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Deforestation and Forest Degradation in the Amazon

Status and trends up to year 2020

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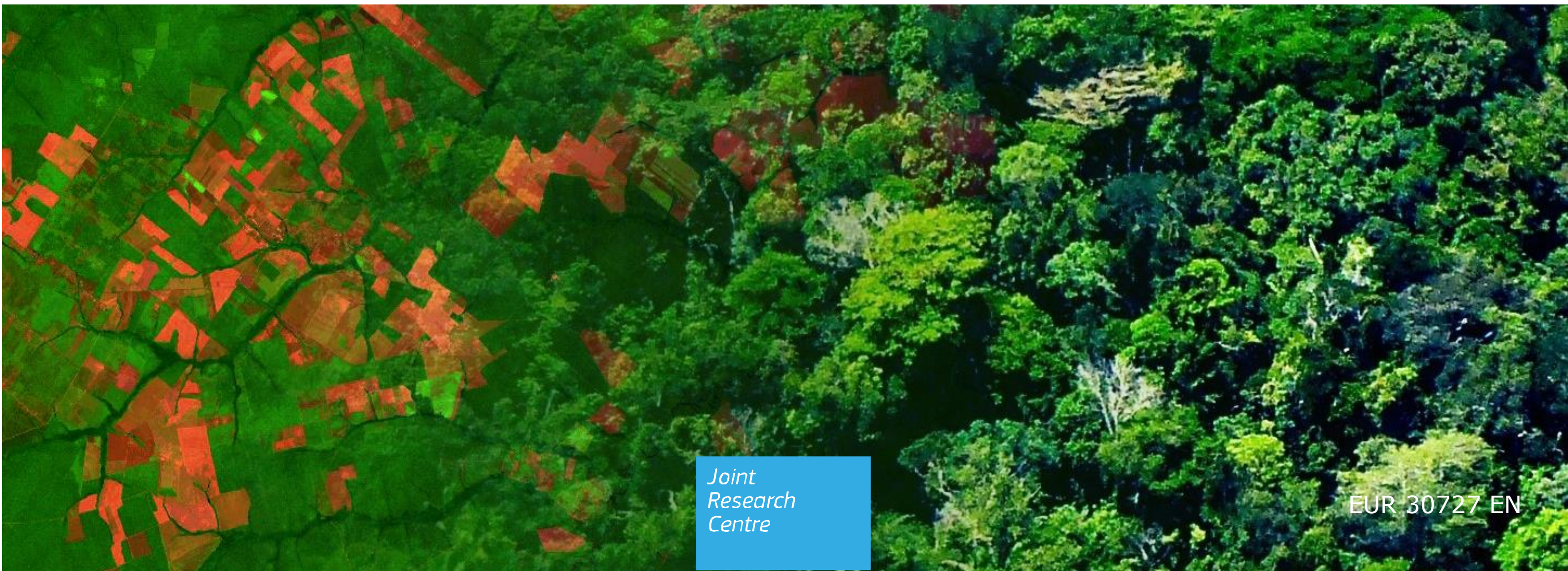

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Contents

Foreword

This report aims to communicate the statistics of deforestation and forest degradation 2002-2020 for the rainforest in the South American countries of the Amazon region, based on the new JRC Tropical Moist Forest (JRC-TMF) dataset. In addition, the report describes the dynamics of deforestation and forest degradation in the region, while putting an emphasis on various types of forest degradation and the effects of forest cover change related to road building, protected areas and the spread of zoonotic diseases. The report is an EC/JRC contribution in the context of the upcoming UN Climate Change Conference of the Parties (COP 26) in Glasgow in November 2021. A specific focus is given to Brazil, the country in the region with the largest share of Amazon rainforest and the largest country of the South American Mercosur trade bloc, on the background of the potential ratification of the EU-Mercosur trade agreement.

The report starts with a description of the geographic concepts of the Brazilian Amazon and the Pan-Amazon (chapter 2).

Chapter 3 provides a description of the processes and drivers of deforestation and forest degradation (forest fragmentation, edge effects, forest fires and selective logging) in the Brazilian Legal Amazon (BLA). Chapter 3 includes also the description of the roles of protected areas, new roads and infectious diseases in relation to forest cover change in the BLA.

In chapter 4, we describe the new JRC spatial dataset called TMF (Tropical Moist Forest). It is produced from time series analysis of satellite imagery (at 30 m resolution) to map forest disturbances (deforestation and forest degradation) over the last three decades in the humid tropics. In this dataset forest disturbances that are only visible for a short time (up to three years) are considered as forest degradation processes (e.g. from forest fires and selective logging), while long-term forest disturbances (visible more than three years) are considered as deforestation, i.e. as conversion from forest cover to non-forest cover. For the three most recent years, the proportions of deforestation versus forest degradation (within the total area of forest disturbances) are estimated based on consolidated historical proportions (average over period 2002-2017).

We examine the recent trends of deforestation and forest degradation in the Pan-Amazon region, in the countries with a share of humid Amazon forest and in the BLA (chapters 4.1 to 4.3). Two main data sources are compared for the status and the reported trends of forest cover change in 2020: JRC-TMF and Global Forest Change (GFC) data from Maryland University (USA).

The comparison with official statistics from the Brazilian National Institute for Space Research (INPE) for the BLA are reported in section 4.3. In addition to annual consolidated deforestation estimates from the PRODES programme (covering the period August to July), INPE provides since 2016 daily alerts of deforestation and forest degradation through their DETER system, based on coarse resolution satellite imagery, i.e. with lower accuracy. In particular the yearly deforestation estimates derived from DETER are in average 34% lower than the annual PRODES estimates. JRC-TMF and INPE-PRODES use different approaches and periods for reporting deforestation but are based on the same type of medium resolution satellite data (Landsat).

INPE-DETER includes the distinction between burned forests and selective logging in their forest degradation alerts. When comparing the DETER areas of degraded forest with a reference JRC dataset in Northern Mato Grosso for years 2016 and 2017, we document an underestimation by DETER of 15% for burned forests and 81% for selective logging areas.

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Executive Summary

The Amazon forest is the largest tropical rainforest in the world, which houses about 10% of the Earth's biodiversity and 16% of the world's total river discharge into the oceans. However, the Amazon forest has already lost up to 20% of its original area since the 1970s and is under constant threat of ongoing deforestation and forest degradation. Disturbances in the forest cover lead to carbon emissions, endanger the livelihoods of indigenous people, and threaten biodiversity in the Amazon.

Deforestation and forest degradation causes and effects are interrelated; selectively logged forest or forest affected by edge effects propagate the susceptibility of forest fires, while heavily burned forests are vulnerable to storms and highly susceptible for deforestation. New roads built into the forest are also a driver for these processes. An increase in forest fragmentation makes the contact between animals and humans more probable and thus leads to a higher risk of animal-to-human spillover of infectious diseases.

After very high annual deforestation rates in the Brazilian Legal Amazon (BLA) at the beginning of the 2000s (reaching 27,772 km^2 in 2004), Brazil had successfully curbed deforestation from the mid-2000s onwards. The lowest deforestation rate since the start of the Amazon deforestation monitoring programme (PRODES) in 1988, reported by the Brazilian National Institute for Space Research (INPE), was reached in 2012 (4,571 km^2). This reduction was related to new forest protection laws and an increased effort by the Brazilian Government to enforce the law by effectively combating illegal deforestation. However, since 2012, INPE-PRODES reports for the BLA a progressive and systematic increase in annual deforestation areas; for the period 2019 to 2020 the increase is at 9.5%, from 10,129 km^2 in 2019 to 11,088 km^2 in 2020.

The JRC dataset on Tropical Moist Forest (TMF) shows that the annual area of forest disturbances (deforestation and forest degradation together) has increased by 18% in the Pan-Amazon region from 2019 to 2020 (from 26,605 km^2 to 31,418 km^2); in the BLA the increase amounts to 24% (from 17,303 km^2 to 21,379 km^2).

Some Pan-Amazon countries show an increase in forest disturbances from 2019 to 2020, ranging from 11% (Ecuador) to 52% (Bolivia). Other countries or regions like Venezuela or the Guiana Shield (Guyana, Suriname and French Guiana) show a decrease in forest disturbances of 5% and 54%, respectively, from 2019 to 2020. Colombia showed almost the same area of forest disturbances of ca. 3,660 km^2 for both years.

1 Introduction

The largest and most well preserved tropical rainforest on Earth, the Amazon rainforest, housed within the extensive Amazon River System, and containing one in ten of global species, is shared by eight South American countries [1]. The Brazilian Amazon rainforest has been under pressure since the 1970ies, when the 'modern' area of deforestation began with the inauguration of the Trans-Amazon Highway [2]. The loss of Amazon forest cover in the last five decades, in Brazil as well as in the other seven countries, has severe consequences for the region, like irreversible biodiversity loss [3], soil degradation [2], lower precipitation [4], rising air temperatures [5] and a larger susceptibility to forest fires [6], but also significant climatic changes on regional scale, like reduction of rainfall for the Brazilian Southern Amazon [7], the La Plata Basin [8], as well as on global scale [9]. Brazil's southern, south-eastern and mid-western regions, which produce the big share of the country's crops, might suffer a trillion dollar loss over the next 30 years, due to the reduction in rainfall as consequence from ongoing forest degradation and permanent forest loss in the Amazon [10].

In recent years, the impact of the Amazon deforestation and forest degradation on public health and infectious diseases has been investigated [11,12]. Although large-scale research into environmental drivers of disease has mostly focused on climate, there is a growing consensus that land use change — the conversion of natural habitats to agricultural, urban or otherwise anthropogenic ecosystems — is a globally important mediator of infection risk and disease emergence in humans [13].

Since the 1970ies, the Brazilian Amazon has lost considerable parts of its old-growth forests, mostly due to conversion into cattle pasture, cash crop fields (mostly soy) and, to a lesser extent, into mining areas and water dams. In the so-called Brazilian Arc of Deforestation on the Eastern and Southern border of the Amazon forest, an area with South America's highest deforestation rates in the last 40 years, the forest area had decreased by more than 24% from 1975 until 2014 [14]. The deforestation rates in the Brazilian Amazon have shown increases and decreases in the last decades, always connected to the political circumstances of the country [15–19].

In recent years, more attention has been given to a collateral effect of deforestation: the increase of forest edges in tropical humid forests due to forest fragmentation. These forest edges, which can reach up to 100 m into the forest, lead to increased tree mortality rates, induced by microclimatic changes in the forest (e.g. changes in sun air humidity, soil humidity etc. due to the sudden exposition of plants and soil to sun and wind) [20]. The biomass collapse at the forest edges contribute significantly to the carbon emissions caused by deforestation.

Since many decades, intensive, and often illegal, selective logging activities have degraded the remaining forests specifically at the Southern and Eastern border of the Brazilian Amazon and along the Amazon River system. The logging activities have started recently also on the Northern border of Brazil and in the South-West of the Brazilian Amazon [21]. However, illegal logging occurs throughout the Pan-Amazon. Estimates on the amount of illegally logged timber range from 80% (Bolivia, Peru), 70% (Ecuador) to 42% (Colombia) [22]; for the Brazilian Amazon, the estimates range from over 50% [23] to 90% [1].

Since ca. 20 years, forest fires have become a major concern with respect to the degradation of the Amazon forest. With the recurrence of extreme draughts in the region, more and more forest fires occurred, either escaping into the forest from burning agricultural areas or of criminal origin, ignited e.g. by illegal loggers or land grabbers [24].

The Pan-Amazon, with predominant tropical humid lowland forest, shows rising overall deforestation and forest degradation in 2020, according to new JRC data on tropical forest cover changes (JRC-TMF, see chapter 4), leading to a 18% increase of overall forest

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[1] https://amazoniareal.com.br/amazonia-em-chamas-90-da-madeira-exportada-sao-ilegais-diz-policia-federal/

disturbances from 2019 to 2020 in the region. However, a study from 2017 shows a high variability of forest loss rates among Latin American countries, depending on the types of forest, on regional to local deforestation and forest degradation dynamics and drivers as well as on general national or local political circumstances, on national nature preservation laws and law enforcement strategies, etc. [25]. This variability is reflected in the JRC-TMF forest cover change statistics for the Amazon countries (see chapter 4.1).

JRC-TMF data gives an account on humid forest cover changes in the Pan-Amazon, on the background that information on tropical forests and their protection from further deforestation and forest degradation is a fundamental factor for climate change mitigation [26–28]. In addition, the data can be of high value for e.g. the definition of priority areas for forest restoration programs of disturbed tropical forests. At stake are some of the most important issues affecting human life on Earth today: climate change and the conservation of natural forest systems essential to our survival as a species.

2 Geographic concepts of the Brazilian Amazon and the Pan-Amazon

Scientists, politicians, farmers and inhabitants all have different views on what the 'Amazon forest' includes. There are different concepts of the Brazilian Amazon and the Pan-Amazon, which are briefly presented here:

2.1 The Brazilian Legal Amazon

The Brazilian Legal Amazon (BLA) is a socio-economic rather than a geographic entity. It has been created in the late 1940 (with the current borders updated in 1988) in order to "concentrate the efforts for the further development of the region" [2]. The BLA encompasses nine Brazilian Federal States that are part of the Brazilian Amazon Basin and consists in 59% of the Brazilian National Territory, including all of Brazil's Amazon forest and 37% of the Brazilian Cerrado biome (see Figure 1).

2.2 The Brazilian Amazon Biome

The Brazilian Biomes were created in 2003 by the Brazilian Institute of Geography and Statistics (IBGE)[3] and the Brazilian Ministry of Environment in order to "define bio-geographic provinces" of Brazil. Six biomes have been designed for the country, the Amazon Biome being by far the largest, covering almost 50% of the Brazilian National Territory (see Figure 1).

2.3 The Brazilian State of Amazonas

Brazil is divided into 26 federal States (plus one federal district with the capital Brasília), with the State of Amazonas being the largest one (1,559,000 km²) (see Figure 1).

Figure 1. Different Brazilian Amazon boundaries: Legal Amazon, Amazon Biome and State of Amazonas (left to right)

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[2] https://www.oeco.org.br/dicionario-ambiental/28783-o-que-e-a-amazonia-legal/

[3] https://www.ibge.gov.br/geociencias/informacoes-ambientais/15842-biomas.html?=&t=o-que-e

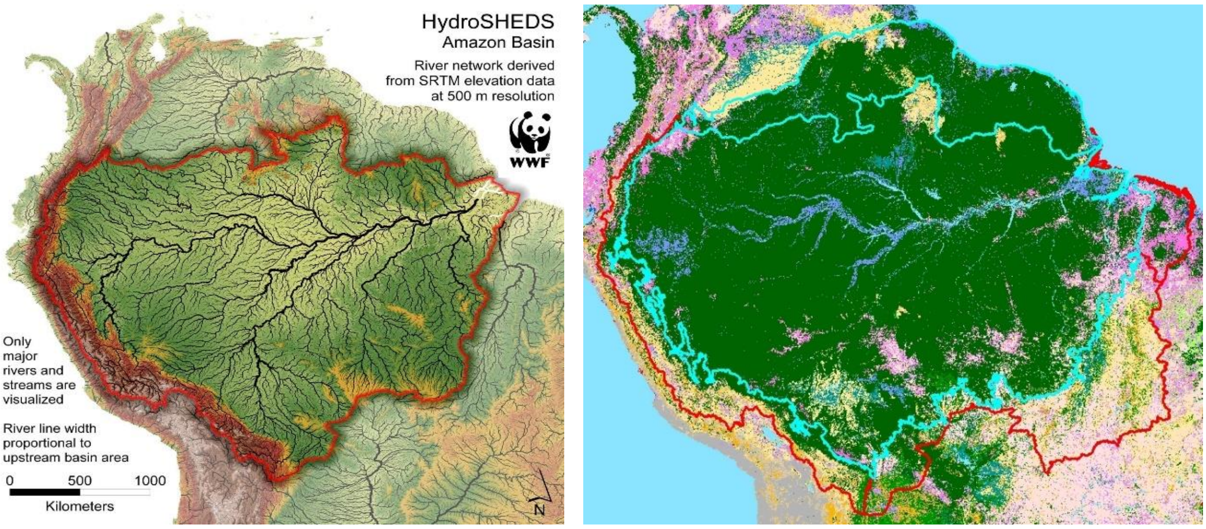
2.4 The Amazon river basin

The Amazon River basin is defined by the Pan-Amazon catchment areas of all rivers that drain into the Amazon River. This concept leaves out the area of the Guyana Shield, i.e. large parts of the Venezuelan Amazon, Guyana, Suriname and French Guiana and a part of the Colombian Amazon [29] (Figure 2).

2.5 Geographic boundaries of the Amazon, according to Eva & Huber (2005)

Upon request from the Amazon Corporation Treaty Organization (ACTO), the Amazon geographic boundary was defined by Hugh Eva and Otto Huber, together with 20 renowned international experts on Amazon biology, ecology, geology, soil science, forests, hydrology and anthropology, in a dedicated workshop at the JRC in 2005 [30] (Figure 2). Today, this Amazon boundary is widely used by scientists working on the Pan-Amazon region.

Figure 2. Different Pan-Amazon boundaries: Amazon Watershed Boundary by WWF (left) and the Amazon Geographic Boundary proposed by Eva & Huber et al. (2005, right). The core lowland humid Amazon forest is highlighted with blue boundaries.

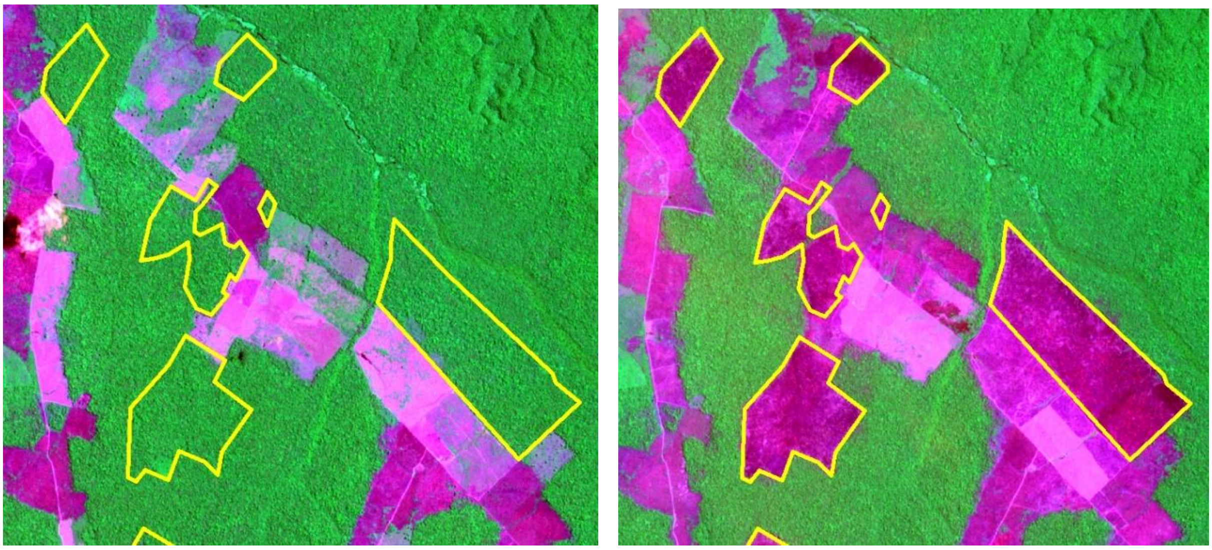


3 Deforestation and forest degradation in the Brazilian Legal Amazon

3.1 Deforestation

Deforestation implies the long-term or permanent loss of forest cover and implies transformation into another land use (FAO 2001)[4]. In the Brazilian Legal Amazon, deforested areas are mainly converted into pastures and crop fields (e.g. soy fields) [31]. Most of the deforestation in this region is illegal, violating the Brazilian Forest Code (BFC) [32], which states that 80% of the native, old growth forest within a land parcel has to be left standing by land owners in the Amazon region [33]. Despite the long period of the BFC's existence, established as early as 1934, the protection of preserved forest areas has been limited, specifically in the Amazon. A sharp increase of deforestation rates in the early 2000s triggered efforts to improve the enforcement of the BFC [34,35]. In consequence, the annual deforestation rates in the Amazon dropped by 84% from 2004 to 2012 [33]. In the following years, the area of forest loss in the BLA increased again [36] from 4,571 km^2 (2012) to 11,088 km^2 (2020)[5], according to official Brazilian statistics. However, specifically in recent years, the federal institutions to monitor deforestation and to enforce forest law in the BLA, the Brazilian Space Research Institute (INPE) and the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), have been weakened by budget cuts and dismissal of key personnel [37,38] [6] [7].

Figure 3. Sentinel-2 images before (2019, left) and after (2020, right) deforestation – near Apui in the South of Amazonas State. The deforested areas in this region become cattle pasture. Image width: ca. 7 km.



Legal and illegal mining operations in the BLA have increased over the last decades and have become an important driver of deforestation, within and beyond mining lease areas, accounting for 9% of the overall deforestation in the region from 2005 – 2015 [39]. It is estimated that the mining indirectly affect forests up to 70 km from large-scale mining sites. A large percentage of the mining operations are gold mines, which are not only a major cause of deforestation but are responsible for long-lasting forest disturbances,

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[4] http://www.fao.org/3/j9345e/j9345e07.htm

[5] http://terrabrasilis.dpi.inpe.br/homologation/dashboard/deforestation/biomes/legal_amazon/rates

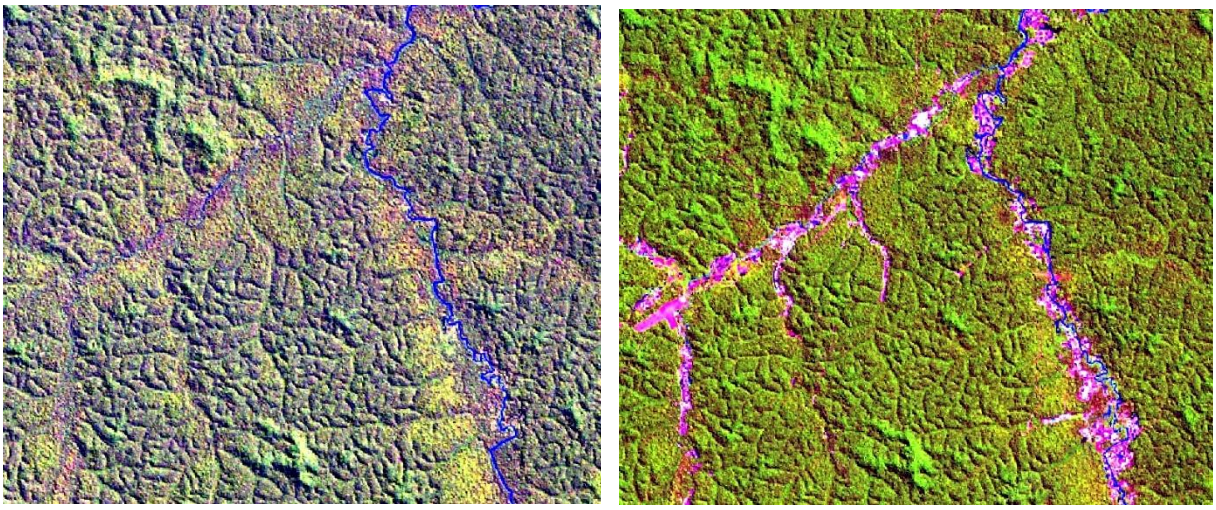
[6] https://www.sciencemag.org/news/2019/08/brazilian-institute-head-fired-after-clashing-nation-s-president-over-deforestation

[7] https://news.mongabay.com/2019/06/brazil-guts-environmental-agencies-clears-way-for-unchecked-deforestation/

mostly in or near riparian forests, due to very low forest biomass recovery rates after the abandonment of the mining pits [40,41]. However, the protection of riparian forests is acknowledged as an essential aspect of protecting a variety of ecosystem services, from water quality and availability to fostering fish spawning grounds, and conserving biodiversity [42].

Mining activities often happen illegally in Indigenous Lands, which are crucial areas for the integrity of the forests, for halting deforestation, for preserving the stability of the regional climate, for mitigating global climate change, and for protecting indigenous rights [43]. In early 2020, the Brazilian Government proposed a new legislation ("mining bill"), setting conditions for private activities in indigenous lands with a particular focus on commercial mining, while not covering social, cultural, or health matters [44]. The "mining bill" is still under discussion, but if approved, this new policy could eventually affect more than 863,000 km^2 of tropical forests in the BLA [45].

Figure 4. Landsat images before (1985, left) and after (2018, right) deforestation due to mineral exploring sites– near the town of Barra in the Southwest of Pará State. Image width ca. 17 km.



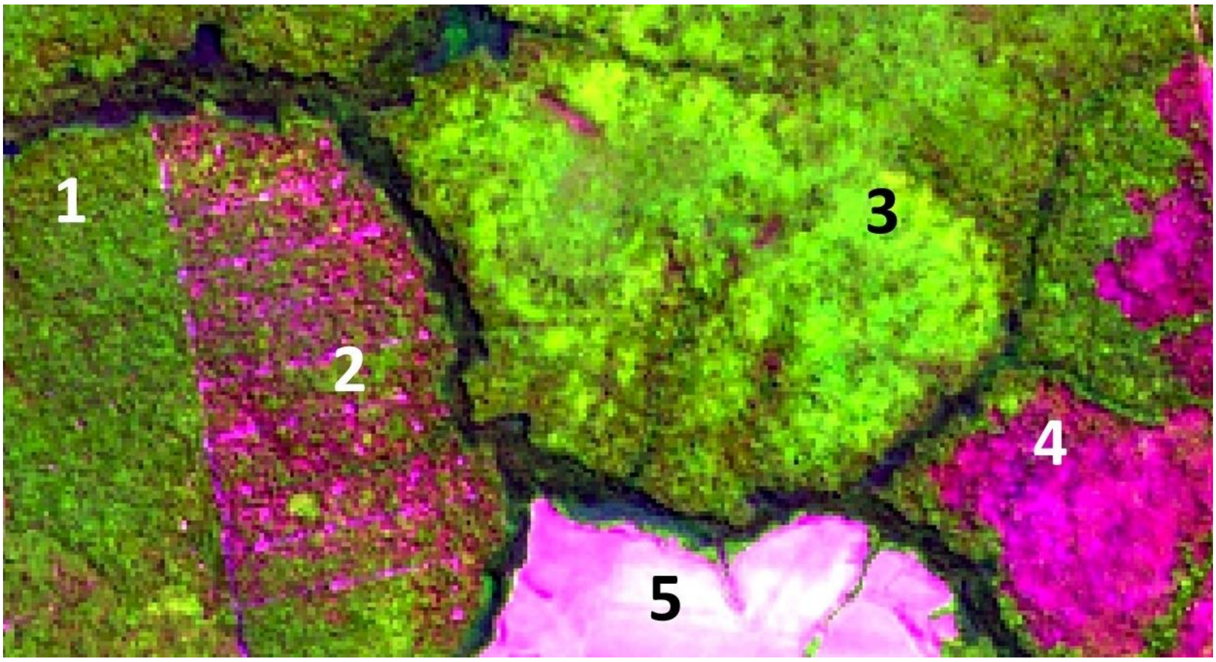
3.2 Forest degradation - forest fragmentation, edge effects, forest fires and selective logging

A degraded forest is the result of a degradation process, negatively affecting the structural and functional forest characteristics [46]. Forest degradation occurs as a result of human activities [47]. This definition implies that a degraded forest remains a forest, even if the changes in the forest structure are severe. From four important causes for forest degradation, two are directly linked to deforestation: forest fragmentation and forest edge effects [20]. The two other main causes for the degradation of forests are forest fires and high-impact (i.e. non-sustainable) selective logging, both of which happen due to human intervention (Figure 5). Forest degradation and deforestation dynamics are complex, often interlinking the causes. Selectively logged forest might burn at some stage; burned forests are often deforested later on, etc. (Figure 6).

Forest degradation plays a key role in biodiversity loss [48] and, in general, for the degradation of forest ecosystem services [49]. Forest degradation is an important cause of carbon emissions, which can exceed the carbon emission from deforestation in the Amazon [50], mainly due to increased forest fire occurrence [51]. Qin et al. (2021) have estimated for the period 2010-2019 that 73% of the overall share of carbon emissions due to forest cover change in the BLA came from forest degradation (leaving only 27% from deforestation) [52]. Degraded forests, in addition, show increased ground temperatures within the forest, increased heat flux and decreased evapotranspiration and carbon storage capacity in comparison with intact forest [53].

Figure 5. Main causes of forest degradation in the Amazon (from left to right): selective logging, forest fire and fragmentation / forest edge effects (images by Hugh Eva and Thais Almeida Lima)

Figure 6. Example of tropical forest cover change dynamics in the Southern Brazilian Amazon (year 2016 Landsat image): 1) forest selectively logged in 2001 and 2011, since then undisturbed regrowth, 2) forest of 2016 selective logging, after a first selective logging in 2003, 3) burned (and partly regrown) forest from a 2010 fire, after selective logging activities in 2001 and 2002, 4) burned forest from 2015 fire, after first burning in 2010 and selective logging in 2002 5) deforested area in 2004, after selective logging activities in 2001 and 2002. Image width: ca 8 km



However, forest degradation has not been included yet in the Brazilian communication on the forest reference emission levels (FREL), as part of the Brazilian REDD+ reporting, neither for the Amazon [8] nor for the Cerrado biome [9]. This is not surprising, because detecting forest degradation with remote sensing imagery is more difficult than deforestation detection [54], due to the weakness of the change signal compared to deforestation [24,55,56]. The forest canopy is not removed entirely by selective logging operations or forest fire, and the change, in consequence, is more difficult to detect with moderate resolution satellite imagery [57]. In addition, the signal of forest canopy change

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[8] https://redd.unfccc.int/files/2018_frel_submisison_brazil.pdf

[9] https://redd.unfccc.int/files/brazil_frel-cerrado-en-20160106-final.pdf

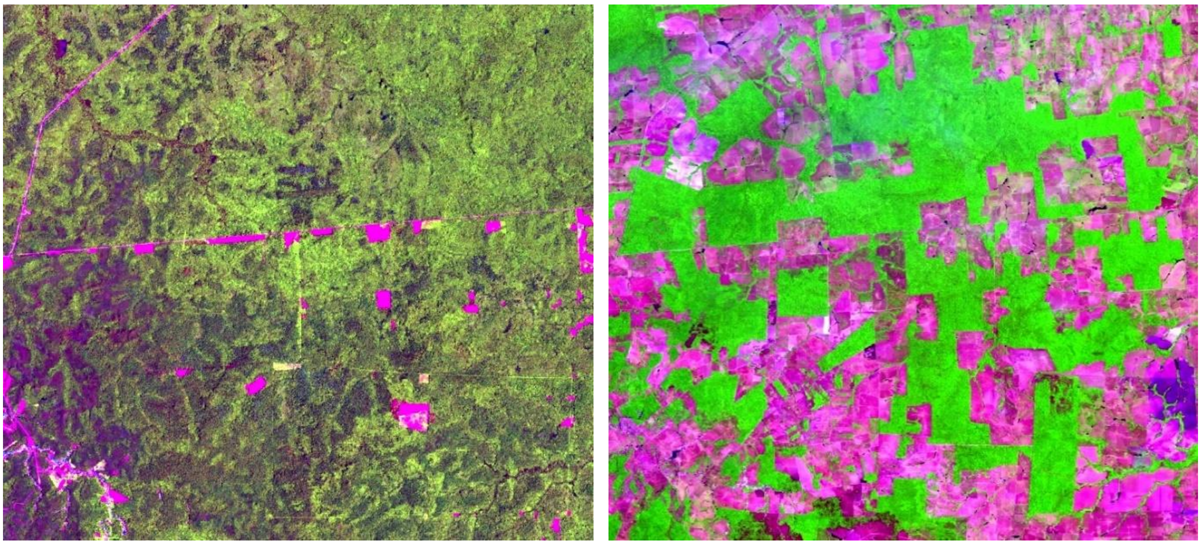
is detectable from the satellite sensor only for limited time because the initial signs of selective logging activity or forest fires visible from satellite data vanish in the humid tropics quickly as a result of fast regrowth of secondary vegetation [58]. A method for robust and reliable large-scale monitoring of tropical forest degradation, including the separation of its causes, thus still needs to be put in place.

The distinction between two of the four main causes of disturbances, leading to forest degradation through sudden changes in the canopy (selective logging and forest fires), cannot be made based on automatic remote sensing analysis alone. The studies in this context, e.g. carried out by Pinheiro et al. (2016) [59], Tyukavina et al. (2017) [60], Beuchle et al. (2019) [61], Shimabukuro et al. (2019) [62], Matricardi et al. (2020) [63] all used semi-automatic satellite image analysis approaches (incl. image interpretation) for the mapping of forest degradation, with the distinction of the two mentioned main causes. For the definition of areas at the forest borders creating edge effects, buffer algorithms (GIS operations) are applied.

3.2.1 Direct collateral damage from deforestation: forest fragmentation and forest edge effects

Formerly extensive tracks of continuous forests now often exist only as patchworks of isolated forest remnants scattered across landscapes of non-forest habitats. Forest fragmentation, through ever-increasing pressure from anthropogenic land use, may lead to the isolation and loss of species and gene pools, to degraded habitat quality, and to a reduction in the forest’s ability to sustain the natural processes necessary to maintain ecosystem health [64].

Figure 7. Increase of forest fragmentation near Alta Floresta, Mato Grosso State, from 1985 until 2020. Landsat image width: 30 km

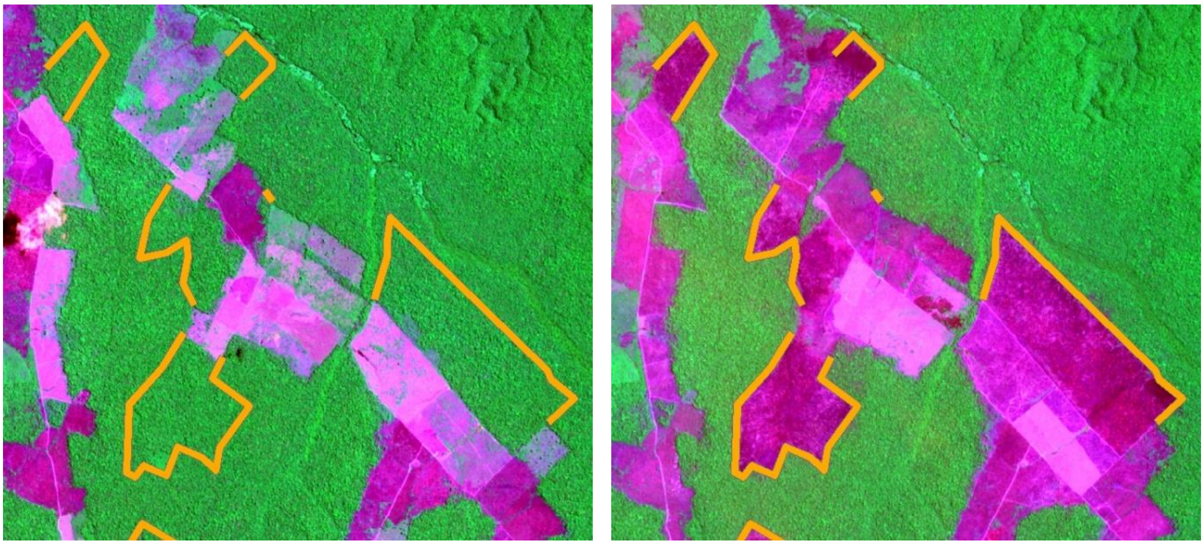


Remaining forest patches support increasingly isolated populations of forest-dependent species [65], increases in fragment number and decreases in fragment size can potentially lead to a decline or to the extinction of plant or animal species [66], due to the negative effects arising from forest patch size, the reduction in fragment connectivity and the enhancement of forest edge effects [67]. The micro-climatic regime in forest fragments differs from intact forest areas. Pasture or agricultural areas surrounding forest fragments are hotter and drier. The effects of drying can penetrate 100 m to 200 m from the border into the forest. Water courses in fragmented landscapes present greater temporal variation in flow than do those in intact forest. These variations promote localized flooding in the wet season and stream failure in the dry season. Together, these climatic and hydrological modifications have large effects on organisms and ecosystem processes, especially near forest edges [68]. Species richness declines with decreasing fragment area, smaller forest fragments are often unable to support specific plant and animal populations like e.g. understorey insectivorous birds, primates, bats, palms or leaf bryophytes [69]. The forest fragment size as well as the connections between the fragments also influence the rate of species losses, with smaller or badly connected fragments losing species more quickly [18]. The number of forest fragments within the Brazilian Amazon forest increased from 2000–2017 by 3.6 million or 68.5%, while the forest fragment average patch size decreased from 77.5 ha to 41.8 ha in the same time period [70].

Tropical humid forests exhibit striking changes in the vicinity of their borders, known as forest edge effects. These effects are mainly driven by microclimatic changes, which occur in forest edges, such as decreased humidity and an increased flux of light, heat and wind [71], which can affect the forest up to 100 – 300 m from the forest edge. The change in the vegetation structure of new forest edges is characterized by increased tree mortality, liana abundance and change of tree species composition [69].

Global field studies have estimated the relative carbon losses in forest edges averaging 11% (with extremes of 50%) of aboveground biomass within the 100 m forest edge zone, modelling studies have shown biomass reductions of up to 70% in small forest fragments. For tropical forest in South and Central America, the fraction of forest edge area is estimated as 16% of the total forest area, of which 83% are anthropogenic (i.e. non-natural), thus caused by the deforestation process [72].

Figure 8. Sentinel-2 images before (2019, left) and after (2020, right) the creation of new forest edges (orange), resulting in degraded forest areas (ca. 100 m – 300m wide) at deforestation borders. Image width: ca. 7 km.



In 2015 the total area of forest edges in the Pan-Amazon was estimated as 175,000 km^2, considering an edge depth of 120 m. Brazil had the highest annual edge creation average of all countries for the period 2001-2015, contributing with 7,600 ± 3,427 km^2 year^{-1}. The deforestation process between 2001 and 2015 in the Pan-Amazon lead to a collateral carbon loss of 37% related to the dynamics of forest edges, with 67 ± 6% year^{-1} thereof coming from (100 m wide) forest edges in the Brazilian Amazon. However, unlike the carbon loss from deforestation, which declined significantly during the period between 2001 and 2015, the additional carbon loss associated with the edge effect remained unchanged, resulting in the decrease over time of the difference between carbon losses from deforestation and forest edge effects. During the studied period, the carbon loss from forest edges in the Pan-Amazon, which contributed to 25% of the overall loss from deforestation in 2001, increased to 48% in 2015 [20].

To a certain extent these forest border effects exist also after selective logging activities, e.g. at the border of large logging decks or logging roads [73], which remain as a gap in the forest for several years until the canopy is closed again [74]. Edge effects of logging roads and logging decks can have an important impact on the surrounding biodiversity [75].

According to Dantas de Paula et al. (2015), it is possible to revert the forest degradation process through forest fragmentation and forest edge effects. Forest degradation simulations show that at a typical edge of large forest fragments, runoff and evapotranspiration values appear 'back to normal' around 100 years after fragmentation in a lowland *terra firme* tropical forest, and that in the core of large forest fragments these 'normal' values are reached sooner (after approx. 70 years) during the forest recovery transitions. Depending on the level of degradation, however, this process can only be accomplished through human interventions, i.e. by institutional, economic and technical measures. The restoration of the degraded forests depends strongly on individual stakeholders and are frequently hindered when short-term economic benefits influence the decision making [71].

3.2.2 Forest fires

The normal conditions of the climate in the humid forest areas of the Amazon, with high humidity and rainfall, do not favour the occurrence of natural fires. However, in recent years the synergism between recurring climatic extremes and human action has provided conditions for the occurrence of forest fires [76].

Table 1. Estimates by different analyses of burned forest percentages within burned areas

study	Percentage forest fire	method	year
IPAM (2020)	36% average (Amazon biome)	Active fires in forest	2016-2019
GWIS (2020)[10]	34% average (BLA)	Burned areas in forest	01/2020-11/2020
Campanharo et al. (2019) [77]	30% average (AC State)	Burned areas in forest	2008-2012
Cano–Crespo et al. (2015) [78]	22% average, 32% average (RO, MT, PA States in Brazil)	Burned areas in forest and secondary vegetation	2008, 2010
Miettinen et al. (2016) [79]	20% average (Amazon biome in MT State)	Burned areas in forest	2000, 2005, 2010
GFED (2020)[11]	11% (Pan-Amazon biome, South of Equator)	Burned areas in forest	2020
INPE (2020)	8% (Brazilian Amazon biome)	Active fires in forest	08/2019-12/2020
Cardil et al. (2020) [80]	Less than 1% (lowland Amazon forest)	Burned areas in forest	2019

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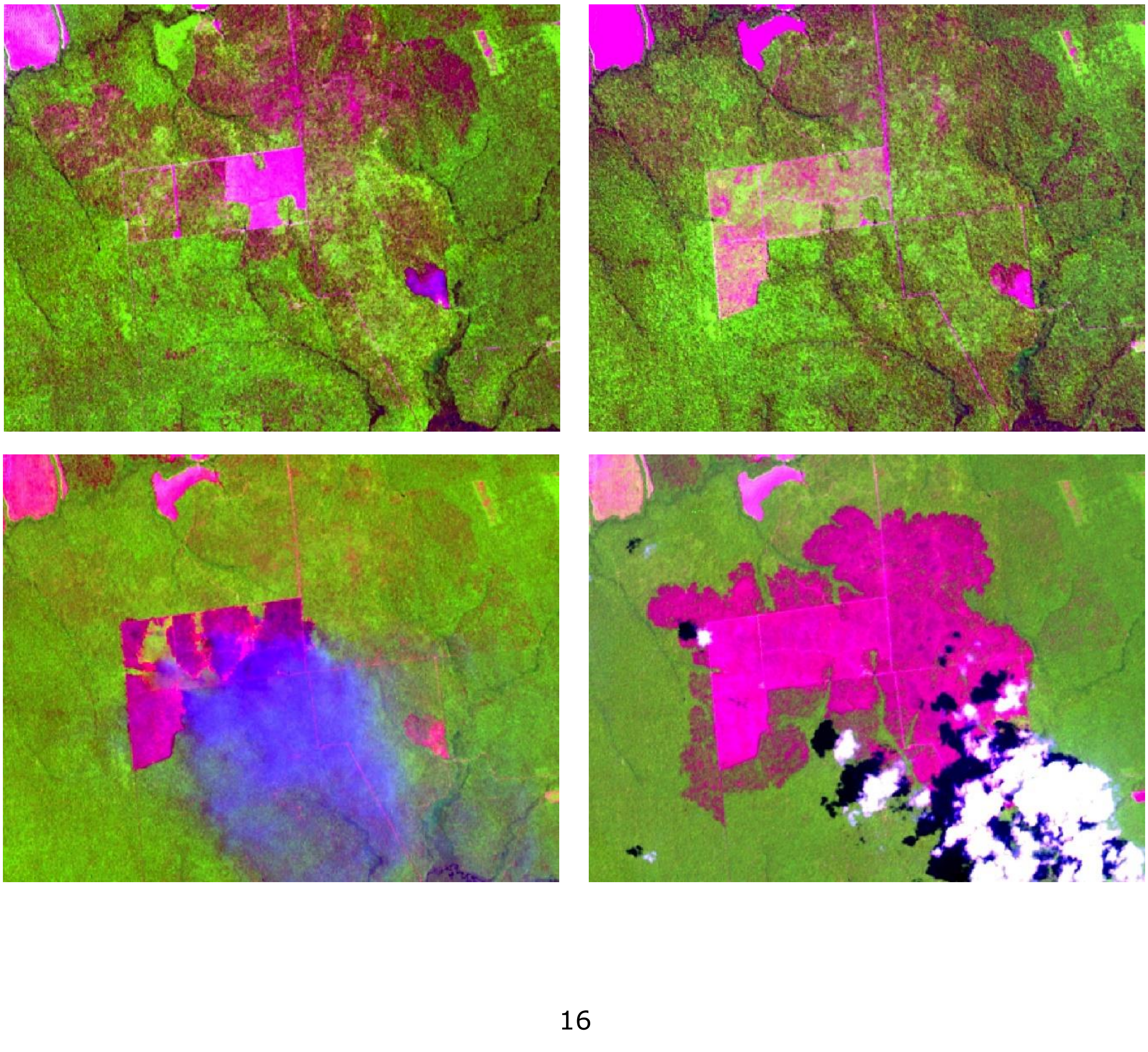
[10] https://gwis.jrc.ec.europa.eu/reports-and-publications/2020-amazon-weekly-reports/

[11] https://globalfiredata.org/pages/pt/amazon-dashboard/

Whereas in the 1990ies and before forest fires were mainly driven by the deforestation process, prolonged dry seasons in the region and raising air temperatures, specifically in the southern and southeastern Amazon [81], paved the way for forest fires being more independent from the activities of loggers. Recently, areas affected by forest fires and areas of recent deforestation are not highly correlated any more in the BLA. A study from 2018 [51] states that the decoupling between fire-related and deforestation-related carbon emissions has been mainly driven by recurrent extreme 21st century droughts. Morgan et al. (2019) [82] confirm the increasing importance of non-deforestation drivers of fire in the BLA. Currently, the forest fire – related carbon emissions dominate the overall figures from forest degradation for the Brazilian Amazon, specifically during extreme drought years.

Not all fires in the BLA are forest fires, in fact most of the fires are either i) savanna fires (a significant portion of the BLA consists in savanna areas), ii) a means to burn the tree remnants (stems, branches) of recently deforested areas or iii) a widely used practice for cattle pasture management [83]. Still, many forest fires occur, mostly due to fire escaping into the forest from either pasture management fires, from clearance fires after deforestation or due to illegal land grabbing practices [37]. The actual percentage of forest fires in comparison to pasture management fires or fires following deforestation is still in discussion (see Table 1).

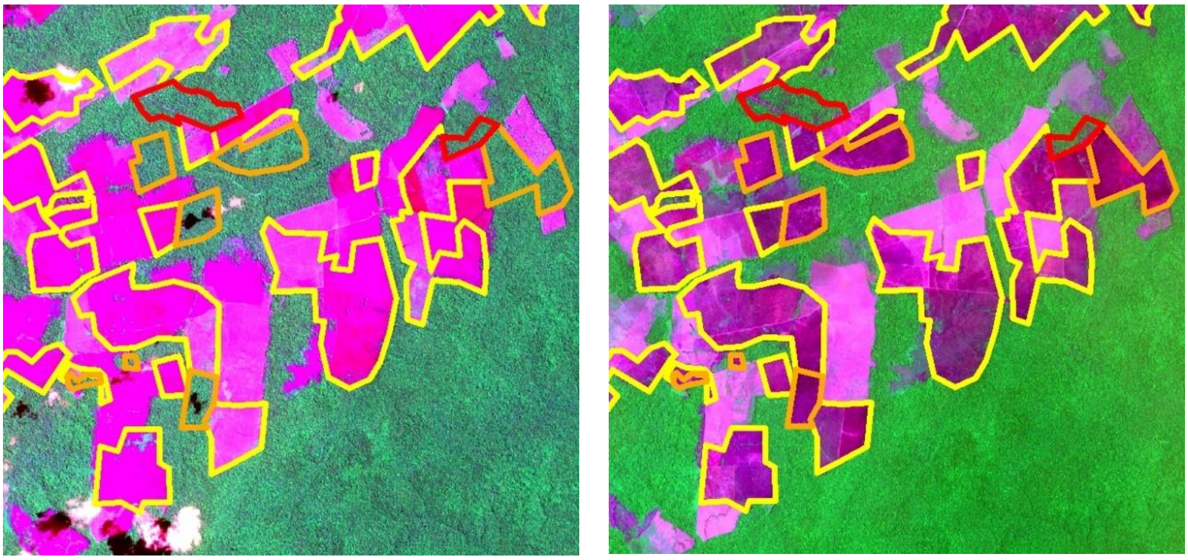
Figure 9. UL: start of deforestation activities in 2014 (image from 14th October 2014), with degraded forest nearby (and signs of selective logging); UR: end of deforestation activities in 2015 (image from 8th July 2015), LL: clearance burning of the newly deforested areas in 2015 (image from 17th October 2015) – active fire is visible as bright orange areas, smoke in blue; LR: burned forest through an 'escape fire' adjacent to the deforested area (image from 18th November 2015). Image width: ca. 12 km



In a recently published study, IPAM (Institute of Environmental Research of the Amazon)[12] gave the percentage of active fires in native vegetation (forest fires) as 30% for the year 2019, while the fires in other areas (recently deforested areas and in consolidated agricultural areas) amounted to 34% and 36%, respectively. Cano–Crespo estimated the burned primary forests in the humid domain of Mato Grosso, Pará and Rondônia States for 2008 and 2010 on average as 25.5%, 17.0% and 24.0%, respectively, related to the overall figure of burned areas [78]. INPE calculated for the BLA the percentage of fires in primary forest from August 2019 to November 2020, with respect to other types of burned land cover, as 8.0%[13]. Cardil et al. (2020) [80] estimate the 2019 forest fires as low as 1% of the total amount of burned land cover, as opposed to recent (2017-2018) deforestation areas as 94%, and consolidated agricultural areas (deforested from 2000-2016) as 5% of the total burned areas.

The consolidation of the distribution of fire across different land cover types is very important to better understand the ecological (and economic) implications of burned areas. The increase of burned areas in the BLA from 2018 – 2020 [84] [14] (increase from 2018–2019 by 40%, from 2019–2020 by 57%) implies an increase of burned forests for this period as well (see Figure 11). Burned forests, after severe burning, have a lower aboveground biomass through increased tree mortality, specifically of large trees; they change their tree species composition [85], e.g. show an increased area extent of bamboo or pioneer tree species [86]. At the same time, burned forests have a significant recovery potential [87], if they are not burned again or exposed to other causes of forest degradation (e.g. windthrow).

Figure 10. Example of the distribution of 2020 pasture maintenance fires (yellow), fires after deforestation (orange) and forest fires (red) over Sentinel-2 imagery from 2019 (31st July, left), and "post-fire"2020 (9th October, right) near the town of Apui in the South of Amazonas State. Interpretation of the burned areas was made interactively on the Sentinel-2 imagery. Image width: ca. 10 km



The effect of fires in the Amazon on human health is well documented. The increase in air pollution levels due to fires causes an increase in the incidence of respiratory diseases, requiring medical treatment [88]. Smith et al. (2014) [89] demonstrated an increase from 1.2% to 267% in the number of hospitalizations of children under 5 years of age, due to the degradation of air quality, associated with fires that occurred during the 2005 drought

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[12] https://ipam.org.br/fogo-em-area-recem-desmatada-na-amazonia-disparou-em-2019/

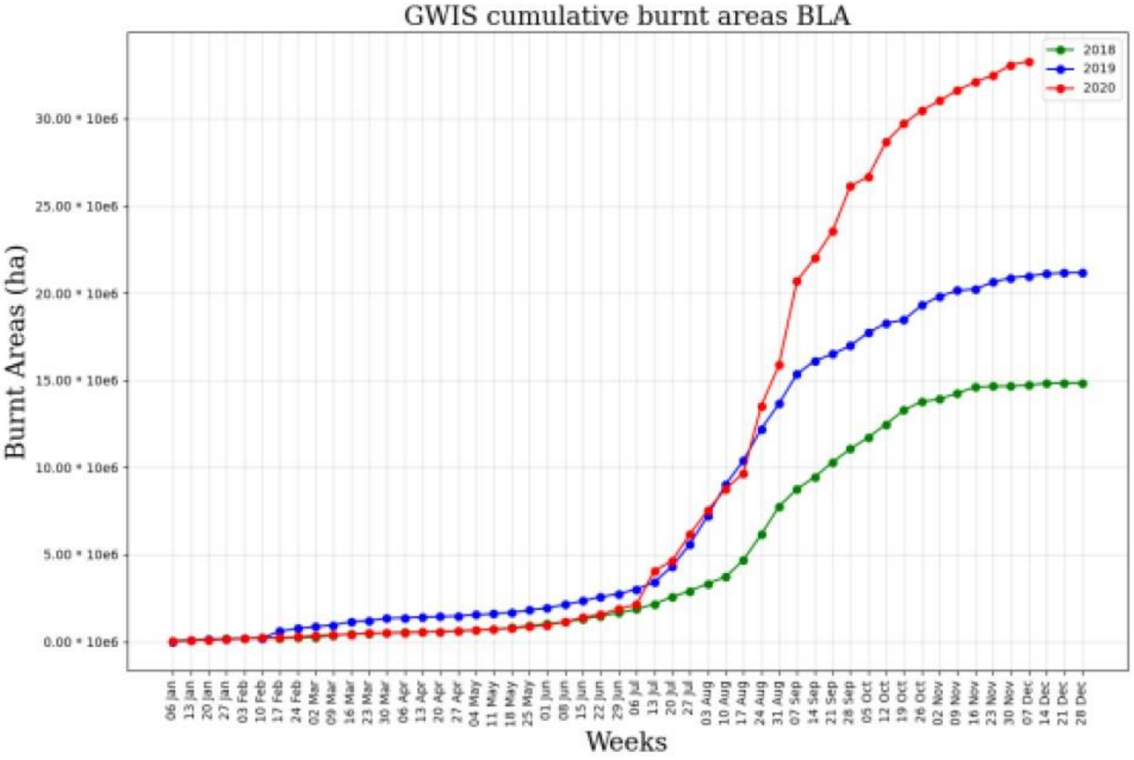
[13] http://terrabrasilis.dpi.inpe.br/app/dashboard/fires/legal/amazon/aggregated/

[14] https://gwis.jrc.ec.europa.eu/reports-and-publications/2020-amazon-weekly-reports/

in the Amazon. Fires associated with deforestation in the Amazon explain 80% of the increase in particulate matter in the atmosphere, reaching all regions of South America.

The likely relationship between air pollutants linked to fire and COVID-19 infection suggests that fire aggravates the current COVID-19 crisis in Amazonia, where infection rates are high. Indigenous peoples are at particular risk, given that they are currently suffering COVID-19 mortality rates that are 1.5 times the Brazil average [12].

Figure 11. Yearly accumulation of burned areas in the BLA for 2018, 2019 and 2020, according to San-Miguel-Ayanz et al. (2020) [84] *[15]*



3.2.3 Selective logging

Selective logging is a form of extraction of timber where trees from selected species, i.e. high-value tree species, are removed from the forest [90]. Declining deforestation rates in the Brazilian Amazon are declared as a conservation success, but illegal selective logging is a problem of similar scale. Selective logging is the single most important cause of tropical forest degradation worldwide [91]. Selective logging that respects the rules of Sustainable Forest Management (SFM) is advocated as a simultaneous means to provide timber, protect biodiversity, and reduce carbon emissions from tropical forests [92]. However, according to a BVRio report from 2016[16], FSC-certified forest management operations accounts for less than 3% of the total log production in the Brazilian Amazon. The main reasons are unfair competition compared to illegal logging operations and extremely difficult control and law enforcement in the region, due to the vastness of the area, the poor infrastructure, a lack of capacity and the large number of actors contributing to deforestation and illegal logging[17]. IBAMA, the federal environmental agency responsible (alongside state environmental secretariats) for monitoring and inspecting the Amazon timber industry, is the authority to collect all issued selective logging permits in the country and, in general, for the law enforcement related to the violation of the Brazilian forest code. However, due to the dysfunctional information flow between regional authorities providing

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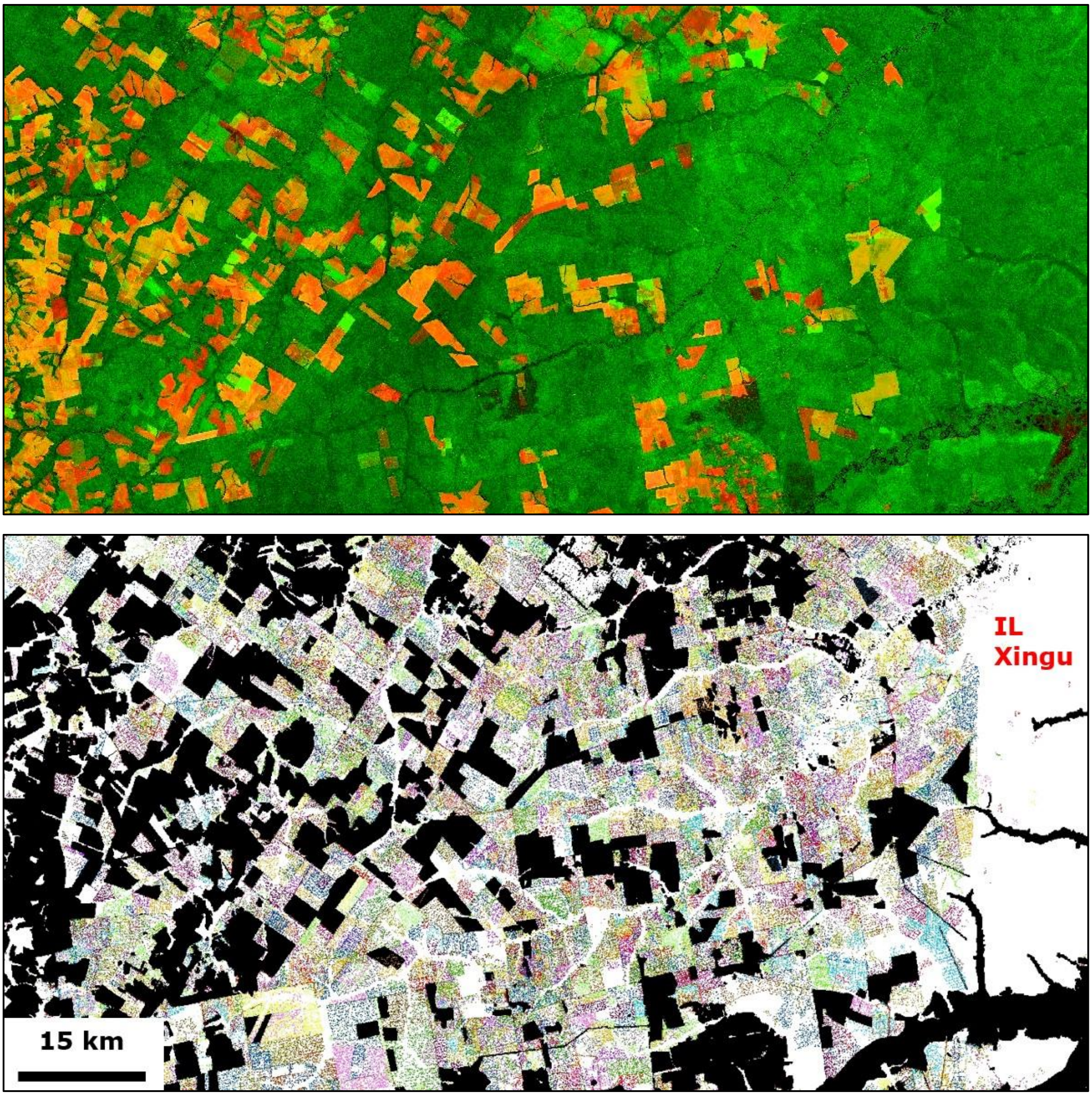
[15] https://gwis.jrc.ec.europa.eu/reports-and-publications/2020-amazon-weekly-reports/

[16] https://www.bvrio.org/publicacao/160/using-big-data-to-detect-illegality-int-the-tropical-timber-sector.pdf

[17] https://www.itto.int/sfm/2005/details/id=12480000

selective logging permits and IBAMA, there is at present hardly any information available for the Brazilian Amazon regarding areas under selective logging, explored timber volumes or information on legality or illegality of selective logging activities[18].

Figure 12. Sentinel-2 imagery of 2018 (above) and mapped 23 years of selective logging (1996-2018) in Northern Mato Grosso State (below), with different colors indicating different years of selecting logging activity [61]. Almost all remaining forest areas 2018 outside the Xingu Indigenous Land (IL Xingu) have been selectively logged at least once within the given time period. Black areas represent non-forest in 2018, as reported by INPE. Image width: ca. 160 km



Timber extraction activities in tropical forests can have reportedly widespread negative effects related to wildlife populations, including population declines and local extinctions [93,94], to reduced timber recovery rates and to irreversible changes in the tree species composition of a forest [95], especially in areas with very high logging intensity, with a short logging cycle or without employed reduced-impact logging practices [96,97].

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[18] IBAMA 2021 (personal information, 13.01.2021)

International rankings place Brazil as one of the highest risk countries for illegality in the timber sector[19]. A Greenpeace report from 2014 estimated that in the two Brazilian States with the largest timber production (and highest deforestation rates), Pará and Mato Grosso, the percentage of illegally harvested timber between August 2011 and July 2012 was at 78% and 54%, respectively[20]. The high percentage of illegal logging in Pará State was confirmed by IMAZON, who have calculated that 70% of all timber extraction in the period from August 2017 to July 2018 happened in non-authorized areas, and was thus logged illegally[21]. In addition, 24% of the legally authorized logging sites showed irregularities like logging activities beyond the authorized forest area, over-logging of the site, or logging in other forest sites than the authorised ones (e.g. in protected areas). In addition, illegal loggers launder illegally cut timber by creating "fake legal logging" licenses: they use an overestimation of high-value timber species volumes within legal logging sites in order to declare timber extraction outside the permitted logging areas as 'legal' [98]. In an interview in 2019, the Head of the Federal Police of Amazonas State, Alexandre Saraiva, estimated that 90% of all timber leaving the Brazilian Amazon was harvested illegally, while considering this estimate "optimistic" [22]. Saraiva, who in 2020 led the largest ever investigation into illegal selective logging in the Amazon [23], was dismissed from his post in April 2021, after criticising the national government for its inefficient environmental policy [24] [25]. In May 2021, the Brazilian Supreme Court has authorized a criminal investigation into allegations that high-level government officials obstructed a police probe related to illegal selective logging and timber trade in the Amazon [26] [27].

Selectively logged forests, if properly managed, can maintain important biodiversity values, carbon stocks and other ecosystem services, unlike deforested areas [99]. Therefore, taking into account that selective logging is the main harvest technique employed in natural tropical forests, efforts to ensure the sustainability of the logging process are of great interest [74]. Legal timber extraction with reduced impact logging (RIL) has been implemented for concessions in public Amazon forests, e.g. under supervision of the Brazilian Forest Service (SFB) [28]. However, RIL techniques in the Amazon are not widely employed by the logging industry and thus a sustained-yield timber production is not ensured [26], caused by the absence of silvicultural practices promoting growth and regeneration in logged stands. In addition, a large number of field technicians at the SFB would have to be trained in best-practices forest management in order to be able to oversee the application of the RIL operations. Moreover, state and national environmental agencies responsible for the monitoring of logging operations and forest law enforcement would need to be better sustained financially to provide an efficient frame to ensure the application of sustainable forest management by the logging industry [100].

The area for logging concessions in public Amazon forests has increased from 2010 to 2014. However, the concessions applying RIL are at a competitive disadvantage, compared to illegal logging operations [26]. Without command and control action, or a policy mix that includes incentive-based instruments, illegal logging provides more appeal than legal logging, as it means unrestricted access to timber and lower transaction costs. This could lead to a significant reduction of timber production from concessions in public forests [101].

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[19] https://www.bvrio.org/publicacao/160/using-big-data-to-detect-illegality-int-the-tropical-timber-sector.pdf

[20] https://www.greenpeace.org/usa/research/logging-the-amazons-silent-crisis/

[21] https://imazon.org.br/publicacoes/sistema-de-monitoramento-da-exploracao-madeireira-simex-estado-do-para-2017-2018/

[22] https://amazoniareal.com.br/amazonia-em-chamas-90-da-madeira-exportada-sao-ilegais-diz-policia-federal/

[23] http://www.mpf.mp.br/am/sala-de-imprensa/noticias-am/operacao-identifica-mais-de-130-mil-metros-cubicos-de-madeira-ilegal-no-para

[24] https://www.cmjornal.pt/mundo/detalhe/policia-federal-do-brasil-demite-superintendente-na-amazonia-que-denunciou-ligacao-do-ministro-do-ambiente-a-madeireiros-ilegais

[25] https://www1.folha.uol.com.br/poder/2021/04/pf-confirma-troca-de-chefe-que-confrontou-salles-e-opositores-de-bolsonaro-cobram-investigacao.shtml

[26] https://www1.folha.uol.com.br/ambiente/2021/06/carmen-lucia-do-stf-determina-abertura-de-inquerito-contra-ricardo-salles.shtml

[27] https://www.euronews.com/2021/06/03/us-brazil-environment-investigations

[28] http://www.florestal.gov.br/documentos/concessoes-florestais

The monitoring of selective logging with satellite imagery comprises the problem of mapping activities, which, in part, happen under the forest canopy. While good-sized logging decks and large felling gaps are normally well detectable by pixel-based remote sensing analysis with medium (30m Landsat - type) and high (10m Sentinel-2 – type) spatial resolution satellite imagery. However, it is often impossible to detect smaller logging features like smaller felling gaps, narrow logging roads and skid trails, which are partly or completely under the forest canopy. Nevertheless, these smaller logging features can have a degrading effect on the forest structure and forest biodiversity. Souza and Barreto (2000) [102] and Matricardi et al. (2005) [103] both concluded that by applying a buffer of ca. 160m to 180m around larger logging features (which can be detected by remote sensing analysis), most smaller-sized logging infrastructure and residual damaged vegetation due to the logging operations should be included [104],[105]. Using a similar approach, Beuchle et al. (2019) [61] estimated that the forest area 'affected by selective logging' in the Southern Brazilian Amazon is up to 5 times larger compared to a strict pixel-based mapping approach, once a buffer of 150 m is applied around the pixels mapped as selective logging.

3.2.4 Interrelation of deforestation, forest fragmentation and degradation

Unsustainable selective logging leads to the degradation of intact old-growth forest. In parts of the BLA, e.g. in Pará and Mato Grosso States, the forest areas under selective logging are larger in comparison to deforested areas or forests affected by fire. A study from Beuchle et al. (2019) [106] on the Northern part of Mato Grosso State (over 400000 km² analysed) provided detailed data on selective logging and forest fire areas, which was intersected with JRC-TMF data [29] on degraded forests for the years 2001-2011. The results show that selective logging causes approximately 75% of forest degradation in this region, while 25% of the JRC-TMF forest degradation areas were burned. Matricardi et al. (2020) had calculated and 3:1 relation between selective logging areas and forest fires in the BLA for the years 1992-2014 [63]. The relation for the period 2000 – 2010, given by Hosonuma et al. (2012), between areas of selective logging and burned forests is roughly 4:1 for tropical Central and South America [107]. The area relation between the two causes of forest degradation, however, has changed in recent years, especially for the Southern and Eastern Amazon, due to a relative increase of burned forest areas compared to areas of selectively logged forests.

Selective logging can increase forest fire susceptibility as the tropical forest becomes more fragmented; in addition, the kindling material left from selective logging increases the chance of spreading fire throughout the fragmented forests in the Amazon region [108]. For the forest of Northern Mato Grosso still existing by the end of 2018 (220,200 km^2 or 53.4% of the total area), Beuchle et al. (2019) [106] analysed the forest's degradation history for the years 1996-2018. The study concludes that the relation between selectively logged areas and burned forest areas is 2:1, comprising an accumulated 32.7% (72,000 km^2) of the forest in 2018 as affected by selective logging and 15.3% (nearly 34,000 km^2) as burned at least once during the previous 23 years. Approximately 4.9% (10,800 km^2) thereof fall in both categories, thus have been selectively logged and burned during the analysed period (Figures 13 and 14). However, the area percentage of forest fires and selectively logged forests and their interrelated dynamics are most certainly different in other parts of the Amazon, which exhibit different interactions between the numerous factors related to forest cover change, like e.g. dry season length, road access, forest protection status or local law enforcement strategies.

Deforestation and forest degradation causes and effects are interrelated. Many degraded forest areas (by fire or selective logging) are deforested at a later stage [50],[109]. On the other hand, as mentioned, deforestation in the Amazon forest causes forest fragmentation and edge effects at the forest borders, both leading to a degradation of

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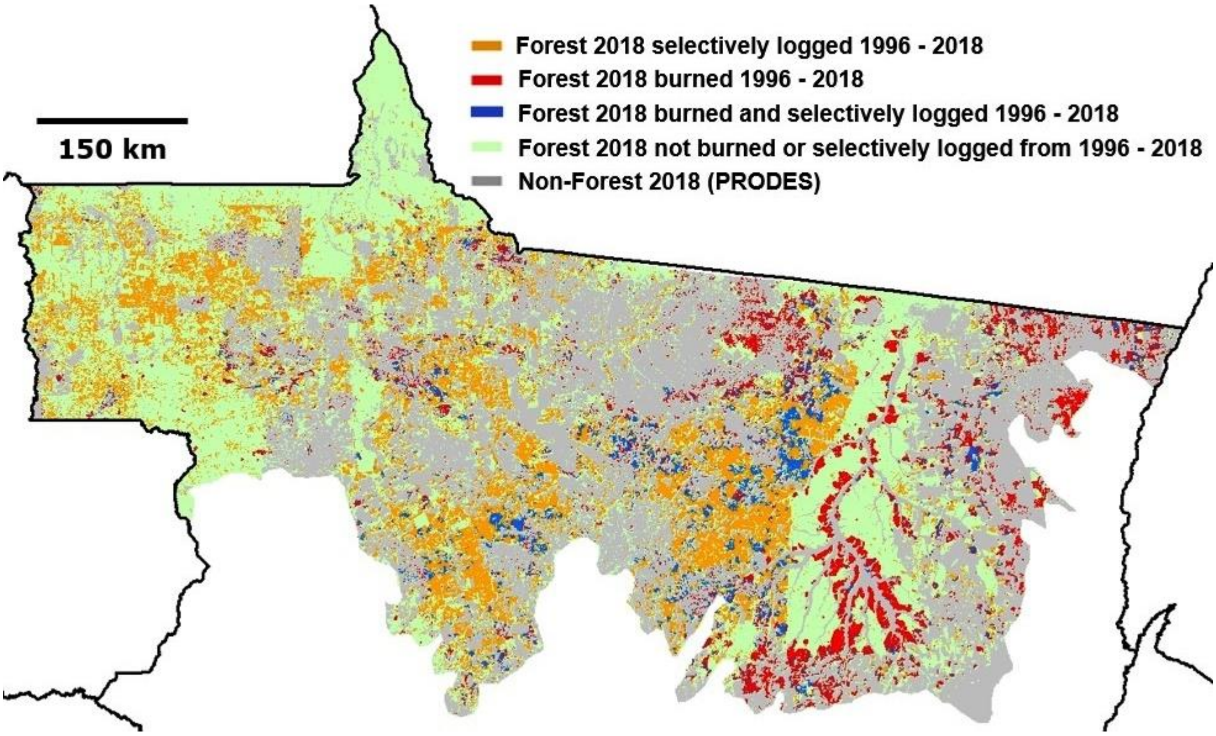
[29] https://forobs.jrc.ec.europa.eu/TMF/

these areas. Forest edges play an important role in the propagation of forest fires, as they often start out as maintenance fires in pastures adjacent to the forest.

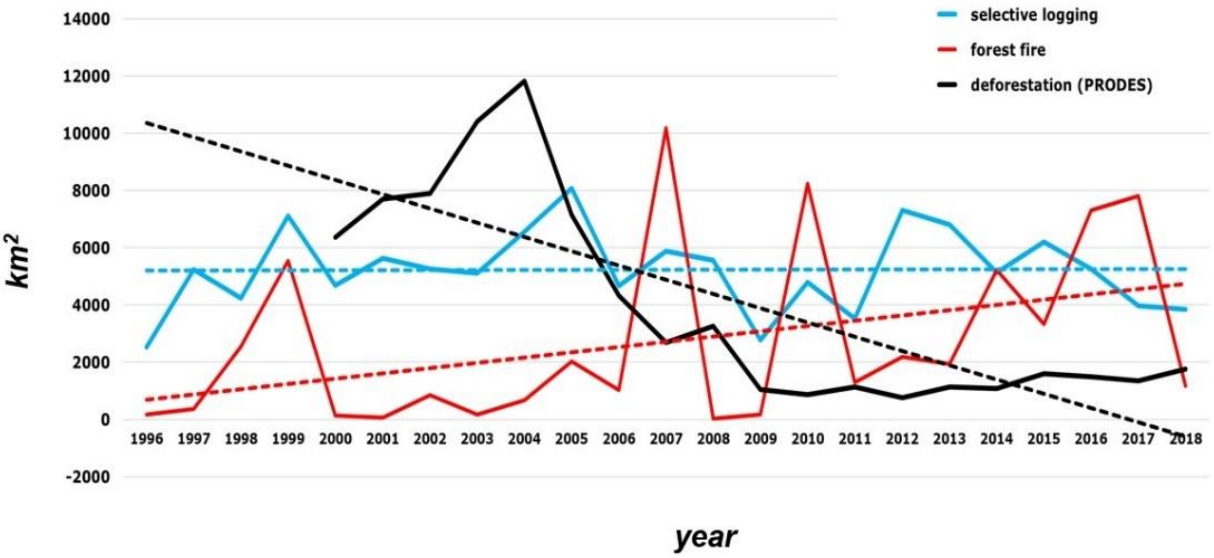
However, there is an interrelation between deforestation borders as well as in selectively logged forest in relation to forest fires [110]. Agricultural management fires increasingly escape into the forest, which is facilitated by the increased heat, dryness, dead wood and leave litter at the deforestation borders (edge effects) [69] and by the increasing frequency of droughts. With droughts increasing in frequency and areal extent, fire leaking into fire-prone forests may be the main force of biome conversion in the future [78].

Figure 13. Forest degradation history from 1996 – 2018 for 2018 forest areas in Northern Mato Grosso (according to INPE-PRODES), not affected (green), affected by selective logging (orange), fires (red) or both by selective logging and fires (blue) [106]. Image width: ca. 1300 km



It has been shown that there are synergistic effects of three kinds of disturbances on a tropical forest: fragmentation, forest fire and windstorms. Forest fires, often leaking from burning pastures into the degraded forest edges, modify the forest structure by damaging tree trunks and thus compromising tree stability while killing some of the trees. The decreasing canopy cover at the burned forest edges leads to an increase of wind-related damage through the torque that wind exerts on individual crowns [111].

Figure 14. Yearly areas of deforestation, selective logging and forest fire in Northern Mato Grosso from 1996 – 2018, according to Beuchle et al. (2019) [106]. Not included are areas of selective logging or burned forests that had been deforested until 2018. The trend lines appear dashed of the same colour.

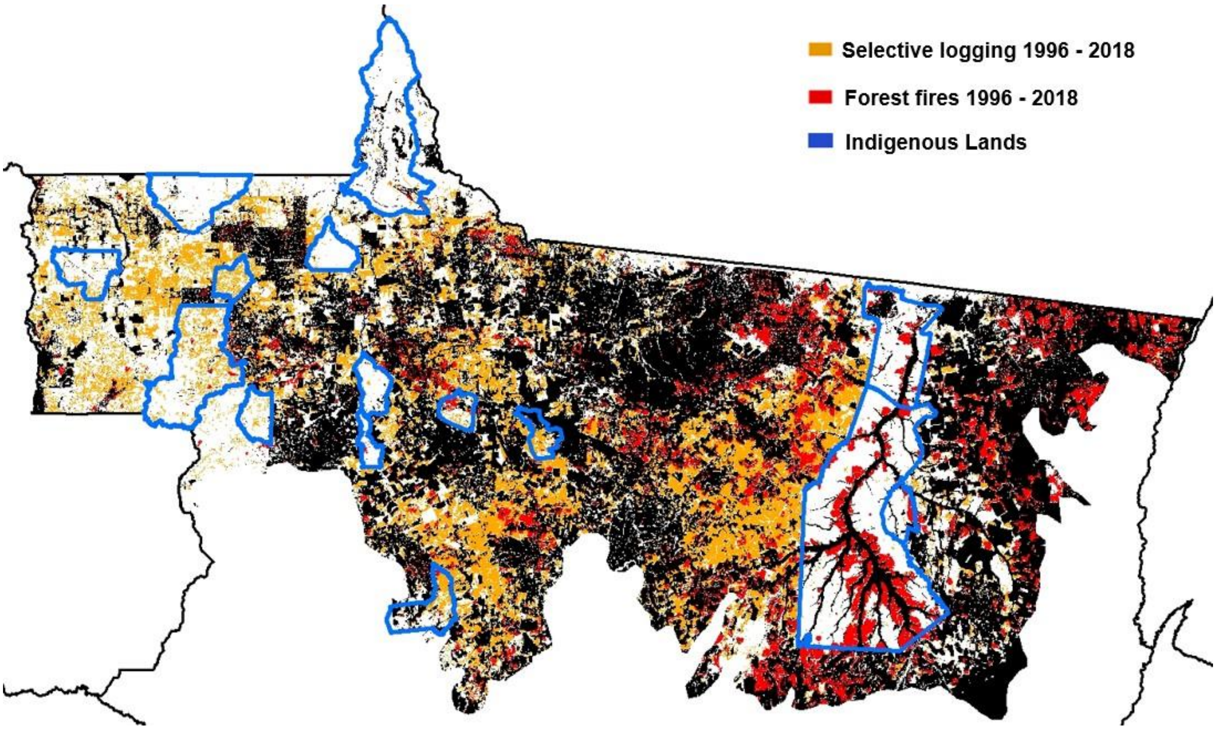


3.3 Protected areas, road building and infectious diseases in relation to forest cover change in the BLA

3.3.1 The role of protected areas for forest preservation in the BLA

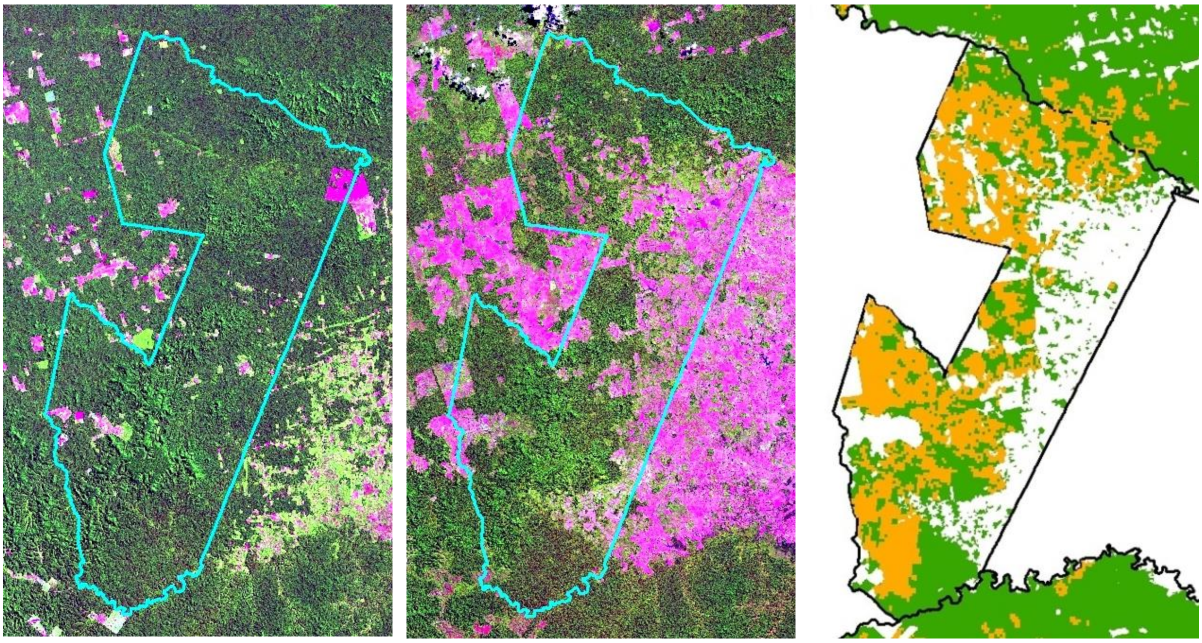
In 2017, almost 48% of the BLA were covered by Protected Areas (PAs), i.e. either Conservation Units (CUs) or Indigenous Lands (ILs), which, if correctly managed, can play an essential role in the reduction of deforestation and forest degradation in the Amazon [112]. In 2017, 374 ILs were demarcated and identified, occupying about 22.8% of the BLA [113], while 25.4% of the BLA were covered by CUs, managed either by the national or by state authorities. While recent trends in deforestation and forest fires in Brazil caused concern, the country's system of PAs, aimed at ecological preservation and curbing deforestation, was an example of effective policy. In general, the efficiency of PAs with respect to deforestation and forest degradation is consensual [114]; however, effectiveness of PAs in this context is not straightforward to measure, as specifically the location of the different PAs (distance to roads and cities) plays an important role in deforestation and forest degradation within (and outside) these areas [112]. Across conservation and deforestation regimes, the PA's impacts, i.e. proven effectiveness, clearly rise with pressure [115]. In consequence, the impacts of the PAs vary considerably, however, including effectively zero impacts in some cases, due to the PA's locations, types, and law enforcement policy [116] and varying local context.

Figure 15. Forest (white), deforestation (black), selective logging (orange) and forest fires (red) outside and within Indigenous Lands in Northern Mato Grosso [106]. The protection works for some, but not for all Indigenous Lands (blue outlines). Image width ca. 1300 km.



Not all ILs show the same protective effect. According to Baragwanath and Bayi (2020) [117], the effectiveness of the forest preservation within the ILs depends on successful common-property resource management with clearly defined boundaries, collective management, and recognition of rights to organize monitoring systems, sanctions, and conflict resolution mechanisms. The authors argue that indigenous territories will only be most effective at curbing deforestation and forest degradation when they are granted full property rights on their territory.

Figure 16. The Indigenous Land (IL) of the Awá-Guajá people in Maranhão State has been recognized in 1992 and received an official protection status in 2005. It is constantly threatened by illegal deforestation and illegal selective logging [118] [30]. Until 2018 ca. 36% of the IL had been deforested, while 54% of the remaining forest had been affected by illegal selective logging between 2000 and 2018 (orange areas) [106]. IL Awa-Guajá in 1988 (left), and in 2020 (centre), mapping of affected areas from selective logging 2000-2016 (right). Images width: 45 km.



Local circumstances affect the effectiveness of ILs regarding forest preservation to a considerable extent. The closeness to roads or cities, to intensively used agricultural land, the population outside and within the ILs, and the ILs internal tribal organization play a role in the success or malfunction of ILs with respect to forest protection. In addition, the applied law enforcement strategies (incl. effective implementation of monitoring and early-warning systems), the status of the ILs (see above) and the overall disposition of the Brazilian government and government organizations towards indigenous rights are equally important factors in this context.

However, in general protected forests experienced less forest loss than did unprotected lands at all distances from roads and navigable rivers. All protected area types mitigated deforestation risk and had overall four times less deforestation than unprotected areas even when highly accessible. The continued presence of protected areas is critical in the Amazon, and is especially crucial where forests are accessible via roads or navigable rivers [119].

Many Indigenous Lands are known to contain valuable undeveloped mineral deposits (including a range of commodities, such as gold, copper, and iron ore). In the beginning of 2020, the Brazilian government signed a new legislation permitting mining inside Indigenous Lands. The proposed policy changes, if approved by Congress, have the potential to not only permanently transform the lives of indigenous communities, but also negatively affect a large extent of biodiverse forests and the ecosystem services they provide [45]. In the wake of the proposed law, the number of requests from mining companies for concessions in Indigenous Lands have hit a new high in 2020 [31]. The final decision on the bill still has to be taken by the Brazilian Congress.

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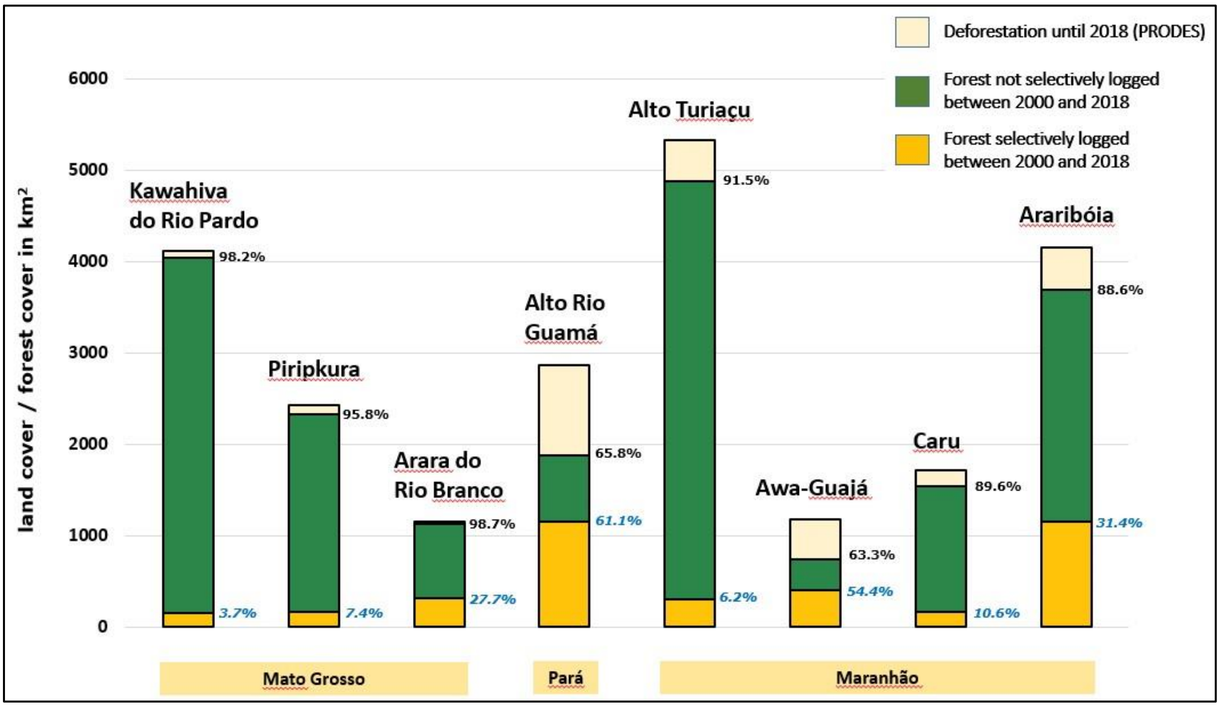
[30] http://www.funai.gov.br/index.php/ascom/1817-a-terra-indigena-awa-guaja

[31] https://pulitzercenter.org/pt-br/stories/com-estimulo-de-bolsonaro-pedidos-para-minerar-em-terras-indigenas-batem-recorde-em-2020

Figure 17. Illegal deforestation and illegal selective logging in eight different Indigenous Lands of "isolated tribes"[32] in Mato Grosso, Maranhão and Pará States [106]. The ILs in Mato Grosso are rather distant from larger towns and roads while the ILs of Maranhão and Pará are easily accessible by roads and are close to large agricultural areas. The percentages in black show the forest cover in the ILs, while the blue percentages show how much of the remaining forest was affected by selective logging from 2000-2018.



3.3.2 The role of roads for deforestation and forest degradation in the BLA

The Brazilian government in 2019 has financed in 2019 the pavement of the last missing stretch of the BR-163 Cuiabá-Santarém Highway, connecting the Southwestern Cerrado in Central Brazil with the Amazon River[33]. However, according to Ferrante and Fearnside (2020), the paving of highways in the Amazonian interior has been shown to increase the number and size of vehicles and to result in increased migration, land speculation, and deforestation [120].

The construction and improvement of primary roads potentially leads to the construction of secondary, tertiary, and even illegal roads in the region. In general, the expansion of the road network, including both official and unofficial roads, into formerly inaccessible forest areas is a key driver of deforestation and forest degradation. Road-driven forest clearing is associated with biodiversity loss, displacement of indigenous communities, increased greenhouse gas emissions and reduced carbon storage. Roads also increase land values in adjacent areas, which in turn drives speculation and deforestation in order to establish and maintain land tenure [121].

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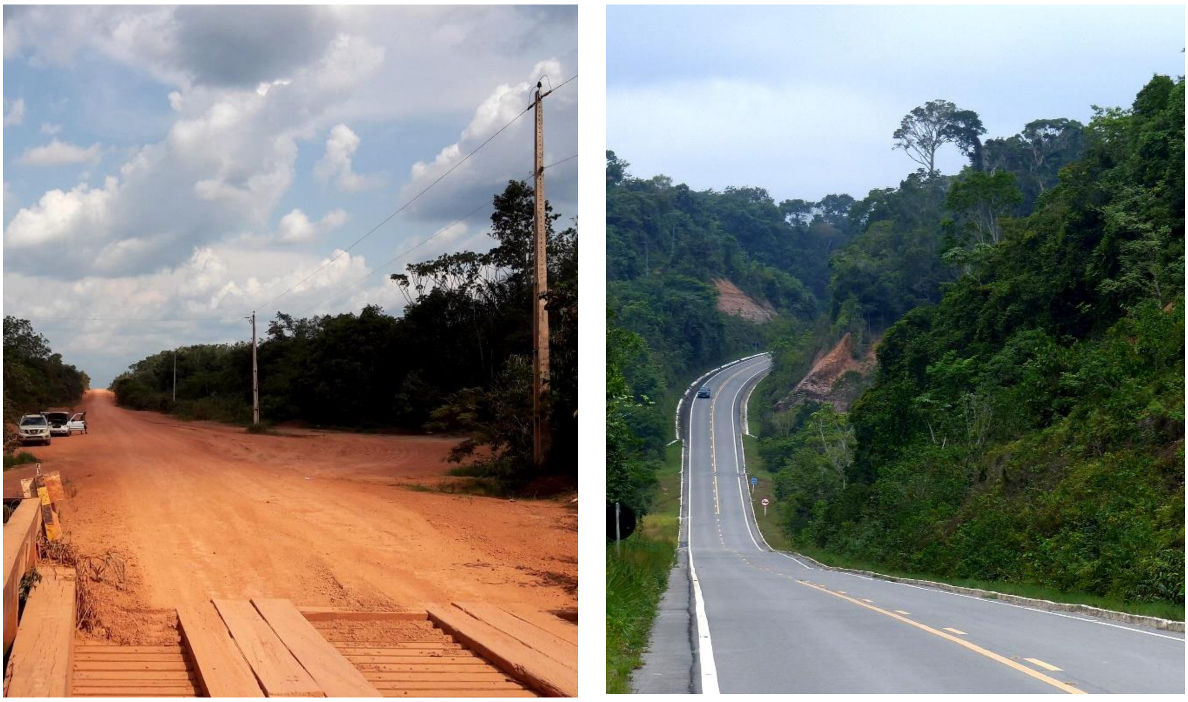
[32] https://pib.socioambiental.org/pt/Onde_est%C3%A3o_os_isolados%3F

[33] https://www1.folha.uol.com.br/poder/2020/10/trecho-da-br-163-foi-asfaltado-no-governo-bolsonaro-como-afirma-post.shtml

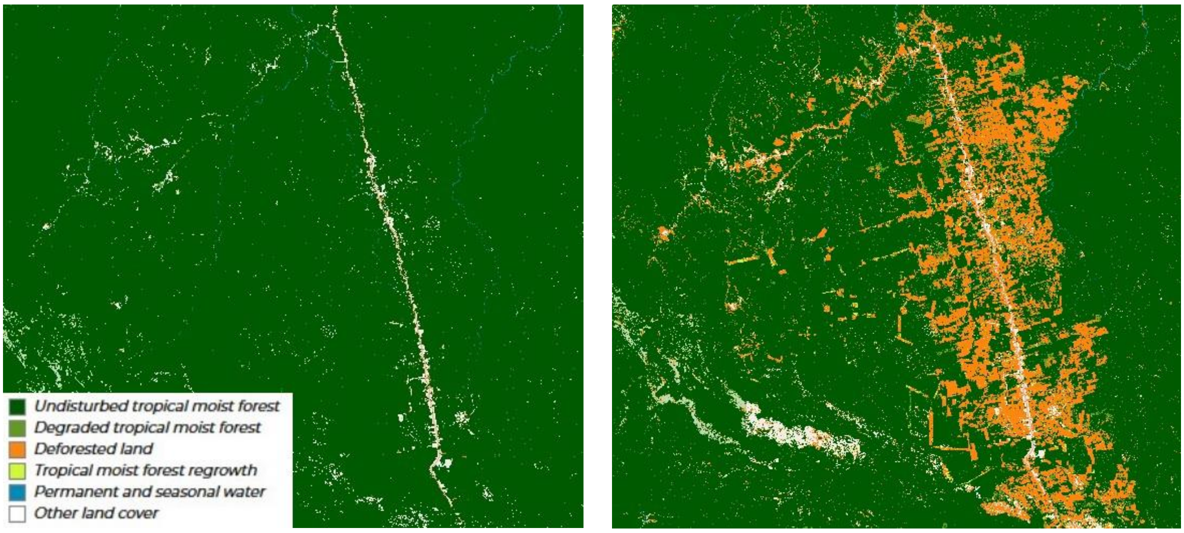
Figure 18. Paved and unpaved highways in the BLA: the Trans-Amazon Highway BR-230 (left) near Santo Antonio do Matupi in the South of Amazonas State, and the BR-174 (right) between Manaus and Boa Vista (photos by Thais Almeida Lima and René Beuchle)



The Brazilian Federal Government built highways in the Amazon with a strategy of land integration and infrastructure for transportation of commodities (BR-163—Cuiabá-Santarém, BR-230—Trans-Amazônica Pará/Amazonas, BR-319—Porto Velho/Rondônia-Manaus/Amazonas) from the 1960s through to the 1980s. While the BR-163, which constitutes an export corridor for soybeans via the Amazon River [122–124], has been completely paved in 2019, the other two roads cutting straight through the Amazon forest are still dirt roads, being practically impassable in the wet season. Paving the BR-319 is high on the political agenda of the current Brazilian government. However, as can be observed for the BR-163 Highway, the buffer of the impact (deforestation, forest degradation, population flux, land grabbing, land conflicts etc.) usually goes well beyond a 40 km buffer, which is considered by the Brazilian road planning process as ‘impacted’. Many indigenous communities along the road will be affected by paving the BR-319, none of which have been consulted yet [125]. Ferrante and Fearnside (2020) [120] estimate that paving the BR-319, together with the following deforestation, would affect 63 official Indigenous Lands with 18,000 people.

Roads can bring social and economic benefits to the region, such as increasing the accessibility of agriculture and industrial products, electricity, and essential public services (e.g., education and health). On the other hand, roads also cause significant environmental and social impacts, such as deforestation and fires, the influx of exotic species, hunting, illegal logging, land speculation and the rise of diseases and criminality. However, even major roads such as BR-319, BR-163, and BR-230 lack development plans that reconcile social, economic, and environmental issues [126,127].

Figure 19. Effect of road building / road consolidation seen on JRC-TMF data: The Cuiabá-Santarém Highway BR-163 near the town of Novo Progresso (Pará) in 1990 (left) as a narrow unpaved road and 2019 (right)[34] mostly paved, in some areas as two-lane highway. Image width ca. 300 km



Two types of roads are predominant in the Amazon: official and unofficial roads. Official roads are extensive roads built mainly by the Federal Government in the 1970s to interconnect the region to the rest of Brazil. Unofficial roads are mostly built by the private sector to explore and access natural resources in the Amazon [128]. Vicinal roads or agro-roads, subtypes of unofficial roads, also occur in the region. They are the driving force behind the expansion of new fronts of deforestation, irregular occupation, fires, and illegal logging, and require constant monitoring of their emergence to combat illegal environmental activities. While assessing relationships between past deforestation and existing networks of highways, navigable rivers, and all other roads, including more than 190,000 km of unofficial roads, Barber et al. (2014) [119] found that deforestation was much higher near roads and rivers than elsewhere in the Amazon. Nearly 95% of all deforestation occurred within 5.5 km from roads or 1 km from rivers.

Currently, political factors and broad but typically unsubstantiated economic aspirations drive the planning and decision processes for infrastructure. Road planning needs to take environmental and social concerns seriously, which does not mean giving up on development [121]. This would mean careful planning with serious impact assessments to account for environmental and social issues that can arise from new roads, and a strong law enforcement strategy in case of collateral environmental and social damages caused by the new roadways, occurring through e.g. illegal deforestation, illegal logging, illegal mining, forest fires or through the compromising of indigenous rights.

3.3.3 The role of tropical deforestation and forest degradation for the spread of zoonotic diseases

Amazonian biodiversity is increasingly threatened due to the weakening of policies for combating deforestation, especially in Brazil [129]. Amazonia has a prominent role in regulating the Earth’s climate, with forest loss contributing to rising regional and global temperatures and intensification of extreme weather events [130]. The association between anthropogenic action in the Amazon rainforest, climate change, alterations in

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[34] https://forobs.jrc.ec.europa.eu/TMF/

vector dynamics, human migration, genetic changes in pathogens and the poor social and environmental conditions in many Latin-American countries can give rise to the "perfect storm" for the emergence and re-emergence of human infectious diseases in Brazil and other Amazonian countries [11].

Deforestation and the shift of natural areas to human-dominated areas result in large-scale loss or degradation and fragmentation of habitats and wildlife populations. The resulting remnants of natural areas show increased risk for zoonotic diseases. Fragmented habitats can lead to an increase of host movement from the patches of nature into areas used for livestock and urban settlements. The increasing human encroachment in fragmented natural areas (including livestock grazing) promotes higher contact rates between pathogens and vectors, with domesticated animals and humans [131].

The edges of the remaining natural areas are thought to be major launch pads for novel viruses that may spill over to humans. Roadless areas, which are highly relevant for the preservation of native biodiversity by ensuring habitat for viable populations, and by functioning as a barrier against invasive alien species and other human influences, are therefore also highly relevant for disease control. For example, the length of the edges of remaining forests increases when forest areas are made accessible by building roads. In these forest edge areas, humans and their livestock are more likely to come into contact with wildlife, especially in areas with a reduction of more than 25% in forest cover. Road building, expansion of human settlements, and livestock and arable land close to remaining forests have led to increasing pathogen spillovers [132].

Strong evidence points to human-animal interactions as the source of COVID-19 as well as past pandemics, including SARS-CoV, MERS-CoV, and Ebola, to name a few. Indeed, it is likely that the next infectious agent to adversely affect humanity will have animal origins [133].

The clear link between deforestation and virus emergence suggests that a major effort to retain intact forest cover would have a large return on investment even if its only benefit was to reduce future virus emergence events. On the specific Brazilian situation, Dobson et al. (2020) [134] state that at an annual cost of $9.6 billion, direct forest-protection payments to outcompete deforestation economically could achieve a 40% reduction in areas at highest risk for virus spillover. According to the authors, widespread adoption of the earlier, successful Brazilian forest protection policy model could achieve the same reduction for only $1.5 billion annually by re-strengthening forest monitoring and law enforcement, removing subsidies that favour deforestation, restricting private land clearing, and supporting territorial rights of indigenous peoples.

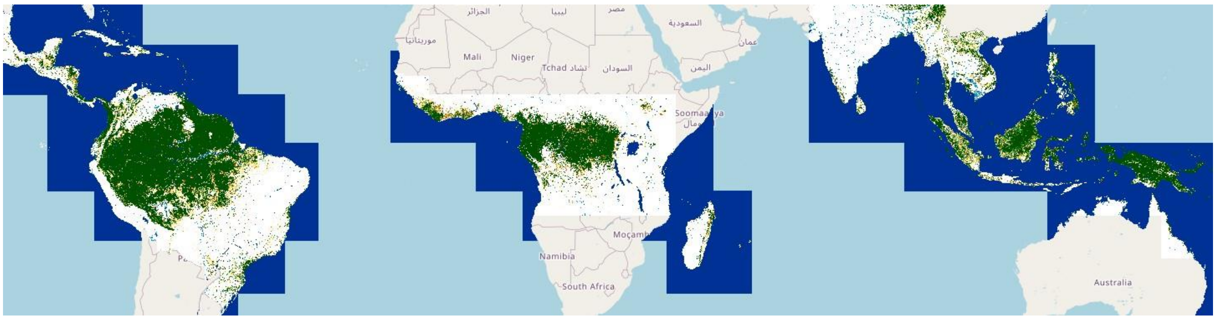
4 Monitoring deforestation and forest degradation in the humid tropics: the JRC-TMF approach

The JRC has carried out a study to accurately characterize the changes in tropical humid forests to support conservation policies and to better quantify their contribution to global carbon fluxes. This study was supported by the Directorate-General for Climate Action (DG-CLIMA) through the Roadless-For pilot project (Making efficient use of EU climate finance: Using roads as an early performance indicator for REDD+ projects) and since 2019 through Lot 2 (‘TroFoMo’ - Tropical moist Forest Monitoring) of the ForMonPol (Forest Monitoring for Policies) project.

The resulting pan-tropical dataset covering the period 1990-2019 is available for visualization (https://forobs.jrc.ec.europa.eu/TMF/) with a JRC Technical Report describing the approach [135] and a publication in *Science Advances* [109].

The JRC dataset on Tropical Humid Forest was created by cloud-computed analysis of imagery from the US-American Landsat satellites that are available over the Amazon region since 1984. The sensors on-board the Landsat satellite have a 30 m spatial resolution and a temporal revisit cycle of 16 days [136].

Figure 20. Pan-tropical coverage of the JRC-TMF dataset



The JRC dataset provides information on changes in the tropical humid forest cover since 1985, it tells us in which year(s) forest pixels had been deforested or degraded, or when non-forest pixels have started to regrow as forest. The data differentiates between short-term forest disturbances (e.g. caused by selective logging) and long-term ones (e.g. by severely burned forest or deforestation). At the pantropical scale, the occurrence of deforestation and the extent of forest degradation are documented on an annual basis.

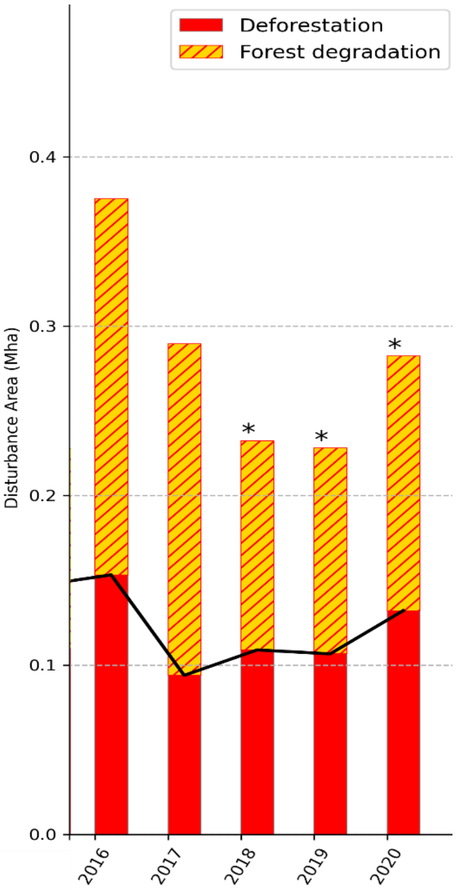
The dataset allows understanding if a forest had been degraded before deforestation, been deforested without previous degradation or where and when a forest has regrown after a disturbance. The complex temporal dynamics of tropical forest cover change can be traced from this dataset at regional, national or local scale.

JRC-TMF data reports on sudden disturbances within the forest or its total destruction, causing changes in the forest canopy (by selective logging or forest fire) or its total removal (deforestation). Forest degradation caused by the edge effects or forest fragmentation (see chapter 3.2.1), i.e. causing protracted changes like lingering changes of forest species composition or insidious degradation of forest ecosystems services, are not reported in the JRC-TMF data.

4.1 Trends in deforestation and forest degradation for the Pan-Amazon between 2002 and 2020 - estimates from the JRC-TMF dataset

We report here the trends in national deforestation rates for the six largest countries in the Pan-Amazon region (Brazil, Colombia, Venezuela, Peru, Bolivia and Ecuador) from 2002 to 2020, as well as for the Guiana Shield region (comprising Guyana, Suriname and French Guiana) and the Pan-Amazon (Amazonia *sensu stricto* and Guiana regions, according to Eva and Huber, 2005) [30]. The figures 24-30 report on forest cover changes of the moist forest in these countries, thus the statistics do not include the changes in e.g. the seasonal or dry forests and savannas of Venezuela, Colombia, Peru and Ecuador, in the Brazilian Caatinga and Cerrado biomes and in the Bolivian Chaco. For comparison, the corresponding statistics from the Global Forest Change (GFC) dataset are displayed in the mentioned figures; a description of GFC data is given in chapter 4.2. Both JRC-TMF and GFC datasets are compared in section 4.3 to the Brazilian estimates of humid forest cover change in the Brazilian Legal Amazon, provided by INPE (PRODES).

Figure 21. Subset of JRC-TMF humid forest disturbances mapping for Peru for the past five years. The stars (for the years 2018-2020) indicate that the distribution of the two classes within the yearly overall forest disturbances is estimated based on the 2002-2017 average



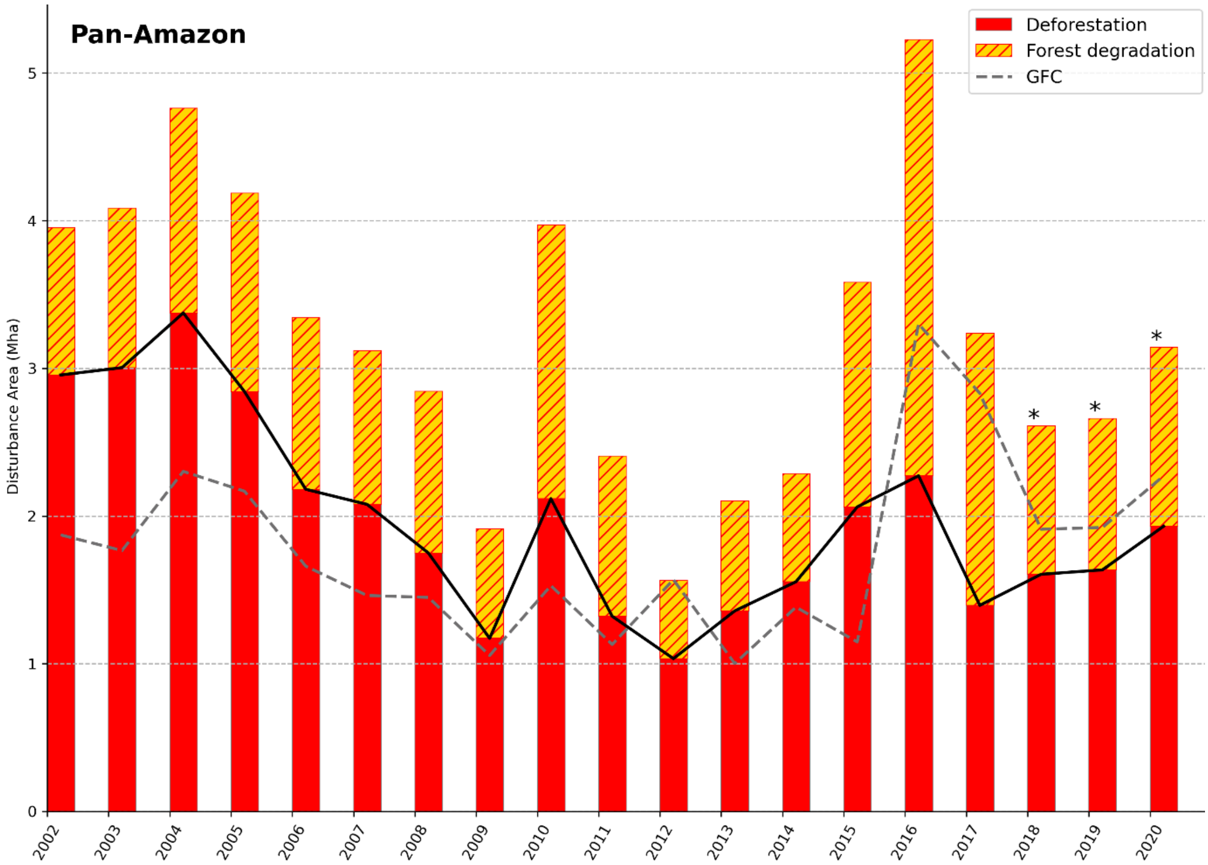
The JRC-TMF classification process starts out by mapping disturbances in the forest canopy on a yearly basis, regardless of their permanence. The distinction between deforestation and forest degradation is made three years after the disturbance occurred by measuring the permanence of the forest disturbance over time. If the forest canopy is disturbed permanently, i.e. shows no signs of forest regrowth over the three years following the disturbance, the 'forest disturbance' pixel falls into the deforestation class. If a 'forest disturbance' pixel shows clear signs of forest regrowth within the three years following the disturbance, it is classified as forest degradation.

In consequence, the distribution of yearly deforestation and forest degradation areas within the measured yearly overall forest disturbance areas are consolidated until 2017, but are estimated (indicated by stars in Figure 21) for the years 2018-2020 on basis of the 16-year average for the period 2002-2017.

We have compared the JRC-TMF statistics in the Figures 22-30 (red/orange bars and black line) with corresponding data on "forest cover loss" from Global Forest Change (GFC)[35] (grey dashed lines). For comparison, we extracted both JRC-TMF data and GFC data for the Pan-Amazon and the BLA based on the area definitions of Eva and Huber (2005) and of PRODES, respectively. For country statistics comparison, we extracted JRC-TMF and GFC data based on the GAUL Level 0 country borders[36] and the year 2000 JRC-TMF humid tropical forest extent as reference layer.

4.1.1 Pan-Amazon

Figure 22. Forest disturbances in the Pan-Amazon humid forest from 2002-2020. The geographic basis are the areas of "Amazonia Sensu Stricto" and "Guiana", according to Eva and Huber (2005) [30]. GFC statistics appear as gray dashed line.



Brazil drives the trend of forest cover change over the past 20 years in the Pan-Amazon, as it covers the largest part of the Amazon forest within the Pan-Amazon region and is the major contributor of deforestation and forest degradation area in the region. The decrease in Brazilian deforestation from 2004 onwards can be observed also in the Pan-Amazon statistics. The large areas of forest degradation in 2010 and 2015-2017 reflect the large amount of burned forest, in Brazil and elsewhere (including e.g. the large Bolivia fires in 2010). The significant increase of forest cover change in 2020 can also, at least in part, be attributed to the increase in burning forests 2020. Altogether, 31,418 km^2 of forest were

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[35] https://earthenginepartners.appspot.com/science-2013-global-forest

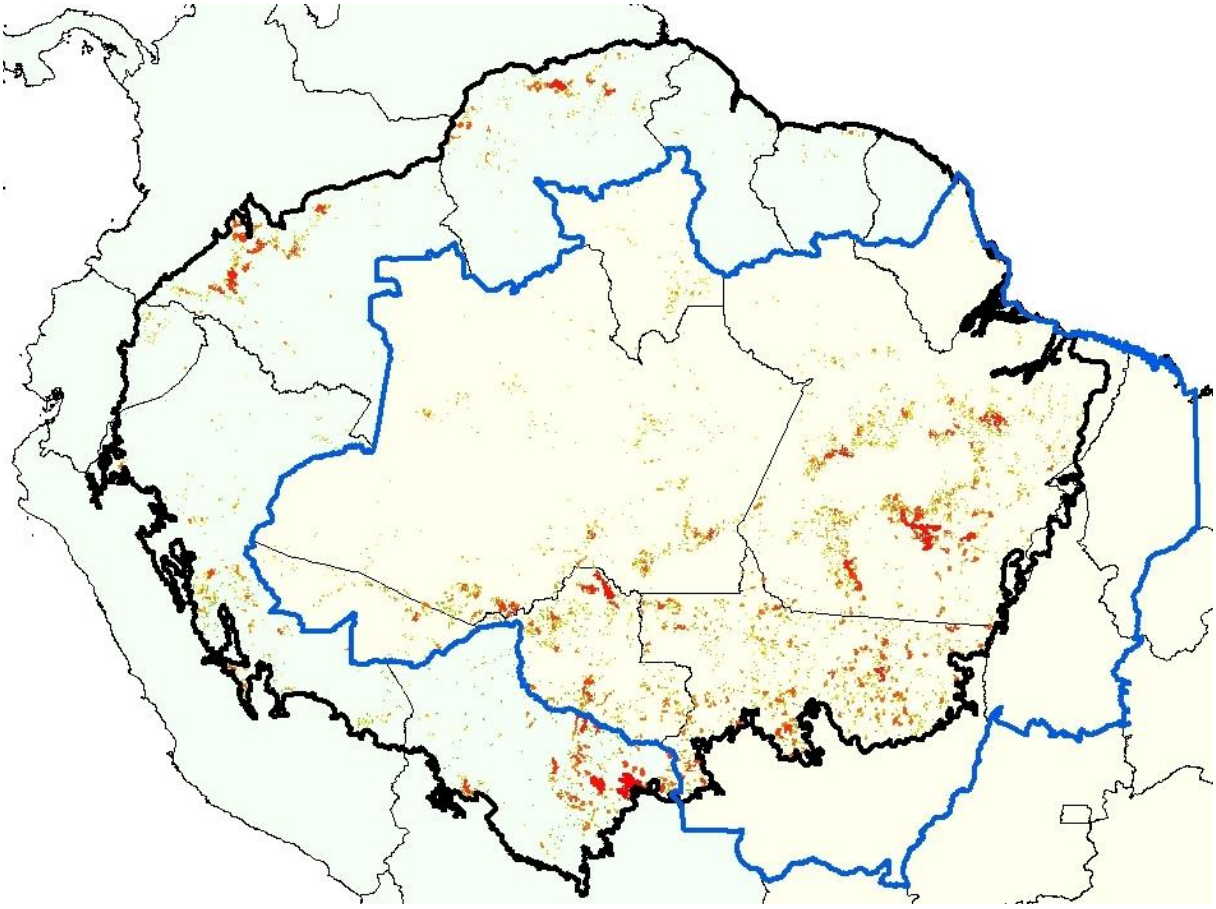
[36] https://developers.google.com/earth-engine/datasets/catalog/FAO_GAUL_2015_level0

either deforested or degraded in the Pan-Amazon in 2020, constituting an increase of more than 18% with respect to 2019.

GFC data shows lower forest loss values than JRC-TMF for the first six years of the comparison (2002-2007), but the two datasets have similar estimates for the following eight years (2008-2015). For 2016 and 2017, the GFC shows considerable more forest loss than JRC-TMF, most probably due to the change in GFC data processing (see chapter 4.2); for the years 2018-2020, the GFC forest loss estimate is constantly ca. 0.2 Mha (2,000 km^2) higher. Large forest fires and some features related to selective logging (e.g. logging decks) are often mapped as 'forest loss' in GFC data, whereas they are mostly mapped as forest degradation in JRC-TMF data.

The deforestation and forest degradation areas of the single countries do not add up to the Pan-Amazon statistics, as for the country statistics also humid forest areas outside the Amazon region are considered by JRC-TMF data, as e.g. the Choco Pacific Forest and the mountain forests in Colombia or the Mata Atlântica in Brazil.

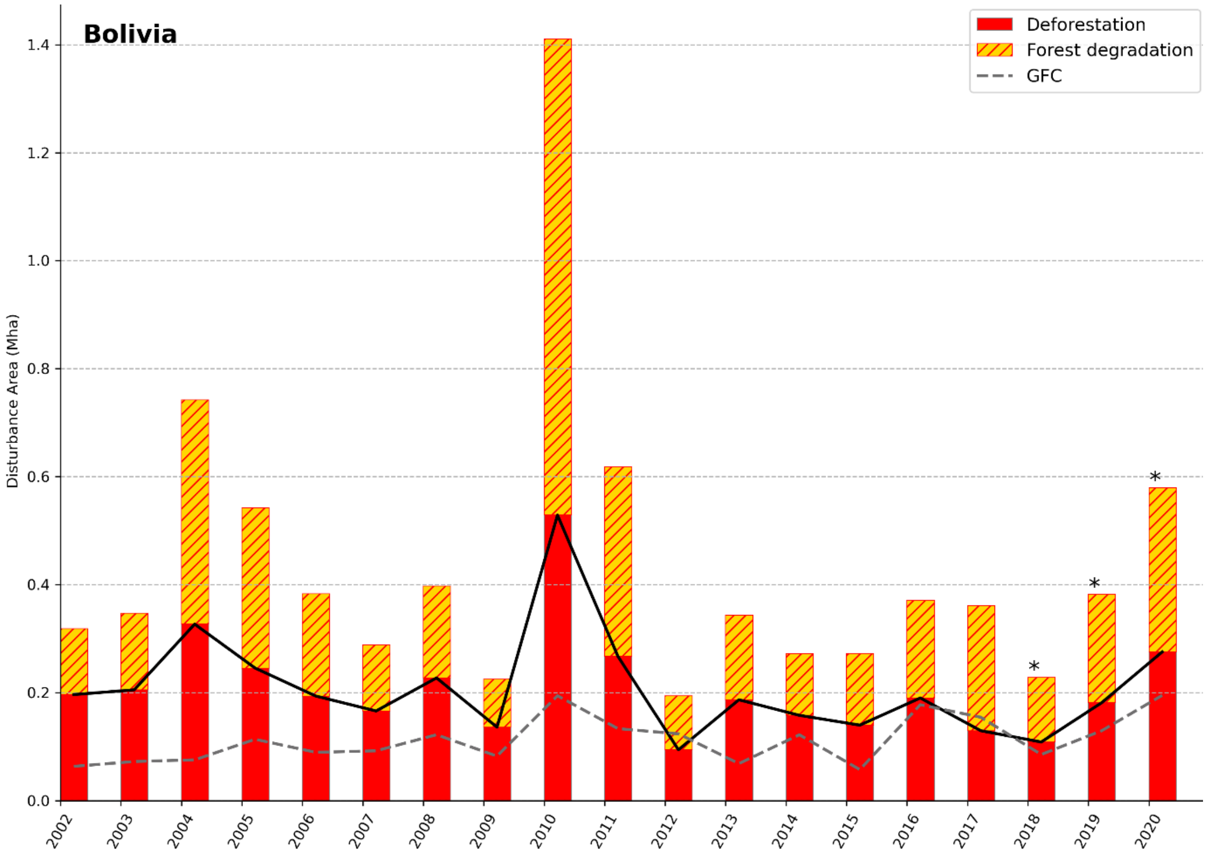
Figure 23. Distribution of JRC-TMF forest disturbances (in red) in the Pan-Amazon humid forest in 2020. The Brazilian territory appears in white, while the other South American countries are shown in light blue. The bold black outline represents the Amazon basin lowland forest and the Guiana Shield, according to Eva & Huber (2005) [30], the blue line represents the Brazilian Legal Amazon, with thin black lines showing the international boundaries and Brazilian State boundaries. Image width ca. 4,250 km^2



For the countries other than Brazil the forest disturbances mostly occur close to the borders of the Amazon biome, e.g. showing the deforestation hot spot at the Northern border of the Colombian and Venezuelan Amazon and some forest cover change activities on the western borders in Peru and Ecuador (Figure 23). In Brazil and Bolivia a number of roads are cutting through the Amazon region (e.g. the BR-230, BR-163 and BR-364 in Brazil or the RN 10 in Bolivia), in consequence, forest disturbances occur often along these transport corridors.

4.1.2 Bolivia

Figure 24. Forest disturbances in the Bolivian humid forest from 2002 – 2020, according to JRC-TMF. GFC statistics appear as gray dashed line.



The FFC trends for Bolivian humid forests in the last 20 years show the highest peaks for years of severe forest fires, as for the year 2010, when the Government announced a national emergency to combat the more than 15,000 km^2 of burning land[37]. While the forest cover change areas stayed on similar levels in the period from 2012 – 2019, a new wave of fires swept through the Bolivian Amazon in November 2020, burning large areas of forest[38]. This is reflected in the JRC-TMF statistics: altogether 5,794 km^2 of humid forest were either deforested or degraded in 2020, which constitutes an increase of ca. 52% with respect to 2019.

GFC estimates are mostly lower than JRC-TMF, but follow a similar yearly trend.

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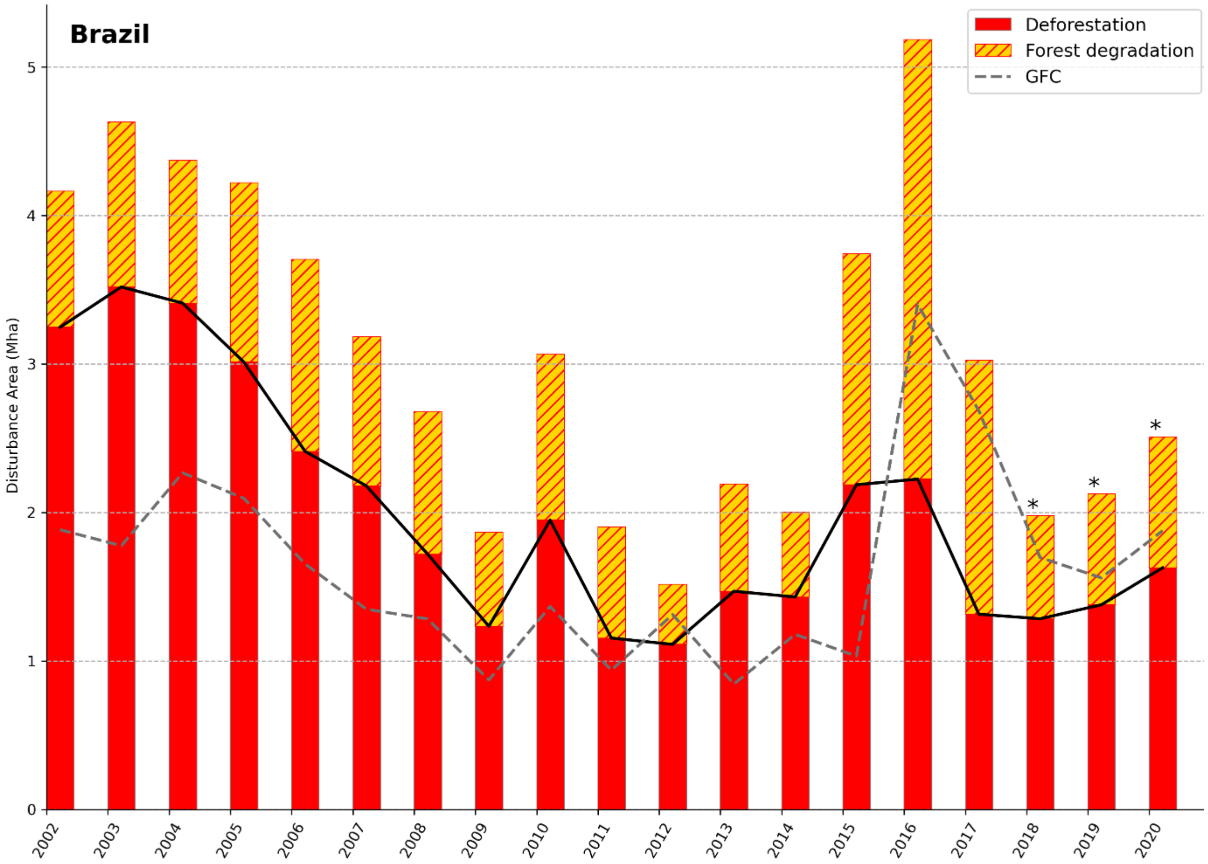
[37] https://www.bbc.com/news/world-latin-america-11033521

[38] https://news.mongabay.com/2020/11/a-million-hectares-ablaze-as-forest-fires-sweep-through-bolivia/

4.1.3 Brazil

Figure 25. Forest disturbances in the Brazilian humid forest from 2002 – 2020, according to JRC-TMF. GFC statistics appear as gray dashed line.



The Amazon being the Brazilian region undergoing most changes in humid forest cover, its forest dynamics clearly drive the overall Brazilian humid forest cover change (FCC) statistics reported by JRC-TMF data. The decrease of the Amazon deforestation after 2004 and the peaks in forest degradation, mostly due to forest fires in 2010 and 2015-2017, are visible in the BLA and the Brazilian statistics from JRC-TMF. Altogether 25,094 km^2 of forest were either deforested or degraded in 2020 in the Brazilian humid forest (i.e. Amazon forest and Mata Atlântica), constituting an increase of more than 18% compared to 2019.

GFC estimates are generally lower than JRC-TMF, specifically in the years until 2007, but show a similar trend. From 2008 onwards, they are closer to JRC-TMF estimates, with the exception of the years 2016-2017. The notable difference for these two years most probably arises from a "temporal inconsistency" in GFC data due to a change of their image processing method after 2015[39] (see chapter 4.2 for more detailed information). The reason for the consistently higher 'forest loss' estimates of GFC data for Brazil from 2018 onwards has been described in the section 4.1.1.

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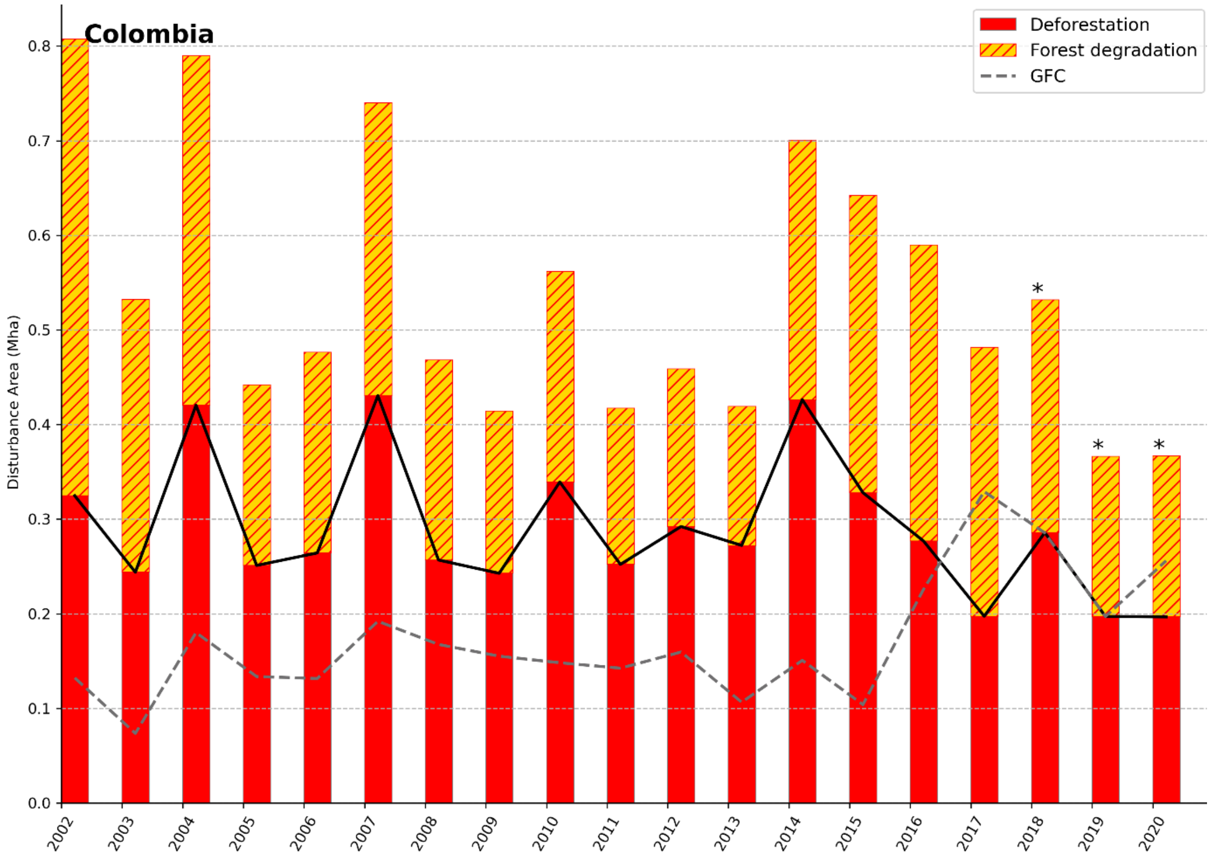
[39] https://www.globalforestwatch.org/blog/data-and-research/tree-cover-loss-satellite-data-trend-analysis/

4.1.4 Colombia

Figure 26. Forest disturbances in Colombian humid forest from 2002 – 2020, according to JRC-TMF. GFC statistics appear as gray dashed line.

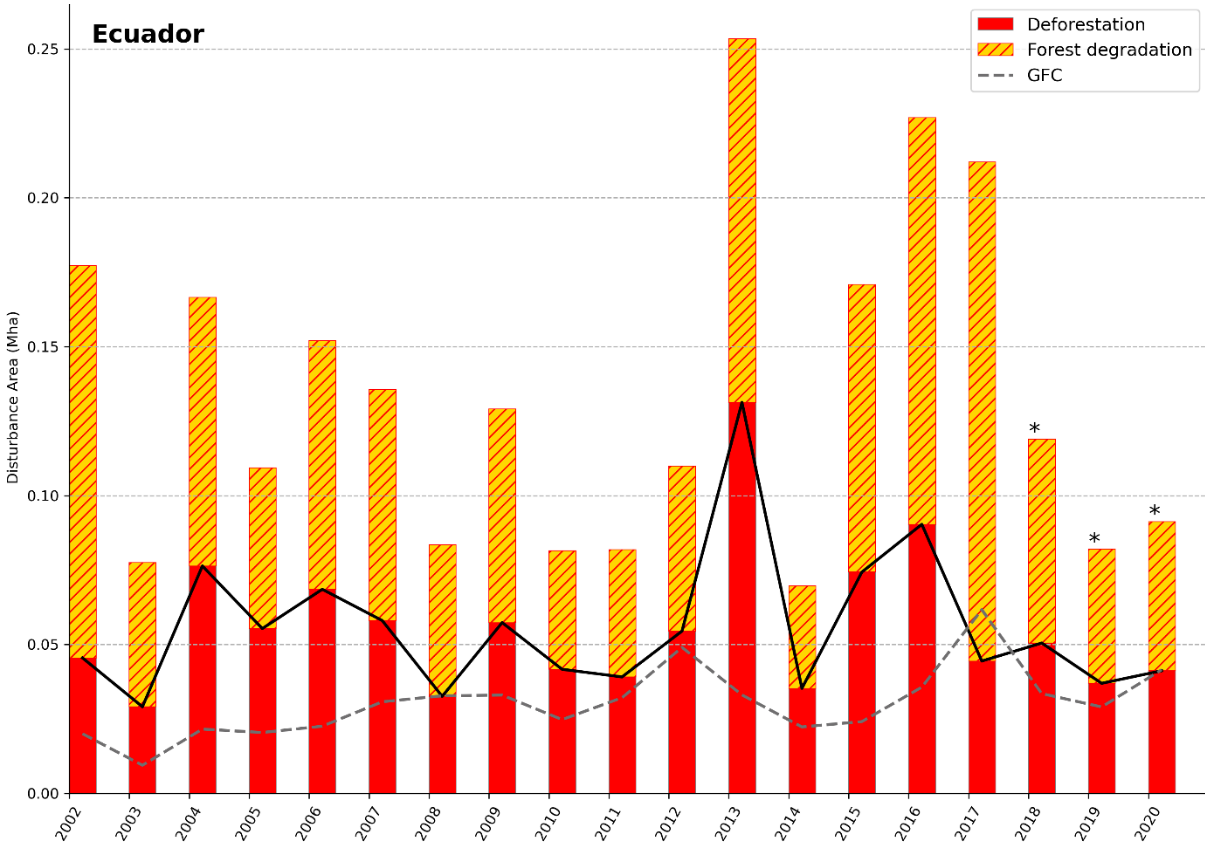


The FFC trends for Colombian humid forests in the last 20 years show increases and decreases staying on a level between ca. 4,000 km^2 and 8,000 km^2. The forest disturbance area of 2020 is with 3,667 km^2 on the same level as in 2019.

GFC estimates are generally lower than JRC-TMF, specifically in the years until 2015. From 2016 onwards, they are closer to JRC-TMF estimates.

4.1.5 Ecuador

Figure 27. Forest disturbances in Ecuadorian humid forest from 2002 – 2020, according to JRC-TMF. GFC statistics appear as gray dashed line.

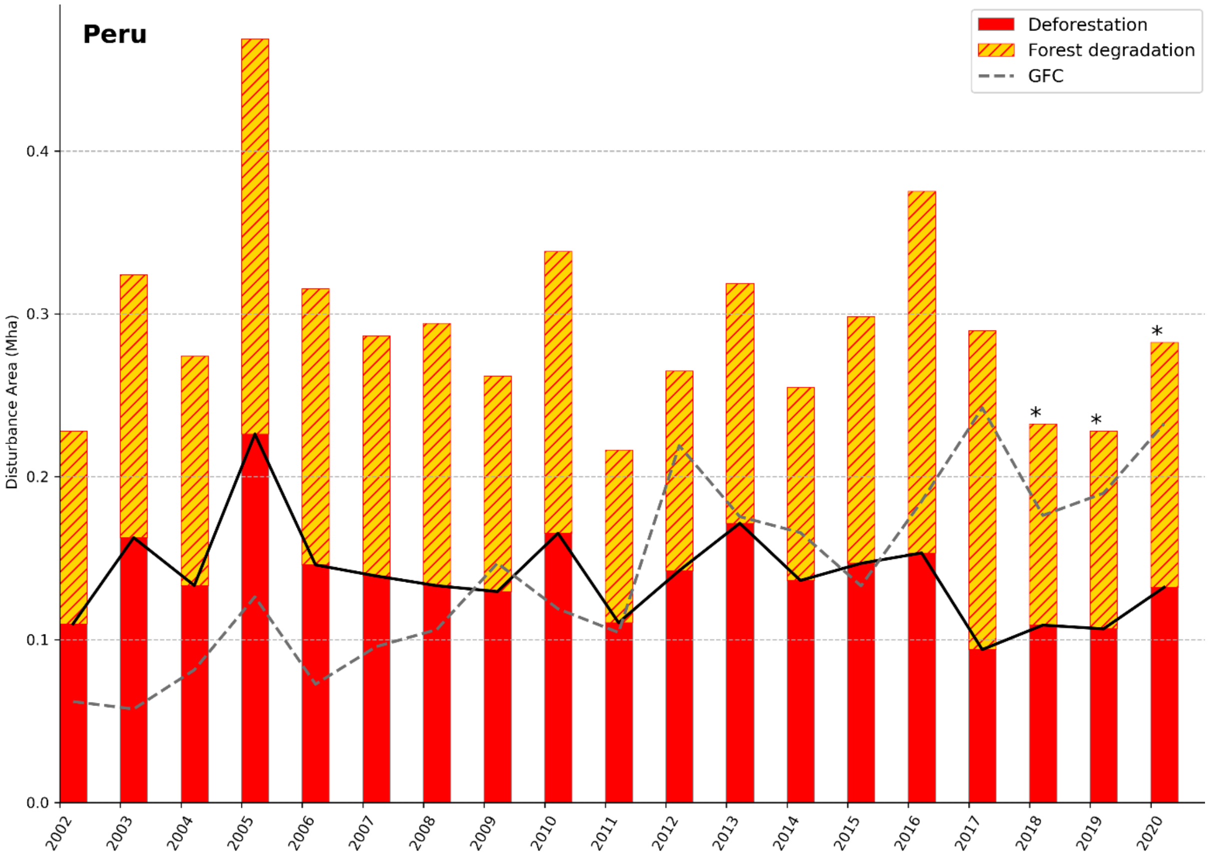


The FFC trend for Ecuadorian humid forests in the last 20 years shows an area of ca. 913 km^2 for 2020, which is around 50% of the highest FCC levels in the past decade, with the largest areas in 2013 (ca. 2,500 km^2) and 2016 (ca. 2,250 km^2). The increase of 2020 forest disturbance area compared to 2019 is around 11%.

GFC estimates are generally lower than JRC-TMF in the earlier years, but show similar trends and are very close to JRC-TMF estimates specifically from 2017 onwards.

4.1.6 Peru

Figure 28. Forest disturbances in Peruvian humid forest from 2002 – 2020, according to JRC-TMF. GFC statistics appear as gray dashed line.

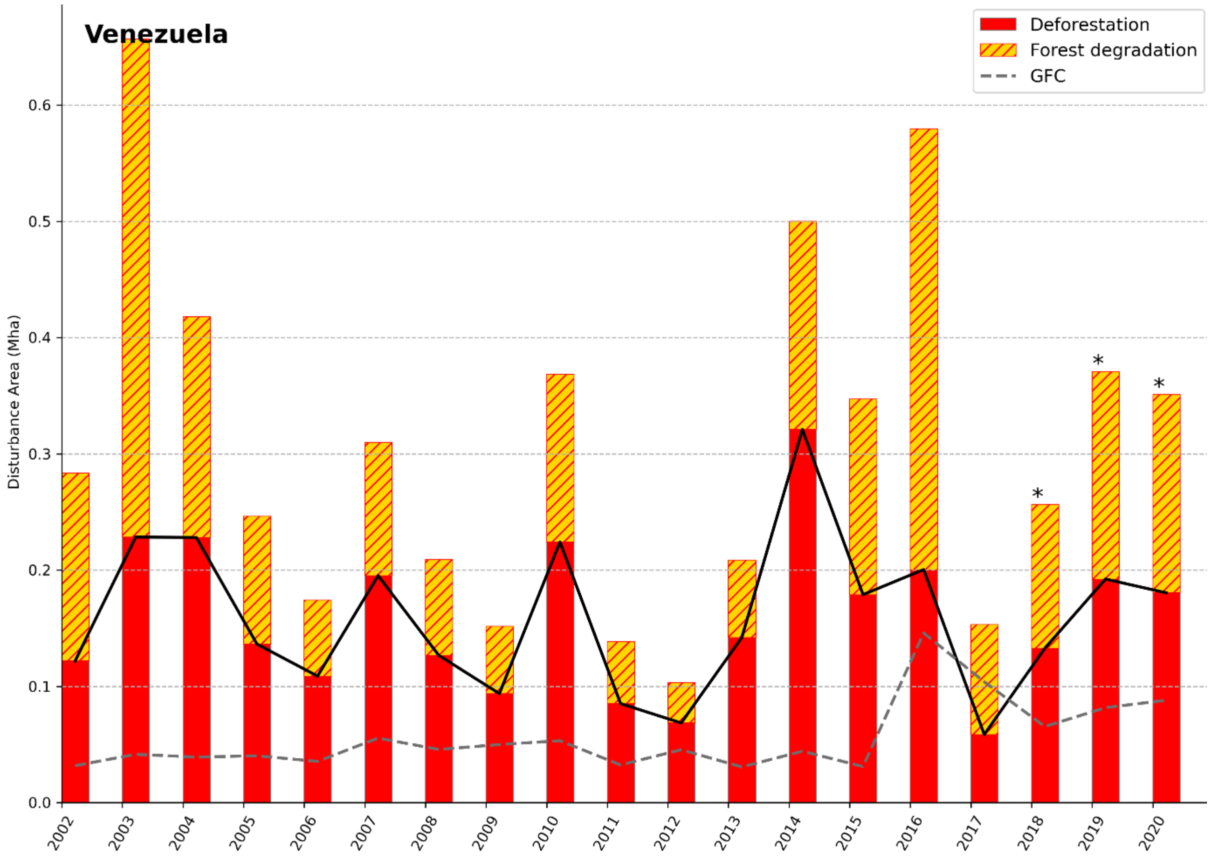


The trend for Peruvian humid forests in the last 20 years shows that the FCC areas for 2020 are with 2,824 km^2, after some years of decreasing deforestation and forest degradation activities, almost on the same level as in 2016, but still off from the worst FCC year in Peru (ca. 4,700 km^2). The increase of 2020 FCC area compared to 2019 is ca. 24%.

GFC estimates start out lower than JRC-TMF in the earlier years, but are almost constantly higher from 2016 onwards.

4.1.7 Venezuela

Figure 29. Forest disturbances in Venezuelan humid forest from 2002 – 2020, according to JRC-TMF. GFC statistics appear as gray dashed line.

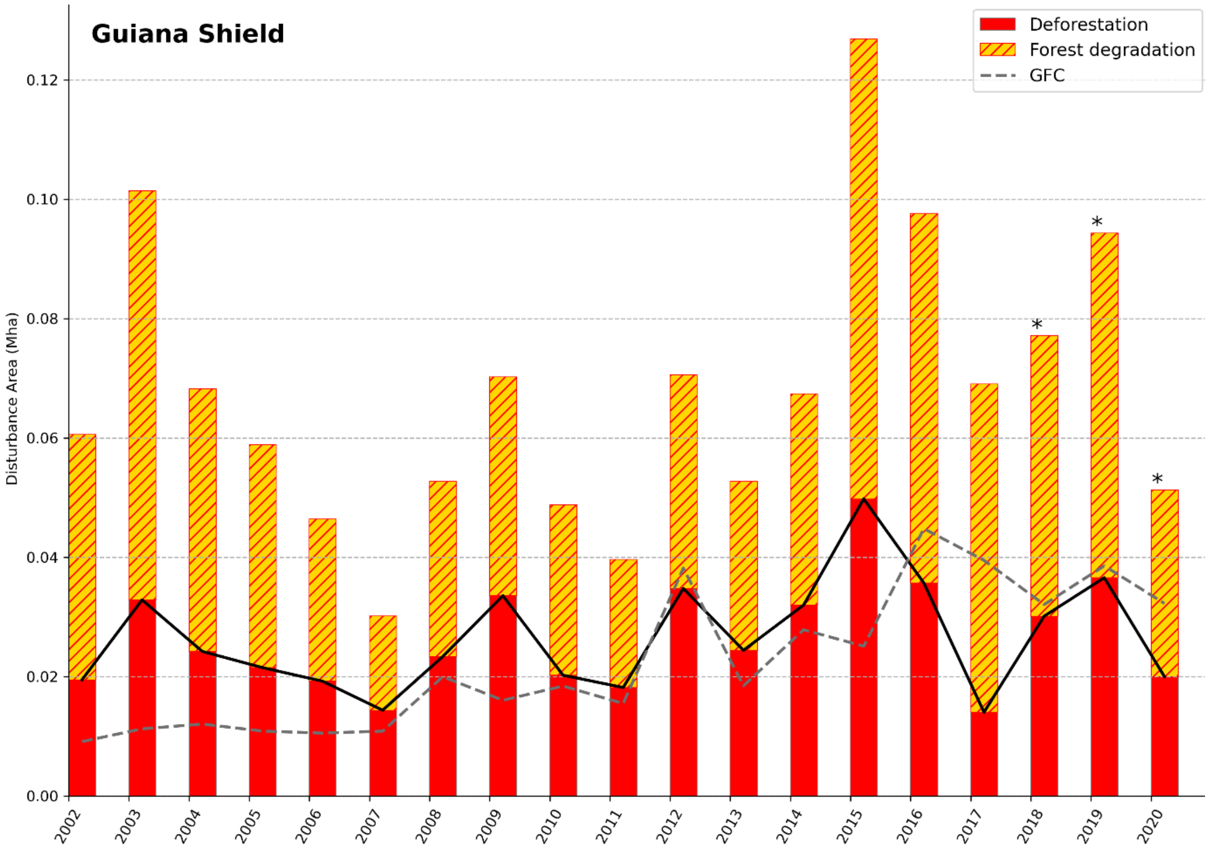


In 2019, Venezuela showed the highest level of forest disturbances since 2016. 3,509 km^2 of humid forest have been either deforested or degraded in 2020, which constitutes a decrease of 5% compared to the year before.

GFC estimates start out much lower than JRC-TMF in the years until 2016, reach JRC-TMF estimates in the years 2016 and 2017, and go back to lower estimates from 2018 onwards.

4.1.8 Guiana Shield (Guyana, Suriname and French Guiana)

Figure 30. Forest disturbances in the Guiana Shield's humid forest from 2002 – 2020, according to JRC-TMF. GFC statistics appear as gray dashed line.



In 2020, forest disturbances in the Guiana Shield (Guyana, Suriname, French Guiana) show a decrease of 54%, compared to 2019, adding up to 513 km^2.

GFC estimates are similar to JRC-TMF statistics throughout the whole period.

4.2 Global Forest Change data (University of Maryland)

The Global Forest Change (GFC) dataset[40] [137] maps changes in tree cover for the world's forests based on cloud-computed time series analysis of Landsat imagery (30 m spatial resolution), with a baseline of forest cover for the year 2000 containing the percentage of tree cover for each pixel. GFC data is freely available (currently from 2000 - 2019) and is widely used for analyses of forest cover change on global, regional, national and sub-national scales. It was the first global wall-to-wall tree cover map based on medium-resolution satellite image analysis.

GFC data has strengths and weaknesses [137–140], with one of the main challenges for GFC data analysis being the selection of the "percentage tree cover" that represents best the forest cover of the area in question [141]. The Global Forest Watch (GFW) website of the World Resource Institute (WRI)[41] shows national forest cover change areas derived from the GFC dataset. For Brazil, GFW uses a threshold of 30% tree cover for the definition of the Brazilian forest extent in the reference year 2000 (for both dry and humid forest domains). The pixels of tree cover loss or gain are summed up on the GFW web site for reporting national forest cover changes.

For reporting here the annual GFC loss areas for the Amazon countries and for the pan-Amazon region, we use the JRC-TMF layer of year 2000 humid forest as reference forest extent for the countries to allow a meaningful comparison between GFC and JRC-TMF estimates of changes in national (humid) forest cover. For the BLA, we use the map of "humid primary forests" from the INPE PRODES project as reference forest extent to compute the forest area losses from the JRC-TMF and GFC datasets in order to allow a meaningful comparison with INPE-PRODES estimates.

GFC data from 2013 onwards are based on an enhanced Landsat processing algorithm that has "resulted in enhanced detection of loss— particularly from 2015 onwards"[42]. However, details on the redefined process and the impact on the GFC results after 2012 have not been published yet. An enhanced detection of tree cover loss can potentially lead to increased forest loss values in GFC data in some regions for the years after 2012, and particularly after 2015 [142,143], specifically for forest cover change due to selective logging and forest fires.

Concerning the impact of the GFC processing change after 2012, WRI states on the GFW website that "Brazilian Amazon and Indonesia are dominated by large-scale clearing and so loss was already well captured by the initial algorithm". However, specifically in the Brazilian Amazon, areas of forest degradation (from selective logging and forest fires) have become much larger in recent years, especially with the increasing occurrence of fires in the region since 2015. The enhancement of the new GFC algorithm combined with the increase of burned forest areas from 2015 onwards may explain the significant increase of the GFC forest loss statistics for the Brazilian Amazon from year 2016. This may be considered as an overestimation of deforestation from GFC with a biased trend between pre- and post- 2016 periods, as observed in the comparison between JRC-TMF and GFC estimates for the Pan-Amazon, Brazil, and the BLA (Figures 22, 25 and 36).

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[40] https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.7.html

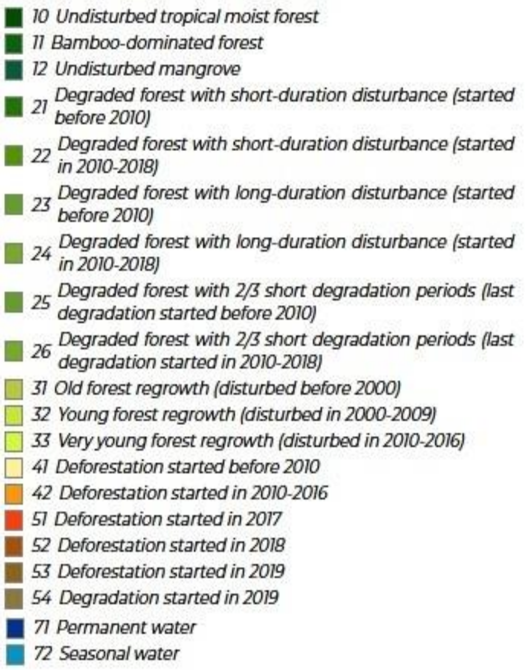
[41] https://www.globalforestwatch.org/dashboards/

[42] https://www.globalforestwatch.org/blog/data-and-research/tree-cover-loss-satellite-data-trend-analysis/

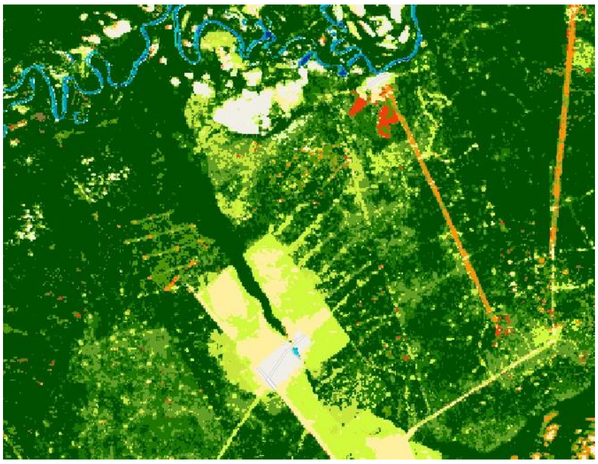
4.3 Trends in deforestation and forest degradation in the Brazilian Legal Amazon detected from the JRC-TMF dataset

We illustrate here below some typical examples of patterns of deforestation and forest degradation in the Brazilian Amazon, as they appear in the JRC dataset[43], like the fishbone-type of deforestation pattern in a new deforestation frontier in the South of Amazonas State (near the town of Apui), a typical forest fire area in the Xingu Indigenous Land and typical signs of selective logging near the town of Cláudia (both in Mato Grosso State).

Figure 31. Excerpt from an aggregated legend of the JRC-TMF "Transition Map", with the relevant classes for the maps shown in Figures 31-34. Below a subset of the corresponding JRC-TMF data layer



- 🟩 *10 Undisturbed tropical moist forest*
- 🟩 *11 Bamboo-dominated forest*
- 🟩 *12 Undisturbed mangrove*
- 🟩 *21 Degraded forest with short-duration disturbance (started before 2010)*
- 🟩 *22 Degraded forest with short-duration disturbance (started in 2010-2018)*
- 🟩 *23 Degraded forest with long-duration disturbance (started before 2010)*
- 🟩 *24 Degraded forest with long-duration disturbance (started in 2010-2018)*
- 🟩 *25 Degraded forest with 2/3 short degradation periods (last degradation started before 2010)*
- 🟩 *26 Degraded forest with 2/3 short degradation periods (last degradation started in 2010-2018)*
- 🟩 *31 Old forest regrowth (disturbed before 2000)*
- 🟩 *32 Young forest regrowth (disturbed in 2000-2009)*
- 🟩 *33 Very young forest regrowth (disturbed in 2010-2016)*
- 🟨 *41 Deforestation started before 2010*
- 🟧 *42 Deforestation started in 2010-2016*
- 🟥 *51 Deforestation started in 2017*
- 🟫 *52 Deforestation started in 2018*
- 🟫 *53 Deforestation started in 2019*
- 🟫 *54 Degradation started in 2019*
- 🟦 *71 Permanent water*
- 🟦 *72 Seasonal water*



The dataset contains yearly information about disturbances in tropical humid forest, starting from year 1984, and about the trajectories over time of each disturbed forest pixel. It differentiates between short-duration and long-duration disturbances, depending on the forest regrowth after the disturbance.

Forest regrowth classes only apply to previously deforested areas, not for forest degradation areas. The dataset differentiates between old, young and very young regrowth, depending on when the forest started to grow back after deforestation.

Deforestation and forest degradation information are aggregated to the periods 'before 2000', '2000-2009' and '2010-2019' in order to make the map easier to read. However, the data contains the full information, i.e. the precise years of first or consecutive forest disturbances, plus their classification into the deforestation or forest degradation classes.

JRC-TMF subset of a dynamic forest area west of the Xingu IL (Mato Grosso State), showing several classes related to land cover and forest cover change, including water, natural non-forest areas (e.g. savannah-type vegetation), undisturbed humid forest, deforestation (cropland or road building), forest regrowth, areas of forest degradation (due to forest fires and selective logging) of different intensities and from different dates. The causes of forest cover change, however, are not indicated in the JRC-TMF data. Image width ca. 10 km.

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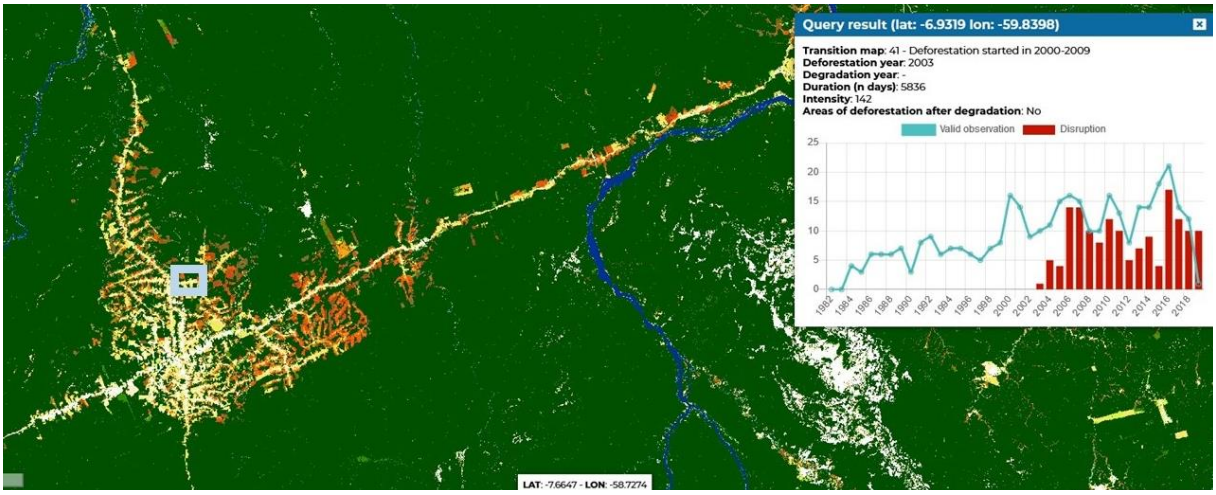
[43] https://forobs.jrc.ec.europa.eu/TMF/

Figure 32. Deforestation near the town of Apui in Southern Amazonas State (at the crossing of two main roads). Image width: ca. 450 km.



Query result (lat: -6.9319 lon: -59.8398)

Transition map: 41 - Deforestation started in 2000-2009
Deforestation year: 2003
Degradation year: -
Duration (n days): 5836
Intensity: 142
Areas of deforestation after degradation: No

Undisturbed forest appears in dark green in Figure 32, deforested areas appear in light yellow to dark red (from older to recent deforestation) in the eastern side of Apui and along the Trans-Amazon Highway BR-230. The white areas in the southeast of the map are natural savannah areas. The inset panel shows the temporal history of observations over a specific pixel (within the light blue rectangle) with the forest disturbance (deforestation in this case) occurring in 2003.

Figure 33*.* Typical forest fire patterns in the Southern Brazilian Amazon near the town of Sinop (Mato Grosso State). Image width: ca. 25 km.

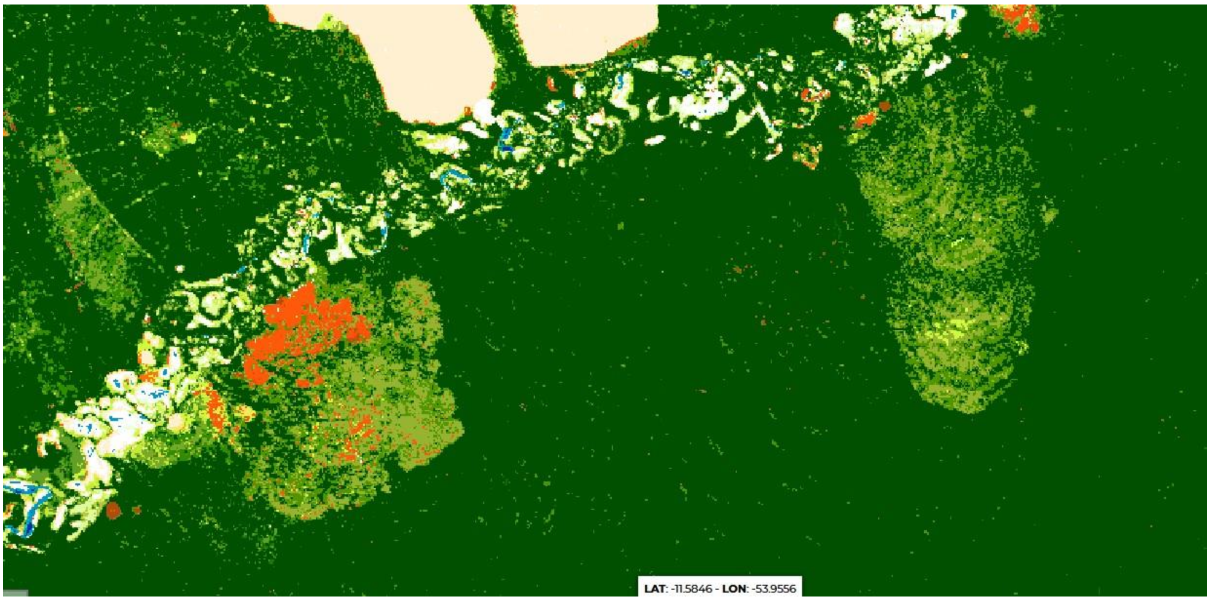
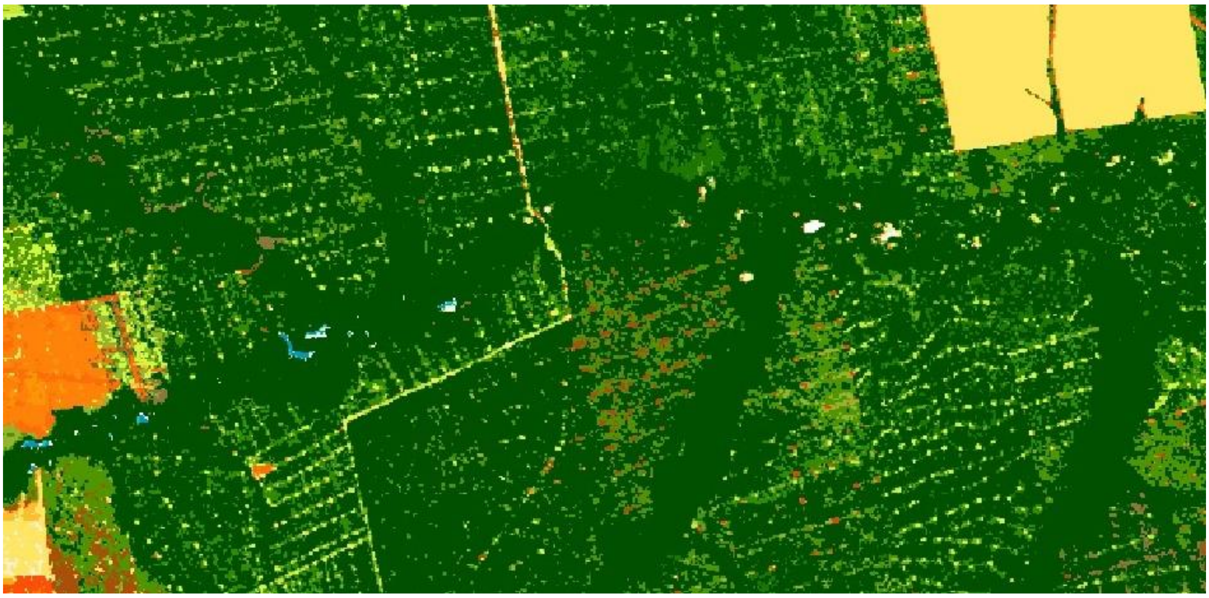


Figure 33 shows typical forest fire patterns, with a type of "ring structure" (reminiscent of tree rings), which is created by circular fire expansion with different fire intensities. The areas with "long duration disturbances" generally represent day fires (higher air temperatures cause fires with higher intensity), areas of "short duration" or no forest disturbances represent night fires (lower air temperatures cause less intense fires). The large bright areas in the North represent consolidated agricultural fields (soy in this case); the broad band of non-forest mixed with forest from northeast to southwest represents a river, tributary to the Xingu River. The fire in the East occurred in 2010, according to JRC-TMF, the one in the West in 2015. The areas of the 2015 fire appearing in red represent forest that had already severely burned in 1999. The consequence of the re-burning of these areas is a largely destroyed forest rather than ‘only’ a degraded one.

Figure 34. Typical selective logging pattern in the Southern Brazilian Amazon near the town of Sinop, Mato Grosso State. Image width: ca. 15 km.



The geometric pattern in Figure 34 represents the regular distribution of logging roads and logging decks. The different logging activities in this area occurred over a period of 20 years (1998 – 2018), for each disturbance pixel (in light green for the degraded forest class) the exact year of selective logging activities is indicated in the data.

In Figure 35 the trend for humid forests in the BLA in the last 20 years shows a decrease of deforestation after 2004 with a historical minimum in 2012 (4,571 km^2). However, the area of forest degradation through selective logging and forest fires stays stable or even increases over the years of decreasing deforestation. The large-scale forest degradation in 2015 and 2016 is due to the large areas of burned forests in these three years. The increase of 2020 overall forest disturbance area (21,379 km^2) in the BLA, compared to 2019, is ca. 24%. One reason for this is the increase of 58% in 2020 of burned areas in the BLA in general[44] (i.e. increasing also the areas of burned forests - see Fig. 11). This is confirmed by a 79% increase of burned forests in 2020 compared to 2019, as reported by the INPE-DETER alerts (see Fig. 42)[45].

The deforestation area (red) increased from 11,664 km^2 in 2019 to 14,162 km^2 in 2020, while forest degradation (orange) increased from 5,839 km^2 in 2019 to 7,217 km^2 in the same period. While the overall area of forest disturbances 2020 is already consolidated by the automatic JRC-TMF method, the distribution of the two different classes of forest disturbances within the overall forest disturbance area can presently only be estimated (on basis of 16-year average values). The consolidation of the area distribution of the different forest disturbances classes (deforestation and forest degradation) for 2020 can only carried out in 2024.

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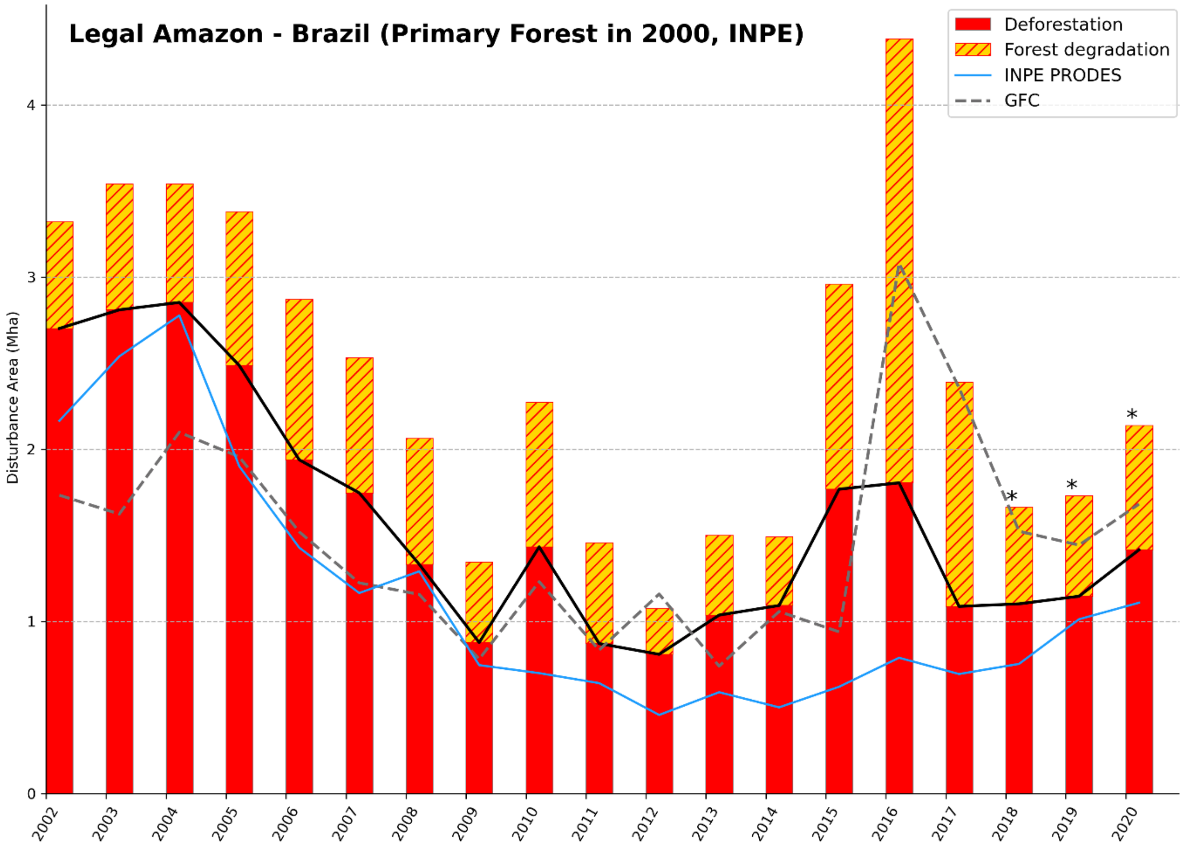
[44] https://gwis.jrc.ec.europa.eu/reports-and-publications/2020-amazon-weekly-reports/

[45] http://terrabrasilis.dpi.inpe.br/app/dashboard/alerts/legal/amazon/aggregated/

Figure 35. Trend in annual deforestation and forest degradation in the BLA from 2002 – 2020, according to JRC-TMF data. Deforestation appears in red, forest degradation appears in orange. For comparison, INPE-PRODES deforestation statistics appear as blue line, GFC statistics appear as gray dashed line.



For the comparison between JRC-TMF, PRODES and GFC data, the INPE forest mask defining the humid forest within the Legal Amazon has been applied to ensure maximum comparability. The deforestation estimates of the three datasets are quite close until 2014, i.e. during the years of large-scale deforestation (until 2004) in the BLA and the significant reduction of deforestation until 2014. The large areas of burned forest, in parts mapped as deforestation by JRC-TMF and not considered by PRODES, are supposedly responsible for the differences in deforestation estimates by the two datasets during the years 2015-2017. The high values of deforestation area by GFC for the years 2016-2017 can most probably be attributed to the change of the GFC analysis method after 2012/2015[46] (see also chapter 4.2).

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[46] https://www.globalforestwatch.org/blog/data-and-research/tree-cover-loss-satellite-data-trend-analysis/

4.4 Comparison of the JRC-TMF estimates with INPE deforestation statistics for the Brazilian Legal Amazon

PRODES deforestation statistics as well as JRC-TMF data show an increase for year 2020. However, even if both methods use the same type of satellite imagery (Landsat, with a 30 m spatial resolution) there are significant differences between the INPE-PRODES [144] and JRC-TMF [109] methods:

a) the yearly analysis period is not the same, i.e. for year 2020 INPE-PRODES looks at the period from August 2019 – July 2020, while JRC-TMF looks at the 2020 'calendar year' (Jan-Dec 2020)

b) INPE PRODES maps deforestation on single Landsat images (as cloud-free as possible), while JRC-TMF analyses the full Landsat time series for a whole year

c) INPE-PRODES does not have a class dealing with forest degradation (unlike JRC-TMF), it only maps deforestation

d) INPE-PRODES maps deforested area only if they are larger than 6.25 ha, while JRC-TMF considers also smaller areas of forest cover change. In consequence, INPE-PRODES data does not contain small areas of deforestation or areas of selective logging, because logging features like logging decks, felling gaps, smaller logging roads etc. are usually considerably smaller than 6.25 ha.

e) INPE-PRODES does not map burned forest as deforested or as degraded forest, while JRC-TMF either puts these areas into the deforestation class, if very severely disturbed for a long period, or in the forest degradation class, if some forest regrowth can be detected in the three years following the burning

f) INPE-PRODES does not take into consideration the deforestation of forest regrowth areas, i.e. areas that, after a first deforestation in the past, had regrown into a dense secondary forest that is subsequently cleared a second time

g) INPE-PRODES is a semi-automatic method that includes image interpretation, while JRC-TMF is a fully automated process based on cloud-processed Landsat time series analysis

4.4.1 Monitoring BLA deforestation and forest degradation in Brazil: the PRODES and DETER projects at INPE

4.4.1.1 PRODES

The institution in Brazil with the mandate to officially producing the statistics on deforestation in the Legal Amazon is the Brazilian Space Research Institute (INPE). The institution has a long history of tropical forest monitoring with remote sensing imagery. Since 1988 INPE is producing annual deforestation statistics for the Brazilian Legal Amazon, which are, specifically since the year 2000 (start of the PRODES Digital Project[47]), a reliable source of open, free and high quality data on forest loss in the Brazilian Amazon. PRODES data is widely used in the scientific community and INPE researchers are globally recognized as high-level scientists in the field.

INPE maps (through the PRODES program) deforested areas over the whole Brazilian Legal Amazon on Landsat imagery with 30 m spatial resolution, excluding from analysis areas within the BLA defined as non-humid forest (with savanna-type vegetation), non-forest, and forest regrowth that had been deforested in an earlier stage.

Based on PRODES data, INPE communicates each December the Legal Amazon deforestation statistics for the so-called 'reference year' (August of the precedent year until

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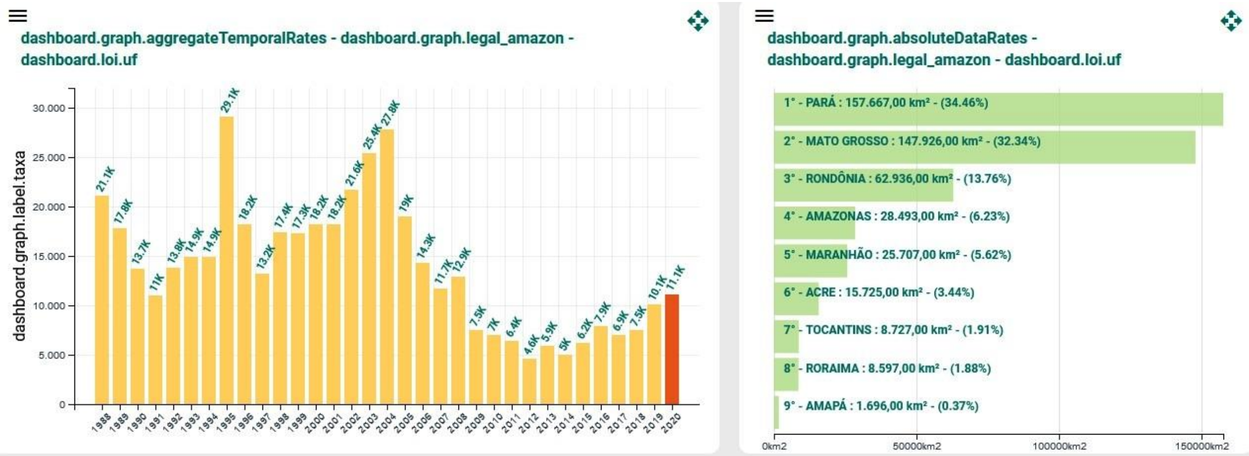
[47] http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes/pdfs/Metodologia_Prodes_Deter_revisada.pdf

July of the current year), using a complex approach which takes into account the cloud coverage in different areas, daily deforestation rates for a given time period, the length of the dry season, etc. (INPE 2019). INPE-PRODES does not map forest disturbances due to selective logging or forest fires; in consequence, INPE does not provide yearly, consolidated forest degradation statistics for the BLA[48]. This type of information is, in consequence, not included in the Brazilian Communication on FREL in the REDD+ context.

One of the main differences between JRC-TMF and INPE-PRODES is the mapping of severely burned forest. PRODES does not map these areas as 'deforestation', as the burned forest area often does not show an obvious change in land use, i.e. is not 'actively' deforested immediately. In consequence, the burned forest areas are only then mapped as deforested, once they are cleared for agricultural use (pasture, crop fields). JRC-TMF often maps severely burned forests as deforested, as severe or recurrent burning of forest may lead to a land cover change through the substantial destruction of the forest. An example of these dynamics is described by Balch et al. (2015) [85], showing that forest, in parts and after several burnings, ceases to exist (i.e. changes land cover class), through high tree mortality rates and invasion of pioneer grass vegetation. The different methods of INPE-PRODES and JRC-TMF explains largely the differences between the two datasets of deforestation areas specifically for draught years with large areas of forest fires (see Fig. 35, e.g. for year 2016).

Burned Amazon forests, however, are mapped in the 'forest fire' class of the INPE-DETER program (see section 4.3.1.2), the INPE daily alert system for deforestation and forest degradation. Yearly accumulated DETER data gives an indication on the approximate areas of forest loss or forest degradation; however, for the forest degradation classes of DETER there is no yearly consolidated area calculation by INPE, as presented, once a year, for deforestation through PRODES.

Figure 36. Yearly official deforestation statistics for the BLA provided by INPE-PRODES (left side of figure). In addition, information on deforestation areas for each State is provided (right side of figure). The official 2020 PRODES deforestation statistics for the BLA were communicated by INPE on the 1st December 2020.



As for the BLA, PRODES also provides yearly consolidated statistics on deforestation areas for the Cerrado biome.

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[48] http://terrabrasilis.dpi.inpe.br/homologation/dashboard/deforestation/biomes/legal_amazon/rates

4.4.1.2 DETER deforestation alerts

In addition to the PRODES project, INPE runs a near-real time alert system for deforestation, called DETER [145] [49] [50], which uses CBERS-4 WFI satellite imagery with a 5-days repeat cycle and with coarse spatial resolution (60 m) to map deforestation (forest clear-cuts, mining) and forest degradation alerts (selective logging, forest fires). DETER data is sent on a daily basis to the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), responsible for the law enforcement related to illegal deforestation and selective logging in the Brazilian Amazon. PRODES and DETER are independent projects, as their purpose, their type of satellite data used, their minimum mapping units (MMUs) and forest change area calculation approaches are very different.

DETER produces daily and monthly (aggregated) deforestation and forest degradation statistics[51] for the BLA and, since May 2018, corresponding monthly deforestation alert figures for the Cerrado biome. INPE-DETER accumulated data gives an indication about the trends of deforestation for a given month or year, e.g. in comparison of the year(s) before (Figures 37 and 38). However, the accuracy of the DETER data, using optical satellite imagery, depends very much on the cloud coverage for the analyzed period and on the detectability of the forest disturbances with satellite imagery of coarser spatial resolution.

Figure 37. Daily near-real-time deforestation alerts provided by INPE-DETER ('calendar year')

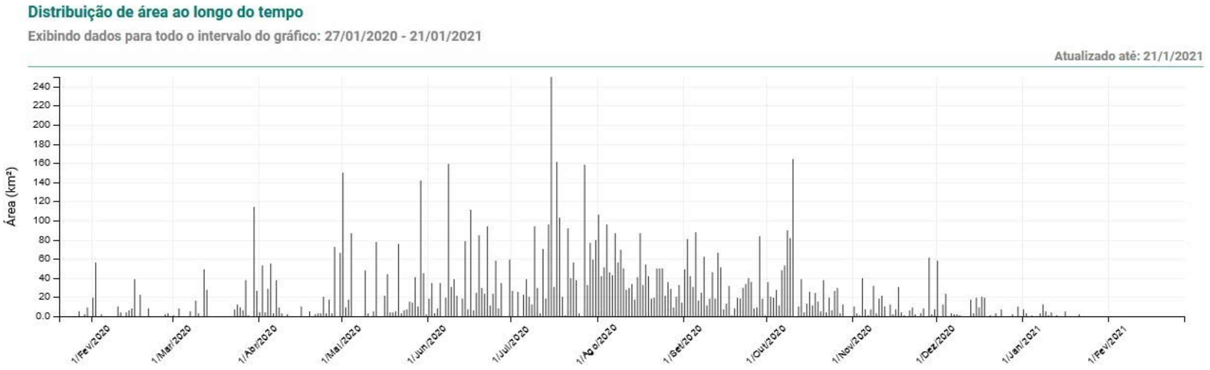
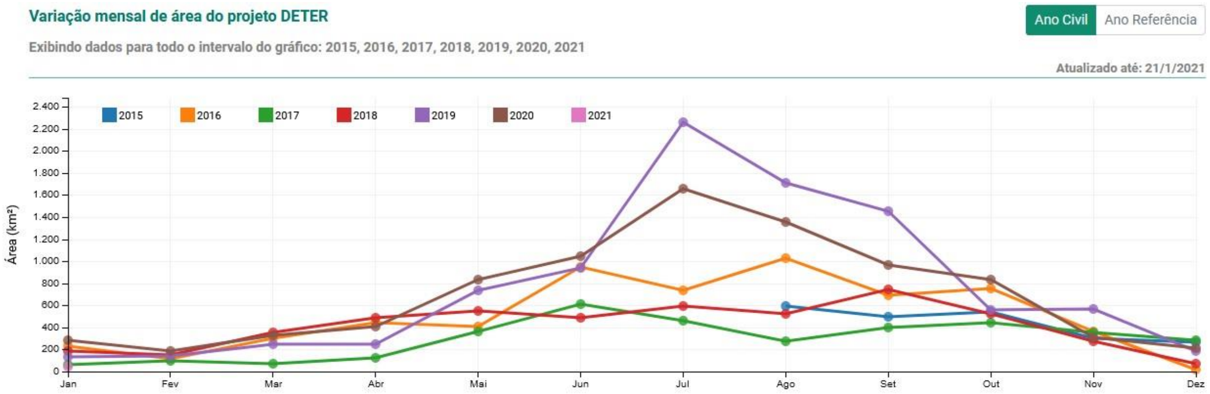


Figure 38. Monthly aggregated near-real-time deforestation alerts provided by INPE-DETER ('calendar year')



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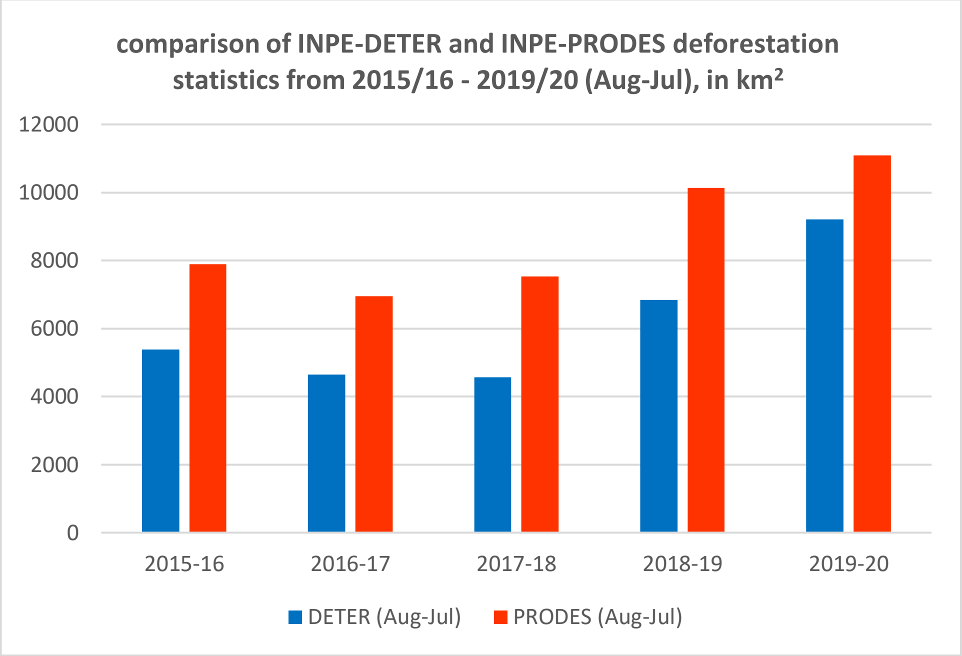
[49] http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes/pdfs/Metodologia_Prodes_Deter_revisada.pdf

[50] http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/deter/deter

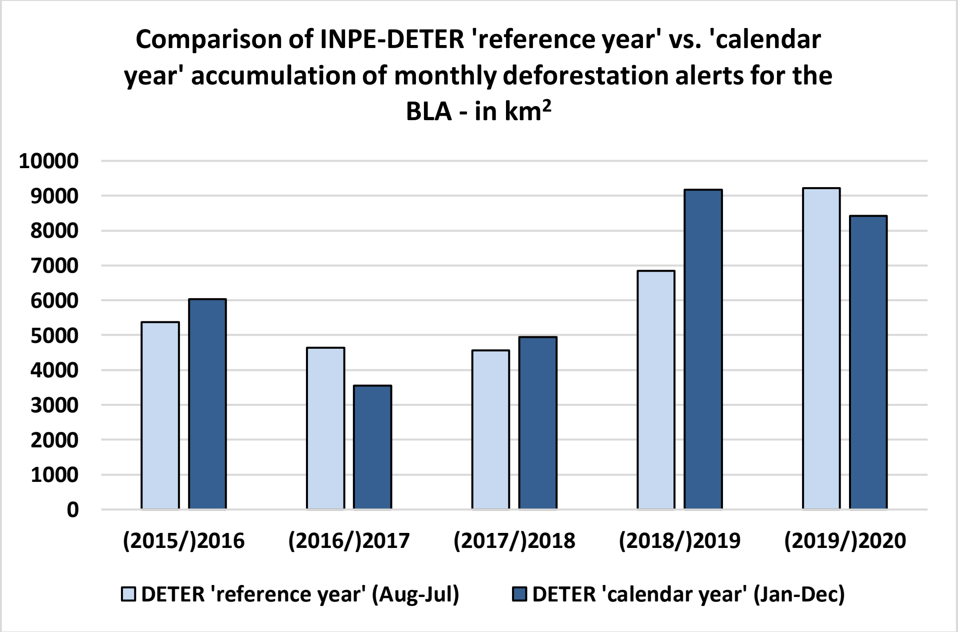
[51] http://terrabrasilis.dpi.inpe.br/app/dashboard/alerts/legal/amazon/aggregated/

Figure 39. INPE-DETER yearly aggregation (blue) of deforestation near-real-time alerts 2015/16 – 2019/20 for the BLA in comparison with INPE-PRODES official deforestation statistics (red) for the same period. The INPE-DETER results for 2020, in relation to PRODES figures, have shown an underestimation of 16.9%. This is a significantly better estimate compared to the years before, with an average of 34.2% underestimation by INPE-DETER.



The comparison between 12 months of DETER accumulated monthly near-real-time alerts and official PRODES deforestation statistics for 2015/16-2019/20 shows differences which are significant but consistent (Figure 39). The yearly aggregated DETER results (Aug-Jul period) for deforestation areas, compared to official PRODES statistics range from 60.7% (2017/18) to 83.1% (2019/20), with an average of 69.2%.

Figure 40. Difference between 'reference year' and 'calendar year' accumulation of INPE-DETER monthly deforestation alerts.



The comparison of different accumulation periods, i.e. for an INPE 'reference year" (e.g. August 2015 – July 2016) and 'calendar year' (January 2016 – December 2016) shows how the deforestation trend for a given year can vary with the observation period (Figure 40). While the yearly accumulated deforestation alerts show an area increase for the 2019/2020 'reference year', the deforestation area decreases slightly for the 2020 'calendar year'. The reason for this discrepancy is the exclusion of the large areas of deforestation alerts in the months of August and September 2019, which are counted for the statistics of the following year (2020) in the 'reference year' accumulation, but are included in the year 2019 in the 'calendar year' statistics. The INPE-PRODES official deforestation statistics apply the 'reference year', while JRC data produces statistics for 'calendar years' hence the difference between the PRODES and JRC deforestation trends for the year 2020.

4.4.1.3 DETER forest degradation alerts

The statistics of the DETER forest degradation alerts for the BLA are shown as charts on the same INPE website (Terrabrasilis)[52] as the deforestation alerts. However, spatial data or statistics for download are only available for deforestation alerts, consisting in the classes "deforestation with bare soil", "deforestation with vegetation" and "mining areas". Although no official Brazilian definition of 'forest degradation' exists [146], INPE files areas of forest fires and selective logging and an additional class of unspecific "degradation" under the topic "forest degradation".

The DETER forest degradation alerts, as the DETER deforestation alerts, are sent to IBAMA on a daily basis for IBAMA's verification and law enforcement mission planning. DETER provides 'conservative' datasets, thus doubtful interpretation is not accepted in order to avoid 'false positive' deforestation or forest degradation alerts, which would have severe consequences for IBAMA's law enforcement missions. For the BLA, DETER overall forest degradation (selective logging and forest fires) trends show a decrease from 2016 to 2018, and taking up again in the following years. The DETER accumulated yearly forest degradation alerts for the BLA (year 2020) are at more than 20,500 km**²**.

Figure 41. INPE DETER forest degradation alerts for the BLA (centre, in colours), the deforestation classes are displayed in grey and are not included in the accumulative yearly bar charts on the right.

Filtro: Cicatriz de Incêndio Florestal,Degradação,Corte Seletivo Tipo 1 (Desordenado),Corte Seletivo Tipo 2 (Geométrico),Corte Seletivo

Due to the mentioned conservative approach, DETER data underestimates to a certain extend areas of deforestation and forest degradation in the BLA. Compared to the Landsat-based (30 m spatial resolution) study of Beuchle et al. (2019) [106] (with a 94% overall accuracy), the DETER alerts underestimate, for the Amazon biome part of Mato Grosso

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[52] http://terrabrasilis.dpi.inpe.br/app/dashboard/alerts/legal/amazon/aggregated/

State and for the years 2016 and 2017, selective logging (DETER selective logging classes 1 & 2) and burned forests (DETER forest fires class plus ‘unspecified degradation’ class), in average by 81% and 15%, respectively. The large discrepancy between DETER and Beuchle et al. (2019) for the selective logging area can be, at least partly, explained by relative scarcity of the satellite signal for this type of forest degradation in combination with the coarser spatial resolution of the satellite imagery used by DETER.

Figure 42. INPE-DETER yearly, accumulated forest degradation alerts for the whole BLA, separated according to causes: Forest fires (left), selective logging (centre) and unspecified forest degradation cause (right). Please note the different scales of the charts. The DETER forest degradation areas can be filtered by State, year, and cause of forest degradation.

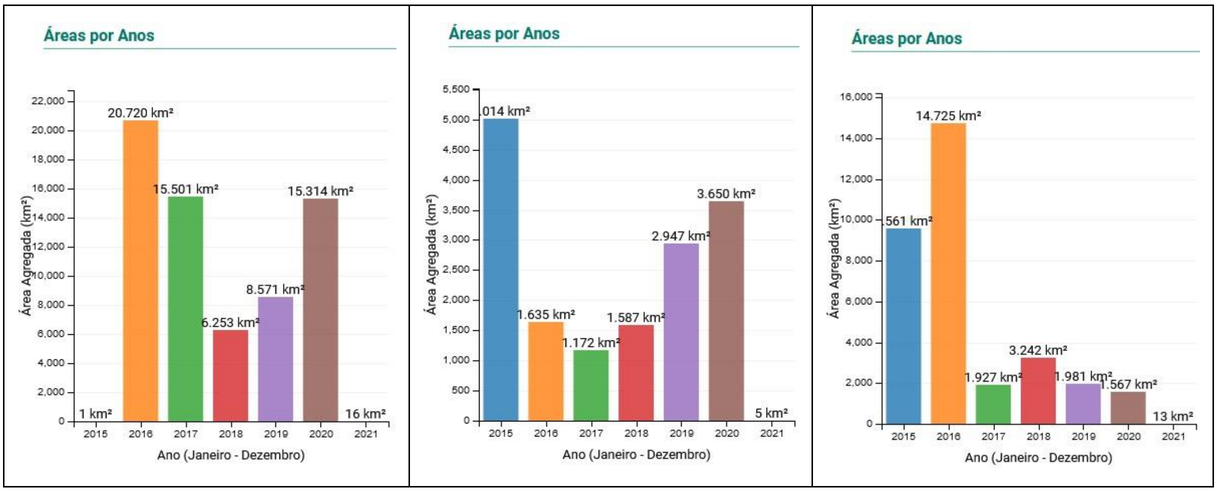
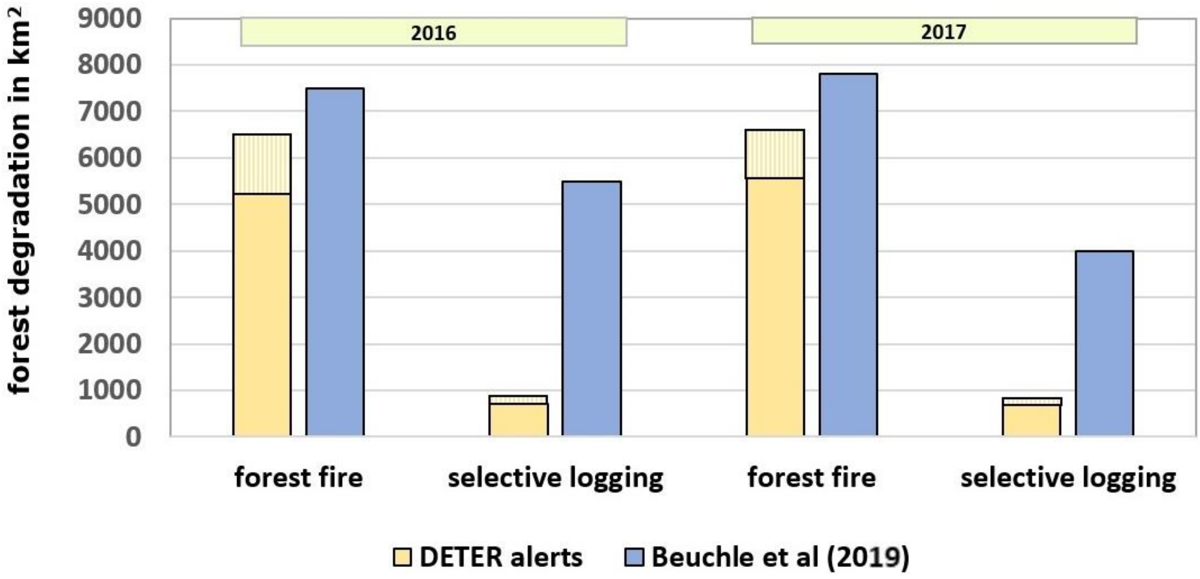


Figure 43. Comparison between INPE-DETER forest degradation alerts (forest fire / selective logging) and the results of Beuchle et al. (2019) for the years 2016 and 2017 for the Amazon biome part of Mato Grosso State. The DETER class “unspecified forest degradation” (dashed brown bar) was added proportionally to both classes.



5 Conclusions

The causes and drivers for forest cover change are diverse within the Pan-Amazon [147], due to different geo-physical, climatic and political circumstances and factors like forest accessibility and forest protection status. These changes of natural forest cover, if not mitigated, will have severe local, regional or global impacts in the future: it will lead to a rise of average temperatures [148], to unrestrained carbon emissions [149], to changes in the precipitation patterns in the whole of South America [81,150,151] to a loss of biodiversity and to a potential increase of infectious diseases on local to global scales.

Forest disturbances (deforestation and forest degradation) in the Pan-Amazon increased by 18% from year 2019 (ca. 26,600 km²) to year 2020 (ca. 31,400 km²), according to JRC-TMF data. An increase of forest disturbances in humid forest from 2019 to 2020 has been recorded for many countries bordering the Amazon forest, ranging from 11% for Ecuador to 24% for the BLA to 54% for Bolivia. Exceptions are Colombia (no increase), Venezuela (5% decrease) and the Guiana Shield, showing a forest disturbance decrease of 54% between the two years.

The causes of forest cover disturbances cannot be easily identified, because a number of processes are interlinked: deforestation causes edge effects at the forest borders, which in turn make the "hard forest borders" susceptible to fires, often escaping from maintenance fires in adjacent pastures or crop fields. Selective logging activities often leave large amounts of dead matter (leaves, branches) in the forest, which provide fuel for more severe forest fires [21].

According to several studies, continuous deforestation and forest degradation will potentially lead to extension of savannahs in the future [152,153], mainly in the eastern and southern Amazon. These areas might extend to the central and south-western Amazon, because these regions are naturally close to the minimum amount of rainfall required for the rain forest to thrive. Forests would be pushed toward savannah configurations due to negative synergies with human-driven global warming, leading to reduced rainfall and increased temperatures, compounded with extensive use of fire [8]. In fact, despite some regionally divergent trends, observations since the year 2000 indicate that the atmosphere over the Amazonian rainforest is drying because of global warming, biomass burning, and land-use change. The moisture produced by forest has diminished, especially in the south-eastern basin, and strong drought and wildfire events have increased in intensity (including in the north-western part of the basin). Drier climates have been developing in the Peruvian Amazon Basin, southern Peru and Chile, south-western Argentina, the Andes, western Central America, and northern South America. From 1980 to 2013, the northern coast of northeast Brazil saw a reduction of 4.6 mm per year in total precipitation during the austral winter [154], and from 1965 to 2009, the Peruvian Amazon Basin had a significant negative trend in total precipitation and consecutive wet days [150]. With present rates of deforestation and forest degradation, Stark et al. (2020) [155] see a significant 'savannization' risk for the Brazilian Amazon.

The future of the Amazon forest in Brazil lies in the combination of various factors. These factors include the role of institutions that have the mandate to monitor deforestation and forest degradation (INPE), to enforce the law upon illegal deforesters, illegal loggers and those who burn the forest illegally (IBAMA and ICMBio), or to ensure the indigenous people's rights (FUNAI). These institutions have proved in the past to work effectively and to collaborate seamlessly for the protection of the forests and the indigenous people in the Amazon. However, since last two years these institutions have been made weaker by the

Brazilian government by cutting of funds and the dismissal of key personnel [1,37,38] [53] [54] [55] [56] [57].

INPE has been criticised by the current Brazilian government about the quality of their data on deforestation, forest degradation and burned areas[58]. However, the Brazilian and international scientific community has used INPE data since two decades, as they are considered as reliable high quality scientific datasets, which, moreover, are freely available (open data policy). Indeed, the PRODES program is considered as a reference system for remote – sensing based tropical forest monitoring and for research on tropical forest cover change [156–158].

INPE is using the same approach in its PRODES program since the early 2000s to monitor deforestation in the BLA (based on Landsat satellite imagery). The method has known shortcomings, as e.g. deforestation areas smaller than 6.25 ha are not mapped, which can lead to an underestimation of deforestation [159,160]. However, INPE is in the phase of modernising their approach for Amazon forest monitoring, in particular by working on the integration of satellite radar data for forest monitoring and forest change alert systems in order to overcome the issue of persistent cloud cover during the rainy season affecting optical satellite imagery [161].

In addition, INPE is developing a "data cubes" technology for cloud-computing of multi-source satellite imagery time series [162]. This data cubes approach is expected to enable INPE to improve their forest cover change assessment and make it applicable for other Brazilian biomes like the Cerrado and the Caatinga. INPE is a regional hub in Latin America for Copernicus data, with priority access to data from the full set of Copernicus Sentinel satellites[59] [60]. New types of freely available and high quality satellite imagery (Sentinel 1-3), together with the new Brazilian satellite "Amazônia-1" (launched on 2nd March 2021) should pave the way for effective forest monitoring in South America, together with new possibilities of cloud-computed time-series analysis. Brazil's neighbours Argentina, Paraguay and Bolivia could potentially profit from INPE's data cube experience to set-up their own systems to monitor e.g. their dry Chaco forests, which are affected by very high deforestation rates [163–167].

Forest degradation is not yet exhaustively reported in present programmes (e.g. JRC-TMF and INPE-DETER). More specifically, areas affected by selective logging are vastly underestimated, due to the difficulty to map small-size logging features like felling gaps, logging roads and skid trails [104]. The effective area affected by selective logging can be up to five times larger than the area mapped by pixel-based analysis [61,103]. For their Forest Emissions Reference Level (FREL), Brazil has been strongly recommended to include Amazon forest degradation in their future REDD+ communication to the UNFCCC. Brazilian institutions need to put an emphasis on the monitoring and reporting of forest degradation. A robust national forest degradation monitoring system has to be put in place to enable reliable mapping of forest fires and selective logging activities. INPE has the technical knowledge and capacity to put in place such a system.

On the 8th December 2020, Brazil has confirmed its commitment related to the Paris Agreement[61]. This commitment implies economy-wide greenhouse gas emission reductions of 37% by 2025 and of 43% by 2030, with reference to 2005. In its initial Nationally

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[53] https://www.sciencemag.org/news/2019/08/brazilian-institute-head-fired-after-clashing-nation-s-president-over-deforestation

[54] https://apnews.com/article/5543141215dcd033711fa8bca08b6995

[55] https://exame.com/brasil/ministro-ricardo-salles-demite-4-superintendentes-do-ibama-no-mesmo-dia/

[56] https://www.reuters.com/business/environment/brazil-cuts-environment-spending-one-day-after-us-climate-summit-pledge-2021-04-23/

[57] https://www.dw.com/pt-br/bolsonaro-quebra-promessa-a-l%C3%ADderes-internacionais-e-corta-verba-para-meio-ambiente/a-57320164

[58] https://g1.globo.com/politica/noticia/2020/09/16/mourao-diz-que-desconhecia-que-dados-de-queimadas-sao-publicos-e-pede-analise-qualitativa-ao-inpe.ghtml

[59] https://www.rnp.br/en/news/copernicus-technology-allied-earth-observation

[60] https://sentinels.copernicus.eu/web/sentinel/missions/international-cooperation/partners

[61] https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Brazil First/Explanatory Letter Brazil.pdf

Determined Contribution (NDC) of year 2015, Brazil committed to reduce deforestation in the BLA by 80% by the year 2020, compared to the baseline of yearly 19,625 km^2 forest loss (average of the 1996-2005 period). However, this NDC target of 3,925 km^2 forest loss was surpassed in 2020 by 182% [17].

This shows that Brazil is heading towards the opposite direction compared to its initial commitments for the Paris Agreement [168],[169]. There is a willingness in the National Congress to relax regulations on mining, timber trade, hydropower dams, road building, and expansion of agriculture activities [170], including e.g. a Constitutional Amendment (PEC 65), which will facilitate licensing for large-scale infrastructure projects. Two new bills, recently proposed by the current Brazilian government, would absolve illegal land grabbers on federal public forests that have not been designated for any specific purpose yet ("florestas públicas não destinadas", i.e. which are without specific protection status)[62] [63]. These "undesignated public forests" (UPF) in the Brazilian Amazon are thus at specific risk of illegal deforestation and misappropriation. In consequence, some form of conservation status for UPFs may be crucial to limit the expansion of agriculture and livestock in these forests [171]. The dismantling of environmental protection in Brazil during the pandemic [64] has the potential to intensify the ongoing loss of biodiversity, increase greenhouse gas emissions, increase the likelihood of other zoonotic disease outbreaks, and inflict substantial harm to indigenous peoples [129]. The building of new infrastructure in or through the Amazon forests must be accompanied with a rigorous impact assessment, accounting for possible socio-economic and environmental impacts [121].

It remains to be seen in the future years how the newly created "National Council of the Legal Amazon" (CNAL)[65] will work, which methods it will apply for the monitoring of the Amazon forest and how the enforcement of the laws related to the forest protection and human rights will be organised. Effective law enforcement is needed in case of illegal construction of side roads, illegal selective logging or deforestation near the newly constructed roads. Effective firefighting and, again, law enforcement is needed to curb the current (high) and future (potentially even higher) levels of burned forest areas. Funding the necessary infrastructures and personnel, and developing advanced methods through international cooperation, is needed to ensure effective forest and fire monitoring systems for the current and future complex challenges related to the protection of tropical forests.

The potential leakage or displacement of deforestation in the BLA to other Brazilian regions or neighbouring countries has to be considered carefully if the laws in the BLA would be enforced more strictly. Such displacements, e.g. to the savannah of the Brazilian Cerrado or to Paraguay and Bolivia (with weaker environmental protection), have been observed in the past [172]. Current monitoring approaches for tropical dry forests, which cover large parts of in the countries and regions mentioned above, are less efficient and operational than for humid tropical forests [173]. Further research efforts are needed for this topic.

The European Union is increasingly concerned by the effects of European imports of commodities on direct or indirect deforestation and forest degradation in Brazil or other countries of South America [174,175]. The implementation of deforestation-free supply chains is being considered as potential solution, but this will require clear ratification conditions, an establishment of best practices and non-compliance consequences [176], and robust operational systems to be put in place at national scales in all countries in South America for verification and monitoring purposes[66].

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[62] https://news.mongabay.com/2021/04/bills-before-brazil-congress-slammed-for-rewarding-amazon-land-grabbers/

[63] https://ipam.org.br/florestas-publicas-nao-destinadas-e-grilagem/

[64] https://www.brasildefato.com.br/2020/06/09/o-que-passou-na-boiada-de-ricardo-salles-durante-a-pandemia

[65] https://www.gov.br/planalto/pt-br/conheca-a-vice-presidencia/conselho-da-amazonia

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List of abbreviations and definitions

ACTO	Amazon Corporation Treaty Organization
AM	Brazilian State of Amazonas
AC	Brazilian State of Acre
BFC	Brazilian Forest Code
BLA	Brazilian Legal Amazon
CBERS	China–Brazil Earth Resources Satellite program
CNAL	Brazilian National Council of the Legal Amazon
COVID-19	Corona Virus Disease 2019
CU	Conservation Unit
DETER	Brazilian alert system for deforestation and forest degradation in the Amazonas biome
DG-CLIMA	EC's Directorate-General for Climate Action
EC	European Commission
ESA	European Space Agency
FAO	Food and Agricultural Organisation of the United Nations
FCC	Forest Cover Change
FREL	Forest Reference Emission Levels
FSC	Forest Stewardship Council
FUNAI	Brazilian National Agency for Indigenous Affairs
GFC	Global Forest Change
GIS	Geo-Information System
GWIS	Global Wildfire Information System
IBAMA	Brazilian National Institute for Environment and Renewable Natural Resources
IBGE	Brazilian Institute of Geography and Statistics
ICMbio	Instituto Chico Mendes de Conservação da Biodiversidade
IL	Indigenous Lands
INPE	Brazilian National Space Research Institute
IMAZON	Brazilian Institute for People and Environment in the Amazon
IPAM	Brazilian National Institute for Amazon Research
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre of the European Commission
MERS	Middle East Respiratory Syndrome
MMU	Minimum Mapping Unit
MODIS	Moderate Resolution Imaging Spectroradiometer
MT	Brazilian State of Mato Grosso

NDC	Nationally Determined Contribution
PA	Protected Areas
PA	Brazilian State of Pará
PRODES	Brazilian program for monitoring deforestation in the Amazonas and Cerrado biomes
REDD	UN programme for Reducing Emissions from Deforestation and Forest Degradation
RIL	Reduced Impact Logging
RO	Brazilian State of Rondonia
SARS	Severe Acute Respiratory Syndrome
SFB	Brazilian Forest Service
SFM	Sustainable Forest Management
TMF	Tropical Moist Forest Project at the JRC
UNFCCC	United Nations Framework Convention on Climate Change
UPF	Undesignated Public Forests
WFI	Wide-Field Imager (as part of the CBERS satellite sensors)

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