temperatures above 35°C will increase, climate models show between 60 and 150 days more per year by the end of the century. Heat stress increases bacterial infestation and degrades water quality, threatening Amazonian fish, whose existence requires rain forest protection.[444]

Forests maintain an evapotranspiration[445] rate year-round, whereas evapotranspiration in pastures is dramatically lower in the dry season. The contribution of dry season evapotranspiration to rainfall in south-eastern South America is important. When evapotranspiration exceeds precipitation, the result is a water deficit in the forests. (Lovejoy and Nobre 2018). Large-scale forest fires lead to drying of surrounding forest and cause a greater vulnerability to fire in the following year.

The hope for a continuation of the strong decline in deforestation between 2005 and 2019 (-84 %) has unfortunately not been fulfilled and has even turned into a very strong increase in forest destruction under the Bolsonaro government. All security and protection criteria such as better satellite monitoring, stricter laws and controls, moratoria on value chains (soybeans, meat), credit freezes in deforestation regions and the expansion of protected areas and Indigenous territories have been disregarded or deliberately not implemented.

When considering the climatic consequences of deforestation in Amazonia, climate variability, the intensity of extreme events such as droughts and floods and the length of the dry season are crucial factors. The average annual precipitation in Brazilian Amazonia is between more than 3000 mm in the west/northwest (absence of a dry season) and about 1700 mm in the south-eastern region, known as "arc of deforestation". In the south-east and south of Amazonia there is a distinct dry season with more than 4 months (monthly <100 mm) (Nobre *et al.* 2016). Large-scale deforestation could lead to a reduction in regional precipitation.

The variability of precipitation is influenced by fluctuations in sea surface temperatures of the tropical Pacific Ocean (El Niño Southern Oscillation, ENSO) and tropical Atlantic Ocean, which are higher than ever before. Severe droughts in the context of El Niño events have been known in Amazonia for a very long time and occurred in modern times e.g., in 1926, 1983, 1992, 1998, 2005, 2010 and 2015 especially in the central and eastern part (Meggers 1994).[446] Human-induced climate change is expected to make them even more common in the future.

A nine months' rainfall deficit during an El Niño event was reported in 1997/1998 (July/August 1997 to April/May 1998), ranging from 500 mm in Belém, 900 mm in Marabá to 1200 mm in Belterra on the Rio Tapajós in Central Amazonia (Nepstad *et al.* 1999; Kohlhepp 2001b, 172, and Fig. 4 and 6), compared with the cumulative amount of rainfall in "average" years. In Roraima, this drought was associated with huge forest and *campo cerrado* fires (Fig. 25). Temperature fluctuations in the Atlantic Ocean (warmer tropical North, cooler tropical South Atlantic) affect west and northwest

444 Webinário da Academia Brasileira de Ciências, Ed.42: Brasil e as mudanças climáticas: Novo relatório do IPCC; August 10, 2021 (www.abc.org.br/transmissão (PT).

445 Evapotranspiration is the sum of transpiration and evaporation, i.e., the evaporation of water from plant and animal life and from soil and water surfaces.

446 Cf. chapter II.3.2.

Amazonia and caused severe droughts. In 2010, about 3 million km² were affected (Nobre *et al.* 2016).

Extreme droughts (2005, 2010, 2015) and floods (2009, 2012, 2014) in the last two decades indicate that extreme events are becoming more frequent and are clear signs of climate change and "could well represent the first flickers of this ecological tipping point" (Lovejoy and Nobre 2018, n. p.).

This has now come true. Since May 2023, with the development of a strong El Niño, an unusually strong warming has been observed in the tropical Pacific as well as in the North Atlantic (2–4°C above average). The months of August, September and October are traditionally dry, with lows occurring in mid-October, but this year the situation has become much more severe. Apparently, cold fronts were prevented from arriving by a dry air bubble.[447]

At the beginning of October 2023, the level of the Solimões river dropped by 30 cm per day; the level of the Rio Negro, which is about 21 m in Manaus at this time, dropped to less than 15 m. This has severely affected shipping, especially regarding supplies to small towns and settlements in the tributary area. Supply to the Manaus Free Trade Zone was also affected. The drought impacted 500 000 people in the state of Amazonas. Many people had difficulties accessing food, drinking water and other important products. Nearly all municipalities depend on water transport. Most rural communities are highly dependent on navigation for their daily lives, to access urban centres and to transport agricultural production to the markets. Health and education services depend on navigation.[448]

Scheduled services on the Rio Solimoes/Amazonas were also affected. At least 90 % of the vessels operating on the state's 116 shipping lines were restricted in their activities. 50 % of the cargo capacity was affected and only 45 % of the total passenger numbers could be served.

This extreme drought was associated with a tremendous fish kill this year. Whether this is solely related to the high water temperature has not yet been clarified. Hundreds of dolphins also died. In Lake Tefé, 550 km above Manaus on the Solimões river in the western state of Amazonas, a water temperature of 39°C was measured, which exceeded the long-term average by approx. 8°C according to the Mamirauá Institute for Sustainable Development.[449]

Manaus has been suffering from another problem associated with the drought: smoke from forest fires. In September 2023, the state of Amazonas had the second highest number of fire outbreaks for the month.

The heavy rainfall in southern Brazil and the increasing drought in the Northeast are further consequences of El Niño.

Lengthening of the dry season (about one week per decade so far) is associated with a later onset of the rainy season in southern Amazonia. This of course also lengthens the duration of the fire season with the corresponding forest losses and is increasing the risk of wildfires. This is particularly the case in southern and south-eastern Ama-

447 https://apublica.org/2023/10/aquecimento-anormal-do-atlantico-agrava-seca-na-amazonia-e-traz--riscos-imprevisiveis/ (accessed October 4, 2023).

448 https://g1.globo.com/meio-ambiente/noticia/2023/10/03/seca-extrema-pode-ter-agravado-desmoronamento-que-engoliu-vila-no-interior-do-amazonas-entenda.ghtml (accessed October 4, 2023).

449 See footnote 447.

zonia, where the intensity of human activities and their impacts is particularly high in the "arc of deforestation" in the border region of rain forest, the transition forest *cerradão* and the *campos cerrados*. Here, "savannisation," i.e., the transition from rain forest to savannah, is particularly to be expected in 30 to 50 % of the Amazon basin, as tropical forests cannot tolerate a dry season longer than 4 months and rainfall below 1800 mm/year (Nobre *et al*. 2016; Hirota *et al*. 2022).[450]

Regional climate change due to large-scale deforestation and the effects of forest fires make tropical rain forests more vulnerable. A substantial reduction of over 60 % in the Amazonian forest area by 2050 must be expected according to all new model calculations (Nobre *et al*. 2021, chapter 23).

The ever-increasing penetration of the Amazon rain forests by human-induced economic activities is leading to a relatively little-discussed topic, which was surprising in times of the Covid-19 pandemic. Increased human interaction with animals (bats, monkeys, mosquitoes) in newly incorporated forest areas increases the chances of a "virulent virus" or bacteria that jumps from one species to another.[451] According to the Instituto Evandro Chagas (Belém), of the 220 different types of viruses in the Amazon region, 15 have the potential to cause epidemics.

Reducing deforestation mitigates emissions of greenhouse gases. At the 2015 COP 21 in Paris, Brazil committed to 12 million ha of reforestation by 2030. This commitment, which would mean a protective wall against the Amazon tipping point (Lovejoy and Nobre 2018), has not yet been fulfilled.

450 According to Hirota *et al*. (2021, n. p.), there are four potential tipping points that Amazonian forests could shift to: "1) a closed-canopy seasonally dry tropical forest state; 2) a native savannah state; 3) an open-canopy degraded state; 4) a closed-canopy secondary forest state." Hirota *et al.* (2021) consider the occurrence of numbers 3 and 4 more likely over large areas, particularly in the "arc of deforestation."

451 Kohlhepp (2020a): Scientific research results of Adalberto Luís Val, INPA. Cf. Ferrante *et al*. (2021).