©Rodrigo Baleia / Greenpeace

Alana
APIB (Articulação dos Povos Indígenas do Brasil)
Article 19
Conectas Direitos Humanos
Engajamundo
Greenpeace Brazil
Instituto Socioambiental
Instituto de Energia e Ambiente
Environmental Science Graduate Program of the University of São Paulo
National Institute of Science and Technology (INCT) for Climate Change Phase 2

_Climate Change: impacts and scenarios for the Amazon

José A. Marengo
General Coordinator of Research and Development at CEMADEN

Carlos Souza Jr.
Senior Researcher at Imazon

SÃO PAULO, DECEMBER 2018

José A. Marengo
General Coordinator of Research and Development at CEMADEN

Carlos Souza Jr.
Senior Researcher at Imazon

_ Climate Change: impacts and scenarios for the Amazon

Final report organized by Alana, APIB, Articulação dos Povos Indígenas do Brasil, Article 19, Conectas Direitos Humanos, Engajamundo, Greenpeace, Social and Environmental Institute of Energy and Environment, Environmental Science Graduation Degree Program University of São Paulo.

Translation: Melissa Harkin and Todd Harkin

São Paulo
2018

1 _Introduction

With the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988, climate science progressed geometrically and confirmed the hypothesis that climate change is indeed occurring with a strong influence of anthropogenic actions, as described in the box below:

In the Fifth IPCC report AR51.2, published in 2013[1], the main conclusion was that global warming has been unequivocal since the mid-1950s and is unprecedented in recent millennia. The atmosphere, ocean, and continents have warmed, the sea level has risen, and concentration of greenhouse gases (GHG) has increased. The human influence on warming is evident, and it is "highly likely" that human actions, such as burning fossil fuels and deforestation, are the primary cause of global warming since the mid-twentieth century. In the Second IPCC Report published in 1996, with less complex models and a less comprehensive database, human influence on the global climate was only "discernible." The Fifth Report (IPCC AR5) shows the IPCC'S and the scientific community's evolution of understanding of climate change and its causes.

Climate change is already happening and is already producing impacts, and the greater the warming, the greater the future impacts and risks that humanity will face, including the possibility of irreversible damage to ecosystems, biodiversity, agricultural production, and the economy and society in general. In the medium term, effectively integrating adaptation to climate change can help build a more resilient society. According to several sources of temperature data, the warming observed in the Amazon, from 1949 to 2018, ranges from 0.6 to 0.7° C. Although there are some systematic differences, all sources point to greater warming in the last couple of decades with 2017 being the hottest year since the mid-20th Century.

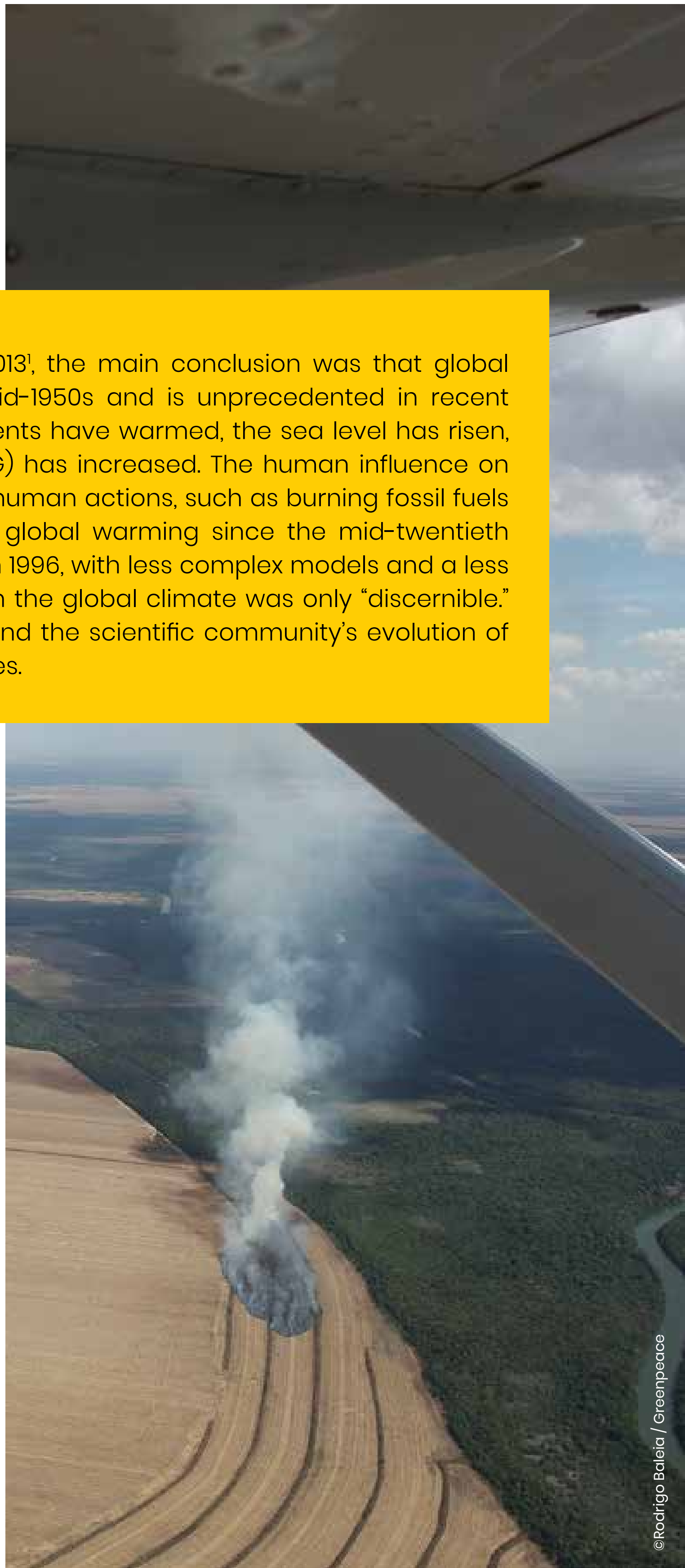
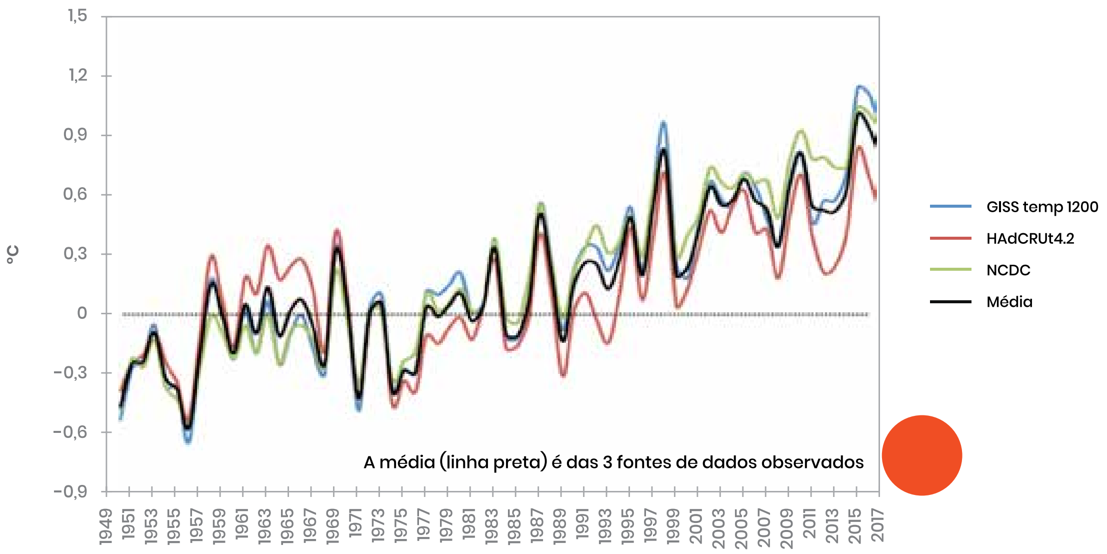


FIGURE 1

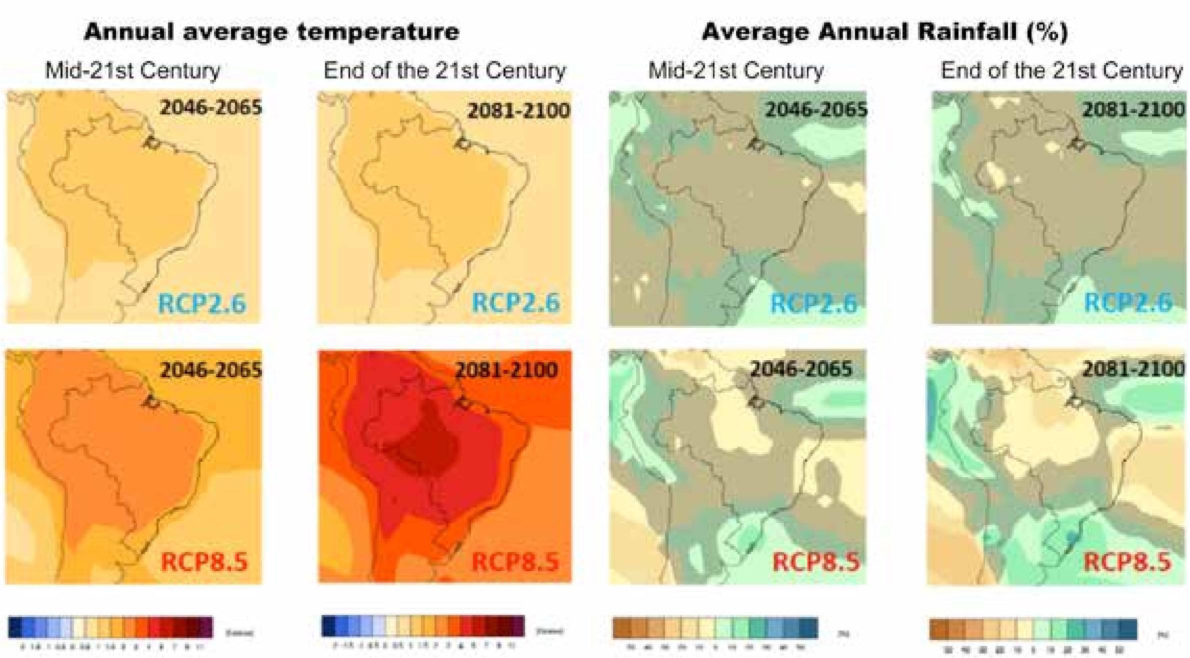
Observed temperature change from 1961-1990 obtained from three different data sets from 1949 to 2017 for the Amazon region.

Temperature anomaly observed from 1961-1990 obtained from three Amazon data sources



Data sources:
GISS-NADA Goddard Institute for Space Studies, USA, NCDC-National Climatic Data Center, USA, HAdCRU-Hadley Centre-Climate Research United, UK.

Climate change scenarios for the Amazon, projected by complex climate models presented by the IPCC[1,2] point to an increase in the average air temperature to be well above 4°C. Projected by the end of the 21st century and up to a 40% reduction in rainfall in the Amazon (Figure 2). This change in air temperature has the potential to generate large imbalances in ecosystems which are vital for the survival of humanity. According to the Plano Nacional de Adaptação à Mudança do Clima3 (National Plan for Adaptation to Climate Change), South America is the continent with the highest risk of species extinction (23%). The attribution of causes suggests that human influence may be more critical in comparison to natural causes, according to previous IPCC reports[1,2] and the recent global warming synthesis above 1.5°C[4].

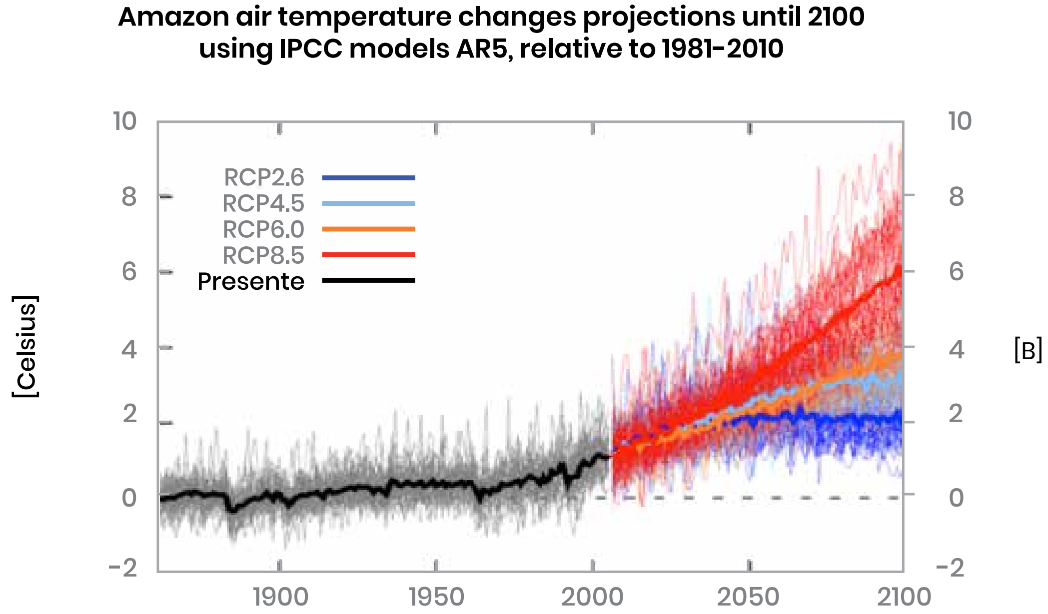


[A]

FIGURE 2

A) Tropical South American temperature and rainfall projections produced by the IPCC AR5 model-set relative to 1981-2010, 2046-2065 and 2081-2100 with low emission scenarios (RCP2.6) and high emission scenarios (RCP8.5) for the 1981-2010 period.

B) Temperature change projections until 2100 for the various IPCC A5 emission scenarios for the Amazon relative to 1981-2010.



The GHG emission scenarios used by the IPCC AR5[1] are called RCPs (Representative Concentration Pathways). RCP2.6 represents a scenario where greenhouse gas emissions would be stable after 2050, and RCP8.5 scenario considers an increase in emissions at the end of the 21st century. In Figure 2, Amazon warming would reach 6°C at the end of the 21st century in RCP8.5 and rainfall would decrease by up to 15-20% in the central and eastern Amazon. It is important to note that the RCP scenarios do not include deforestation or urbanization rates in their configuration.

Amazon climate change: Global warming and deforestation can affect the ecosystems' balance and the services they offer. New evidence shows, beyond a shadow of a doubt, that the Amazon works as the heart of South America concerning one of the resources from which life is directly dependent, water. The destruction of the Amazon forest may have already passed the limit that would allow its recovery. This means that, due to lack of water, the economy of several countries in the region would be drastically affected in a short period.

Global warming can have many consequences. Many terrestrial, aquatic, and marine species have already changed their geographical distribution, seasonal activities, migration patterns, volumes, and intraspecific interactions in response to ongoing climate change (high confidence)[2]. According to IPCC AR5, extreme weather events and impacts, such as droughts and forest fires, reveal some of the ecosystems' significant vulnerability and exposure – and of many human systems – to the current climate variability. Impacts of such climate-related extremes include the alteration of the ecosystems, as it is in the case of the Amazon.[2]

Deforestation is one of the vectors of regional and global climate change. Among the human activities that most contribute to GHG emissions are the burning of fossil fuel, biomass, and changes in land use[6], especially deforestation[7]. In the latter, urbanization and deforestation of natural forest vegetation areas in the Amazon, *Cerrado*, Atlantic Forest, and *Caatinga* can change the physical processes between the atmosphere and terrestrial and oceanic ecosystems, leading to changes in rainfall patterns (i.e., precipitation), temperature, and air humidity on local, regional, and global scales[8].

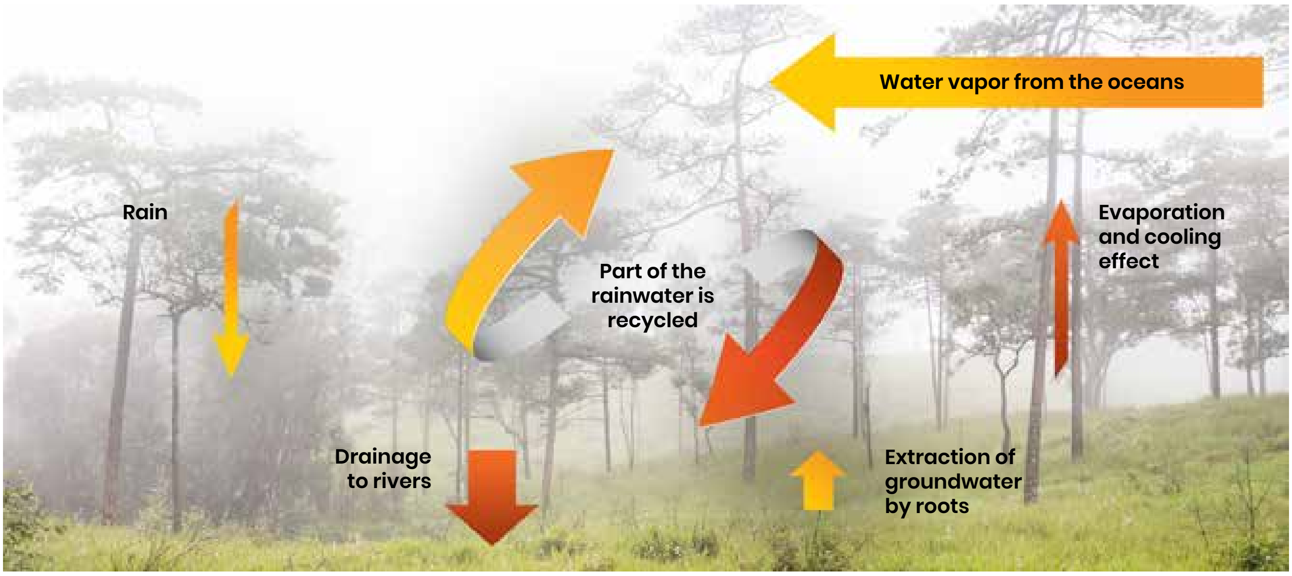
Reducing tropical forest deforestation is an urgent issue on environmental agendas, especially in regards to its essential role in regulating global climate and its impact on cultural and biological diversity. In the Brazilian Amazon, a series of policies and measures to reduce deforestation in the region were established by the Brazilian government in 2004, known as the *Plano de Proteção e Controle do Desmatamento na Amazônia*, PPCDAm (Amazon Deforestation Protection and Control Plan). A greater understanding of the factors behind the initial success and current failures in policies to contain deforestation in the Brazilian Amazon can support the formulation of conservation policies as well as guide the efforts of other countries to reduce their rates of deforestation.

Deforestation is a devastating activity that can spread over time to new areas, i.e., when a measure to discourage environmental crime is operational in a region, the perpetrators begin to practice it in new areas. There is, however, a recurrence of environmental crimes in certain places, as in the case of Flona Jamanxim. This happens to be a process characteristic of the expansion of the land border. However, the opposite also happens; instead of moving, the deterring effect is operational in neighboring regions. This is known as 'diffusion of benefits.' Finding evidence on the extent to which surveillance shifts deforestation and/or its deterring effect is widespread in the area and with time remains an issue with significant implications for policies to reduce deforestation.

2 _The importance of the Amazon on the regional and global climate

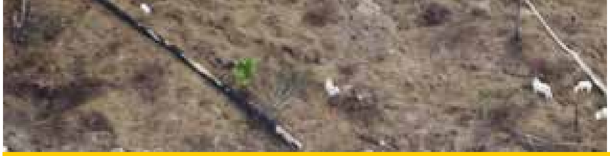
The Amazon rainforest also plays a crucial role in the South American climate because of its effect on the regional hydrological cycle. The forest interacts with the atmosphere to regulate the humidity inside the basin. Humidity is transported to the Amazon region by trade winds from the tropical Atlantic. After the rain, the rainforest produces intense evaporation and recycling of moisture, and then, much of that evaporation returns to the Amazon region in the form of rainfall (Figure 3).

FIGURE 3
Amazon regional hydrological cycle



Source: J. Marengo-CEMADEN

Scientific studies conducted in Brazil (INPE, INPA, USP), with international collaboration since the 1980s, show that the Amazon rainforest plays a crucial role in the climate system, helping to direct the atmospheric circulation in the tropics by absorbing energy and recycling approximately half of the regional rainfall[10]. Several studies have characterized changes in the availability of water resources in the Amazon, as well as their dynamics in time and their distribution in the region[11-13], analyzing the natural climatic variations already observed, as well as climate models' projections for the coming decades up until 2100[14]. These studies suggest that rainfall variability in the Amazon depends on local factors (forest) and remote factors (Pacific and tropical Atlantic Ocean surface water temperatures), on interannual and decadal time scales, which determines periods of droughts and floods in the Amazon. Even if no gradual rainfall reduction has been detected in the Amazon, it is clear that there is a solid scientific basis on the relationship between forest and climate and its impacts



Analyses based on observational studies and climate models suggest that there is already undisputed evidence on the Amazon rainforest's role as the provider and regulator of water. In addition, this situation adds to what is known about the role of the Amazon as a colossal reserve of carbon stocks in soils, subsoils and biomass, whose release by deforestation and degradation can significantly increase global temperature. The combination of the two processes, both caused by the disorderly and abusive occupation of the Amazon Basin, multiplies the gravity of the situation and makes it more imminent.

©Rodrigo Baleia / Greenpeace

on regional water, food, energy, and socio-environmental security.

The forest plays a vital role in local and regional rainfall, contributing to the hydrological cycle and transport of moisture inside and outside the region, affecting the hydrological cycle and the levels of the Amazonian rivers. Climatic modeling studies simulating partial and total Amazon deforestation show significant reductions in rainfall in an Amazon with no forest, affecting regional hydrology and resulting in negative consequences for vulnerable populations in the Amazon region.

Estimates show that between 30% and 50% of rainfall in the Amazon Basin consists of water recycled by the forest by evapotranspiration. Also, the moisture originating in the Amazon Basin is transported by winds to other parts of the continent and is considered important in the creation of precipitation in regions far from the Amazon.

Recycling of moisture: On the local and regional scales, the Amazon forest controls precipitation and temperature through evapotranspiration (sum of plant transpiration and evaporation of water deposited in the plant), in a process known as "moisture recycling." A measure of the recycling would be defined by the relation between precipitation/evapotranspiration. A series of studies attempted to quantify the water balance in the Amazon Basin. Professor Enéas Salati developed the concept of Amazon rainfall recycling in the 1980s, and numerous studies have been developed using this concept in the latter decades considering observations, model results, and satellite measurements. The estimation of percentage rates of recovery varies starting at about 35% and up to more than 80%[5,69]. Regional evapotranspiration in the dry season tends to be equal to or greater than in the wet season[70]. Thus, the high-water vapor flow generated by forest evapotranspiration during the dry season would play an essential role at the beginning of the rainy season[36].

The reduction of forest affects the transport of atmospheric humidity to other regions by means of the “aerial rivers,” an essential atmospheric circulation mechanism that transports the humidity which will later create rains in regions like the Prata basin[18-20] with some analyses on its relation to subtropical rainfall. The concept of aerial rivers is proposed as a framework: it is an analogy between the central pathways of moisture flow in the atmosphere and surface rivers. This proves a rain-forest connection of the Amazon with the well-being of the population. Due to the current deforestation that already affects almost 20% of the Brazilian Amazon and other forest degradation activities that may be affecting a much larger area, the Amazon has already lost from 40% to 50% of its capacity to pump and recycle water[20]. It is as if half the cells a person’s heart were dead or diseased and therefore, could no longer pump the blood through the entire body. Those parts of the body that receive no blood, less blood, or that receive blood more slowly die. This is what awaits the humid Argentine Pampas and the currently most productive lands of southeast and midwest of Brazil and the Paraná-La Prata Basin.[20]

Aerial Rivers: The flow of moisture carried by the trade winds from the tropical Atlantic Ocean couples with the recycled moisture pumped by the Amazon rainforest through atmospheric moisture currents that function as arteries. It circulates through the Amazon itself, channeled through the Andes and carrying this flow of humidity to the southeast of South America, where it discharges its life supporting precipitation.

3 The Amazon is already suffering from climate change: more "extreme" extremes in the present Amazonian climate and its impacts

Until a few decades ago, in the Amazon, there were only two seasons, the rainy season and the less rainy season. Today, the Amazon passes from catastrophic floods to droughts so radical that even water is lacking. Other new devastating actions aggravate and complicate the problem, such as the forest fires, that are now routine, and the increase in temperature due to climate change resulting from the carbon released into the atmosphere[35,51].

Human economic activities such as urbanization, cattle ranching, and agricultural expansion affect forest coverage in the Amazon[15,16], derived from deforestation and forest biomass degradation processes by means of forest fires, logging, and non-timber forest resources[17] (when not practiced sustainably). The extent and intensity of anthropogenic changes in the Amazon forest generate impacts on the climate on the local, regional, and global scales[8].

Although it is essential to know the future characteristics of total rainfall in the region, it is also imperative to detect and predict the beginning and end of the rainy season, as well as the variability of wet and dry seasons, not only through modeling experiments but also through observational analysis. Science already has a good understanding of how changes in land use impact the energy balance at the forest-non-forest-atmosphere and the interactions of these activities with the climate and the potential impacts on the different Amazonian ecosystems. This understanding comes from the results of empirical models and observations in the field and satellite data.

More frequent mega-drought occurrences: Evidence that the Amazon is already vulnerable to the impacts of climate is not only due to the effects of increasing concentrations of greenhouse gases in the atmosphere, but also to changes in land use and the conversion of forests to deforestation. As an example of external causes of natural origin, we have the climatic variability caused by anomalies in the surface temperature of the tropical oceans of the Tropical Pacific (El Niño/La Niña) and the Tropical Atlantic, which has severe consequences of droughts and floods in the Amazon Basin[59,60,56,61,62]. Just as some historical droughts were associated with El Niño (e.g., 1912, 1925, 1983, 1987, 1998), the most recent droughts of 2005, 2010 and 2016 were associated with a North Atlantic Tropical Ocean, and only the drought of 2016 occurred in a year under El Niño's influence. This is an example of additionality to the local and regional climate's external factors. Anthropogenic activities, such as Amazonian deforestation, can escalate the impact of natural causes by lengthening the dry season and increasing the risk of fire[53].

The rainy season during the recent drought of 2015-2016 had a later onset than normal[51] and caused the most significant number of fires in the 21st century, with five months with more than 10,000 fires and the highest number of fire incidences per square kilometer of deforested land[53]. According to IMAZON, just in the state of Pará, an area of 7,350 km^2 of forest was burned, leading to an increase in carbon emissions to the atmosphere, in addition to deforestation. This combination of a longer dry season, a higher frequency of extreme droughts, and an increased fire risk of due to accumulation of dry material in the soil from previous deforestation can play a critical role in the future scenario of the Amazon rainforest's degradation, further compromising the resilience of this tropical rainforest in a high atmospheric CO_2 environment[63].

Since 2002, there has been no significant increase in the number of fires in the Amazon (Figure 5), but in the dry years (2005, 2010 and 2016) the number of fires was higher[47]. In those years, the increase in fires was due to the large-scale drought that was associated with the natural variability of the climate (El Niño, warmer tropical North Atlantic) and which worsened as a result of deforestation, allowing the accumulation of combustible biomass material that burned in the next drought.

Prolonged dry season: In the 2015-16 Amazon drought, during the transition from dry season to the wet season (between August 2015 and October 2016), observations showed the most pronounced proportional decline in precipitation, which infers that the dry season is being prolonged, thereby shortening the rainy season (Figure 4)[51]. A prolongation of the dry season and changes in the frequency and intensity of extreme drought episodes are probably the most critical factors for the Amazon considering non-mitigation of climate change scenarios. In 2016, a longer dry season determined conditions that made forests more vulnerable to burning[52], with an increase in the number of fires in the Amazon. This led to a more significant carbon and aerosol release in the smoke resulting from the burning of accumulated material due to the previous deforestation and also affecting human systems[47,53].

FIGURE 4

Hovmöller diagram showing monthly rainfall from 1951 to 2014 in the south of the Amazon (mm/month). The 100 mm/month isoline is an indicator of dry months[37]. Drought years are indicated in the figure. Red lines show the beginning and end of the dry season and yellow lines shows the deviation in the dry season (adapted from Marengo and collaborators[35] and updated until 2014).

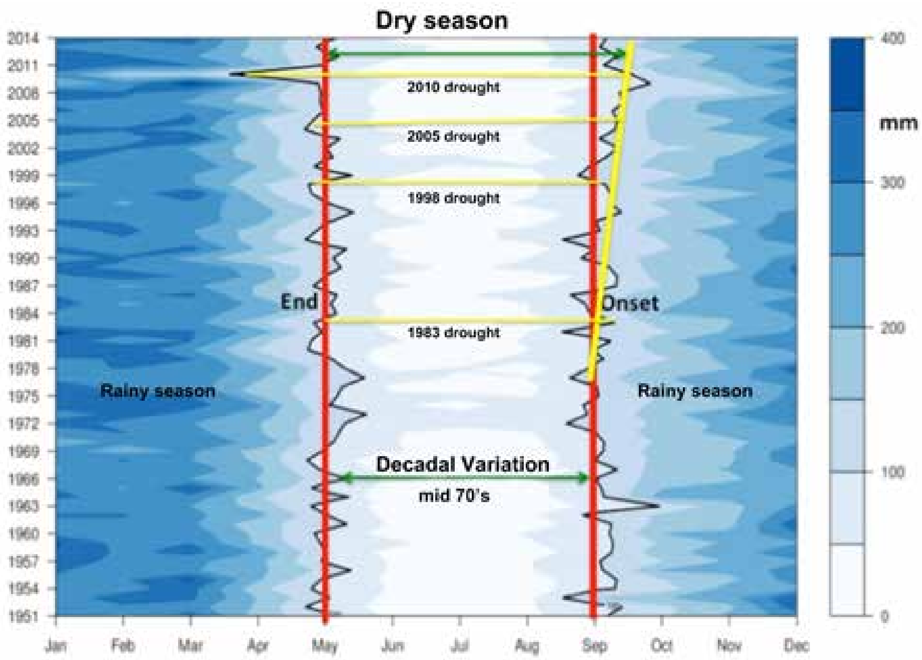
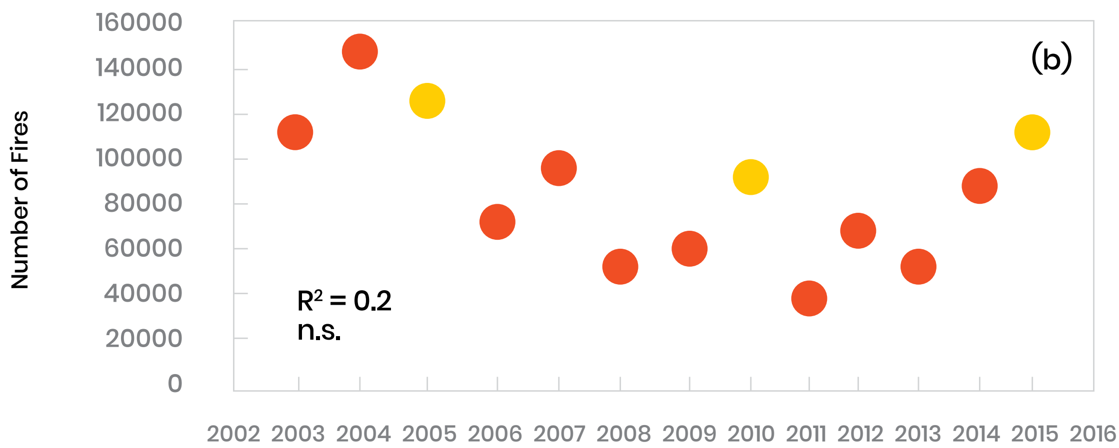


FIGURE 5

Distribution of the number of fires in the Amazon - red dots show the dry years in the Amazon[47].



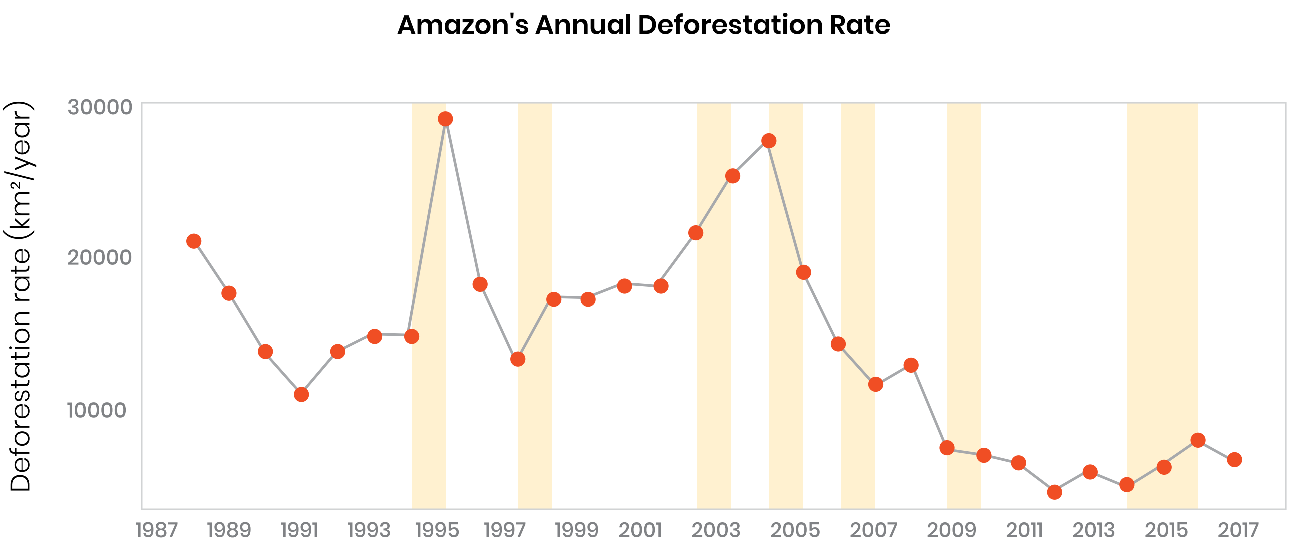
If the conditions facilitate the start and spread of fires in regions where deforestation is projected, then the fire will have the potential to play an important role in further deforestation and degradation. In drought conditions, the fires associated with deforestation reach larger areas. Burning, drought, and tree felling increase susceptibility to future fires, not to mention the deforestation, smoke, and the release of aerosols by fires all can inhibit rainfall[57], exacerbating the already high risk of fire, as well as harming human health and disrupting river transport (which happened in the Amazon during the droughts of 1925, 1983, 1998, 2005 and 2010)[47].

Regarding the attributing causes of droughts to deforestation, estimates show that although droughts and fires may have natural causes, such as in 2005, 2010, and 2016, human activities, however, such as deforestation potentiate and overlap natural causes, increasing the number of fires, as in 2003 and 2004. In 2004, the expansion of livestock[47] lead to a peak of deforestation. This highlights the urgency of understanding the underlying causes of the late onset, or disappearance, of the rainy season and the lengthening of the dry season, as well as of expanding our capacity to predict them. The evidence of the possible human role (deforestation, an increase of greenhouse gases and released aerosols due to biomass burning or urban pollution) on the region's precipitation and the variability of river flows and levels began to appear in the literature recently[5,9,54-56].

Studies indicate that the burning of dead biomass resulting from deforestation creates an increase in aerosol concentration and can substantially alter the Amazon's spatial patterns and temporal precipitation. The initial work of researchers from the University of São Paulo, INPE, and the Max Planck Institute in Germany[57,58] suggests that the aerosols contained in the biomass burning smoke in the Amazon can delay the rainy season's onset in southern Amazonia, but little is known about the aerosols' impact on precipitation and the hydrologic cycle throughout the Amazon region.

FIGURE 6

The Amazon's Annual deforestation rate from 1988 to 2017 based on data from Prodes (INPE)[45]. The El Niño years are indicated by the pink bars.



Source: http://ggweather.com/enso/oni.htm
Prodes: http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes

Livestock is the only land-use variable correlated with deforestation in the Brazilian Amazon, and the 2004 deforestation peak (Figure 6) was mainly the result of increased livestock production. Through better monitoring, strict legal actions, and responsible market practices, deforestation in the Amazon has diminished from 27,000 km² in 2004 to 6,500 km² in 2010. Climate models' projections suggest the region will have an escalation of the frequency and intensity of these extreme events, and field observations also corroborate climate modeling's results. As a consequence, climatic events of extreme droughts increase the natural and human systems' vulnerability and increases CO_2 emissions into the atmosphere due to forest fires[64,65].

By reducing deforestation in the Amazon, Brazil has avoided an immediate threat. As shown by the PRODES results, if the pace of deforestation had kept pace with the 2000s, a forest collapse in the medium term could have occurred. Brazil, according to the federal government, has already reached its goals of reducing greenhouse gas emissions, with the reduction of deforestation. Although, in the last three years (2015 to 2017) deforestation has returned to growth, which may jeopardize the gains already achieved.

However, the Amazon faces a threat that Brazil alone cannot avoid. If developed nations do not assume their historical responsibilities and reduce their per capita emissions of greenhouse gases, Amazonian ecosystems may collapse.

Brazil should also revise its goals and propose more ambitious goals for reducing illegal deforestation in the Amazon and other biomes.

Climate-deforestation-natural climate variations in the Amazon: The variations that occur naturally in the Amazonian climate overlap with the effects of deforestation and the climatic changes caused by human activities. There is no reason to expect natural variations to occur independently of climatic changes caused by anthropogenic activities. It is possible that natural variations overlap a climate trend or that climate change may affect the characteristics of climate cycles variability. For example, climate change is likely to affect the processes that control El Niño/La Niña behavior, which can modify aspects such as the magnitude, frequency or, period of El Niño/La Niña episodes (this is already observed), but deforestation can compound the consequences of drought impacts associated with El Niño.

Although it is not clear how El Niño/La Niña will behave in the future, the relationship between climatic changes and climate systems' variability, as well as their impacts on drought behavior in the Amazon[59,60,64,66], may be aggravated because of deforestation[68].

Changes in seasonal distribution, rainfall magnitude, and rainy season duration may be important in Amazonian hydrology and other sectors (energy and food production, and access to water), as rainfall reductions, predominantly in dry and transitional seasons from July to November, raise the air temperature, as observed during the extreme droughts of 2005, 2010, and 2016. Declining rainfall decreases river water to shallow levels, and hydric stress causes high fire-induced tree mortality, particularly in deforested areas[34,67]. In this scenario, the possibility of having more frequent regional fires increases and becomes a critical factor for forest conservation[68].

©Daniel Beltra / Greenpeace

4 Climate change and deforestation: impacts on the forest

Satellite measurements, field observations, and climate models show that the deforestation's impact on climate can depend on a threshold of converted forest area by deforestation, spatial deforestation arrangement in relation to a forest matrix, different soil use practices, and the external factors caused by climate change on a global scale[8]. For small enclaves of deforestation in extensive forest areas, studies point to increased rainfall in deforested areas and 'small' changes in local climatic conditions (i.e., evapotranspiration, average temperature, and rainfall frequency). However, small-scale deforestation is not predominant in the region[22,23], it was practiced for the subsistence of traditional and indigenous populations, before the scale of the intensive occupation of the region. Currently, the forest to pasture and agriculture conversion is predominant[24]. This leads to climate change with negative impacts on local and global[28,29] ecosystems, biodiversity, and socioeconomics.

Brienen et al. (2015) shows that in the last decade there has been a reduction in the net increase of aboveground biomass, suggesting a decline in the Amazonian forests' atmospheric carbon absorption capacity. This essential ecological function of the Amazon rainforest is weakened by the effects of the region's mega-droughts, deforestation, and forest degradation associated with fires. Considering the high severity of the 2000's, 2010's, and 2015-2016's mega-drought events, more extensive and frequent fires have become an important source of carbon emissions[47,71].

Drought-fire in the Amazon: Despite a 76% reduction in deforestation rates over the past 13 years, the incidence of fires increased by 36% during the 2015 drought when compared to the preceding 12-year average. Aragão et al. (2018) it is estimated that forest fires during drought years alone contribute annual emissions equivalent to one billion tons of CO_2 to the atmosphere, corresponding to more than half of the emissions associated with deforestation. In addition to the natural causes of drought (El Niño and the warmer Tropical North Atlantic Ocean), fires from burning dry, combustible material in the soil due to deforestation may also be caused by regional processes that may affect fire dynamics. Regional deforestation can accelerate and potentiate the impacts of natural climate variability. This is because forest fires can spread extensively during droughts and this process can influence carbon emissions in the Amazon for decades.

The Amazon can be classified as a region under great risk due to the variations and change in climate. The risk is not only because of projected climate change, but also through synergistic interactions with other existing threats, such as deforestation, forest fragmentation, and forest fires.

Reducing the forest's ability to sequester carbon: In z 2010, as a consequence of intense drought and fires, the Amazon became a carbon source, failing to behave as a carbon sink, that is, in this dry year, in particular, the dieback scenario (a term used to refer to a possible collapse of the Amazon forest) seemed to be proven[52].

Loss of the Amazon forest in the short term by direct deforestation, or long-term by climate change, could have widespread impacts, such as increased drought and fire risk, which has the potential to exacerbate changes in climate or forest cover in a vicious circle. Also, these two factors triggering changes in forest cover probably do not act independently of one another.

Reduction of the Amazon Forest's resilience: A triggering environmental factor for changes associated with deforestation in the Amazon is the fragmented forest's increased vulnerability to "edge effects" such as strong winds and, especially, forest fires. Climate change in a region already fragmented by deforestation can be presumed to produce more significant effects than in an adjacent region with continuous forest (e.g., a conservation area). Fragmentation exposes the forest to ignition points, which are generated primarily by human action, whether deliberate or not. Of course, natural fires also occur and influence the transition from forest to deforested area. A simplified climate-vegetation-natural-fire model estimated that, under current climatic conditions, the tropical forest would penetrate 200 km into the savanna if there were no lightning fires[65]. Agricultural expansion, in some regions associated with increased precipitation, has affected fragile ecosystems such as the edges of the Amazon rainforest and the tropical Andes[2].

The extreme drought events and the increase in the incidence of fires[73] are more pronounced at the edges between deforested areas and protected forest areas, indicating a relation between deforestation and fire or burnings[47]. The primary mitigation options related to the Agriculture sector, Forests, and Other Land Uses that have a positive effect on biodiversity are a reduction of deforestation, forest management, reforestation, and forest restoration[86]. With regard to reducing deforestation, it is possible to work with a focus both on reducing factors pressuring the forest and on increasing its protection.

Ways to reduce deforestation, and therefore CO_2 emissions, are increasing protection of the standing forest. Protected areas (PAs) are a crucial tool to avoid deforestation. Soares Filho[87] and colleagues analyzed the effect of protected areas in the Brazilian Amazon on the reduction of emissions from deforestation and found, for the period from 1997 to 2008, an inhibitory effect by the three distinct types of PAs: Indigenous Lands, fully protected conservation units, and sustainable use conservation units[1]. Also, according to the authors, the expansion in protected areas occurred at the beginning of the 2000s was responsible for 37% of the reduction in observed deforestation from 2004 to 2006, without provoking an increase in deforestation in other areas. Subsequently, Kere and contributors[88], with the same objective of evaluating the effect of protected areas on deforestation in the Amazon, found a positive effect of PAs on deforestation reduction between 2005 and 2009. This draws attention to the importance of the PAs' category (Indigenous lands tend to be more efficient for sustainable use and full protection than conservation units) and for the temporal factor (More recently created PAs have a more significant effect).

1 Translator's Note (TN): The National System of Conservation Units (Sistema Nacional de Unidades de Conservação da Natureza, SNUC) is a formal, unified Brazilian system for federal, state and municipal parks created in 2000. Also, Brazilian legislation provides for two types of protected areas - especially protected areas (espaços territoriais especialmente protegidos) and conservation units (unidades de conservação). The term "conservation units" is the closest one to the IUCN protected area concept.

5 What have we learned from climate modeling science?

While climate change is a threat to the Amazon rainforest in the long term, deforestation is a more immediate threat due to warming temperatures and possible reductions in rainfall. The Amazon is vital to the whole world because it captures and stores carbon from the atmosphere and plays a crucial role in the South American climate due to its effect on the local hydrological cycle. The forest interacts with the atmosphere to regulate humidity within the Amazon Basin, but it is believed that its influence extends far beyond its borders, reaching other parts of the continent. Deforestation, forest degradation, and forest fires affect the climate system on local, regional and global levels[8].

The conversion of forests by deforestation changes the interactions between the atmosphere and the forest, and between the atmosphere and agricultural areas, which in turn, affect the hydrological cycle and precipitation[8,30]. These interactions cannot be studied on site due to lack of observations, thus using the climate models. These numerical models represent the various processes of the terrestrial system and their interactions, trying to simulate what happens in nature closer to reality. However, the limitations on natural processes knowledge in the mathematical representation of these processes can lead to uncertainties, which are inherent in any modeling process.

In the case of deforestation, we try to estimate the difference in the balance of energy in forest areas that are converted by deforestation on different scales (i.e., local, regional, meso, and global). These models have also been used to simulate scenarios of climate change, considering low and even extreme forest conversion from deforestation and an increase in greenhouse gas concentration. For example, model studies indicate that complete of tropical forest conversion (i.e., on the global scale) from deforestation would lead to an increase in the mean atmospheric temperature from 0.1ºC to 0.7ºC[31,32], with no impact on global mean rainfall. However, climate models indicate that deforestation impacts on other scales (i.e., local, regional, and meso) would be significant.

Climate Model: Climate models use quantitative methods to simulate the interactions of the atmosphere, oceans, continental surfaces, and ice. They have various purposes ranging from the study of the dynamics of the climate system to future climate projections.

Uncertainty: Uncertainty is inherent in all projections of the future and not just for climate modeling. Climate change and the associated uncertainties are related to the future path of emissions, as a result of the global development of technology, the world population's energy consumption, and many other socioeconomic factors, as well as the limitation in the climate models due to limited climate system knowledge and the necessary simplifications in such models.

The scenario of complete forest loss from deforestation is unlikely but serves as a warning to society and decision makers about the potential risks of deforestation on climate change. Deforestation has a local effect on other nearby forests. The humidity of the forests is shifted to the deforested areas contributing to an increase in cloud formation and the consequent increase of rainfall in deforested areas.

When considering the climate models' results on only a regional scale, that is, on the Amazon scale, the deforestation's impact on the climate is more severe. The studies point to an increase in annual average temperature ranging from 0.1ºC to 3.8º C, and a reduction of 10-30% in annual precipitation, which would lead to changes in the region's climatic seasons and also in local scope8. In addition to the model results, empirical measurements indicate that the variability of wet and dry seasons is already occurring, affecting the beginning and end of these seasons and, therefore, altering their duration[33,34]. In the southern Amazonia, these studies show that the dry season has increased by about a month since the beginning of the 1970s[35,36]. Also, the duration of the dry season presents variations in the inter-annual and decadal scales, associated with the climate's natural variability, changes in regional land use also had an influence, particularly in the form of deforestation[89].

How the Amazon's climate is presently changing and how it will change until the end of the 21st century: Field observations point to an increase in the Amazon's mean air temperature of 0.6ºC from 1973 to 2013[38]. Unfortunately, there are no warming estimates for the Amazon's different regions due to the lack of meteorological information. According to IPCC reports AR5[1,2] and the Painel Brasileiro de Mudanças Climáticas[39] (Brazilian Panel on Climate Change), the temperature in the Amazon should progressively increase from 1ºC to 1.5ºC by 2040 – with a 25% to 30% decrease in rainfall volume – between 3ºC and 3.5ºC, from 2041 to 2070 – with a reduction of 40% to 45% rain occurrence – and between 5ºC and 6ºC between 2071 and 2100, for higher greenhouse gas emissions scenarios. Scenarios that generate these changes include changes in greenhouse gas concentration, but do not include land use change due to deforestation or urbanization.

While the climate changes associated with global changes may jeopardize the biome in the long term, the current deforestation issue resulting from intensive land use activities represents a more immediate threat to the Amazon, with the loss of its biodiversity, and to society, with the reduction of its ecosystem services.

6 – *Tipping points* in the Amazon, hypothesis or reality?

Local deforestation rates or increasing greenhouse gases globally drive regional changes and can lead the Amazon forest to cross a critical threshold *(tipping point)* where a relatively small disturbance can qualitatively alter a system's state or development[40,61,84,21].

Several models project risk of reduced rainfall, higher temperatures, and hydric stress, which can lead to the forest's abrupt and irreversible replacement by the savanna under a high emission of greenhouse gases scenario, from 2050-2060 to 2100[61,84]. The possible "savannization" or "dieback" of the Amazon region would potentially have large-scale impacts on climate, biodiversity, and the people in the region. The possibility of this death scenario, however, is still an open question and the uncertainties are still very high.[82].

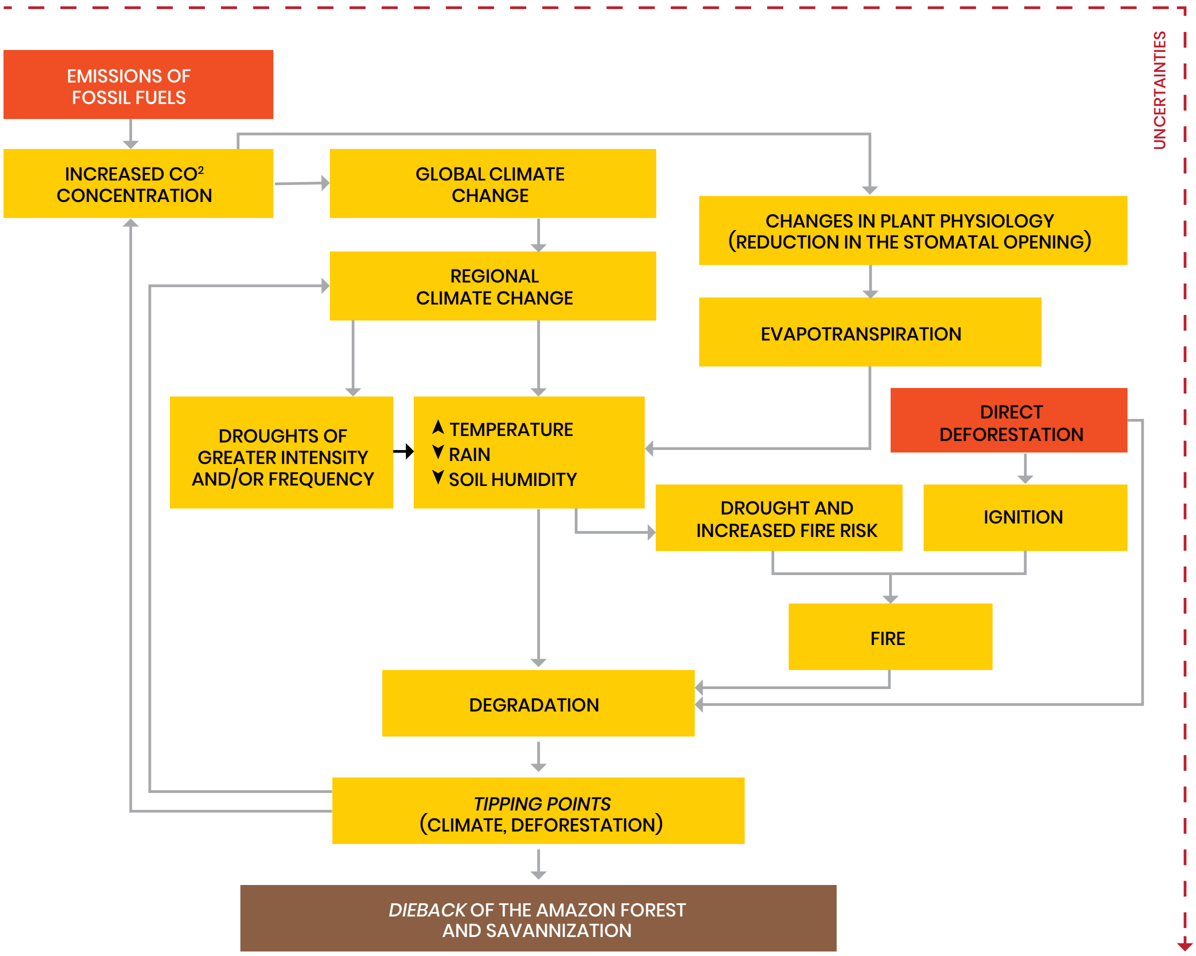
Climate models are getting better and already consider deforestation's gradual, cumulative effects, rather than considering rainforests' complete and instantaneous removal. The models also improved by incorporating forest cover's local characteristics of their arrangement in the landscape, and forest's interaction with other ecosystems. This implies differences in predictions of climate change when applying models on different scales. The concept of the *tipping point* can be considered as a developing concept, with a certain degree of uncertainty about its occurrence. This demands more studies for its validation, and an important aspect is that the climate modeling process is helping to scientifically understand what the tipping point represents.

Tipping point: Turning point, inflection, or no return in which the damages are irreversible and, worse, they occur faster and faster. In the case of climate modeling, the tipping point would be that threshold value of increase in air temperature, CO_2 concentration, or deforested area that if exceeded, can lead to a new state of equilibrium, where climate extremes can irreversibly affect the Amazon forest until it collapses and changes to a more savannah-like type of vegetation (the "dieback" process of the Amazon-Figure 7).


©Rodrigo Baleia / Greenpeace

FIGURE 7

Summary of Amazon Forest's possible dieback (collapse mechanisms). Carbon dioxide (CO_2) is not the only greenhouse gas emitted, but it is highlighted here because of its importance in climate change, its role in Earth's carbon balance, and its effects on the Amazon rainforest's plant physiology. Through regional and global climate effects, Amazon forest loss may also have implications for climate, ecosystems, and populations outside the Amazon Basin[35].



The concept of the *tipping point* was introduced by Tim Lenton[40] of the University of East Anglia, UK, to describe theoretical thresholds above which a system's state of equilibrium can be affected, leading to a new state of equilibrium. In the Amazon climate context, this concept was introduced by Peter Cox[64] of the UK Met Office and Carlos Nobre and collaborators of INPE[61,74,83,84] to describe possible changes in the Amazon forest due to increases in temperature, greenhouse effect, or in the deforested area. Other studies suggest that the forest could be more resilient and that if there were a change, it would be to a secondary forest and not to a savanna-like type of vegetation, as discussed by Yadvinder Mahli[75,82,36] of the University of Oxford, and Chris Huntingford of the Center for Ecology and Hydrology of Wallingford-UK[63].

The first models developed to answer the possibility of a *tipping point* and dieback of the Amazon in terms of the extent of deforestation areas showed that this tipping point could be reached if deforestation reached 40%. In this scenario, the Amazon's Central, Southern, and Eastern regions would register less rainfall and have a longer dry season. In addition, the Southern and Eastern regions' vegetation could become similar to the savannas[74]. In this way, the regional changes resulting from the deforestation effect will be added to the global changes and are prerequisites for the savannization of the Amazon – a problem that tends to be more critical in the eastern region.

The future climate with a *tipping point* reality would be characterized by an extension in the dry season duration and would cause regional surface heating up to 4 °C[21,39] with impacts on the other regions' climate on a global scale, more difficult to predict[32,41].

There are also models that point to greater resilience of the Amazonian ecosystems, with *tipping points* higher than 50%. If deforestation reaches 40% in the region in the future, there will be a drastic change in the pattern of the hydrological cycle, with a 40% reduction in rainfall from July to November. In any case, the rainforest could be affected, and this causes changes in the region's hydrological and carbon cycle, as well as nearby regions.

In recent decades, factors other than deforestation have begun to impact the Amazonian hydrological cycle, such as climate change and the agriculturalists' indiscriminate use of fire during dry periods – to eliminate felled trees and clearing areas to turn them into crops or pastures. The combination of these three factors indicates that the new inflection point from which ecosystems in the eastern, southern, and central Amazon may no longer be a forest. It will come to be if deforestation reaches 20-25% of the original forest. Estimates show that the Amazon is very close to reaching this irreversible limit. The Amazon has 20% of deforested area, equivalent to one million square kilometers, although 15% of this area [150,000 km^2] is recovering[85].

The models also evaluate the effect of structure and size of the deforested area on climate change, on a local and regional scale, and interactions between forest and deforested areas at the edges. Without deforestation, water vapor flows generate high rates of precipitation. Local deforestation can affect rainfall, and runoff increases while evapotranspiration decreases. Regional deforestation can influence circulation, strengthening convection, and increasing heavy rains on the edges of deforested areas, which can generate floods, flash floods, and increase soil erosion. A deforestation scenario throughout the basin would determine a severe decline in evapotranspiration and then in precipitation recycling, and although unlikely, could weaken the hydrological cycle and the moisture recycling in the Amazon as a whole[90].

The models also evaluated deforestation spatial structure in relation to a forest matrix[90]. If the deforested area has a chess-like spatial pattern, with deforested areas and forest masses interspersed and regularly distributed in the landscape, the effects on the climate will be more significant and may affect the climate-soil-atmosphere system's stability. Thus, considering the protected areas as the areas interspersed with deforested areas, these forest areas' preservation also depends on the preservation of the surrounding areas.

Even with climate modeling science advancing in the last ten years, increasing the scale of the models' detail and their complexity (including, for example, information on landscape composition and structure), there is still uncertainty about the tipping point threshold relative to the percentage of forest area loss that could lead to significant changes in the Amazon's future ecosystems. However, field observations (empirical) and satellite data have enabled the identification, measurement, and monitoring of the effects of climate change and deforestation already underway in the Amazon, as well as deforestation's impact on present local and regional scales in the Amazon[72,73].

In general, we can say that climate models are becoming more complex and able to represent previous inconclusively understood processes of interaction between climate-oceans-vegetation. However, we can also say that the models represent complex natural processes in a "simplified" manner so that they can be processed in the computers. Models are the only way to represent interactions of natural processes in the Amazon, for example, vegetation changes or of greenhouse gas concentration that can be "mathematically represented" and their results for the future climate can be estimated, with some margin of uncertainty. In this scenario, caution is required while interpreting the models' projections.

7 – *Tipping points* are the greatest risk of the forest ecosystem's collapse (dieback)

A recent analysis by Lovejoy and Nobre[85] suggests that factors such as climate change, deforestation, and widespread fire use influence the region's natural water cycle. Adverse interactions between these factors mean that the Amazon will become a non-forest system in the east, south, and central part of the region if deforestation reaches anything between 20% and 25% of the region's extent. The severity of 2005, 2010, and 2015-2016 droughts may represent the first reflections of this ecological inflection point. These events, coupled with the torrential floods of 2009, 2012, and 2014, suggest that the whole system is wavering. In addition, large-scale factors, such as warmer sea-surface temperatures on the Tropical North Atlantic, also seem to interact with changes in land use.

There is a consensus in the scientific community that the forest ecosystem can be affected by the driest, hottest projected climate by the end of the 21st century[5], as shown in Figure 7. There are still uncertainties regarding the occurrence of a scenario that leads to desertification or savannization of the Amazon (i.e., dieback scenario), with vegetation similar to that of the *Cerrado*. However, it is possible to affirm that with higher temperatures and higher hydric stress, the forest is vulnerable to droughts and a higher risk of fires. This dieback scenario that occurs when the *tipping point* is exceeded would put the Amazon rainforest as a carbon emitter (and no longer as a carbon sink)[61,64,65,74,75]. However, some studies point out that the forest may be more resilient than one might think and could not be affected by dieback[63].

The vegetation's ability to access water from the deeper layers of the soil[76] and the "CO_2 fertilization effect" were raised as possible aspects related to the forest's resilience to drought[61]. The effect of CO_2 fertilization is due to the increased concentration of this gas in the atmosphere, which could potentially increase forest productivity, offsetting emissions[77-79].

Despite some uncertainties over the long-term continuity of this process[80,81,82], some model projections consider the favorable effect of CO_2 enrichment in studies on biological climate stability[81]. However, as has been pointed out previously, the combination of extreme droughts, with higher temperatures, and reduced precipitation, coupled with increased fires, reduces forest resilience. Under these conditions, the model projections pointed to the risk of replacing the perennial forest cover with a more seasonal one[81,83,84] (Figure 8).

8 Amazon deforestation in general and in protected areas

Deforestation continues to generate threats and pressures on Amazonian protected areas (PAs). The average annual deforestation rate between 2015 and 2017 was 7015 km²/year, being 35% above the lowest recorded rate in 2012 since the official satellite monitoring program began in 1988 (Inpe, 2018). One of the factors that contributed to the increase in deforestation was the changes in the new Forest Code in 2012, with a series of concessions and weakening of environmental laws (Araújo et al., 2017), a reduction in command and control operations and low compliance with zero deforestation agreements in the livestock and soy sectors. The reduction of deforestation control, directly and indirectly, impacts the PAs, also contributing to the reduction of their limits and/or re-categorization of PAs, for the implementation of infrastructure projects, such as road paving hydroelectric power plant constructions, and the attempt to legalize illegal occupations within conservation units (Martins et al., 2017). These factors generate threats and pressures that cannot be measured and monitored by satellites.

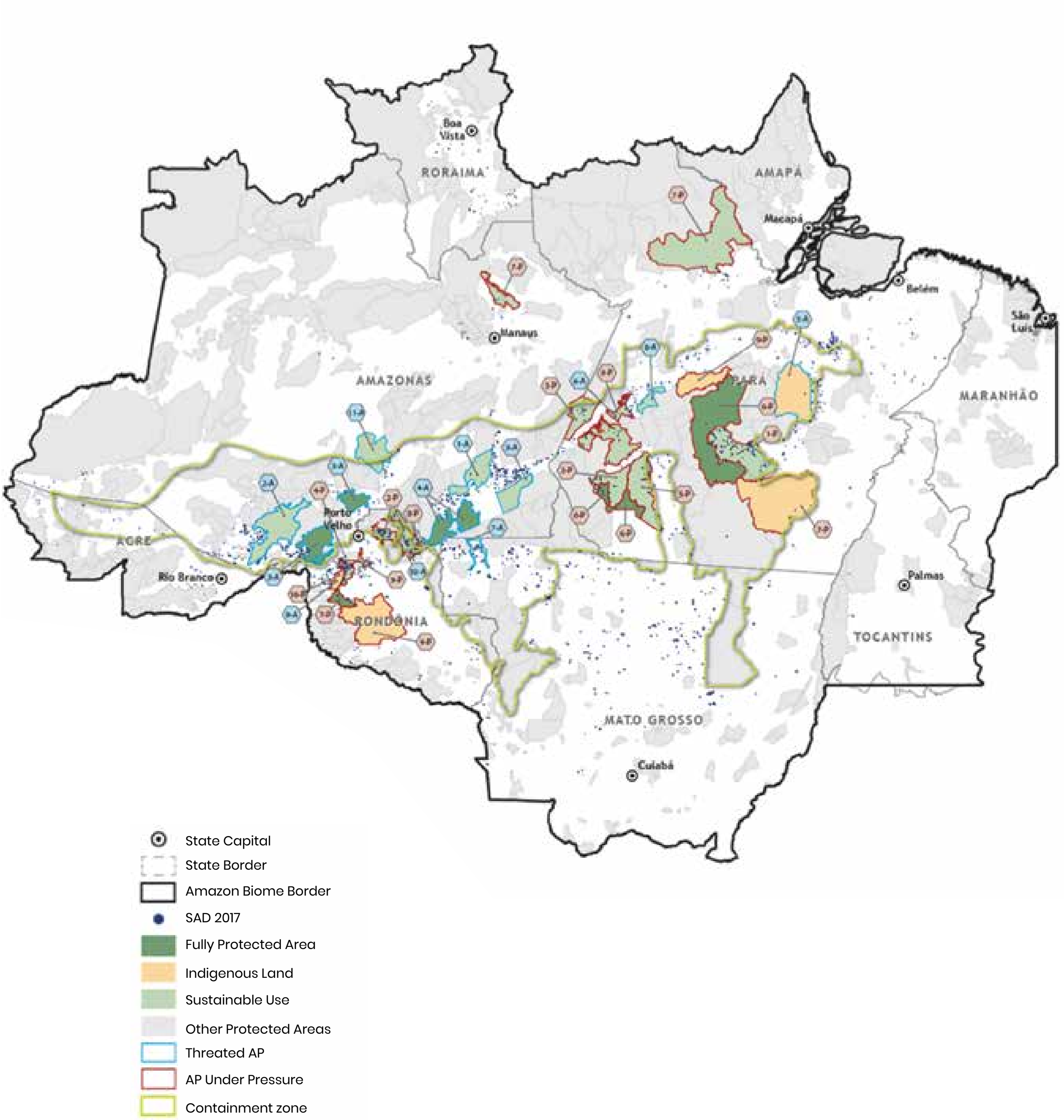
Total deforestation in PAs in 2016 was 1,225 km², which contributed with 15.5% of the Amazon's total deforestation this year. In 2017, the total deforested area in PAs in the Amazon was 929 km². This points to a 13% reduction in deforestation in PAs compared to 2016. Despite the reduction in deforestation pressure this year, PAs remain under high deforestation pressure. This pressure is distributed, in the PAs' categories, as follows: 12% in Indigenous Lands (116 km²), 82% in conservation units for sustainable use (759 km²), and 6% in Fully Protected conservation units (54 km²). The most heavily deforested protected areas, that is, with the conversion of forests into their interior, were identified based on monthly Imazon deforestation alerts for the year 2017. These protected areas are in the Containment Zone of the agricultural expansion fronts of the *Macrozoneamento Ecológico-Econômico da Amazônia Legal - MacroZEE*[2] (Law 7378, of December 1, 2010) (Figure 8). The Containment Zone objective was partially achieved, with the creation of several conservation units, beginning in the early 2000's. However, this area has recently been the target of deforestation to expand productive fronts, which is in line with its purpose established in the *MacroZEE da Amazônia Legal*.[3]

As already discussed above, the central Amazon region is one of the most susceptible to the increase in temperature derived from climate change. This means that deforestation must also be combated outside the boundaries of protected areas. With the continued high rates of deforestation in the Amazon, this enormous environmental heritage bestowed upon Brazilian society due to the creation of protected areas in the Amazon will be at great risk of drier climates and *tipping point* processes.

2 TN: Portuguese name and acronym for Ecological-Economic Macrozoning of the Legal Amazon
3 TN: Same as footnote #2.

FIGURE 8

Distribution of the most threatened or under pressure protected areas by deforestation in 2017.



Source: Imazon - Ameaça e Pressão do Desmatamento em Áreas Protegidas.
(Threat and Deforestation Pressure in Protected Areas) https://imazon.org.br/PDFimazon/Portugues/outros/AmeacaPressao_APs_fevereiro-maio-2018.pdf

9 Other Risks of Climate Change in the Amazon

There are also Amazon climate change impacts in the social and economic area, and on biodiversity. As a consequence of increased water stress during droughts, agricultural and pasture productivity can be drastically affected by reduced rainfall. For example, pasture productivity may decrease from 28 to 33% and soybean yield by 25%, with a 60% reduction in some sites[3, 39].

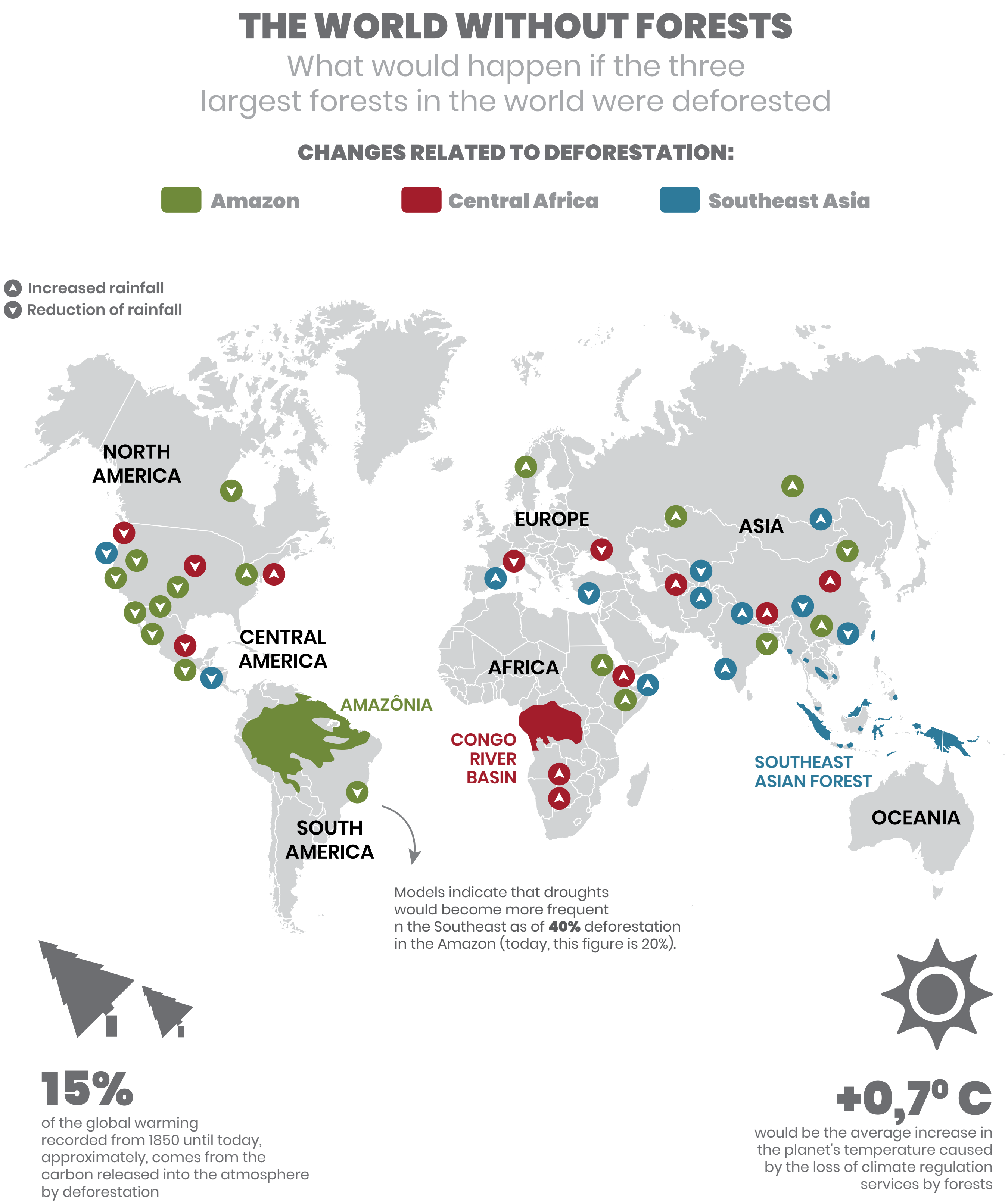
The report of the Painel Brasileiro de Mudança do Clima[39] (Brazilian Panel on Climate Change) and the Plano Nacional de Adaptação as Mudanças Climáticas[3] (National Plan for Adaptation to Climate Change) reveal that the Brazilian territory will suffer an incremental increase, over time, in the average temperature throughout the country, but with varying intensity, mainly affecting the Amazon forest. It can be pointed out that the leading climate change impacts on species and populations will be transformations: 1) in phenology, 2) in biotic interactions, 3) in extinction rates and 4) in species distributions. In addition to the impacts associated with the ecosystems' and their species' direct exposure to climatological variables, the ecosystems' sensitivity is affected by "non-climatic" variables that include: deforestation conversion and ecosystem fragmentation, fire incidence, and weaknesses and gaps in governance.

Climate change due to deforestation of global tropical forests (among them, the Amazon) affects areas beyond the Amazon and the South American continent, causing changes in the hydrological cycle, precipitation, and temperature, using a process called teleconnections by atmospheric circulation currents. These changes can affect other continents, which means that the carbon emissions caused by deforestation in the Amazon generate impacts on the climate that go beyond its limits, and that can generate impacts on the global scale. If the Amazon were totally or partially deforested, the climatic problems that the absence of the forest would cause to agriculture would be felt in the United States or even China[8]. Such teleconnections would cause deforestation in Indonesia, for example, affecting Turkey, or a Congo deforestation affecting France. In addition to causing problems such as prolonged droughts or storms, a deforested planet would have an extra share of global warming. Because of the imbalance in the global hydrological cycle, the planet would be 0.7°C warmer on average – not counting the warming that would be caused by all the CO_2 emitted by deforested areas. Figure 9 shows the impacts expected from general deforestation in the tropical regions.

[3]TN: Same as footnote #2.

FIGURE 9

Generalized consequences from deforestation on climate and agriculture in the tropical region (adapted from Lawrence and Vandecar, 2015[8]).



10 Conclusions and Public Policy Recommendations

Our planet possesses a series of complex and dynamic systems, which govern its evolution, its present state, and its future conditions for all its inhabitants. Human action is profoundly altering various aspects of the fundamental functioning of our planet, including radiation balance, and carbon balance, water availability, biodiversity, and moisture transportation to other regions of the continent, as well as the atmosphere's composition. Understanding the complex terrestrial climate system in all its components, including socioeconomic, is a vast scientific challenge for the country.

> We urgently need to formulate science-based public policies on issues such as water availability, to ensure energy, water, food, and health security, the urgent need to adapt to climate change, and to mitigate greenhouse gas emissions.

Climate science has already advanced significantly, and even with uncertainties that still need to be overcome (e.g., what is the tipping point of forest collapse?), The last decades' observations corroborate the predictions of climatological models of a warmer Amazon scenario, with extreme and prolonged droughts, resulting in a forest more vulnerable to degradation and loss of its ecological functions for sequester carbon, maintain carbon stocks and biodiversity, and regulate the hydrological and biogeochemical cycles.

Controlling deforestation and forest degradation is the fastest and most effective way to mitigate climate change's effects, which is already underway, and to avoid catastrophic loss of forest ecosystem resilience, leading to its conversion to another type of ecosystem. If deforestation in the Amazon ceases and Brazil fulfills its commitment to reforestation, by 2030 the fully deforested areas in the Amazon would be around 16% to 17% 85.

Final Message:

Deforestation in the Amazon continues to advance in recent years, with an increase in relation to control targets to reduce greenhouse gas emissions in Brazil. Our country needs to revise its goals and propose more ambitious goals that aim for zero illegal deforestation, and large-scale forest restoration targets to effectively implement the Forest Code, considering all biomes. Another essential step is to ensure the integrity and conservation of protected areas, now threatened by land grabbing, deforestation, illegal logging, and mining. In addition to drastically reducing greenhouse gas emissions, this strategy can contribute to carbon sequestration, maintain the forests' environmental services, and add value to Brazilian agricultural products, and reduce the risks of climate change.

References

1. IPCC. IPCC Fifth Assessment Report (AR5) - The physical science basis. IPCC (2013). doi:10.1017/CBO9781107415324.004
2. IPCC. IPCC Fifth Assessment Synthesis Report-Climate Change 2014 Synthesis Report. IPCC Fifth Assess. Synth. Report-Climate Chang. 2014 Synth. Rep. pages: 167 (2014).
3. Ministério do Meio Ambiente, B. Plano Nacional de Adaptação VolumeII à Mudança do Clima. Plano Nac. Adapt. à Mudança do Clima Vol. II, 394 (2015).
4. Peters, G. P. The 'best available science' to inform 1.5 °C policy choices. Nature Climaté Change 6, 646–649 (2016).
5. Magrin GO, Marengo JA, Boulanger JP, Buckeridge MS, Castellanos E, Poveda G, Scarano FR, Vicuna S. 2014. Central and South America. In Climate Change 2014: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK.
6. Wolff, E. et al. Climaté Change Evidence & Causes. Natl. Acedemy Sci. 36 (2014). doi:10.17226/18730
7. Fearnside, P. M. & Laurance, W. F. Tropical deforestation and greenhouse-gas emissions. Ecol. Appl. 14, 982–986 (2004).
8. Lawrence, D. & Vandecar, K. Effects of tropical deforestation on climate and agriculture. Nature Climaté Change 5, 27–36 (2015).
9. Spracklen, D. V. & Garcia-Carreras, L. The impact of Amazonian deforestation on Amazon basin rainfall. Geophys. Res. Lett. 42, 9546–9552 (2015).
10. Weng, W., Luedeke, M. K. B., Zemp, D. C., Lakes, T. & Kropp, J. P. Aerial and surface rivers: downwind impacts on water availability from land use changes in Amazonia. Hydrol. Earth Syst. Sci. Discuss. 1–36 (2017). doi:10.5194/hess-2017-526
11. Kiang, J. E. & Eltahir, E. A. B. Role of ecosystem dynamics in biosphere-atmosphere interaction over the coastal region of West Africa. J. Geophys. Res. 104, 31173–31189 (1999).
12. Marengo, J. A. Interdecadal variability and trends of rainfall across the Amazon basin. Theor. Appl. Climatol. 78, 79–96 (2004).
13. Bookhagen, B. & Strecker, M. R. in Amazonia, Landscape and Species Evolution: A Look into the Past 224–241 (2010). doi:10.1002/9781444306408.ch14
14. Sorribas, M. V. et al. Projections of climate change effects on discharge and inundation in the Amazon basin. Clim. Change 136, 555–570 (2016).
15. Ometto, J. P., Aguiar, A. P. D. & Martinelli, L. A. Amazon deforestation in Brazil: effects, drivers and challenges. Carbon Manag. 2, 575–585 (2011).
16. Mertens, B., Poccard-Chapuis, R., Piketty, M. G., Lacques, A. E. & Venturieri, A. Crossing spatial analyses and livestock economics to understand deforestation processes in the Brazilian Amazon: the case of Sao Felix do Xingu in South Para. Agric. Econ. 27, 269–294 (2002).
17. Cochrane, M. A. & Barber, C. P. Climaté change, human land use and future fires in the Amazon. Glob. Chang. Biol. 15, 601–612 (2009).
18. Arraut, J. M., Nobre, C., Barbosa, H. M. J., Obregon, G. & Marengo, J. Aerial rivers and lakes: Looking at large-scale moisture transport and its relation to Amazonia and to subtropical rainfall in South America. J. Clim. 25, 543–556 (2012).
19. Marengo, J. A., Soares, W. R., Saulo, C. & Nicolini, M. Climatology of the low-level jet east of the Andes as derived from the NCEP-NCAR reanalyses: Characteristics and temporal variability. J. Clim. 17, 2261–2280 (2004).
20. Nobre, A. D. O futuro climático da Amazônia: relatório de avaliação científica. ARA (Articulación Regional Amazónica) (2014).
21. Sampaio, G. et al. Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. Geophys. Res. Lett. 34, (2007).
22. Rosa, I. M. D., Souza, C. & Ewers, R. M. Changes in Size of Deforested Patches in the Brazilian Amazon. Conserv. Biol. 26, 932–937 (2012).
23. Ewers, R. M. & Laurance, W. F. Scale-dependent patterns of deforestation in the Brazilian Amazon. Environ. Conserv. 33, 203–211 (2006).
24. Barona, E., Ramankutty, N., Hyman, G. & Coomes, O. T. The role of pasture and soybean in deforestation of the Brazilian Amazon. Environ. Res. Lett. 5, (2010).
25. López-Carr, D. & Burgdorfer, J. Deforestation drivers: Population, migration, and tropical land use. Environment 55, 3–11 (2013).
26. Geist, H. J. & Lambin, E. F. What Drives Tropical Deforestation? A meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence. LUCC International Project Office 4, (2001).
27. Austin, K. G., González-Roglich, M., Schaffer-Smith, D., Schwantes, A. M. & Swenson, J. J. Trends in size of tropical deforestation events signal increasing dominance of industrial-scale drivers. Environ. Res. Lett. 12, (2017).
28. Malhi, Y. et al. Climaté change, deforestation, and the fate of the Amazon. Science 319, 169–172 (2008).
29. Lawrence, D. & Vandecar, K. The impact of tropical deforestation on climate and links to agricultural productivity. Nat. Publ. Gr. 5, 174 (2015).
30. Chambers, J. Q. & Artaxo, P. Biosphere-atmosphere interactions: Deforestation size influences rainfall. Nature Climaté Change 7, 175–176 (2017).
31. Feddema, J. J. et al. The importance of land-cover change in simulating future climates. Science 310, 1674–8 (2005).
32. Badger, A. M. & Dirmeyer, P. A. Remote tropical and sub-tropical responses to Amazon deforestation. Clim. Dyn. 46, 3057–3066 (2016).
33. Espinoza, J. C. et al. The extreme 2014 flood in south-western Amazon basin: The role of tropical-subtropical South Atlantic SST gradient. Environ. Res. Lett. 9, (2014).
34. Marengo, J. A., Tomasella, J., Soares, W. R., Alves, L. M. & Nobre, C. A. Extreme climatic events in the Amazon basin. Theor. Appl. Climatol. 107, 73–85 (2012).
35. Marengo, J. A., Tomasella, J., Alves, L. M., Soares, W. R. & Rodriguez, D. A. The drought of 2010 in the context of historical droughts in the Amazon region. Geophys. Res. Lett. 38, (2011).
36. Fu, R. & Li, W. The influence of the land surface on the transition from dry to wet season in Amazonia. Theor. Appl. Climatol. 78, (2004).
37. Sombroek, W. Spatial and temporal patterns of Amazon rainfall. Consequences for the planning of agricultural occupation and the protection of primary forests. Ambio 30, 388–96 (2001).
38. Almeida, C. T., Oliveira-Júnior, J. F., Delgado, R. C., Cubo, P. & Ramos, M. C. Spatiotemporal rainfall and temperature trends throughout the Brazilian Legal Amazon, 1973–2013. Int. J. Climatol. 37, 2013–2026 (2017).
39. PBMC, P. B. de M. C. in Mitigação das mudanças climáticas. Contribuição do Grupo de Trabalho 3 do Painel Brasileiro de Mudanças Climáticas ao Primeiro Relatório da Avaliação Nacional sobre Mudanças Climáticas 463 (2014).
40. Lenton, T. M. et al. Tipping elements in the Earth's climate system. Proc. Natl. Acad. Sci. 105, 1786–1793 (2008).
41. Duffy, P. B., Brando, P., Asner, G. P. & Field, C. B. Projections of future meteorological drought and wet periods in the Amazon. Proc. Natl. Acad. Sci. 112, 13172–13177 (2015).
42. D'Almeida, C. et al. The effects of deforestation on the hydrological cycle in Amazonia: A review on scale and resolution. International Journal of Climatology 27, 633–647 (2007).
43. Jiménez-Muñoz, J. C., Sobrino, J. A., Mattar, C. & Malhi, Y. Spatial and temporal patterns of the recent warming of the Amazon forest. J. Geophys. Res. Atmos. 118, 5204–5215 (2013).
44. Erfanian, A., Wang, G. & Fomenko, L. Unprecedented drought over

tropical South America in 2016: Significantly under-predicted by tropical SST. Sci. Rep. 7, (2017).

45. INPE. Projeto Prodes: Monitoramento da floresta Amazônica Brasileira por satélite. Instituto de Pesquisa Espacial http://www.obt.inpe.br/prodes/index.html (2016).

46. Shimabakuro, Y. E., dos Santos, J. R., Formaggio, A. R., Duarte, V. & Rudorff, B. F. T. in Global forest monitoring from earth observation 167–183 (2012). doi:10.1201/b13040-10

47. Aragão, L. E. O. C. et al. 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. Nat. Commun. 9, 536 (2018).

48. Jiménez-Muñoz, J. C. et al. Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015-2016. Scientific Reports 6, (2016).

49. Lewis, S. L., Brando, P. M., Phillips, O. L., van der Heijden, G. M. F. & Nepstad, D. The 2010 Amazon Drought. Science (80-.). 331, 554–554 (2011).

50. Davidson, E. A. et al. The Amazon basin in transition. Nature 481, 321–328 (2012).

51. Alves, L. M., Marengo, J. A., Fu, R. & Bombardi, R. J. Sensitivity of Amazon Regional Climaté to Deforestation. Am. J. Clim. Chang. 6, 75–98 (2017).

52. Gatti, L. V. et al. Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements. Nature 506, 76–80 (2014).

53. Aragão, L. E. O. C. et al. Environmental change and the carbon balance of Amazonian forests. Biol. Rev. 89, 913–931 (2014).

54. Summers, P. M., Browder, J. O. & Pedlowski, M. A. Tropical forest management and silvicultural practices by small farmers in the Brazilian Amazon: recent farm-level evidence from Rondonia. For. Ecol. Manage. 192, 161–177 (2004).

55. Marengo, J. A. et al. Recent Extremes of Drought and Flooding in Amazonia: Vulnerabilities and Human Adaptation. Am. J. Clim. Chang. 2, 87–96 (2013).

56. Marengo, J. A. et al. Two contrasting severe seasonal extremes in tropical South America in 2012: Flood in Amazonia and drought in Northeast Brazil. J. Clim. 26, 9137–9154 (2013).

57. Andreae, M. O. et al. Smoking rain clouds over the Amazon. Science (80-.). 303, 1337–1342 (2004).

58. Gonçalves, W. A., Machado, L. A. T. & Kirstetter, P. E. Influence of biomass aerosol on precipitation over the Central Amazon: An observational study. Atmos. Chem. Phys. 15, 6789–6800 (2015).

59. Marengo, J. A. et al. The drought of Amazonia in 2005. J. Clim. 21, 495–516 (2008).

60. Tomasella, J. et al. The droughts of 1996-1997 and 2004-2005 in Amazonia: Hydrological response in the river main-stem. Hydrol. Process. 25, 1228–1242 (2011).

61. Borma, L. S., Nobre, C. A. & Cardoso, M. F. in Climaté Vulnerability: Understanding and Addressing Threats to Essential Resources 2, 153–163 (2013).

62. Ovando, A. et al. Extreme flood events in the Bolivian Amazon wetlands. J. Hydrol. Reg. Stud. 5, 293–308 (2016).

63. Huntingford, C. et al. Simulated resilience of tropical rainforests to CO2-induced climate change. Nat. Geosci. 6, 268–273 (2013).

64. Cox, P. M. et al. Increasing risk of Amazonian drought due to decreasing aerosol pollution. Nature 453, 212–215 (2008).

65. Marengo, J. A. & Espinoza, J. C. Extreme seasonal droughts and floods in Amazonia: Causes, trends and impacts. International Journal of Climatology 36, 1033–1050 (2016).

66. Trancoso, R. et al. Deforestation and conservation in major watersheds of the Brazilian Amazon. Environ. Conserv. 36, 277–288 (2009).

67. Asner, G. P., Nepstad, D., Cardinot, G. & Ray, D. Drought stress and carbon uptake in an Amazon forest measured with spaceborne imaging spectroscopy. Proc. Natl. Acad. Sci. U. S. A. 101, 6039–6044 (2004).

68. Aragão, L. E. O. C. et al. Spatial patterns and fire response of recent Amazonian droughts. Geophys. Res. Lett. 34, L07701 (2007).

69. Shuttleworth, W. J. et al. Post-Deforestation Amazonian Climate - Anglo-Brazilian Research to Improve Prediction. J. Hydrol. 129, 71–85 (1991).

70. Shuttleworth, W. J. Evaporation from Amazonian Rainforest. Proc. R. Soc. B Biol. Sci. 233, 321–346 (1988).

71. Anderson, L. O. et al. Disentangling the contribution of multiple land covers to fire-mediated carbon emissions in Amazonia during the 2010 drought. Global Biogeochem. Cycles 29, 1739–1753 (2015).

72. Nepstad, D. C., Stickler, C. M., Filho, B. S. & Merry, F. Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. Philos. Trans. R. Soc. B Biol. Sci. 363, 1737–1746 (2008).

73. Nepstad, D. et al. Amazon drought and its implications for forest flammability and tree growth: a basin-wide analysis. Glob. Chang. Biol. 10, 704–717 (2004).

74. Nobre, C. A. et al. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. Proc. Natl. Acad. Sci. 113, 10759–10768 (2016).

75. Malhi, Y. et al. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. Proc. Natl. Acad. Sci. 106, 20610–20615 (2009).

76. Jipp, P. H., Nepstad, D. C., Cassel, D. K. & Reis De Carvalho, C. Deep soil moisture storage and transpiration in forests and pastures of seasonally-dry Amazonia. in 395–412 (1998).

77. Curtis, P. S. & Wang, X. A meta-analysis of elevated CO2effects on woody plant mass, form, and physiology. Oecologia 113, 299–313 (1998).

78. Norby, R. J. et al. Forest response to elevated CO2 is conserved across a broad range of productivity. Proc. Natl. Acad. Sci. 102, 18052–18056 (2005).

79. IPCC. in Climate Change 2001: The Scientific Basis 183–237 (2001). doi:10.1256/004316502320517344

80. DeLucia, E. H., Moore, D. J. & Norby, R. J. Contrasting responses of forest ecosystems to rising atmospheric CO2: Implications for the global C cycle. Global Biogeochem. Cycles 19, 1–9 (2005).

81. Lapola, D. M., Oyama, M. D. & Nobre, C. A. Exploring the range of climate biome projections for tropical South America: The role of CO2 fertilization and seasonality. Global Biogeochem. Cycles 23, (2009).

82. Rammig, A. et al. Estimating the risk of Amazonian forest dieback. New Phytol. 187, 694–706 (2010).

83. Oyama, M. D. & Nobre, C. A. A new climate-vegetation equilibrium state for Tropical South America. Geophys. Res. Lett. 30, n/a-n/a (2003).

84. Salazar, L. F., Nobre, C. A. & Oyama, M. D. Climaté change consequences on the biome distribution in tropical South America. Geophys. Res. Lett. 34, (2007).

85. Lovejoy, T. E. & Nobre, C. Amazon Tipping Point. Sci. Adv. 4, eaat2340 (2018).

86 Serviço Florestal Brasileiro (2010) Florestas do Brasil em resumo - 2010: dados de 2005-2010. Serviço Florestal Brasileiro. – Brasília: SFB, 2010. 152 p., il.;

87 Soares-Filho BS, Nepstad DC, Curran LM, Cerqueira GC, Garcia RA, et al. (2006) Modeling conservation in the Amazon Basin. Nature 440:520–523. DOI: 10.1038/nature04389.

88 Kere EN, Choumert J, Motel A, Combes JL, Santoni O, Schwarts S (2017) Addressing Contextual and Location Biases in the Assessment of Protected Areas Effectiveness on Deforestation in the Brazilian Amazônia., Ecological Economics,136, 148-158

89 Wang, G., Sun, S. & Mei, R. Vegetation dynamics contributes to the multi‐decadal variability of precipitation in the Amazon region. Geophysical Research Letters 38(19), 1–5 (2011).

90 D'Almeida, C. et al. The effects of deforestation on the hydrological cycle in Amazonia: A review on scale and resolution. International Journal of Climatology 27, 633–647 (2007).

Authors

Translation: Melissa Harkin and Todd Harkin www.melissaharkin.com

w5.com.br

José A. Marengo

General Coordinator of Research and Development at CEMADEN, *Centro Nacional de Monitoramento e Alertas de Desastres Naturais* (National Center for Monitoring and Early Warning of Natural Disasters). José holds a degree in Physics and Meteorology from the Universidad Nacional Agrária de Lima, in Peru, (National Agrarian University of Lima), a Ph.D. in Meteorology from University of Wisconsin-Madison, and a postdoc in climate modeling from NASA-GISS and Columbia University (USA).

Contact
jose.marengo@cemaden.gov.br

Carlos Souza Jr.

Carlos is a senior researcher at Imazon, where he monitors and maps forest transformations, contributing to the MabBiomas Project in Brazil and the Pan-Amazon countries for the (RAISG) *Rede Amazônica de Informação Socioambiental* (Amazonian Socio-Environmental Information Network). He holds a degree in Geology from the Universidade Federal do Pará (Federal University of Pará), a Master's Degree in Soil Science from Penn State University, and a Ph.D. in Geography from the University of California (USA).

Contact
souzajr@imazon.org.br

alana

ARTICULAÇÃO DOS POVOS INDÍGENAS DO BRASIL (Coordination of the Indigenous Peoples of Brazil)

ARTICLE 19

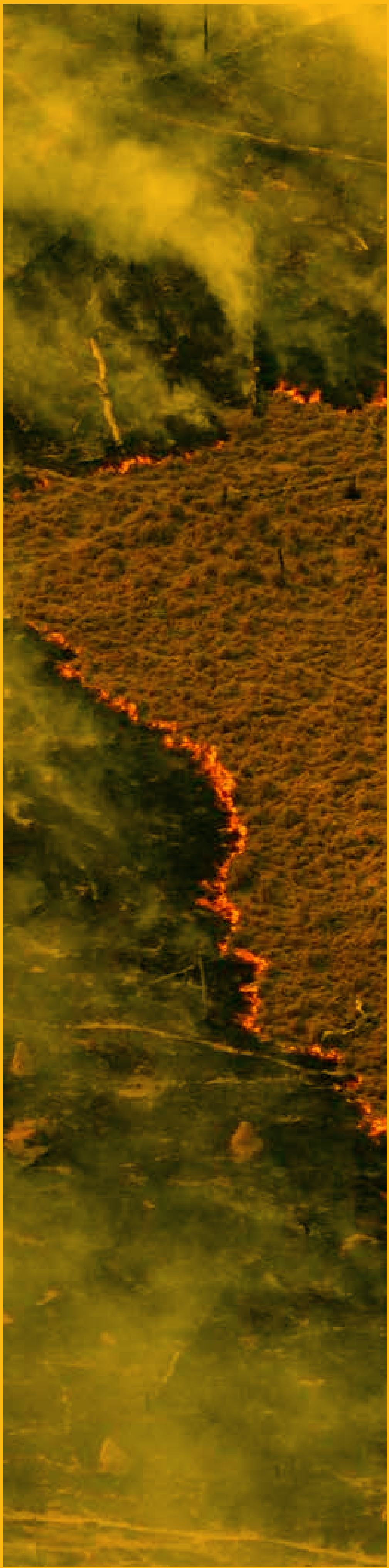
conectas direitos humanos

ENGAJAMUNDO

GREENPEACE

Instituto Socioambiental

ENVIRONMENTAL SCIENCE GRADUATE PROGRAM OF THE UNIVERSITY OF SÃO PAULO



Translation: Melissa Harkin and Todd Harkin www.melissaharkin.com

w5.com.br