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Deforestation and Forest Degradation in the Amazon

Updated status and trends for the year 2021

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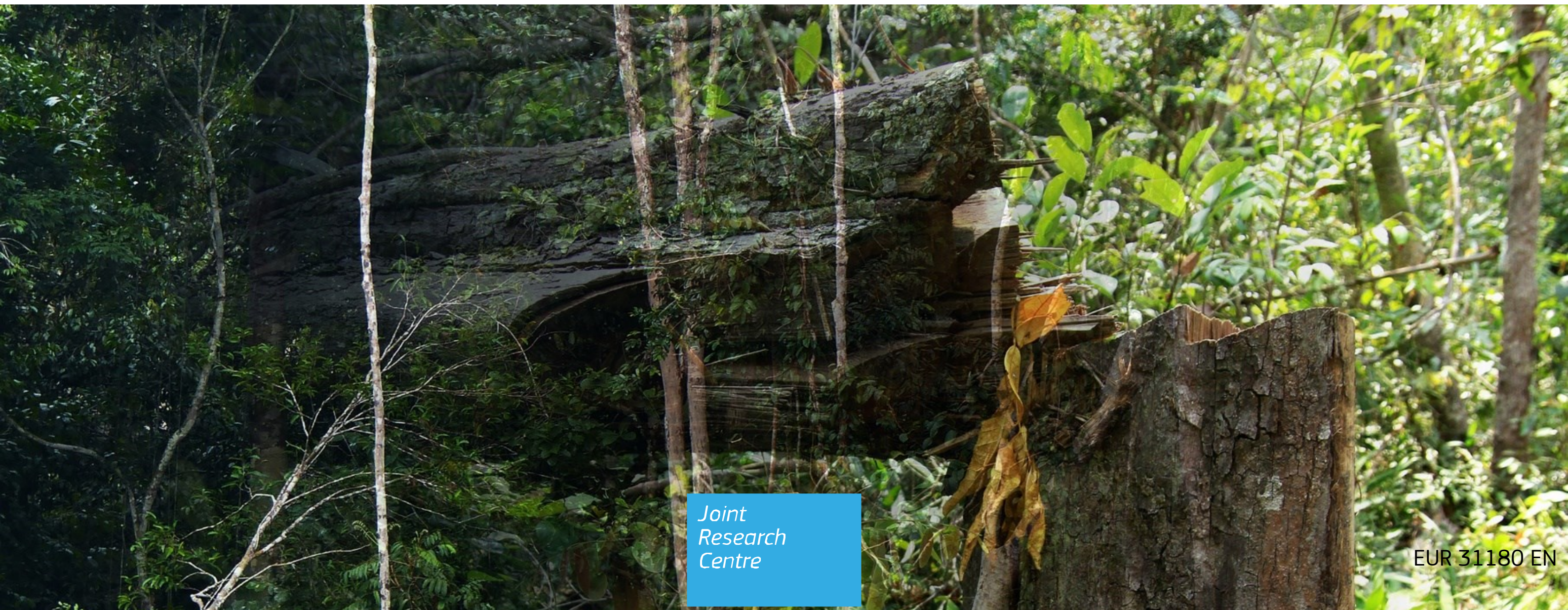
2022



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Contents

Abstract

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.

In 2021, according to the JRC-TMF data, the Pan-Amazon region showed a 37% decrease in forest disturbances (comprising deforestation and forest degradation) compared to the previous year (23,383 km^2 of new disturbances in 2021 vs. 37,293 km^2 in 2020). This decrease can be mainly explained by the decrease in forest fires in 2021, which apparently has been a year of high precipitation during the 'fire season' (July-November) in the Southern and Eastern Amazon regions. However, the decrease of burned areas in 2021 has been measured also in many other Amazon countries, leading to a significant decrease of forest disturbances in Colombia (38%), Brazil (38%), Ecuador (39%), Bolivia (59%), and Venezuela (85%).

In addition to the statistics of year 2021, the report provides an overview regarding the deforestation and forest degradation in the Brazilian Amazon for the first seven months in 2022 (January – July), as reported by the INPE-DETER alert system. It shows a deforestation increase of 7% compared to the previous year, while forest degradation increased by 27% for the same period. A second, independent deforestation alert system for the Brazilian Amazon, IMAZON SAD, reports a 19% increase of deforestation for the period from January to June 2022.

Foreword

This report aims to provide the statistics of deforestation and forest degradation during year 2021 for the rainforest in the countries of the Amazon region, based on the Joint Research Centre's Tropical Moist Forest (JRC-TMF) dataset. It is an update of a previous report on 'Deforestation and Forest Degradation in the Amazon' released in June 2021, which had reported on Amazon forest disturbances until year 2020 [1][1].

As with the previous report, a specific focus is given to Brazil here, the country in the region with the largest share of Amazon rainforest and the largest country of the South American Mercosur region. On this background the 2021 and 2022 deforestation and forest degradation statistics for the Brazilian Legal Amazon, provided by the Brazilian National Space Research Institute (INPE), are presented and compared to JRC-TMF data.

A number of law proposals that the Brazilian government has recently introduced into the national ratification process are presented in section 3 of this report, in particular the bills on the demarcation of indigenous lands, on land grabbing, on environmental licensing, on legal mining in protected areas, and the proposed reduction of the Brazilian Legal Amazon area.

Between mid-2021 and the first half of 2022, numerous new research articles were published, covering many aspects related to forest, deforestation, forest degradation and forest regrowth in the Amazon region. Important new scientific findings are reported in the annex (section 5). The covered topics include, amongst many others, the mercury contamination of indigenous people due to illegal gold mining in their territories, the change of local and regional temperature and precipitation patterns in South America due to deforestation in the Amazon, the consequences of road consolidation in a region of intact Brazilian public forests.

[1] https://op.europa.eu/en/publication-detail/-/publication/7fc3c506-c8c9-11eb-84ce-01aa75ed71a1/language-en

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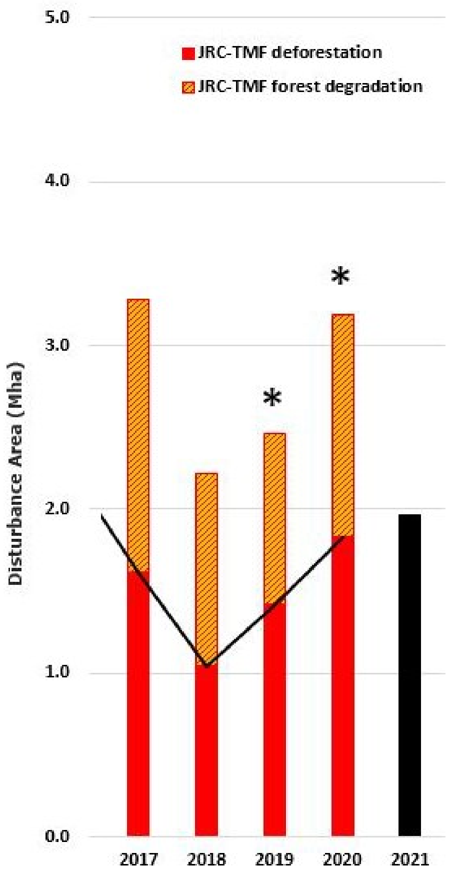
1 Trends in deforestation and forest degradation for the Pan-Amazon between 2002 and 2021 - estimates from the JRC-TMF dataset

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 2021, 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) [2].

Figure 1. Subset of JRC-TMF humid forest disturbances statistics for Brazil for the past five years. The stars (2019/2020) indicate that the distribution of the two classes within the yearly overall forest disturbances is an "educated guess" while the black bar for 2021 indicates that a separation of disturbance classes is not yet possible



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 2018, but are estimated ("educated guess"), indicated by stars in Figure 1, for the years 2019-2020. For 2021, the separation of classes is not yet possible.

All statistics are based on the JRC-TMF dataset [3][2 3]. The figures 6-12 report on forest cover changes of the moist forest in the Amazon countries, thus the statistics do not include the changes in e.g. the seasonal or dry forests and savannahs 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)[4] dataset are displayed in the mentioned figures. Both JRC-TMF and GFC datasets are compared in section 1.9 to the estimates of deforestation in the Brazilian Legal Amazon, provided by INPE-PRODES, the Brazilian Space Research Institute's deforestation monitoring program[5].

We have compared the JRC-TMF statistics in the Figures 2 and 7-14 (red/orange and black bars and black line) with corresponding data on "forest cover loss" from Global Forest Change (GFC) data from the University of

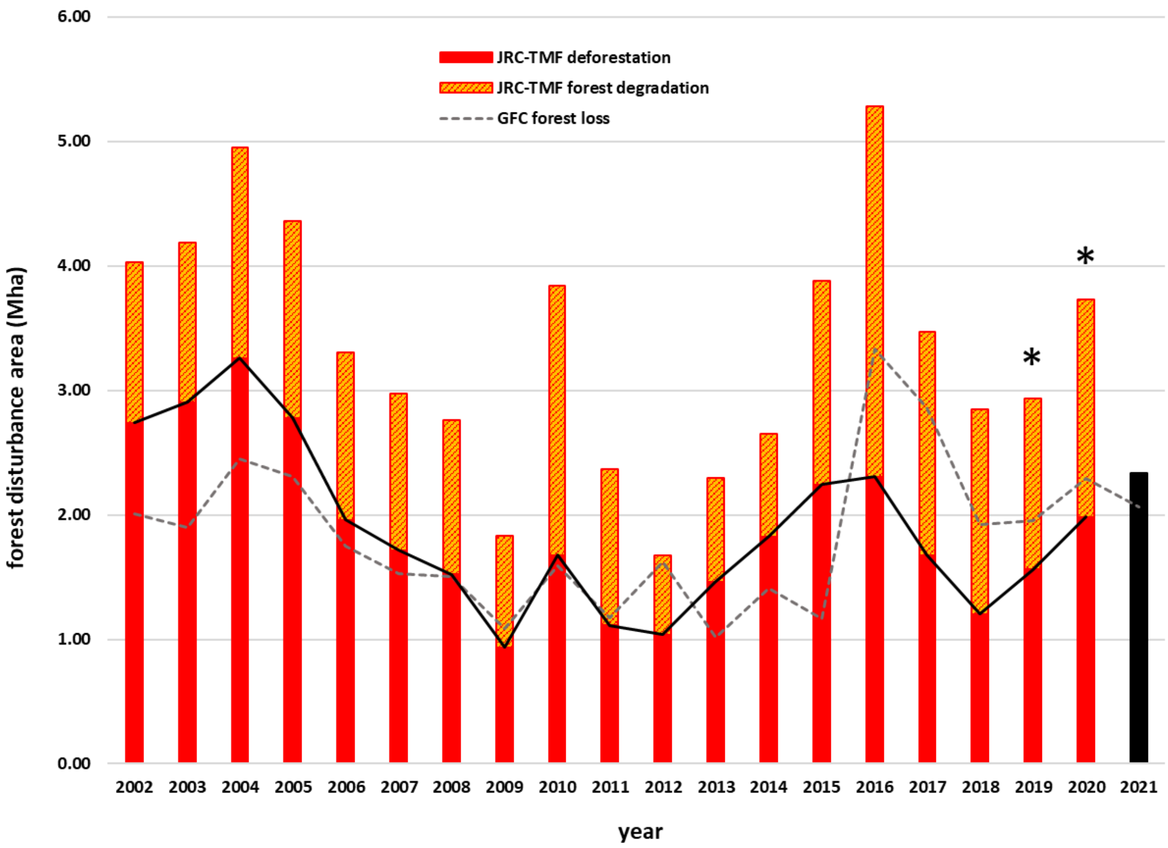
[2] https://forobs.jrc.ec.europa.eu/TMF/
[3] https://forobs.jrc.ec.europa.eu/TMF/explorer.php
[4] https://earthenginepartners.appspot.com/science-2013-global-forest
[5] http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes

Maryland (grey dashed lines). For comparison, we extracted both JRC-TMF data and GFC data for the Pan-Amazon and the Brazilian Legal Amazon (BLA) based on the area definitions of Eva and Huber (2005) [2] and of INPE-PRODES, respectively. For country statistics comparison, we extracted JRC-TMF and GFC data based on the Global Administrative Unit Layer (GAUL) Level 0 country borders[6] and the year 2000 JRC-TMF humid tropical forest extent as reference layer. For the comparison of the three datasets JRC-TMF, PRODES and GFC data for the Brazilian Legal Amazon, the INPE-PRODES forest mask defining the humid forest within the BLA[7] has been used additionally to ensure maximum comparability.

1.1 Pan-Amazon

From 1990 – 2021, the Pan-Amazon has lost more than 820,000 km² (14.5%) of undisturbed humid forest, according to JRC-TMF data, decreasing from 5,664,024 km² to 4,840,000 km². The percentage of degraded forest area (from forest fires or selective logging over the whole period) in relation to the area of undisturbed forest in 2021 is 6.7% [8]. Brazil drives the trend of forest cover change over the past 20 years in the region, as it covers the largest part of the Amazon forest within the Pan-Amazon and is the major contributor of deforestation and forest degradation area in the region (see also Figures 4, 6 and 8).

Figure 2. Forest disturbances in the Pan-Amazon humid forest from 2002-2021. The geographic basis are the areas of "Amazonia *Sensu Stricto*" and "Guiana", according to Eva and Huber [2]. GFC statistics appear as grey dashed line. The stars (2019/2020) indicate that the distribution of the two classes within the yearly overall forest disturbances is an "educated guess" while the black bar for 2021 indicates that a separation of disturbance classes is not yet possible.



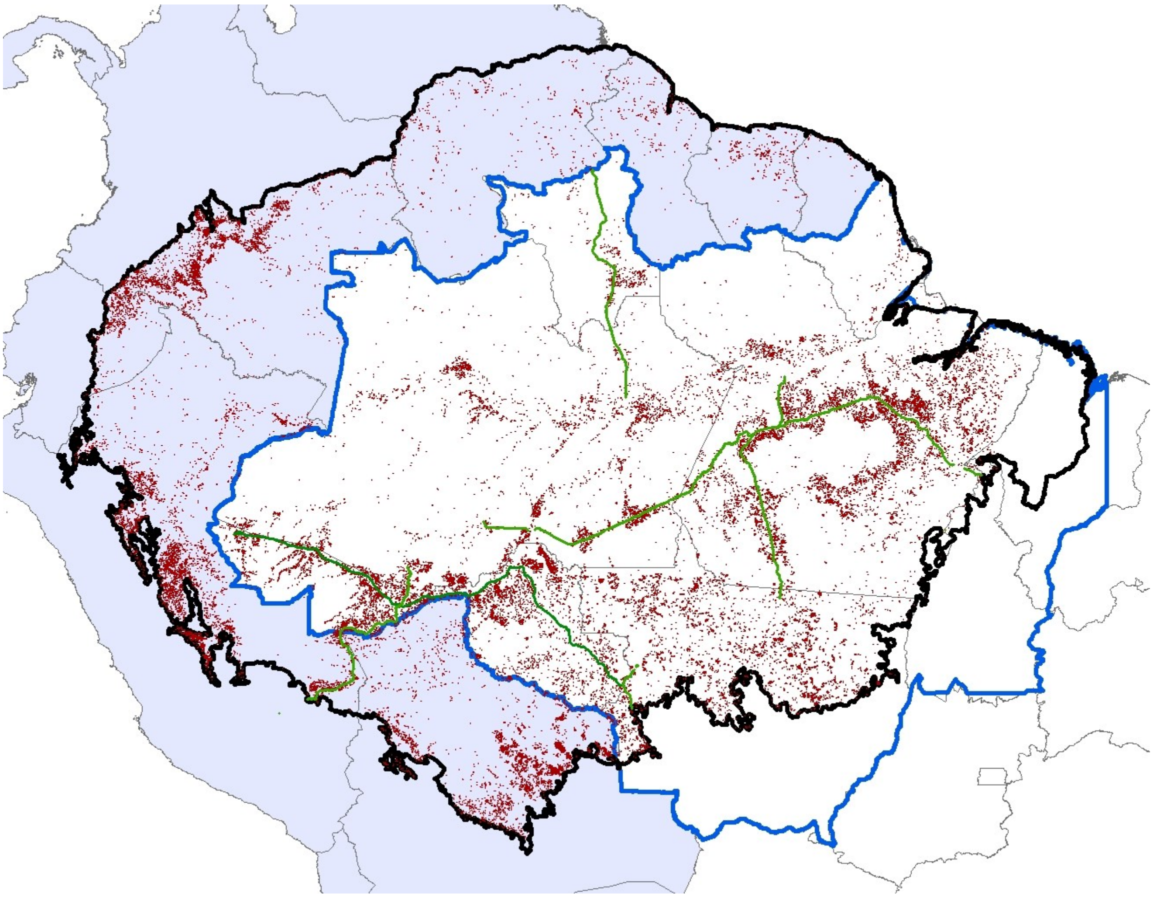
Altogether, 23,383 km² of forest were either deforested or degraded in the Pan-Amazon in 2021, constituting a decrease of more than 37% with respect to 2020. The decrease, as for Brazil and the Brazilian Legal Amazon,

[6] https://developers.google.com/earth-engine/datasets/catalog/FAO_GAUL_2015_level0
[7] https://dados.gov.br/dataset/prodes/resource/75c40917-901a-4b57-9503-8e8089f26431
[8] The degraded forest area contains existing forests in 2021 which had been selectively logged or burned at some point in the last 32 years

can be mostly attributed to the significant decrease of forest fires in 2021 due to the very humid conditions (high precipitation) in the Amazon throughout the year. This decrease is confirmed by the INPE-DETER forest degradation alert system[9], which reports a decrease of forest fires in 2021 by 78% compared to year 2020. The Global Wildfire Information System (GWIS)[10] also reports a significant decrease of burned areas for 2021 in Brazil, Venezuela, Colombia and Ecuador[11]. In addition, the COVID pandemic, causing possibly reduced financial resources for logging activities, might have played a role in the significant decrease of forest disturbances.

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, the mountain forests in Colombia or the Mata Atlântica in Brazil.

Figure 3. Distribution of JRC-TMF forest disturbances (in dark red) in the Pan-Amazon humid forest in 2021. 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 and Huber (2005) [2], the green lines show important roads cutting through the Amazon region, 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 Amazon and some forest cover change activities on the Western borders in Peru and Ecuador (Figure 3). In Brazil and Peru a

[9] http://terrabrasilis.dpi.inpe.br/app/dashboard/alerts/legal/amazon/aggregated/
[10] https://gwis.jrc.ec.europa.eu/
[11] https://gwis-reports.s3.eu-west-1.amazonaws.com/Amazon_Weekly_reports/2021_reports/11.29-12.05.2021/Weekly%26Monthly_Wildfires+in+the+Amazon+November+29+-+December+05+2021%2C+JRC+Technical+Report_vfinal.pdf

number of roads are cutting through the Amazon region (e.g. the BR-174, BR-230, BR-163 and BR-364 in Brazil and the 30 C in Peru), in consequence, forest disturbances occur often along these transport corridors. In the Southern and Eastern Amazon multiple access routes to the forest exist, thus the forest disturbance areas are more widespread rather than being concentrated along single roads.

The Amazon country statistics regarding the forest disturbance areas (i.e. comprising deforestation and forest degradation) show that Brazil was driving the overall absolute values, which is not surprising given the country's large share of the Amazon forest and current forest disturbance dynamics (Figure 4). However, if the areas of forest disturbances are related to the country areas of remaining intact humid forest, according to the JRC-TMF data, Bolivia has the highest scores in both years 2020 and 2021, while e.g. Venezuela drops from the 3rd place in 2020 to the second last in 2021 (Figure 5). The country statistics only cover the countries' rainforests, but include humid forest outside the Amazon region.

Figure 4. Humid forest disturbance area of 2020 and 2021 for Amazon countries, according to JRC-TMF data

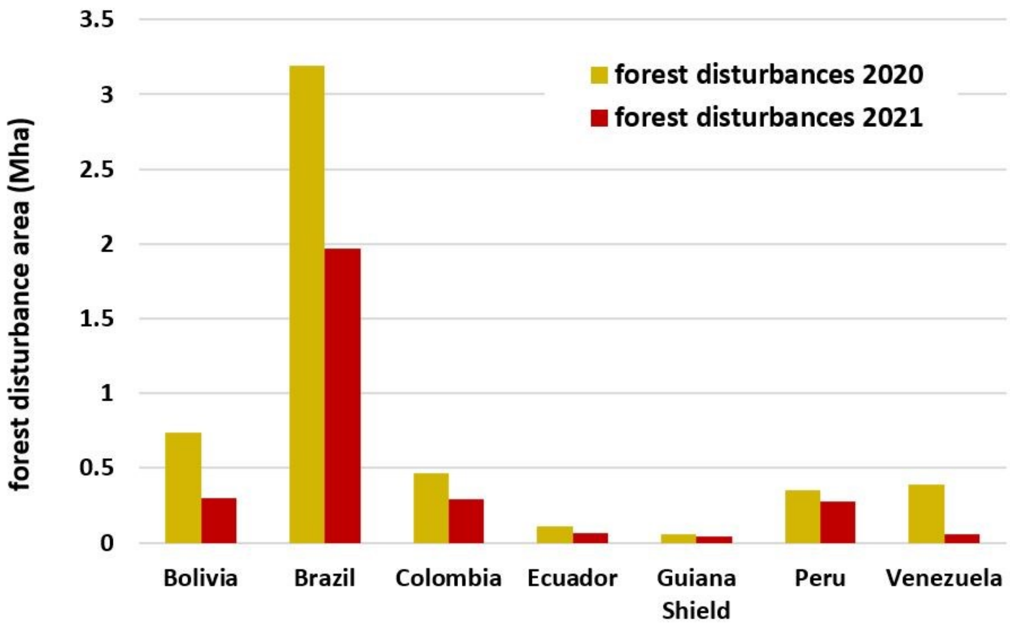


Figure 5. Humid forest disturbance area in relation to remaining intact rainforest for Amazon countries for 2020 and 2021, according to JRC-TMF data

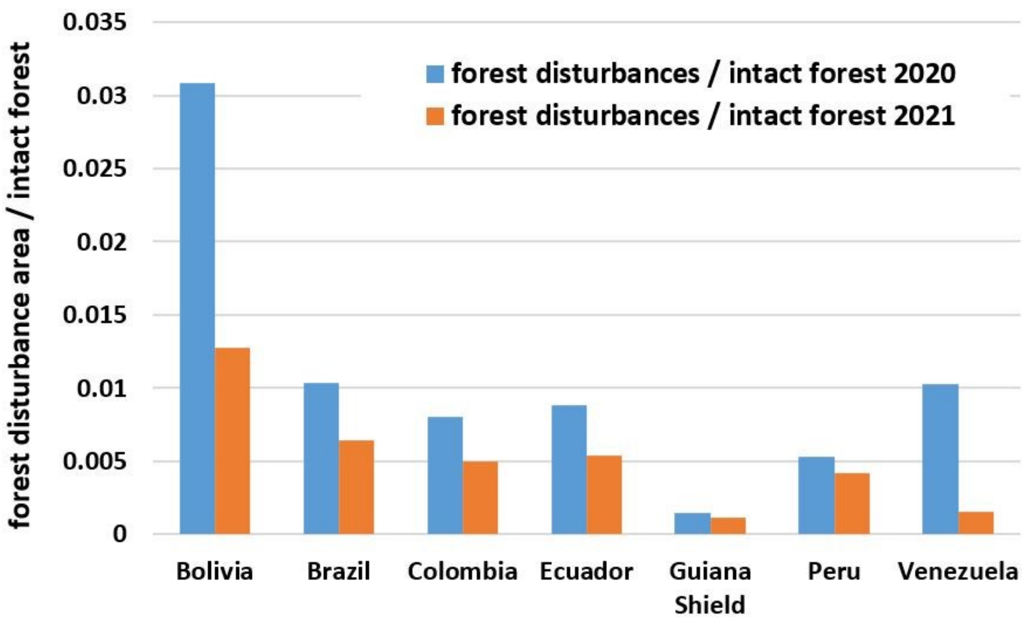
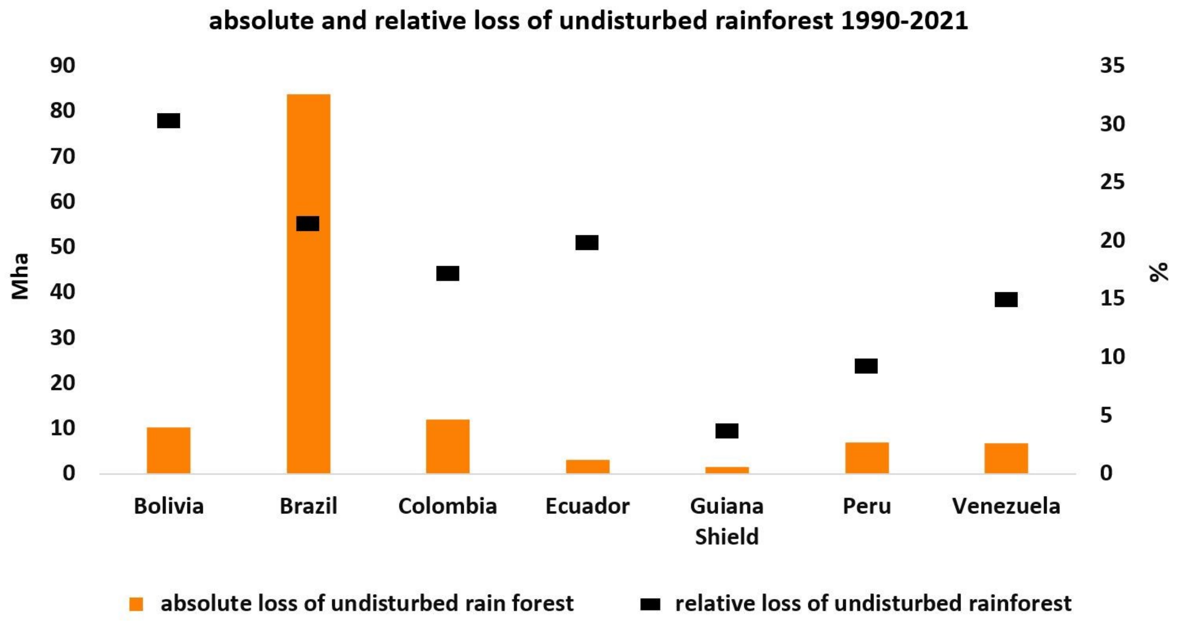


Figure 6. Absolute and relative loss of undisturbed rainforest[12] 1990-2021 for Amazon countries[13], according to JRC-TMF data

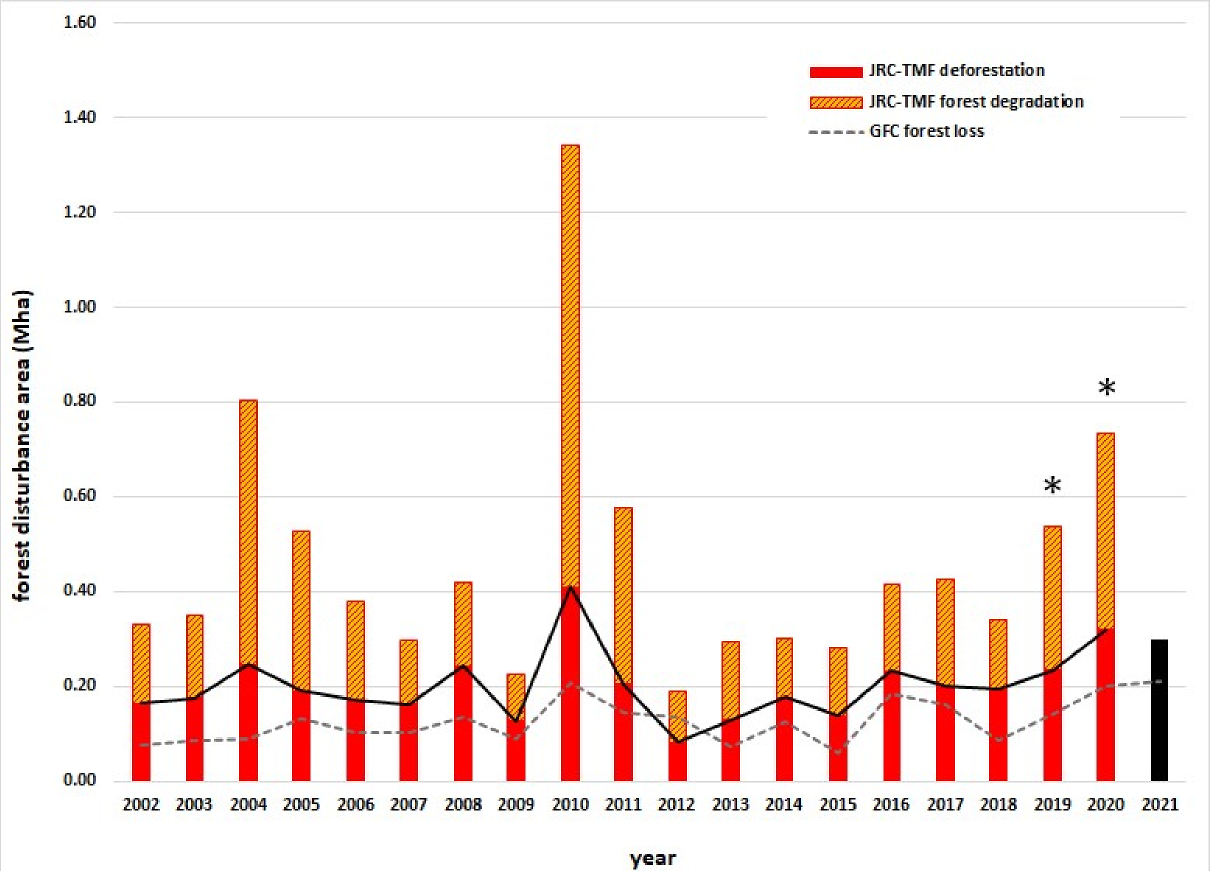


Looking at a larger time frame of forest disturbances, Brazil has lost ca. 83 million ha (Mha) of undisturbed rainforest from 1990 until 2021, according to JRC-TMF data, constituting a decline from 389 to 306 Mha during this period (or 21.5%). Only Bolivia has a higher loss percentage with 30.3%. (loss of 10.3 Mha). The other Amazon countries' losses of undisturbed rainforest range between 19.9% (Ecuador) and 3.7% (Guiana Shield countries).

[12] The 'loss of undisturbed rainforest' consists in the change to degraded forest or to non-forest
[13] The countries' undisturbed forest loss area includes rainforest loss outside the Amazon region

1.2 Bolivia

Figure 7. Forest disturbances in the Bolivian humid forest from 2002 – 2021, according to JRC-TMF. GFC tree cover loss statistics appear as grey dashed line. The stars (2019/2020) indicate that the distribution of the two classes within the yearly overall forest disturbances is an "educated guess" while the black bar for 2021 indicates that a separation of disturbance classes is not yet possible.



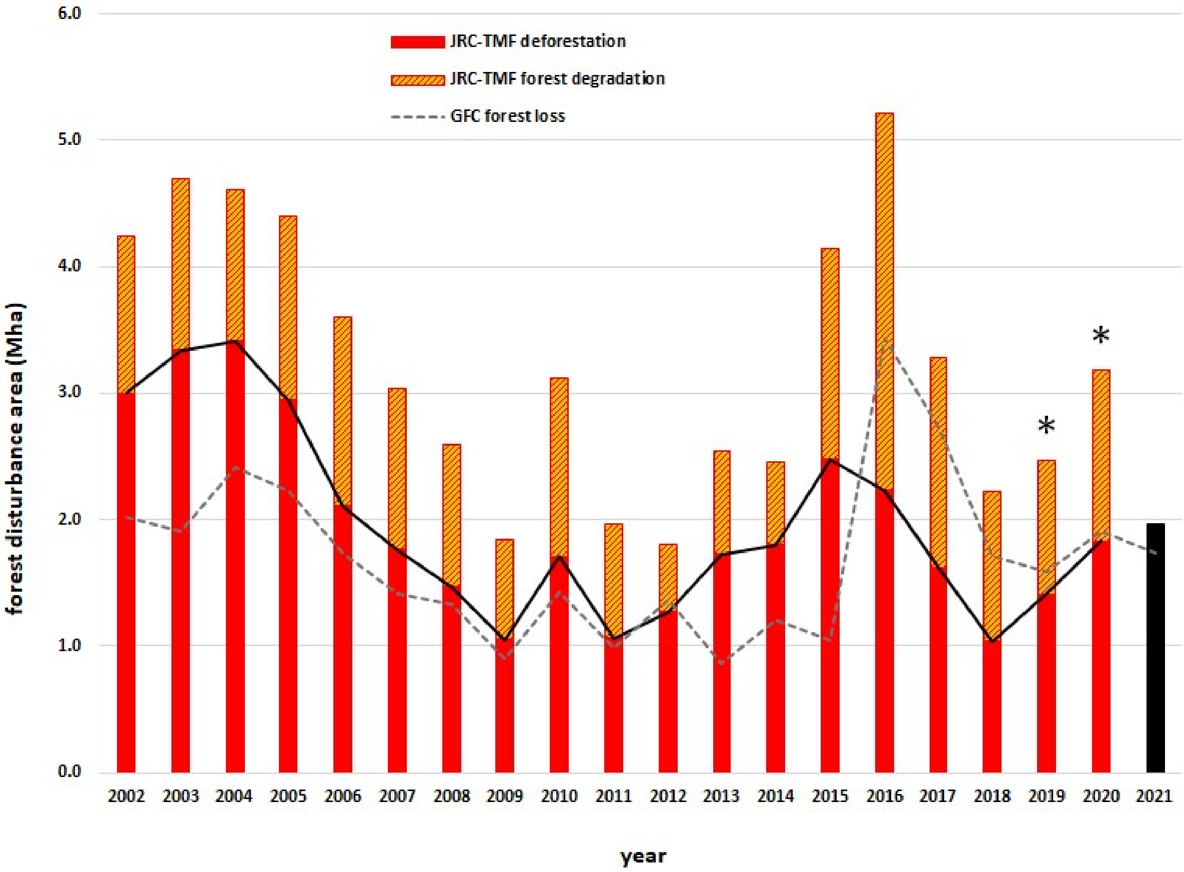
The forest disturbances for Bolivian humid forests in the last 20 years show the highest peaks for years of severe forest fires, as for the year 2010, when the Government announced a national emergency to combat the more than 15,000 km^2 of burning land[14]. In 2021, altogether 3,002 km^2 of humid forest were either deforested or degraded, which constitutes a decrease of 59% compared to 2020.

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

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

1.3 Brazil

Figure 8. Forest disturbances in the Brazilian humid forest from 2002 – 2021, according to JRC-TMF. GFC tree cover loss statistics appear as grey dashed line. The stars (2019/2020) indicate that the distribution of the two classes within the yearly overall forest disturbances is an "educated guess" while the black bar for 2021 indicates that a separation of disturbance classes is not yet possible.

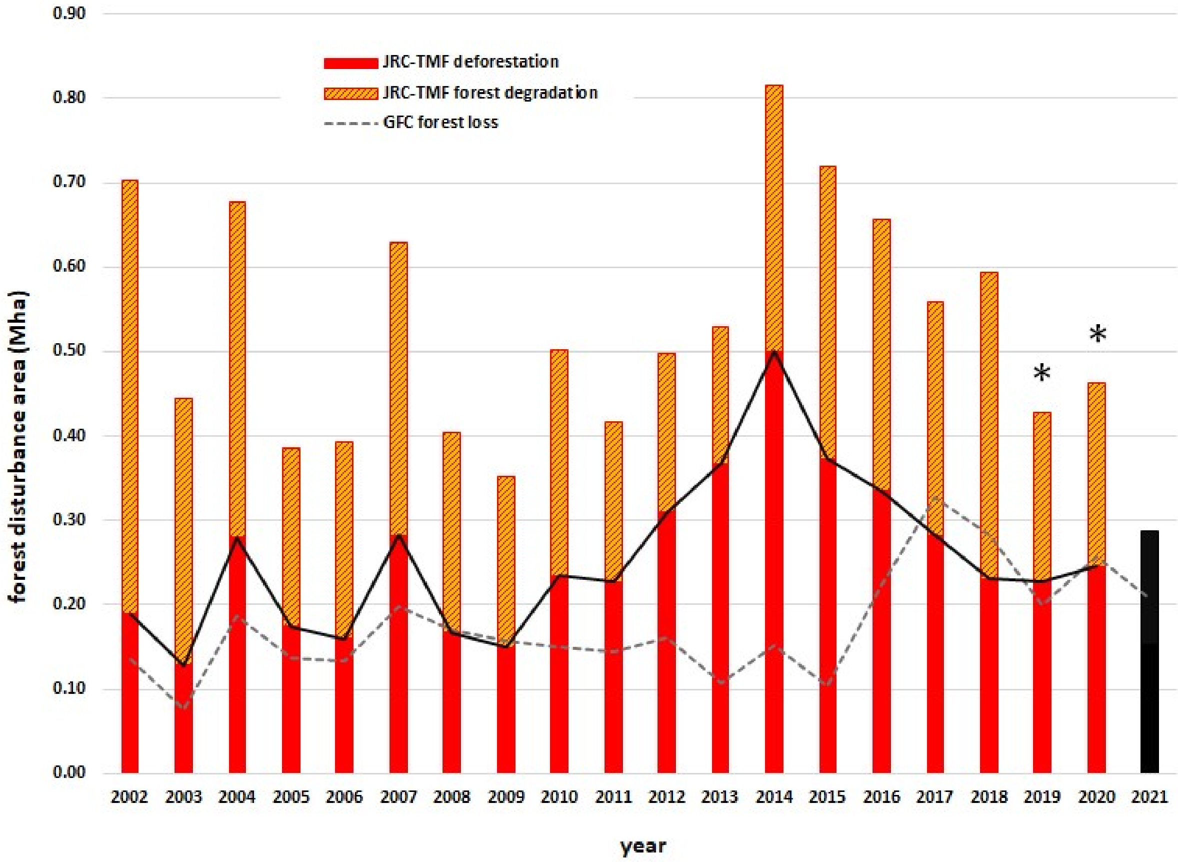


The Amazon being the Brazilian region undergoing most changes in humid forest cover, its forest dynamics clearly drive the overall Brazilian humid forest cover change (FCC) statistics reported by JRC-TMF data. The decrease of the Amazon deforestation after 2004 and the peaks in forest degradation, mostly due to forest fires in 2010 and 2015-2017, are visible in the BLA and the Brazilian statistics from JRC-TMF. Forest fires were responsible for a large part of the Brazilian forest degradation in 2020, which diminished considerably in 2021 due to the intensive rains in the region during the year. In this context, INPE-DETER calculated the decrease in forest fire alerts of 79% for the Brazilian Legal Amazon from 2020 to 2021.

According to JRC-TMF statistics, 19,665 km^2 of forest were either deforested or degraded in 2021 in the Brazilian humid forest (i.e. Amazon forest and Mata Atlântica), constituting a decrease of more than 38% compared to 2020.

1.4 Colombia

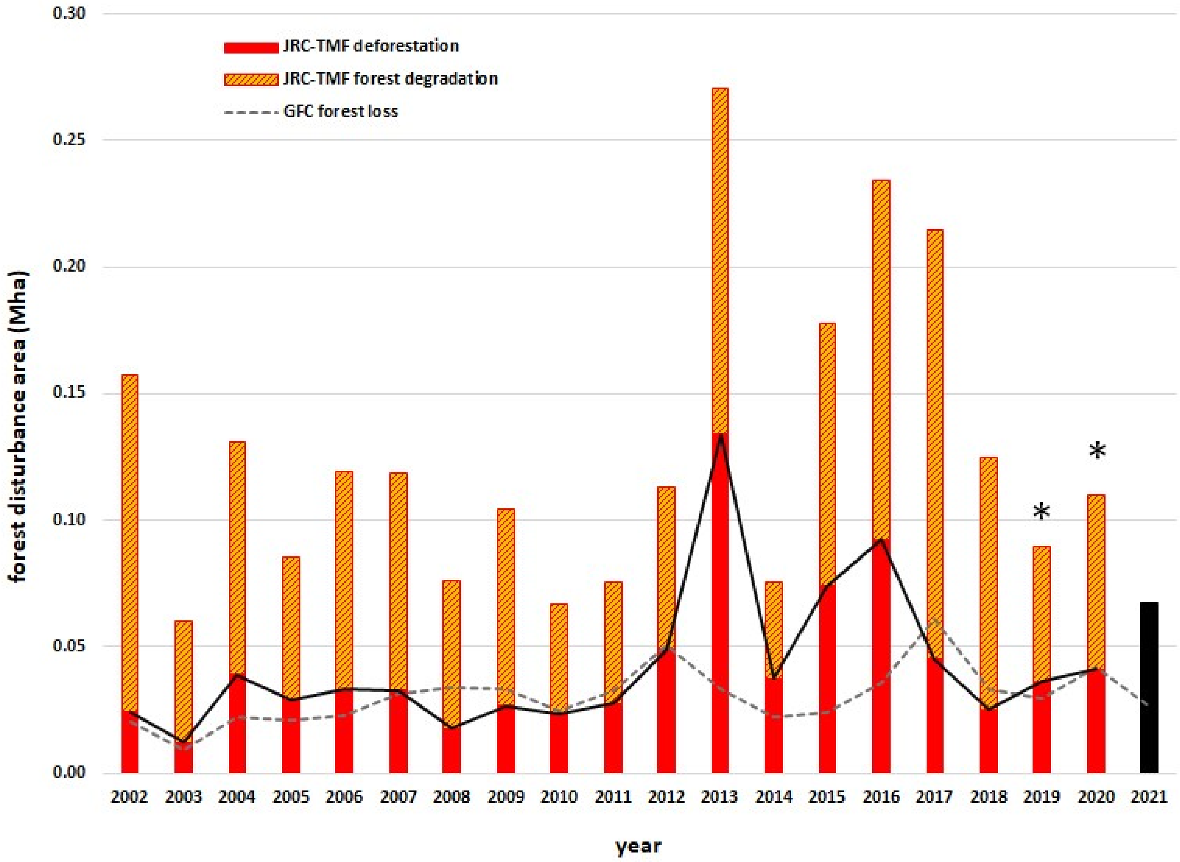
Figure 9. Forest disturbances in Colombian humid forest from 2002 – 2021, according to JRC-TMF. GFC tree cover loss statistics appear as grey dashed line. The stars (2019/2020) indicate that the distribution of the two classes within the yearly overall forest disturbances is an "educated guess" while the black bar for 2021 indicates that a separation of disturbance classes is not yet possible.



The forest disturbance 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 2021 is with 2,873 km^2 constitutes a decrease of 38% in comparison with 2020. The overall forest disturbance area is the lowest since 2002.

1.5 Ecuador

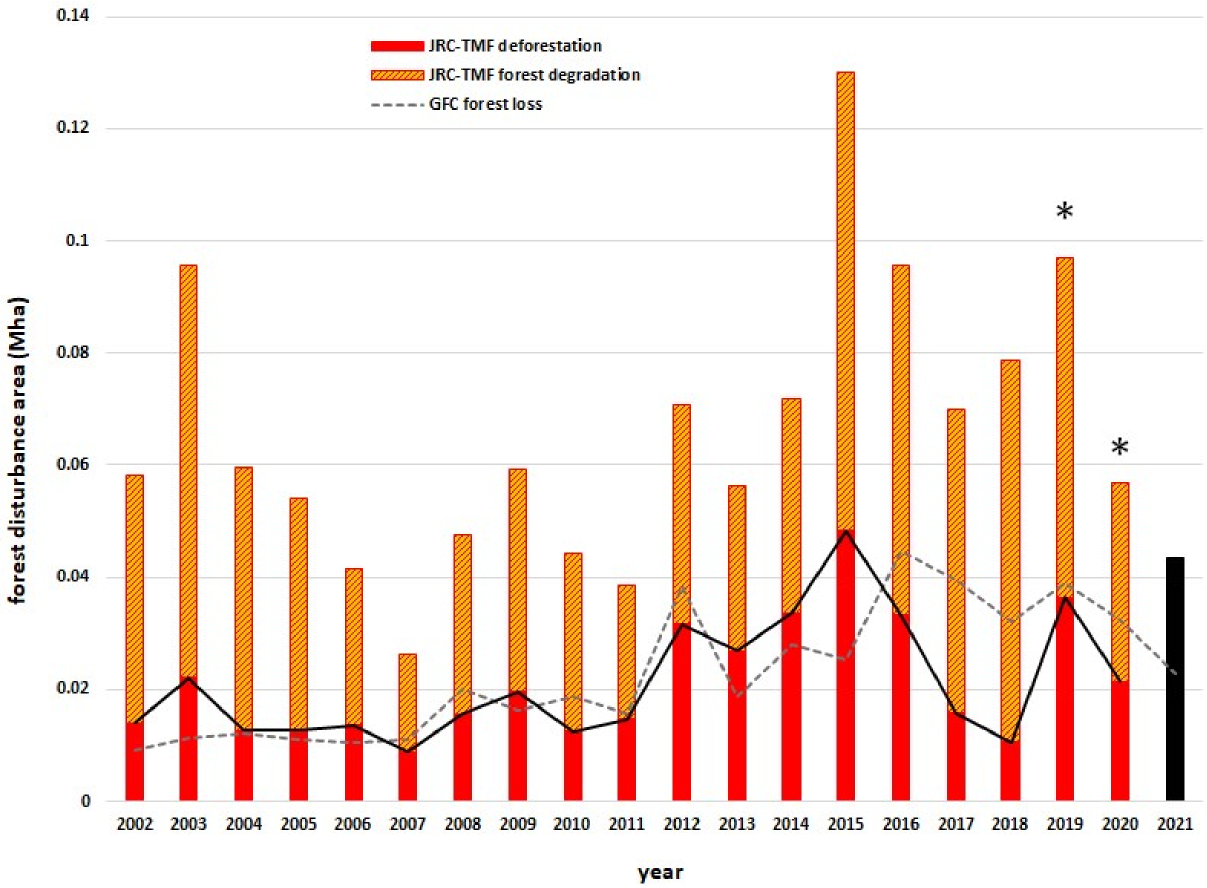
Figure 10. Forest disturbances in Ecuadorian humid forest from 2002 – 2021, according to JRC-TMF. GFC tree cover loss statistics appear as grey dashed line. The stars (2019/2020) indicate that the distribution of the two classes within the yearly overall forest disturbances is an "educated guess" while the black bar for 2021 indicates that a separation of disturbance classes is not yet possible.



The forest disturbance trends for Ecuadorian humid forests in the last 20 years show an area of ca. 1,101 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 decrease of the 2021 forest disturbance area (673 km^2), compared to 2020, is around 39%.

1.6 Guiana Shield (Guyana, Suriname and French Guiana)

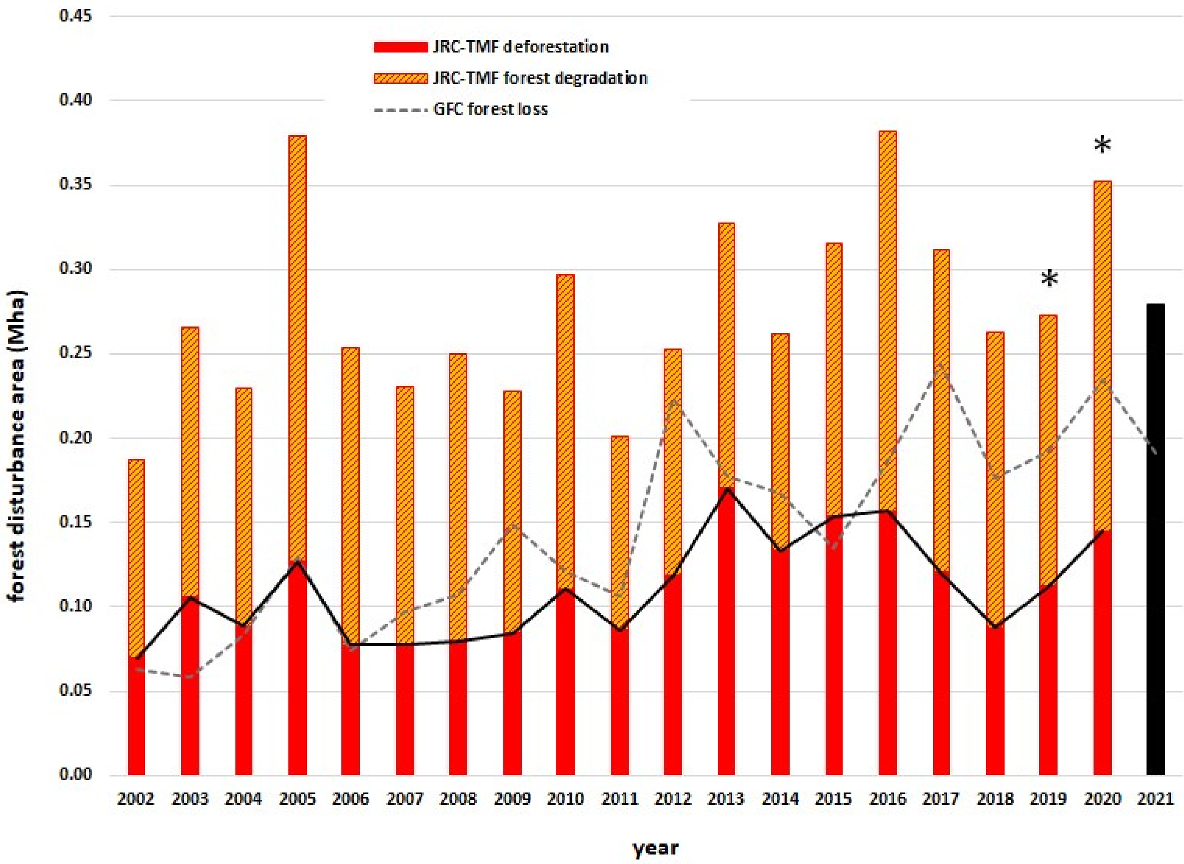
Figure 11. Forest disturbances in the Guiana Shield's humid forest from 2002 – 2021, according to JRC-TMF. GFC tree cover loss statistics appear as grey dashed line. The stars (2019/2020) indicate that the distribution of the two classes within the yearly overall forest disturbances is an "educated guess" while the black bar for 2021 indicates that a separation of disturbance classes is not yet possible.



In 2021, forest disturbances in the Guiana Shield (Guyana, Suriname and French Guiana) show a decrease of 24%, compared to 2020, adding up to 434 km^2.

1.7 Peru

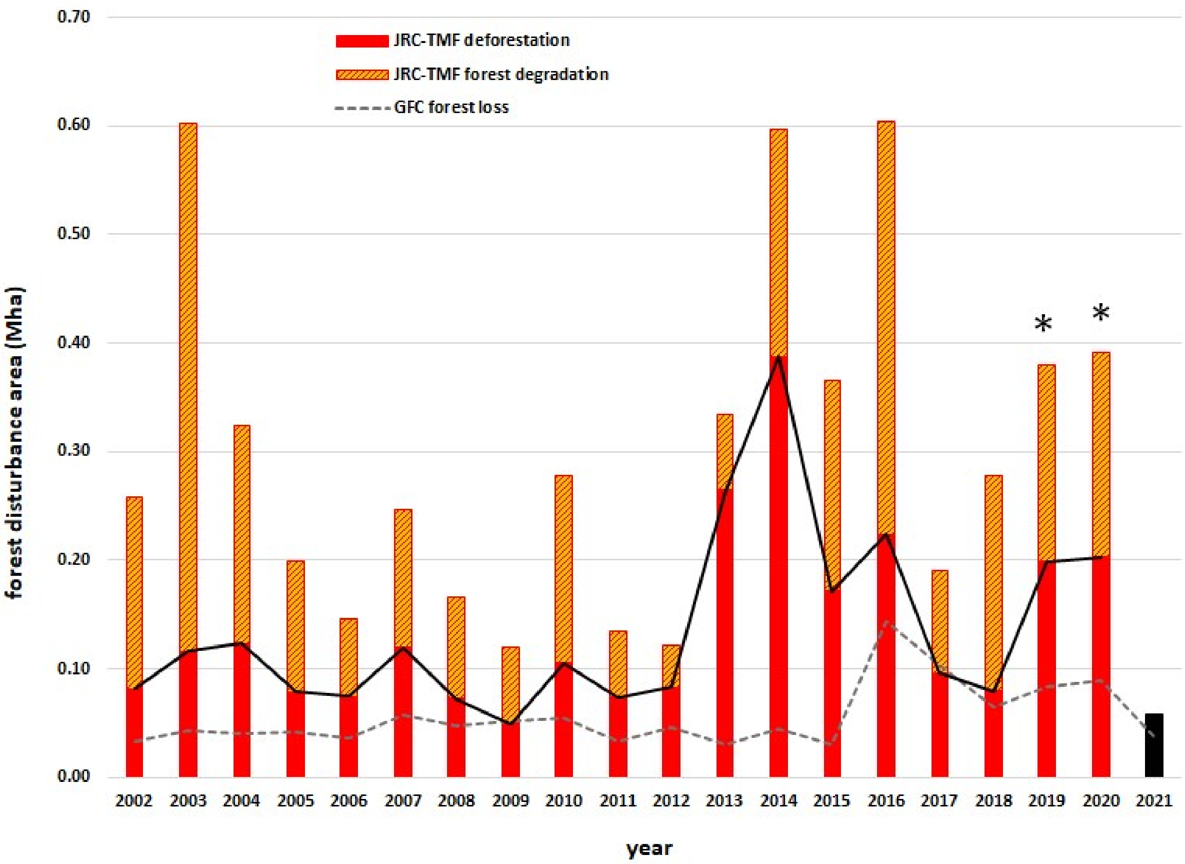
Figure 12. Forest disturbances in Peruvian humid forest from 2002 – 2021, according to JRC-TMF. GFC tree cover loss statistics appear as grey dashed line. The stars (2019/2020) indicate that the distribution of the two classes within the yearly overall forest disturbances is an "educated guess" while the black bar for 2021 indicates that a separation of disturbance classes is not yet possible.



The trend for Peruvian humid forest disturbances in the last 20 years shows that, with 2,792 km^2, year 2021 is at an average level. The decrease of the 2021 forest disturbance area, compared to 2020, is ca. 21%.

1.8 Venezuela

Figure 13. Forest disturbances in Venezuelan humid forest from 2002 – 2021, according to JRC-TMF. GFC tree cover loss statistics appear as grey dashed line. The stars (2019/2020) indicate that the distribution of the two classes within the yearly overall forest disturbances is an "educated guess" while the black bar for 2021 indicates that a separation of disturbance classes is not yet possible.

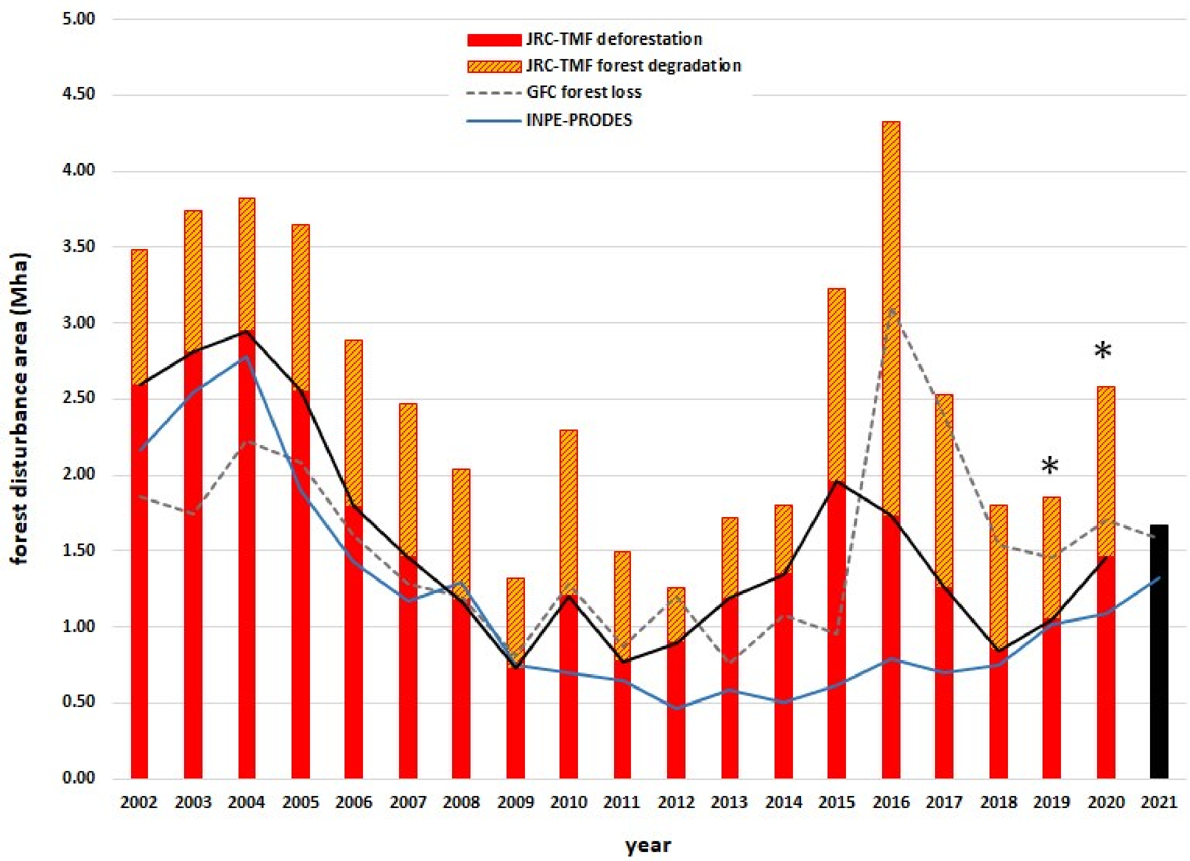


Venezuela showed large areas of forest disturbances in 2020, when 3,915 km^2 of humid forest have been either deforested or degraded. Compared to 2020, forest disturbances decreased by 85% in 2021 (579 km^2).

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

From 1990 – 2021, the Brazilian legal Amazon has lost more than 816,995 km^2 (18.3%) of undisturbed humid forest, according to JRC-TMF data, decreasing from 3,535,806 km^2 to 2,888,739 km^2. The percentage of the degraded forest area in relation to the area of undisturbed forest in 2021 is 8.0% [15].

Figure 14. Annual deforestation and forest degradation in the BLA from 2002 – 2021, 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 grey dashed line. The stars (2019/2020) indicate that the distribution of the two classes within the yearly overall forest disturbances is an "educated guess" while the black bar for 2021 indicates that a separation of disturbance classes is not yet possible.



The overall forest disturbance area in the BLA decreased by 35% from 25,840 km^2 in 2020 to 16,674 km^2 in 2021. The decrease is, for a large part, due to the decrease of forest fires in 2021 (compared to 2020), caused by the wet climatic conditions in the region throughout the dry season 2021. In fact, according to the CHIRPS precipitation data[16], 2021 was the year of highest precipitation in the BLA since the beginning of CHIRPS data collection in 1981 and the second highest rainfall (after 1985) for the Brazilian Arc of Deforestation (AOD) [4] for the whole year. Looking at the AOD in the fire season (July to November), 2021 was the year with the fourth highest rainfall in the last 40 years. This drop in forest fires in 2021 is also reflected in the INPE-DETER forest degradation statistics, which show a forest fire decrease of 79% (see Figure 18). The Global Wildfire Information Network (GWIS) reported a 50% decrease in burned areas (including forest fires and non-forest fires) for the Brazilian Legal Amazon in 2021 in comparison with 2020[17].

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[15] The degraded forest area contains existing forests in 2021 which had been selectively logged or burned at some point in the last 32 years

[16] https://www.chc.ucsb.edu/data/chirps

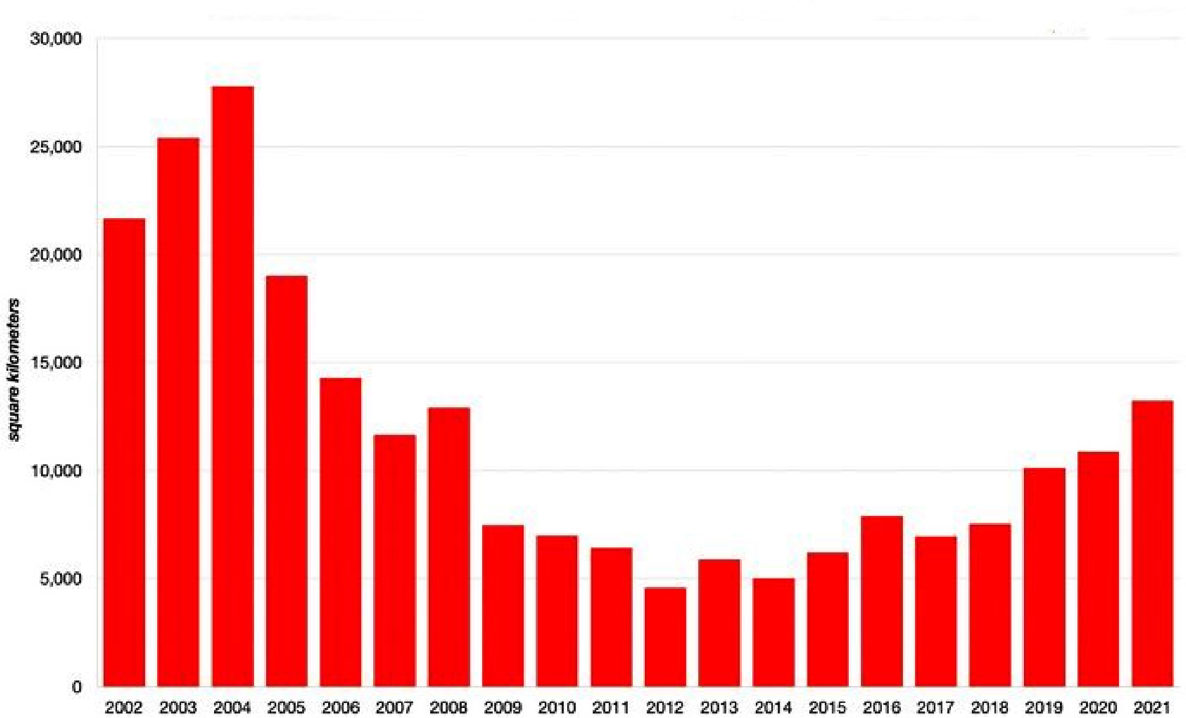
[17] https://gwis-reports.s3.eu-west-1.amazonaws.com/Amazon_Weekly_reports/2021_reports/11.29-12.05.2021/Weekly%26Monthly_Wildfires+in+the+Amazon+November+29+-+December+05+2021%2C+JRC+Technical+Report_vfinal.pdf

2 Monitoring BLA deforestation and forest degradation in Brazil: the PRODES and DETER projects at INPE for 2021

2.1 INPE-PRODES

The PRODES consolidated statistics on the deforestation of humid forest in the Brazilian Legal Amazon showed 13,038 km^2 for the period of August 2020 until July 2021[18], which constitutes an increase of 20% in comparison with the corresponding period in 2019/20. For the Cerrado biome, which constitutes a part of the Brazilian Legal Amazon, the deforestation area given by INPE for the same period was 8,531 km^2, an increase of 8% compared to 2019/20 [19]. The current Brazilian government recently decided to create a technical body to evaluate data on deforestation, while leaving out any environmental institutions in the process. Scientists fear that the new instance could delay or change the information regarding INPE statistics on deforestation and burned areas[20] [21].

Figure 15. Yearly official consolidated deforestation statistics for the BLA provided by INPE-PRODES



[18] https://www.gov.br/inpe/pt-br/assuntos/ultimas-noticias/nota-tecnica-prodes/NotaTecnica_consolidado_PRODES_2021_rev.pdf
[19] https://www.gov.br/inpe/pt-br/assuntos/ultimas-noticias/nota-tecnica-prodes-cerrado-2021
[20] https://g1.globo.com/jornal-nacional/noticia/2022/06/06/governo-cria-camara-tecnica-para-avaliar-dados-de-desmatamento-mas-deixa-de-fora-orgaos-ambientais.ghtml
[21] https://amazonia.org.br/governo-cria-comite-para-qualificar-dados-do-desmatamento/

Figure 16. Yearly official deforestation statistics for the Brazilian Cerrado biome, provided by INPE-PRODES

The future monitoring of the Cerrado biome by INPE-PRODES is in question, due to the lack of funding.

2.2 INPE-DETER deforestation and forest degradation alerts

2.2.1 INPE-DETER deforestation alerts 2021

The trends given by the yearly INPE-DETER deforestation alert areas are normally in line with the official consolidated deforestation figures for the BLA reported by INPE-PRODES. The comparison between 12 months of DETER accumulated monthly near-real-time alerts and official PRODES deforestation statistics for 2015/16-2020/21 shows differences which are significant but overall consistent (Figure 16). 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 68.9%. The exceptional year 2019-20 with a high DETER percentage (compared to PRODES) is the reason that the DETER deforestation estimates between the periods 2019-20 and 2020-21 are decreasing (by 5%), while the PRODES consolidated deforestation areas are increasing (by 20%).

In 2021 ("calendar year", Jan-Dec) INPE-DETER deforestation alerts for the Brazilian Legal Amazon[22] recorded an area of 8,219 km^2, which constitutes a decrease of 2.4% compared to 2020. If the "reference year" (Aug-Jul) is taken into account (rather than the "calendar year") as with PRODES, the decrease from August 2020 – July 2021 is almost 5%, compared to the previous reference year period (Figure 17). This deforestation decrease of 5% was reported by the Brazilian delegation at the COP 26 in Glasgow, while the official INPE statistics were already available[23,24,25], reporting a 20% increase of deforestation in the region.

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

[23] https://www.jb.com.br/pais/2021/11/1034145-governo-bolsonaro-segurou-divulgacao-de-dados-de-desmatamento-antes-da-cop26.html

[24] https://climainfo.org.br/2021/12/01/governo-bolsonaro-colocou-dado-errado-sobre-desmatamento-em-documento-oficial-para-a-cop26/

[25] https://www.otempo.com.br/politica/governo/governo-omitiu-na-cop-26-que-amazonia-teve-maior-desmatamento-em-15-anos-1.2571984

Figure 17. INPE-DETER yearly aggregation of deforestation near-real-time alerts 2015/16 – 2020/21 for the BLA in comparison with INPE-PRODES official consolidated deforestation statistics (red) for the same period.

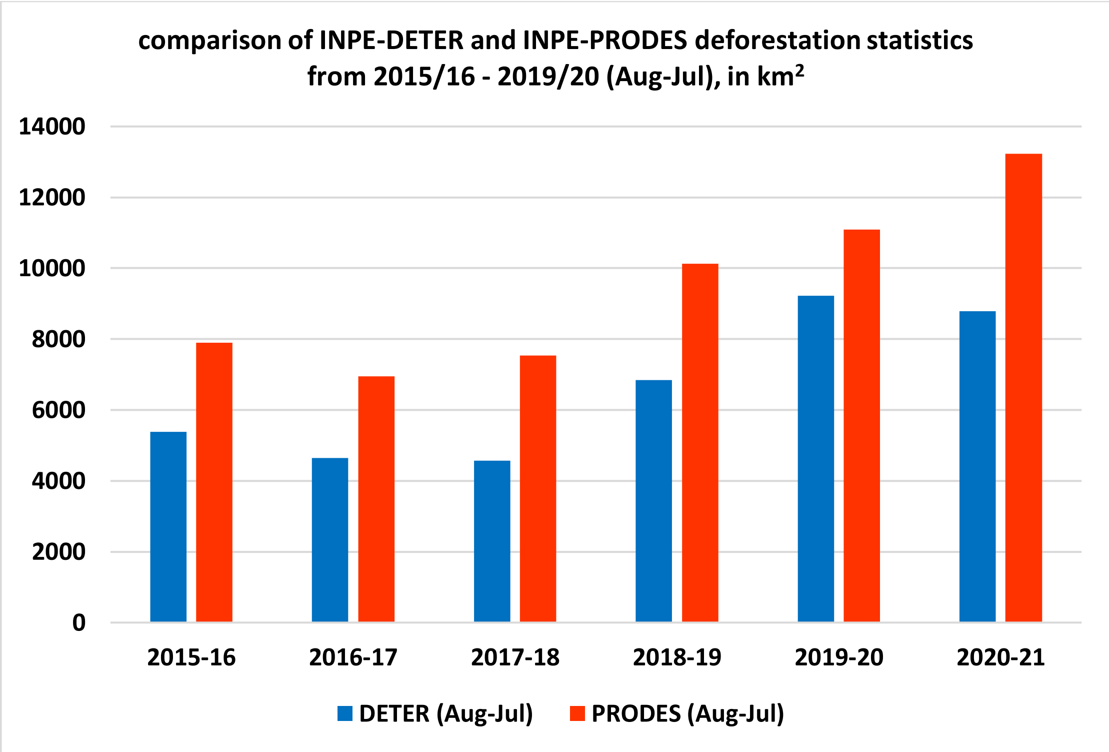
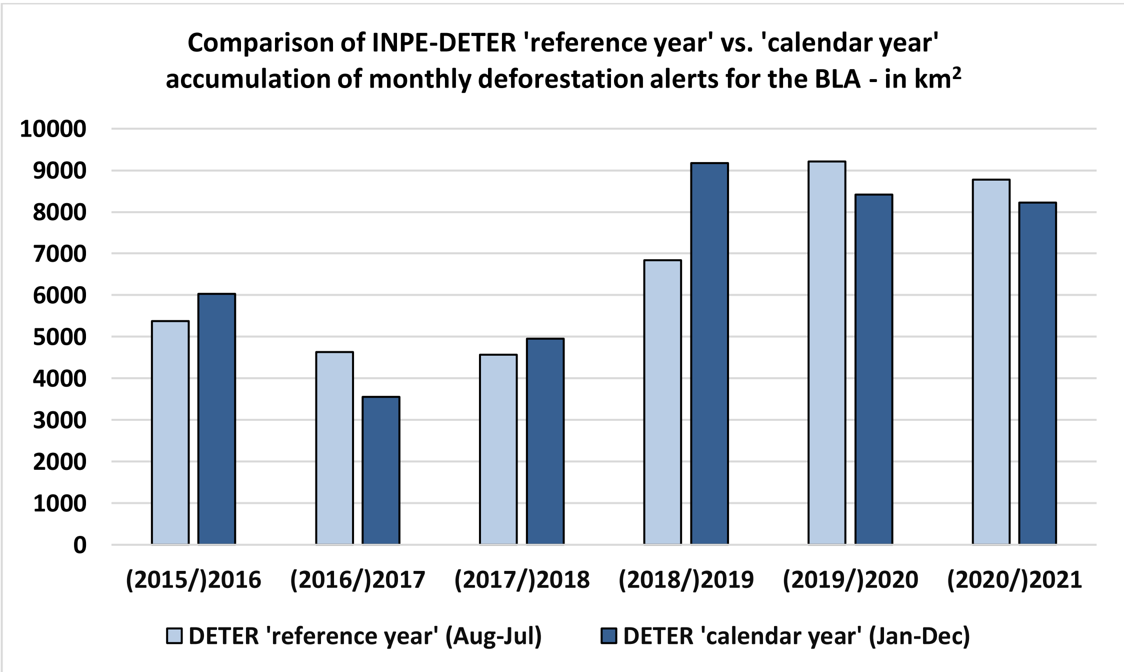


Figure 18. Difference between 'reference year' and 'calendar year' accumulation of INPE-DETER monthly deforestation alerts.



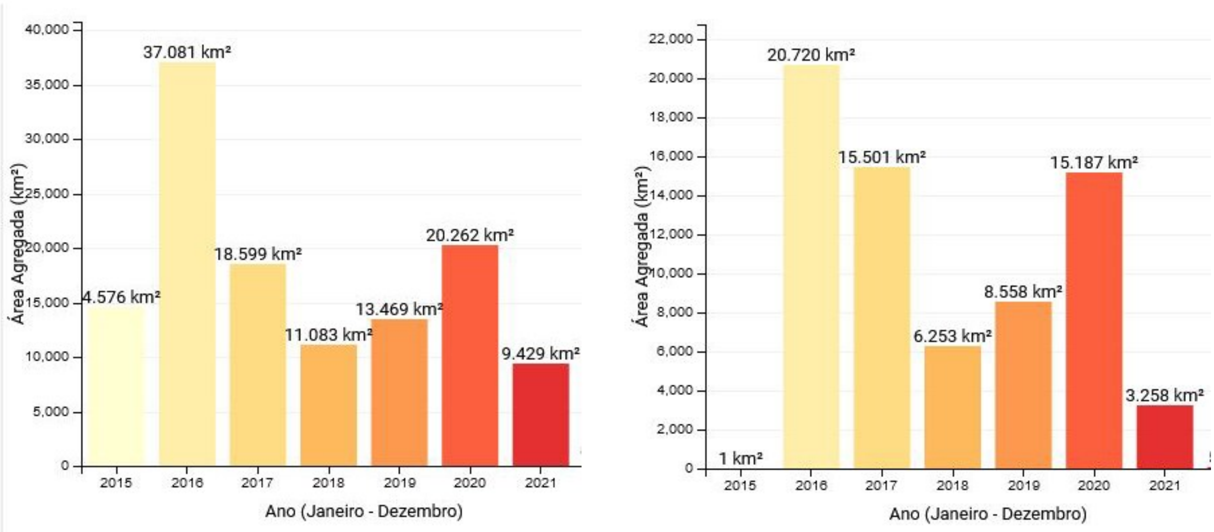
The comparison of different accumulation periods, i.e. for an INPE 'reference year" (e.g. August 2015 – July 2016) and 'calendar year' (January 2016 – December 2016) shows how the deforestation trend for a given year can vary with the observation period (Figure 17). While the yearly accumulated deforestation alerts show an area increase for the 2020/2021 'reference year', the deforestation area decreases slightly for the 2021 'calendar year'. The reason for this discrepancy is the exclusion of the large areas of deforestation alerts in the months of August and September 2020, which are counted for in the statistics of the following year (2021) in the 'reference year' accumulation, but are included in the year 2020 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.

2.3 INPE-DETER forest degradation alerts

2.3.1 INPE-DETER forest degradation alerts 2021

INPE-DETER alerts on forest degradation areas comprise the classes 'selective logging', 'forest fires' and 'unspecified forest degradation'. The statistics for 2021 show a decrease of overall BLA forest degradation of 53%, while forest fires alone decrease by 78% between 2020 and 2021 (Jan-Dec)[26]. The overall decrease of forest degradation is clearly driven by the decrease of forest fires in 2021. The alerts of selective logging and 'unspecified forest degradation' increased in 2021 by 16% and 34%, respectively.

Figure 19. left: INPE-DETER forest degradation alerts for the BLA, right: INPE-DETER forest fire alerts for the BLA



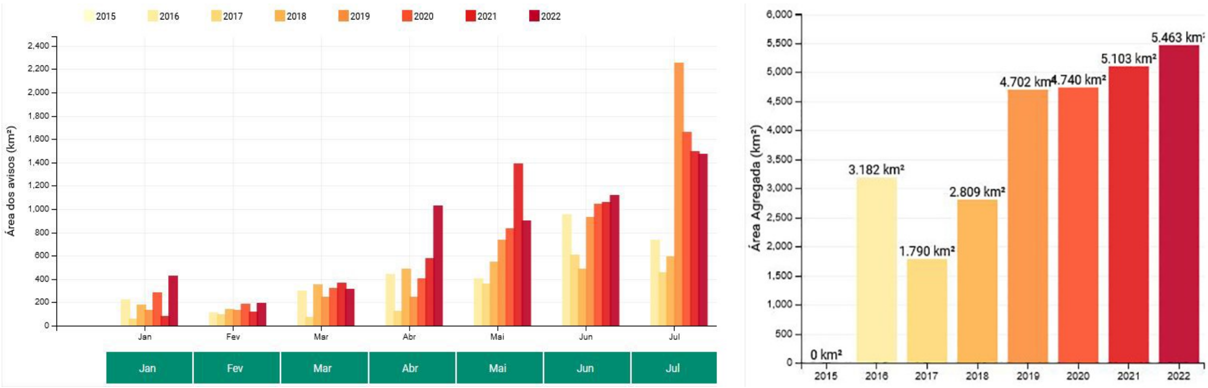
2.3.2 INPE-DETER deforestation and forest degradation alerts 2022

In the first seven months of 2022, the areas of deforestation and forest degradation (incl. selective logging, forest fires and 'unspecified forest degradation) in the Brazilian Legal Amazon have increased by 7% (5,463 km^2 in 2022 vs. 5,103 km^2 in 2021) and 27% (3,825 km^2 in 2022 vs. 3,007 km^2 in 2021) respectively, compared to the same period in 2021, according to the INPE-DETER alert system. In this context, it is important to note that monthly alert statistics have a high variation due to e.g. cloud cover obstructing forest cover change

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

detection. In consequence, comparing monthly figures has limited meaningfulness, while observing trends in accumulated statistics gives a better picture of the situation (Figure 19).

Figure 20. Left: monthly statistics of INPE-DETER deforestation alerts for the BLA (January – July), right: INPE-DETER accumulated deforestation alerts for the BLA (January – July)



For the Cerrado biome, an increase of 28% in deforestation area is recorded by INPE-DETER for the first seven months of 2022, compared to the same period in the previous year.

2.4 INPE-DETER deforestation alerts vs. IMAZON SAD deforestation alerts

Both deforestation alerts systems, one run by INPE, the other by the Amazon Institute of People and the Environment (IMAZON)[27]. While INPE is a governmental agency, IMAZON, as an NGO, tracks deforestation independently of the Brazilian Government. Their systems have a similar scope and area of interest, but use different data and image analyses techniques. INPE uses optical imagery with a spatial resolution of 64 m from the WFI sensor on board of the CBERS-4A satellite with a 3-day repetition rate[28] to detect newly deforested areas in near-real time. IMAZON uses different optical and radar satellite data (Landsat 8, Sentinel-1 and Sentinel-2)[29]. Both systems report deforestation alerts on a monthly basis, while DETER has the mandate to provide deforestation detections on a daily basis to law enforcement entities like the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA)[30]. For the first half of 2022, both systems report similar accumulated deforestation alert area for the Brazilian Amazon region (Fig. 20) as well as an acceleration of deforestation from April 2022, which is the month where precipitation starts to get less towards the end of the rainy season. The accumulated deforested area reaches 5,463 km^2 according to INPE-DETER (January – July, as mentioned above), and 4,789 km^2 according to IMAZON SAD (January – June)[31]. These figures constitute an increase of deforestation alert area in 2022, compared to the respective periods in 2021, of 7% and 19%, respectively.

[27] https://imazon.org.br/en/about-us/who-we-are/
[28] www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes/pdfs/Metodologia_Prodes_Deter_revisada.pdf
[29] https://imazon.org.br/publicacoes/faq-sad/
[30] http://www.ibama.gov.br/index.php
[31] IMAZON-SAD statistics for July 2022 were not available yet at the time of publication of the report

Both deforestation alert system have changed over the years, with new satellite data being available and new analysis techniques being applied. Figure 21 shows the difference in the results of both deforestation alert systems from 2008 onwards.

Figure 21. Monthly deforestation alerts from January – July 2022 (left), according to INPE-DETER and IMAZON-SAD[32], with accumulated deforestation alerts of both systems (right)

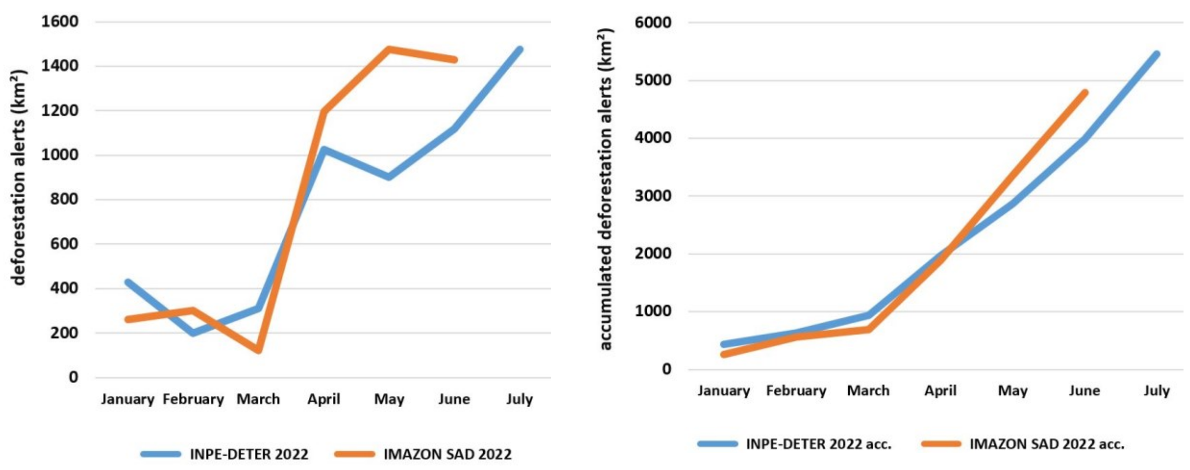
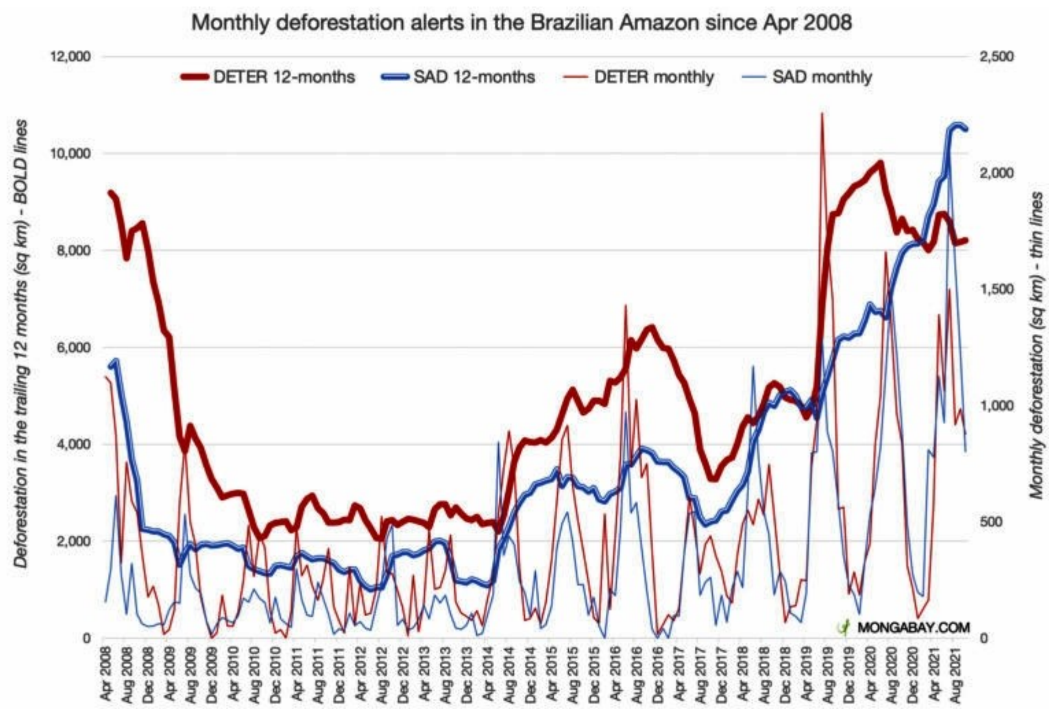


Figure 22. Monthly deforestation alerts according to INPE's deforestation alert system DETER and IMAZON's SAD system[33 34].



[32] IMAZON-SAD statistics for July 2022 were not available yet at the time of publication of the report
[33] https://rainforests.mongabay.com/amazon/deforestation-rate.html
[34] https://imazon.org.br/publicacoes/

3 Government Policy in Brazil, related to deforestation and forest degradation in the Amazon (status June 2022)

In recent years, environmental protection and the protection of indigenous peoples has suffered in Brazil, also due to political decisions leading to the dismantling of environmental agencies and research institutes (like IBAMA and INPE), to the lack of law enforcement in case of illegal deforestation and illegal selective logging, and to the lack of effective forest fire fighting.

In the years 2017-2021, i.e. after the impeachment of the former Brazilian president, deforestation in the BLA increased by 64% compared to the 2012-2016 period (according to INPE statistics) [35]. The Brazilian environmental agencies' funding stagnated or slightly decreased in the years from 2010 to 2016. Since 2017 the federal environmental and research agencies, as well as Brazilian science in general, suffer a growing funding gap [5,6], which is accompanied by an accelerated dismantling of Brazilian environmental protection policies [7–9].

Since the current Brazilian government was elected in 2019, many federal policy initiatives were launched, or re-launched, related to the weakening of environment protection policies on various fronts:

The current government is pushing for the consolidation (asphalting) of the whole length of the BR-319 Highway Porto Velho – Manaus. In its current state the highway is already leading to deforestation and forest degradation along its route, affecting numerous Indigenous Areas, while good governance and law enforcement in the area are essentially non-existent; the planned road consolidation would most certainly increase these negative effects [10–12] (see also section 'roads' in the annex)[36] [37] [38].

At the same time, the current Brazilian Government plans to install a new railway line (EF-170) of almost 1000 km length called Ferrogrão between Sinop (Mato Grosso State) and Miritituba (Pará State) on the Tapajos River[39]. The plan for the railway line had been on the table since many years, but was not followed up by previous governments. It can potentially have considerable environmental impact, like an increased risk of deforestation without necessary mitigation measures in place[40] [41]. Ferrogrão will reduce export costs and thus increase the competitiveness of the region's grain producers, potentially creating incentives for deforestation.

The project of consolidating (asphalting) the whole MT-322 state highway between the town of Novo Mundo (Mato Grosso) and the State of Goiás would cut the Xingu Indigenous Land in two. Under weak environmental governance, a better road access through asphalting, specifically in the rainy season, could trigger deforestation of indigenous people's forest and the foreseen new bridge across the Xingu River (to replace the ferry), would weaken the control of the Xingu indigenous groups to control the access to their land[42].

Figure 23. Mato Grosso State (blue outline) would be deducted from the BLA (red outline), according to the proposed law 337/2022, with severe consequences for the State's forest protection

[35] http://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/legal_amazon/rates

[36] https://www.theguardian.com/environment/2022/jul/29/paved-highway-to-run-through-amazon-gains-initial-approval-in-brazil

[37] https://infoamazonia.org/2022/08/03/plano-do-ministerio-da-economia-para-br-319-pode-regularizar-fazendas-com-indicio-de-grilagem/

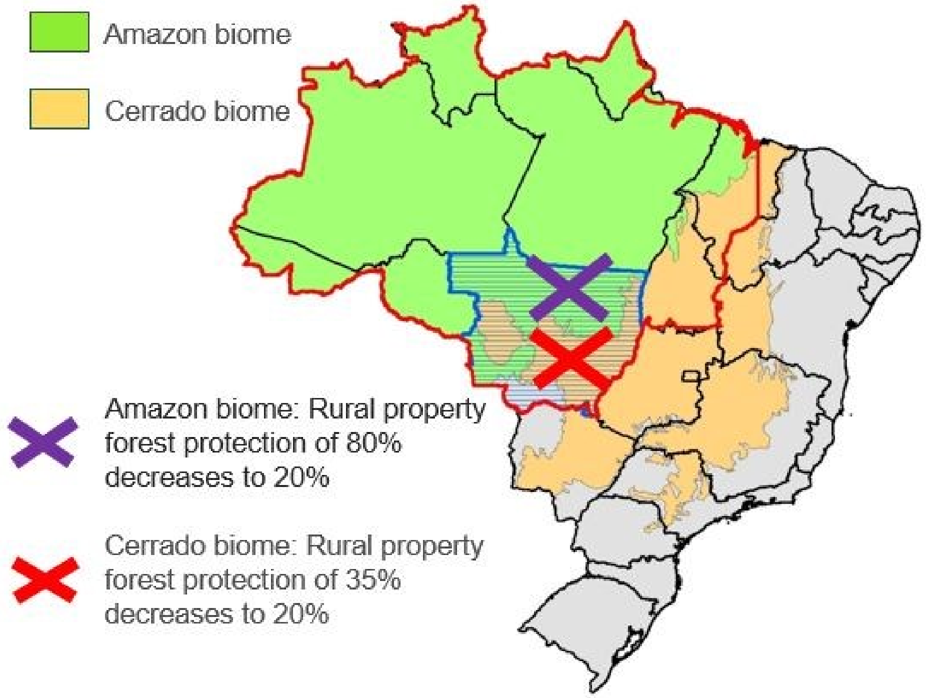
[38] https://bibliotecadigital.fgv.br/dspace/handle/10438/30185

[39] https://portal.antt.gov.br/ferrograo-ef-170

[40] https://www.climatepolicyinitiative.org/wp-content/uploads/2020/03/PB_The-Environmental-Impacts-of-the-Ferrograo-Railroad-1.pdf

[41] https://csr.ufmg.br/csr/wp-content/uploads/2020/11/Ferrograo_policy-brief_.pdf

[42] https://csr.ufmg.br/csr/wp-content/uploads/2021/07/Nota-MT-322_final_EN.pdf



PL 337/2022: The current government wants to exclude the State of Mato Grosso from the Brazilian legal Amazon (see Figure 22), weakening considerably the State's forest protection laws[43] [44] [45].

PL 191/2020 [46] ("Mining Bill"): The bill would allow mining operations inside indigenous lands, potentially leading to conflicts between miners and indigenous peoples. Mining in indigenous lands will lead to deforestation, forest degradation and to the release of mercury in air, soil and water. It puts indigenous peoples at a high risk of mercury poisoning [13–18][47] [48] [49] [50].

PL 6299/2002 ("Poison Bill"): The law would determine that the Ministry of Agriculture will be the only agency to register new pesticides, reducing IBAMA and the Brazilian Health Regulatory *Agency (*ANVISA)[51] to homologating agencies. It would soften the rigor of the current legislation by opting to work with a generic concept of risk management that analyses the effects on health and the environment and political and economic factors. In addition, it would remove the autonomy of health agencies to publish analyses about pesticides in food[52]. If approved, the bill is highly likely to lead to a rise in the number of registrations, authorizations, and use of pesticides, without proper assessment of their socio-environmental consequences. This trend is clear in the mainstream economic and political pressures coming from the agribusiness industry [19].

PL 2633/2020 and 510/2021 (Land Grabbing): The laws would allow claims to land occupied by 2014 to be legalized on the basis of a mere "self-declaration" of ownership. In addition to "self-declarations," they are expected to allow legalization of occupations up to 2018, thus providing even greater stimulation for land

[43] https://www.camara.leg.br/noticias/857242-projeto-exclui-o-estado-de-mato-grosso-da-amazonia-legal/
[44] https://news.mongabay.com/2022/04/brazil-bill-seeks-to-redraw-amazon-borders-in-favor-of-agribusiness/
[45] https://csr.ufmg.br/csr/wp-content/uploads/2022/03/NT_estimativas_RL_MT_150322.pdf
[46] https://www.camara.leg.br/proposicoesWeb/prop_mostrarintegra?codteor=1855498
[47] https://news.mongabay.com/2020/09/mercury-from-gold-mining-contaminates-amazon-communities-staple-fish/
[48] https://www.reuters.com/article/us-climate-brazil-amazon-mercury-idUSKBN2IW03Q
[49] https://www.science.org/content/article/illegal-gold-mines-flood-amazon-forests-toxic-mercury
[50] https://theintercept.com/2022/06/07/yanomami-fetos-mercurio-garimp-paulo-basta/
[51] https://www.gov.br/anvisa/pt-br/english
[52] https://www.oc.eco.br/wp-content/uploads/2022/03/OC_PLs-em-risco_EN.pdf

grabbing [20,21][53] [54] [55], and creating a cycle of environmental destruction and criminality, which, with the certainty of impunity, come to be one of the main motors of deforestation in the Amazon region[56].

PL 3729/2004 (Environmental Licensing General Law): The law weakens the environmental licensing in Brazil. Among other consequences, the law allows that some infrastructural works are dispensed from environmental licensing, like sanitation works, road and port maintenance, electric energy distribution lines, works considered as "insignificant" for the licensing authority and activities related to agriculture, including chemical compounds with high contaminating potential. The article also brings the term of the "single license", which allows the addition of previous licenses, and will be done through self-declaration of the entrepreneur. This removes the veto power of indigenous and quilombo communities from impact analyses and from the adoption of damage prevention measures when they have not yet had their lands demarcated or titled; in addition to excluding the analysis of direct and indirect impacts on Conservation Units[57]. One of the first Amazonian infrastructure projects likely to benefit from the new licensing procedures is the planned reconstruction of the environmentally disastrous Highway BR-319, which, together with its planned side roads, would open a vast area of Amazonia to deforestation [22,23].

PL 490/2007 (Changes to the demarcation of Indigenous Territories and related issues): The law would put under threat land rights and culture of Brazilian Indigenous peoples. Under the 1988 constitution, the Brazilian state must demarcate, protect and ensure the land and resource integrity of Brazilian Indigenous populations. However, if the so-called *Tese do Marco Temporal* (Timeframe Thesis) is approved, many indigenous peoples are likely to be expelled from their current territories. The Timeframe Thesis prevents the demarcation of indigenous lands not occupied or legally disputed by indigenous peoples at the date of October 5, 1988 – the date when the current Brazilian Constitution was enacted [58]. However, many indigenous groups had already been displaced from their ancient territories by this date, while having no or very limited access to legal action. In consequence, the official demarcation of historic indigenous lands, often taking years to finalise, could be suspended, thus opening the way to deforestation, selective logging, mining and land grabbing [24] [59].

[53] https://wwfbr.awsassets.panda.org/downloads/factcheckpl_510_fev_22.pdf
[54] https://oeco.org.br/reportagens/pl-510-abrira-caminho-para-ocupacao-de-24-milhoes-de-hectares-de-florestas-publicas/
[55] https://news.mongabay.com/2021/04/bills-before-brazil-congress-slammed-for-rewarding-amazon-land-grabbers/
[56] https://csr.ufmg.br/csr/wp-content/uploads/2021/04/Rajao_21_Nota_PL-510-regularizacao-fundiaria_FINAL_n.pdf
[57] https://www.crbio03.gov.br/index.php/institucional/noticias/1727-sistema-cfbio-crbios-envia-ao-senado-manifesto-contra-o-pl-3729-2004
[58] https://infoamazonia.org/en/2021/09/03/end-time-limit-thesis-protect-climate/
[59] https://g1.globo.com/politica/noticia/2021/08/27/o-que-e-o-marco-temporal-sobre-terras-indigenas-entenda-o-que-esta-em-jogo-no-julgamento-do-stf.ghtml

4 Conclusions

The year 2021 was a year of an overall decrease of forest disturbances in the Amazon region. This was, to a large part, probably caused by the exceptionally wet 'dry season' in the South and East of the Amazon basin, which prevented large areas of forest fires. Also in the other parts of the Amazon the forest disturbances decreased in 2021 (which is confirmed by other datasets such as GFC), and while this is a positive sign for forest conservation, the reasons for the decrease are difficult to assess.

Only in spring 2023, a first "educated guess" can be obtained about the classification of the JRC-TMF overall forest disturbances 2021 into 'deforestation' and 'forest degradation' classes, once a forest regrowth can either be detected or not.

Deforestation has increased by 7% in the first seven months of 2022 in the Brazilian Legal Amazon, compared to the same period in 2021, according to the INPE-DETER alert system, while forest degradation alerts have increased by 27% in the same period. The increase of deforestation alerts is confirmed by IMAZON-SAD, which reports a respective increase of 19% from January–June 2022. Regarding forest degradation, specifically the area of the forest fires 2022 in the Brazilian Amazon will depend much on the precipitation before and during the 'fire season' (July-November) in the Southern and Eastern Brazilian Amazon.

The Brazilian government has launched various law initiatives, which will, if finally approved, increase the pressure on the Amazon forest. The consolidation (pavement) of the BR-319 Highway from Porto Velho – Manaus (granting easy access to intact forest), the law proposal to promote "land grabbing", the initiative to exclude the State of Mato Grosso from the Brazilian Legal Amazon (lowering the region's forest protection status), all of these initiatives favour the exploitation of the old-growth Amazon forest by clear-cutting and illegal selective logging. At the same time, indigenous people are being put at high risk through initiatives that allow mining on their lands (causing deforestation and mercury poisoning), while the demarcation of indigenous lands might be more difficult or altogether impossible, due to the proposed law on the "*marca temporal*". Contemporarily, the federal institutions with a mandate to monitor Brazil's Amazon forest (INPE) and to enforce the forest protection laws (IBAMA, amongst others) are underfunded and suffer from bad management [8]. As one of the consequences, little more than 2% of the deforestation alerts, provided by INPE, had an action of law enforcement launched by IBAMA[60] [61] [62]. With rising deforestation rates and the new law initiatives that further weaken forest protection, Brazil takes the opposite direction with regard to its deforestation commitments. Given the key role of the Land Use and Forestry sector in Brazil's NDC and the huge global importance of its forests for environmental services, biodiversity, and carbon sequestration, the Brazilian government urgently needs to strengthen forest monitoring, forest law enforcement and other mitigation action (e.g. intensified forest restoration) in this sector, instead of weakening it[63].

On 21st March 2022 Brazil updated its Nationally Determined Contribution (NDC) to the UN's Framework Convention on Climate Change (UNFCCC), stating that "…the Brazilian government has chosen to go even beyond already existing laws and policies and commit to eliminate illegal deforestation by 2028" [64], thus anticipating the target date by two years. However, the updated document apparently does not increase the country's climate ambition, but rather backtracks in this context[65]. This view is backed by the 2022 increase of deforestation and forest degradation in the Brazilian Amazon reported by the INPE-DETER and IMAZON SAD forest monitoring systems.

[60] https://news.mongabay.com/2022/05/governmet-inaction-sees-98-of-deforestation-alerts-go-unpunished-in-brazil/
[61] https://www.france24.com/en/live-news/20220503-brazil-responds-to-less-than-3-of-deforestation-alerts-study
[62] https://ipam.org.br/bibliotecas/desmascarando-a-impunidade-do-desmatamento-ilegal-na-amazonia-brasileira-um-apelo-a-fiscalizacao-e-responsabilizacao/
[63] https://climateactiontracker.org/countries/brazil/
[64] https://unfccc.int/sites/default/files/NDC/2022-06/Updated%20-%20First%20NDC%20-%20%20FINAL%20-%20PDF.pdf
[65] https://www.politicaporinteiro.org/wp-content/uploads/2022/04/Brazils-NDC-2022-analysis_V0.pdf

5 Annex: New research results on forest, deforestation, forest degradation and regrowth in the Amazon (status June 2022)

The continued deforestation in the Amazon region, which has already a heavy impact of the region's biodiversity, starts to create problems for the general population as well as for farmers in Brazil, as the weather patterns, specifically the temperature and precipitation patterns, are already changing in the region. South and Central Brazil have frequent water crises, which are, at least partly, triggered by high deforestation rates and increasing forest degradation in the Amazon region. Numerous new high-level scientific publications examine and describe the causes and the effects of continuous disturbances of the Amazon forest, while they shows at the same time how forest degradation and deforestation is interlinked with many aspects of the socio-ecosystem through a series of negative impacts and feedback loops.

5.1 Forest

There are an estimated 73,000 tree species globally; including ca. 9000 tree species yet have to be discovered. Roughly, 40% of the undiscovered tree species are found in South America; moreover, almost one-third of all tree species to be discovered may be rare, with very low populations and limited spatial distribution. These findings highlight the vulnerability of global forest biodiversity to anthropogenic changes in land use and climate, which threaten rare species and thus, global tree richness [25].

Half of the known tree species found the Amazon region are, one way or the other, useful to humans, representing 84% of estimated individual trees in the region. Useful species have mean populations sizes six times larger than non-useful species, and their abundance is related with the probability of usefulness, suggesting that indigenous people and local communities have contributed to plant abundance through long-term management [26].

Of the worldwide known tree species, ca. 30% are threatened with extinction. The main threats to tree species are forest clearance and other forms of habitat loss, direct exploitation for timber and the spread of invasive pests and diseases. Climate is also having a clearly measurable impact. Of the known 8847 tree species in Brazil, approximately 20% (or 1788) are classified as threatened by the authors [27].

Water availability is the major driver of tropical forest structure and dynamics of Amazonian forests. While most research has focused on the impacts of climatic water availability, remarkably little is known about the influence of water table depth and excess soil water on forest processes. Water supplied by both precipitation and groundwater affects forest structure and dynamics, but in different ways. Forests with a shallow water table (depth <5 m) had 18% less aboveground woody productivity and 23% less biomass stock than forests with a deep water table. Forests in drier climates (maximum cumulative water deficit < −160 mm) had 21% less productivity and 24% less biomass than those in wetter climates. Productivity was affected by the interaction between climatic water deficit and water table depth. On average, in drier climates the forests with a shallow water table had lower productivity than those with a deep water table, with this difference decreasing within wet climates, where lower productivity was confined to a very shallow water table. The two extremes of water availability (excess and deficit) both reduce productivity in Amazon upland (*terra-firme*) forests. Biomass and productivity across Amazonia respond not simply to regional climate, but rather to its interaction with water table conditions, exhibiting high local differentiation [28].

An all-encompassing compendium about the history, the status and the future of the Amazon region was published in 2021, called the 'Amazon Assessment Report' [29]. In 34 chapters[66], the Amazon geography, the region's history before and after the discovery of South America by Europeans, the current transformation of its nature and society with the challenges and problems that arise as consequence and the possible sustainable pathways for future development of the Amazon region are described.

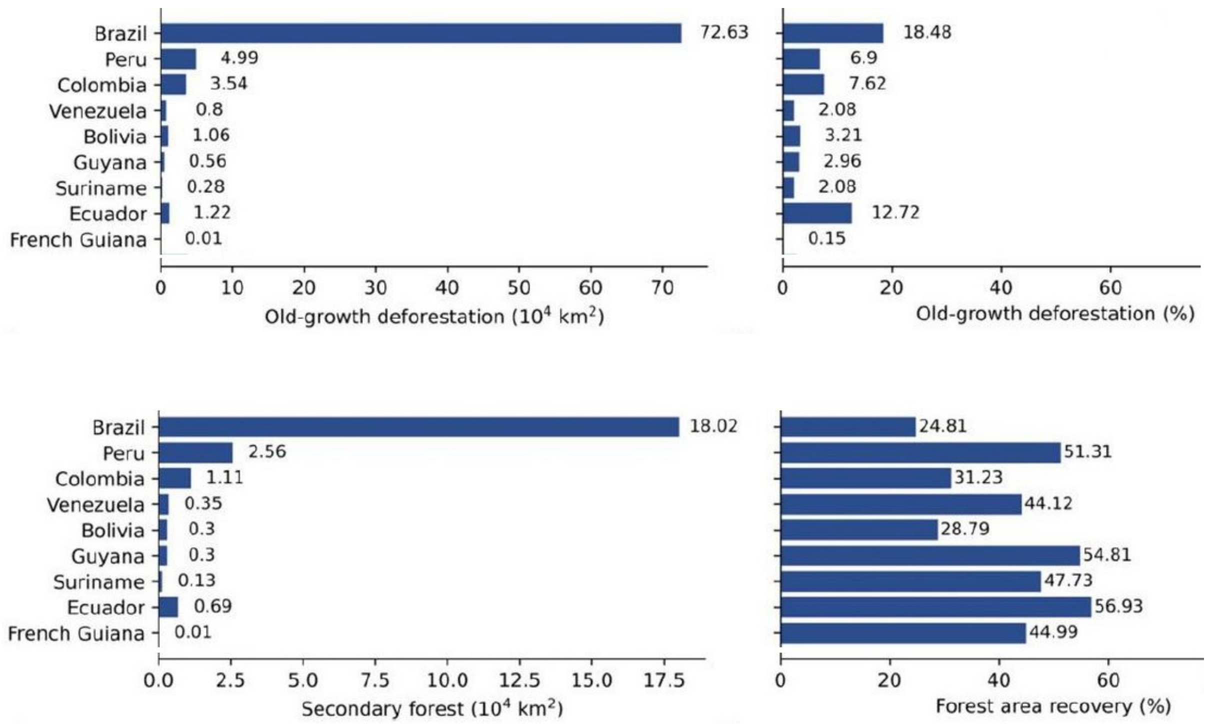
[66] https://www.theamazonwewant.org/amazon-assessment-report-2021/

5.2 Forest cover change in the Amazon and its effects on rainfall, temperature, carbon emissions, heat stress, health, agriculture, tree biodiversity etc.

5.2.1 Deforestation

In the Amazon region, 28.8% of the deforested areas were covered by secondary forest in 2017, which lead to an offset of carbon emissions caused by deforestation by 9.7%. Of all countries with a share of the Amazon forest, the Brazilian Amazon has the highest loss of old-growth forest (17.6%) and the lowest recovery rate to secondary forest (24.8%), with the lowest offset (9%) of the carbon emission caused by deforestation of all Amazon countries (Smith et al 2021) [30].

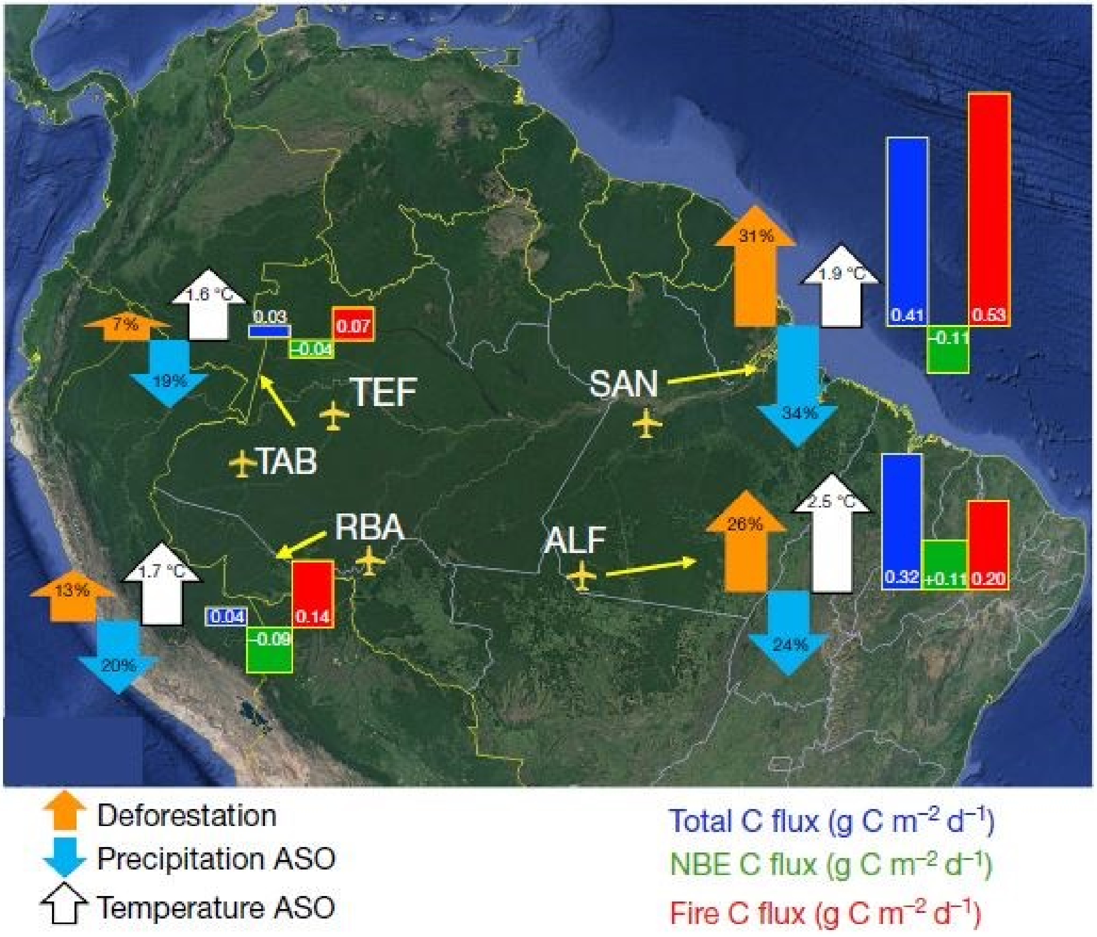
Figure 24. Old-Growth Deforestation (OGD) and Secondary Forest Recovery (SFR) in Amazonian countries in 2017, the proportional values for OGD (upper right) are measured as the percentage of original OG forest extent (measured as the total area capable of supporting forest) that has been deforested, the percentage of SFR (lower right) are of deforested land occupied by SF [30]



Deforestation and climate change, through increasing dry-season length and drought frequency, may already have pushed the Amazon close to a critical threshold of rainforest dieback. According to the authors, more than three-quarters of the Amazon rainforest has been losing resilience since the early 2000s, while resilience is being lost faster in regions with less rainfall and in parts of the rainforest that are closer to human activity [31].

Amazonia hosts the Earth's largest tropical forests and has been shown to be an important carbon sink over recent decades. This carbon sink seems to be in decline, however, as a result of factors such as deforestation and climate change. Amazonia's carbon budget is investigated and the main drivers responsible for its change into a carbon source, based on 590 aircraft vertical profiling measurements of lower-tropospheric concentrations of carbon dioxide and carbon monoxide at four sites in Amazonia (two in western Amazonia, two in eastern Amazonia) from 2010 to 2018. Total carbon emissions are greater in eastern Amazonia than in the western part, mostly as a result of spatial differences in carbon-monoxide-derived fire emissions. Southeastern Amazonia, in particular, acts as a net carbon source (total carbon flux minus fire emissions) to the atmosphere. Over the past 40 years, eastern Amazonia has been subjected to more deforestation, warming and moisture stress than the western part, especially during the dry season, with the southeast experiencing the strongest trends. The effect of climate change and deforestation trends on carbon emissions at four study sites is an intensification of the dry season, while an increase in deforestation promotes ecosystem stress, increase in fire occurrence, and higher carbon emissions in the eastern Amazon [32].

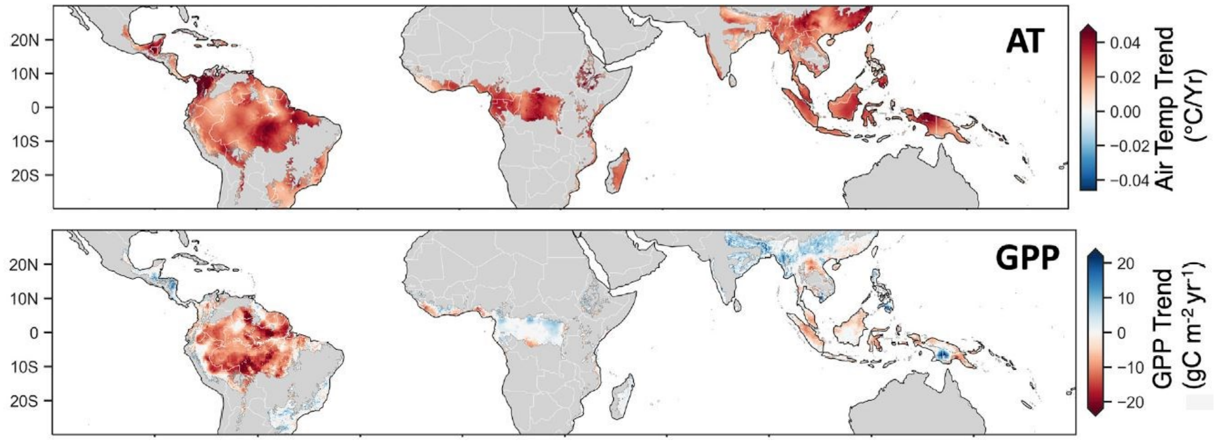
Figure 25: Summary of historical trends and fluxes for the regions upwind of each site: historical deforestation (orange arrows), reduction in precipitation during August/September/October (light blue arrows), increase in temperature in August/September/October (white arrows) and carbon fluxes (total, dark blue bars; Net Biome Exchange (NBE), green bars; fire, red bars) [32].



Twenty years of deforestation has led to a warmer and dryer lower troposphere over the Amazon region. As a result, the warmer and dryer lower troposphere enhanced updraft winds that impeded external water supplies from the tropical Atlantic Ocean, which would otherwise moisten the lower atmosphere. The observed atmospheric desiccation suppresses vegetation growth and may offset CO2 fertilization effects at large spatial scales. In addition, the severe atmospheric desiccation in the southern and eastern Amazon cannot be compensated by enhanced water supplies from the Atlantic Ocean, indicating that the Amazon hydrological system is approaching an irreversible transition exacerbated by rapid deforestation [33]

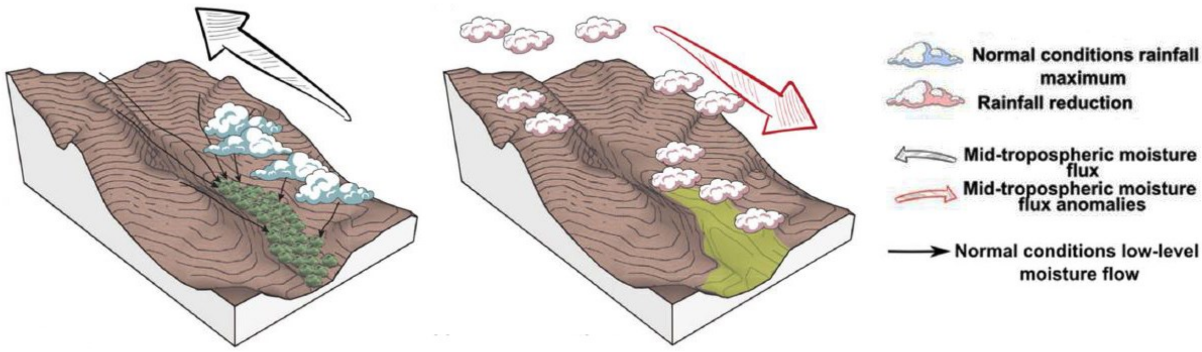
Saatchi et al (2021) examine stressors like deforestation, fire, air temperature, water deficit of global tropical humid forests and the ecosystem's responses like gross primary production, above-ground biomass, evapotranspiration and biodiversity intactness. Using satellite observations, it is shown how increasing threats from large-scale deforestation and severe climate conditions over the past four decades have substantially impacted the ecological functions of these forests regionally, pushing them toward a critical point of no recovery and a dryer and less diverse state. Among tropical forests, the Amazon shows significantly more vulnerability to climate and land-use stressors than forests in Africa and Asia, while forests in continental Africa, although impacted by similar levels of climate stress as the Amazon, show more resilience [34].

Figure 26. One of the environmental stressors (air temperature) and one of the responses (gross primary production) of global tropical humid forests [34]



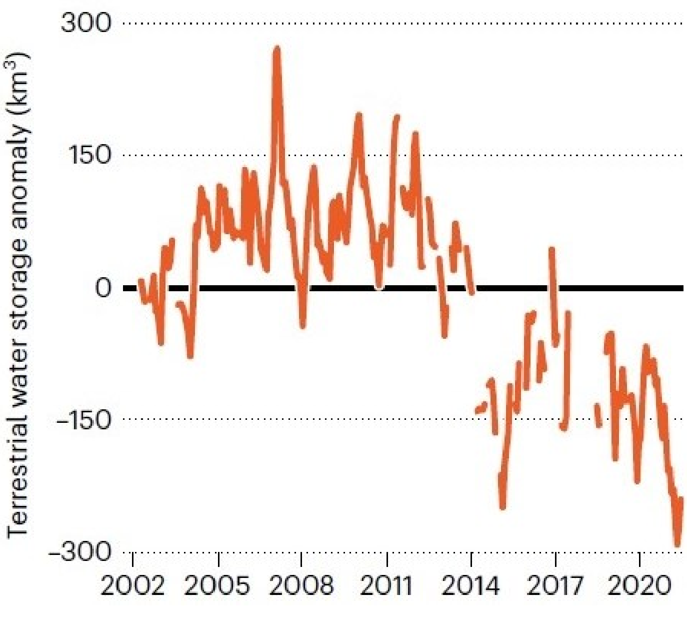
Sierra et al (2021) evaluate the effect of Amazon deforestation on the hydro-climatic connectivity between the Amazon and the eastern tropical Andes during the austral summer (December–January–February) in terms of hydrological and energetic balances. Regionally, deforestation leads to a reduction in the surface net radiation, evaporation, moisture convergence and precipitation (~ 20%) over the entire Amazon basin. The Amazon-Andes transition region, the rainiest and biologically richest area of the entire Amazon basin, encompasses complex Andean topography, ranging from almost sea level in the Amazon lowlands to more than 6000 m height over the Andean summits. There, high precipitation rates lead to large values of runoff per unit area, providing most of the sediment load to Amazon rivers. Particularly, the Amazon-Andes transition region exhibits the largest precipitation recycling (portion of the precipitated water previously transpired by the Amazonian rainforest) of the Amazon catchment. Therefore, this region can potentially be highly sensitive to Amazon deforestation effects. During the heart of the wet season (Dec-Jan), nearly 50% of total annual precipitation falls over the region. Since Amazonian groundwater recharge during wet periods can sustain forest transpiration rates during dry months, alterations in rainfall patterns during the named period may have a profound impact in the Amazon watershed hydrology. Taking into account the potential sensitivity of the Amazon-Andes transition region to deforestation, the present work analyses the deforestation land-use change impacts on regional energy and water budgets, as well as rainfall alterations at a local scale [35].

Figure 27. Climatological atmospheric conditions (Dec-Jan) at local scale in an Andean valley under normal (left) and deforestation (right) conditions [35]



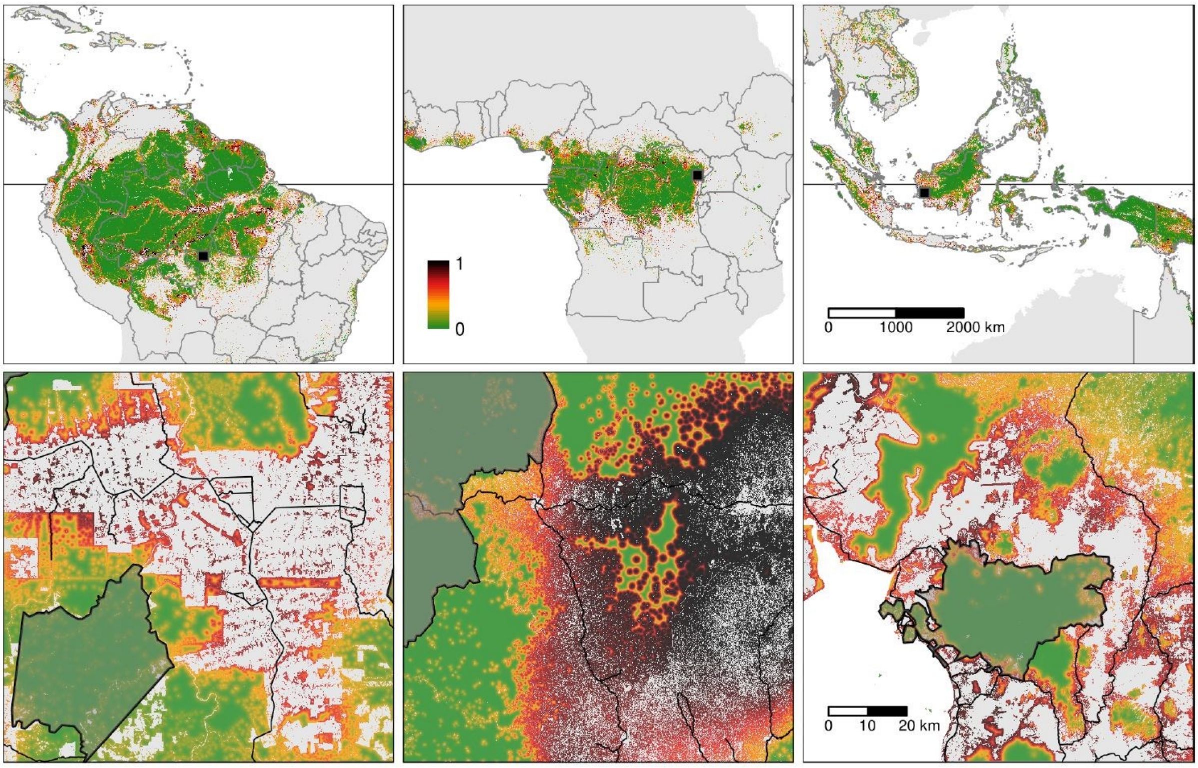
Getirana et al (2021) examine the water crisis in Southern and Central Brazil and connects it to knock-on effects of Amazon deforestation together with the failure to treat water as an essential national resource, which has led Brazil to a long history of persistent water mismanagement. Water crises can originate from many types of drought: meteorological, hydrological, agricultural and socio-economic. Meteorological droughts are dry weather patterns due to periods of little rainfall or high temperatures, which increase evaporation rates. These can cause hydrological droughts, water shortages on land surfaces such as rivers and lakes. Agricultural droughts — a decline in soil moisture levels — can result. These can jeopardize crop yield and increase food insecurity. Shortages to the domestic and industrial supply — socio-economic droughts — can also follow. This might lead to rationing, disease, conflict and migration. At the same time the nation's groundwater and meteorological monitoring is sparse and insufficient to properly track water variability and availability across the country. Brazil monitors groundwater at 409 sites nationwide, which is a small fraction of the sites of countries or regions of comparable size (North America, India). In addition, there are no nationwide systems in place to track soil moisture in Brazil, and monitoring of water use is patchy [36].

Figure 28. Water storage level anomalies in South and Central Brazil from 2002 - 2021



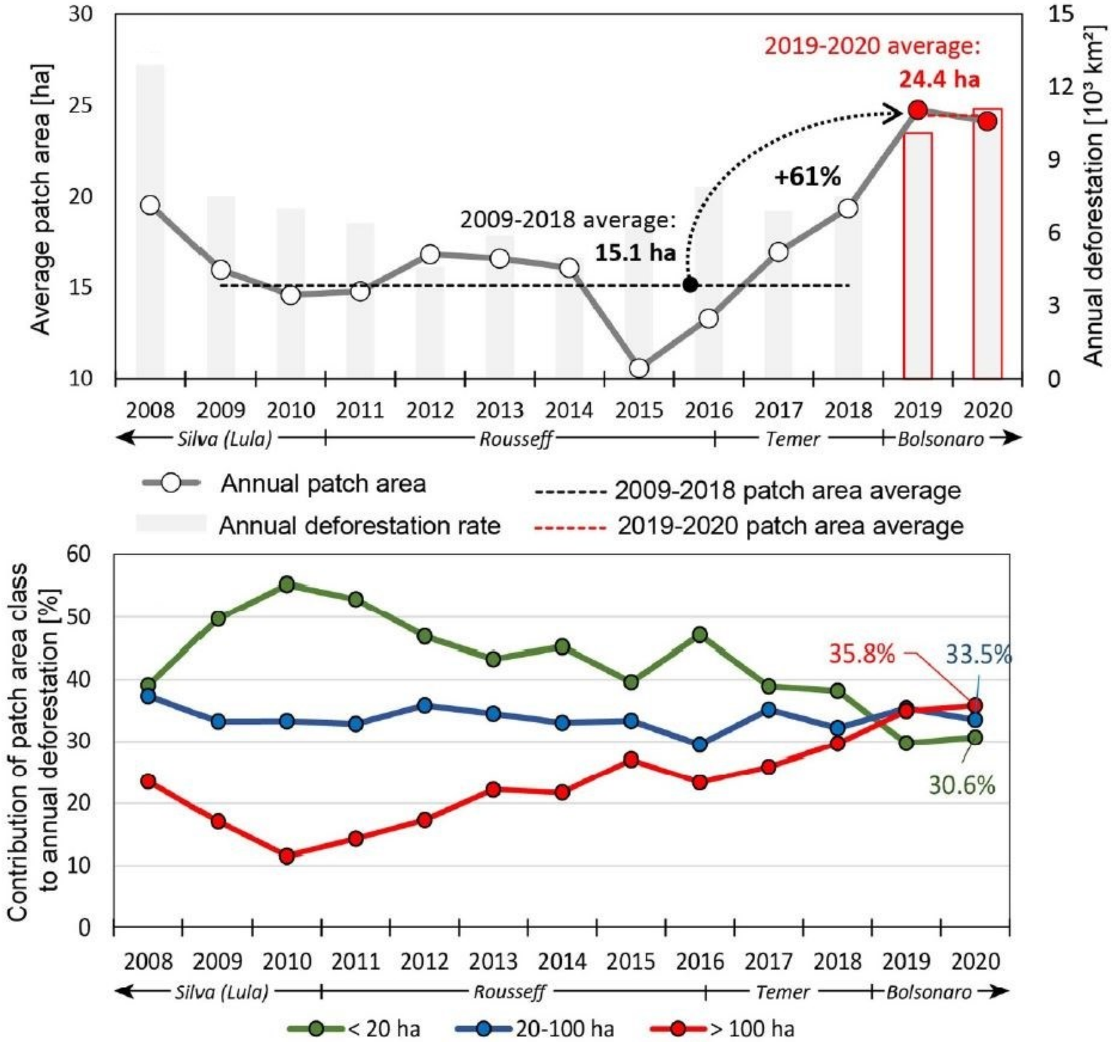
Vieilledent et al (2022) confirm the effectiveness of protected areas in displacing deforestation and the negative impact of roads and landscape fragmentation on forest conservation in the tropics. Using models, they derive high-resolution pantropical maps of the deforestation risk and future forest cover for the 21st century under a "business-as- usual" scenario, based on the deforestation rates observed in the 2010s. Although under this scenario, large areas of tropical moist forest should remain in the heart of the Amazon, in the Congo Basin, and in New Guinea in 2100, 48% (39–56%) of all forest cover is expected to disappear during the course of the 21st century, and many countries will have lost all their forests by 2100. The remaining forests will be highly fragmented and located in remote places. As future deforestation will concern forests with higher aboveground carbon stocks, annual carbon emissions associated with tropical deforestation are expected to increase by +0.161 Pg/yr (+35%) between the 2010s and the 2090s [37].

Figure 29. Upper panels: Maps of the spatial probability of tropical deforestation at 30 m resolution for the three continents. Coloured pixels represent forest for the year 2020. Inside each study area, forest areas in dark red have a higher risk of deforestation than forest areas in green. Lower panels: Detailed maps for three 100 × 100 km regions (black squares in the upper panels) in the Mato Grosso State (Brazil), the Albertine Rift mountains (Democratic Republic of the Congo), and the West Kalimantan region (Borneo, Indonesian part). Deforestation probability is lower inside protected areas (black shaded polygons) and increases when the forest is located at a distance closer to roads (dark grey lines) and forest edge [37]



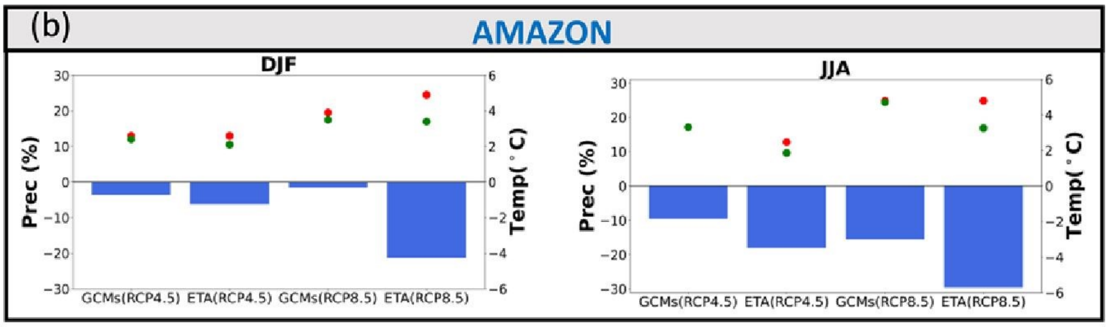
Market and public policies govern deforestation trends and patterns globally. In the Brazilian Amazon, the largest tropical forest in the world, the size of deforestation polygons - the individual portions of cleared forest patches - has significantly increased in response to the current environmental governance. The average size of deforestation polygons in the current government is 61% greater than in the 10 previous years when environmental policies and programs were maintained. As a result, very large polygons (> 100 ha) are now dominating deforestation, suggesting a remarkable change in deforestation patterns and a new wave of destruction of the Amazon forest. To control increasing deforestation trends and changing patterns, command and control policies need to be strengthened along with interventions in the supply chain of Amazon commodities and sustainable development incentives, ensuring a transition to an environmentally sustainable economy [38].

Figure 30. Above: Averaged area of deforestation patch from 2008 to 2020 and annual deforestation. The dashed black line shows a ten year average for previous deforestation (2009–2018) and the dashed red line shows a two year average of recent deforestation (2019–2020). The dotted black arrow indicates a 61% increase in the recent deforestation patch area. Recent averaged patch area and annual deforestation are highlighted in red.
Below: Changes in the contribution of deforestation patch area classes to annual deforestation from 2008 to 2020. Large patches (>100 ha) are increasing in their overall contribution to the annual deforestation and are now dominating total deforestation. The timeline shows the presidents of Brazil and changes in political leadership over time [38].



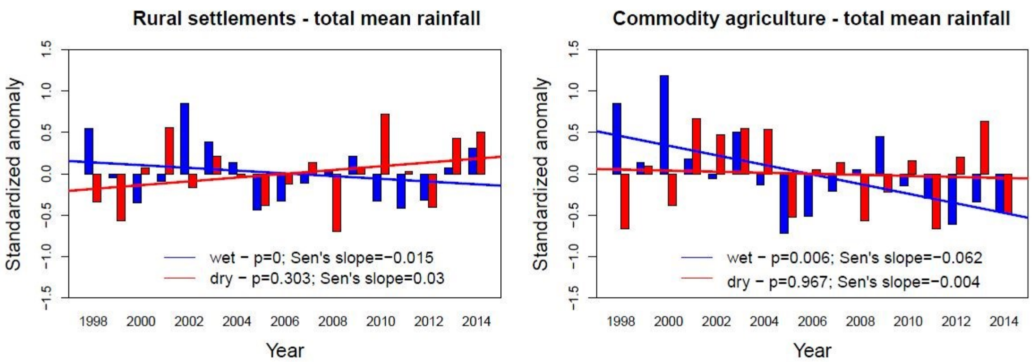
In various scenarios, Reboita et al (2021) have calculated for the Brazilian Amazon, that dry conditions, higher temperatures amid precipitation decrease characterize the climate changes in this biome. Concerning the species distribution, the dry and warmer conditions in the Amazon Forest can lead to a savannisation of this region. Precipitation is projected to decrease between 20 and 30%, while the temperature might increase by up to 5%. Observational studies also have shown a substantial reduction in the leaf area index (LAI) as forest loss increased with evapotranspiration (ET) showing a decline. These variations are related to changes in temperature, with increased warming as deforestation increased. In the different scenarios, the changes in the temperature range from 2 to 4 °C for the Brazilian Atlantic Forest. As more than 60% of the Brazilian people live within the Atlantic Forest domain, climate changes in this biome can cause significant social vulnerability. Regarding the distribution of species, changes in precipitation and increased temperature can lead to the animals' extinction since habitat becomes inadequate for the species. For the Cerrado, a future precipitation decrease may significantly affect the water supply and other activities in this region. These simultaneous changes in decreasing precipitation and increasing temperature (3 - 4 °C) may compromise agriculture and hydropower generation and trigger more fires in the region. While 35.4% of the biome are high-risk areas exposed to high climate anomalies and poor native vegetation, only 13% of the territory may be potential refugia for bird species since those areas are more likely to retain native vegetation and face low climatic anomalies. Under all scenarios, the soy and corn production decreased by 2050, but specifically so in the Northern Cerrado [39].

Figure 31: various scenarios resulting in projected changes in precipitation (blue bars) and minimum (green) and maximum (red) temperatures for the 2050-2080 period in the Brazilian Amazon biome [39]



Clarifying the climatic impacts of different land uses in the Amazon is crucial to foster informed plans for sustainable land management, in particular those aiming at strategies for climate change mitigation, maintenance of ecological functioning, and guarantying provision of essential ecosystem services. It is hypothesized that forest conversion to large-scale commodity agriculture is more detrimental to local climate than conversion to rural settlements. Does land uses associated with commodity agriculture and rural settlements lead to quantitatively distinguishable land cover spatiotemporal patterns in regions with similar deforestation rates (1985 to 2018) and total deforested area in 2018? Has forest clearing associated with commodity agriculture or rural settlements affected local rainfall, surface temperature, and latent heat flux? Forest loss associated with rural settlements caused an average land surface temperature increase of 1.05 °C during the wet seasons and 1.25 °C during the dry seasons, while in areas of commodity agriculture, warmings of 1.57 °C and 2.11 °C were observed in the wet and dry seasons, respectively. In addition, a significant decline in wet season rainfall volumes occurred in areas dominated by large-scale commodity agriculture, while same decline was not observed in an area where deforestation was mainly caused by rural settlements [40].

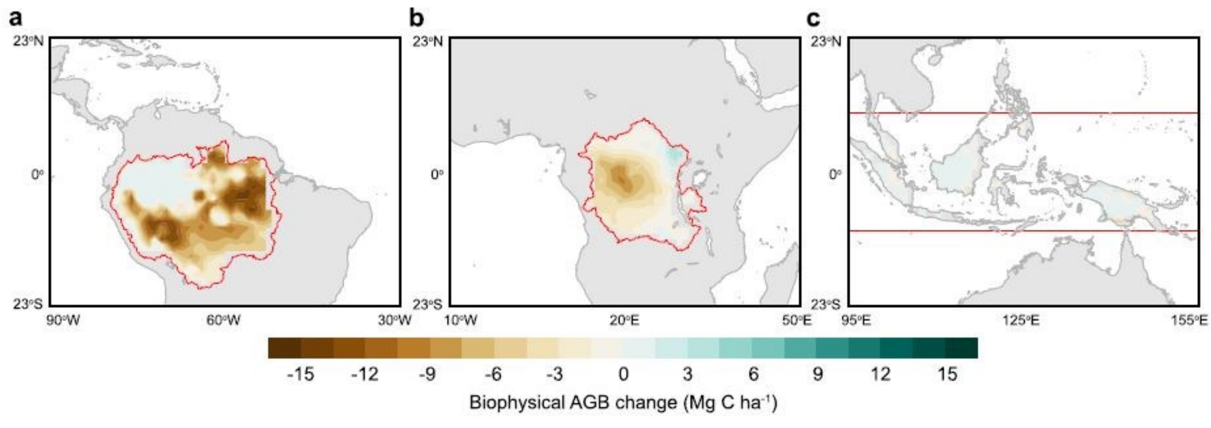
Figure 32: total mean rainfall standardized anomalies of rural settlements and commodity agriculture [40]



Marengo et al (2022) report changing weather patterns in Brazil for the transition zone between Eastern Amazonia and the Cerrado. According to the authors, several large-scale drivers of both anthropogenic and natural environmental changes are interacting nonlinearly in the region, considered to be another Brazilian agricultural frontier. Land-use change for agribusiness expansion together with climate change in the transition zone between eastern Amazonia and the adjacent Cerrado may have induced a worsening of severe drought conditions over the last decade. The largest warming and drying trends over tropical South America during the last four decades are observed to be precisely in the eastern Amazonia–Cerrado transition region, where they induce delayed wet season and worsen severe drought conditions. The study reports an increase in temperature, vapour pressure deficit, subsidence, dry-day frequency, and a decrease in precipitation, humidity, and evaporation, plus a delay in the onset of the wet season, inducing a higher risk of fire during the dry-to-wet transition season. These findings provide observational evidence of the increasing climatic pressure in this area, which is sensitive for global food security, and the need to reconcile agricultural expansion and protection of natural tropical biomes. Consequential, a key region responsible for agricultural production in Brazil is at increased risk of climate driven impacts [41].

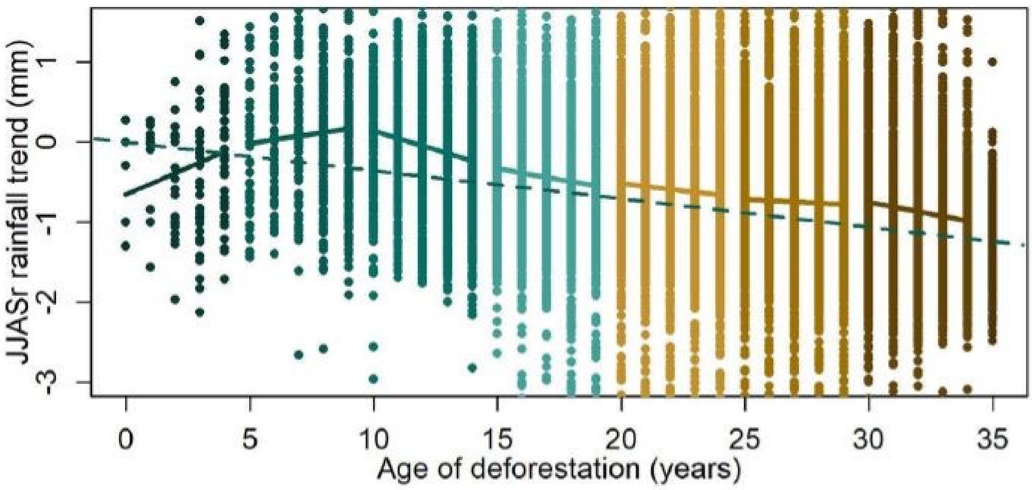
Biophysical effects from deforestation have the potential to amplify carbon losses but are often neglected in carbon accounting systems. Earth system model simulations and satellite–derived estimates of aboveground biomass are used to assess losses of vegetation carbon caused by the influence of tropical deforestation on regional climate across different continents. In the Amazon, warming and drying arising from deforestation result in an additional 5.1 ± 3.7% loss of aboveground biomass. Biophysical effects also amplify carbon losses in the Congo (3.8 ± 2.5%) but do not lead to significant additional carbon losses in tropical Asia due to its high levels of annual mean precipitation. The additional carbon losses occur as a consequence of remaining intact forests experiencing hotter and drier conditions that reduce carbon storage in aboveground biomass. The findings suggest that the value of avoided deforestation and forest degradation may be underestimated if current carbon assessment methodologies focus only on the direct carbon stock and emission changes associated with the land-use change. The regional differences in the deforestation biophysical changes in forest carbon stocks that we uncover may also provide insight about a more equitable approach for assigning carbon credits in the context of Reducing Emissions from Deforestation and forest Degradation projects (REDD+) and other climate policy frameworks. An important next step in this context is to combine the deforestation biophysical climate effect identified here with AGB losses associated with local edge effects in order to estimate an integrated indirect carbon benefit associated with avoided deforestation (or reforestation) projects in the tropics [42].

Figure 33: Biophysical impacts of deforestation on aboveground biomass (AGB) in the tropics. a–c show biophysical AGB changes of deforestation estimated from the product of deforestation-induced changes in climate (mean annual precipitation and mean annual temperature), and the observational sensitivity of the AGB to precipitation and temperature [42]



Rainfall in the Amazon is influenced by atmospheric circulation dynamics on multiple spatiotemporal scales. Anthropogenic influences such as deforestation, land-use changes, and global climate change are also critical factors in determining rainfall in South America. Spatiotemporal trends in rainfall between 1981 and 2020 and relationships with deforestation age in the Brazilian Legal Amazon (BLA) have been analysed by Yu and Jones (2022) on the basis of an improved rainfall dataset obtained by calibrating the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) data with observations from a rain gauge network in the BLA. While large spatial variability is observed, the results show coherent relationships between negative dry-season rainfall trends and old-age deforested areas. Deforestation aged up to a decade enhanced rainfall and older deforested regions have reduced rainfall during the dry season. These results suggest substantial changes in the hydro-climate of the BLA and increased vulnerability to future land cover change [43].

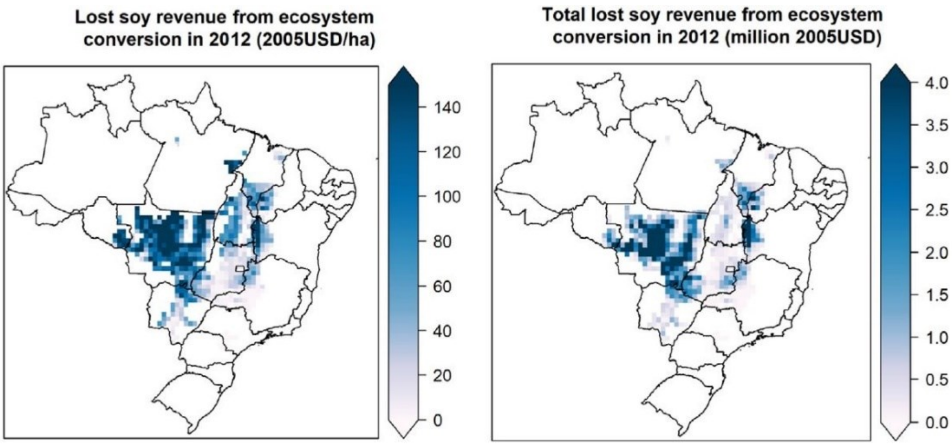
Figure 34: Scatterplot of the age of deforestation and dry season (JJAS - June/July/August/September) rainfall trend in the BLA. The solid lines indicate the regression slope for each group at the 5 years interval. The dashed line indicates the overall trend line [43]



Deforestation affects the ecological integrity of rivers and streams, threatening biodiversity and ecosystem services worldwide. Tropical streams are analysed and tested, whether the stable isotopic ratios of nitrogen (N, δ15N) and carbon (C, δ13C) and the ratio of C:N of ecosystem components vary along a forest cover gradient. In addition, the ecological integrity of streams is assessed by in situ measurements using physical features commonly used in stream quality assessments. The results showed that the δ15N of most aquatic components, δ13C of particulate matter and omnivorous fish, and C:N of particulate matter and algae vary significantly with forest cover, indicating the important role of terrestrial vegetation. The use of stable isotopes to monitor watershed deforestation is supported, highlighting the need for reassessment of the effects of anthropogenic inputs on δ15N increase in globally distributed inland waters, since the loss of forest is a significant cause. The sensitivity of stream ecological components to deforestation in the drain basin suggests a potential increase of stream δ15N and δ13C in other locations with concomitant effects on biogeochemistry and food web analyses, especially in other tropical areas where deforestation has been intensified in recent years [44]. In addition to the status of the forest cover along streams, the integration of the streams' forest cover change history enhances the evaluation of ecological effects of land-use change, especially when contemporary landscape conditions are similar but the temporal path to those conditions differs [45].

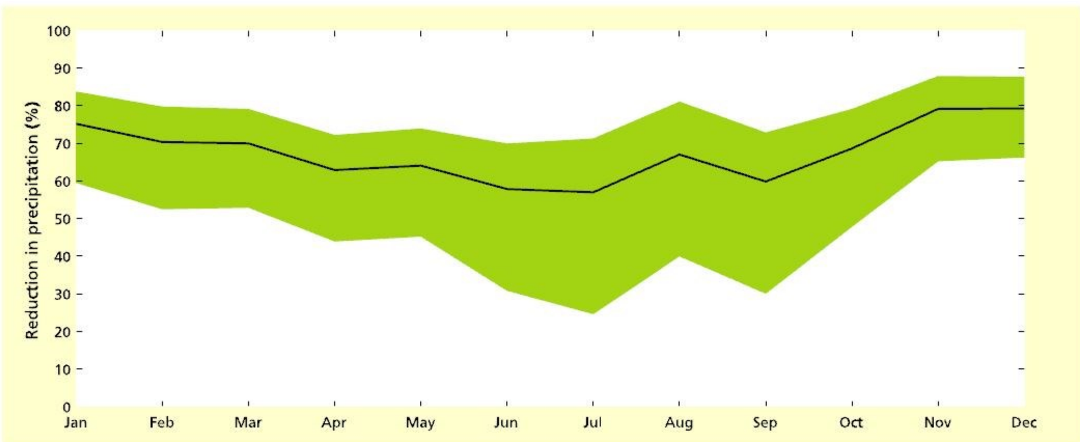
Flach et al (2021) modelled the loss of soybean production due to the increase of extreme heat caused by deforestation in the Brazilian Amazon and Cerrado biomes. Two types of extreme heat regulation values were assessed: the value of avoided extreme-heat exposure of soy from the conservation of neighbouring ecosystems and the value of lost revenue due to increased extreme heat exposure from increased ecosystem conversion. For the most part, estimates of extreme-heat regulation value were smaller than estimates of land value, suggesting that extreme heat regulation alone would provide an insufficient case for ecosystem conservation in most locations. However, in combination with carbon price, the value of extreme heat regulation and other ecosystem services could exceed the opportunity cost of conservation, particularly in the region at the southeastern fringe of the Amazon Basin, where land conversion rates are currently high and soybean cultivation is widespread, owing to limited conservation measures. Quantifying the economic value of climate regulation from ecosystem conservation can help to address a key challenge for ecosystem conservation and restoration—gaining the support of agribusinesses and other stakeholders. These stakeholders greatly benefit from ecosystem services, and their decisions can strongly shape the efficacy of ecosystem conservation and restoration efforts and, ultimately, regional development [46].

Figure 35: loss of soy revenue due to ecosystem conversion-related extreme-heat exposure in 2012 (2005USD/ha) per grid cell (left), total loss of soy revenue due to ecosystem conversion-related extreme heat exposure in 2012 (2005USD) per grid cell (right) [46]



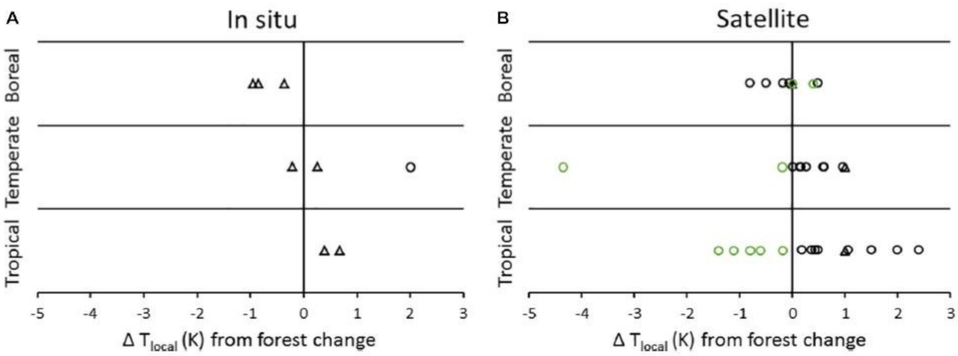
Baudena et al (2021) look at the relation between water transpiration by forest and precipitation for a large area in the Amazon basin. To see how forest cover change is affecting precipitation patterns, the authors relate observed hourly precipitation levels to atmospheric column water vapour and estimate the transpiration component in column water vapour in the study area on basis of atmospheric trajectories of moisture from tree transpiration, which are available for whole Amazon. Finally, precipitation reductions was estimated for column water vapour levels without this transpired moisture, based on the newly found non-linear relationship. Although loss of tree transpiration from the Amazon causes a 13% drop in column water vapour, we found that it could result in a 55%–70% decrease in precipitation annually. The consequences of this nonlinearity might be twofold: although the effects of deforestation may be underestimated, it also implies that forest restoration may be more effective for precipitation enhancement than previously assumed [47].

Figure 36: Monthly percentage reduction in precipitation in the study area for 2003–2014 due to the removal of the contribution of transpiration (by deforestation) from the Amazon basin. [47]



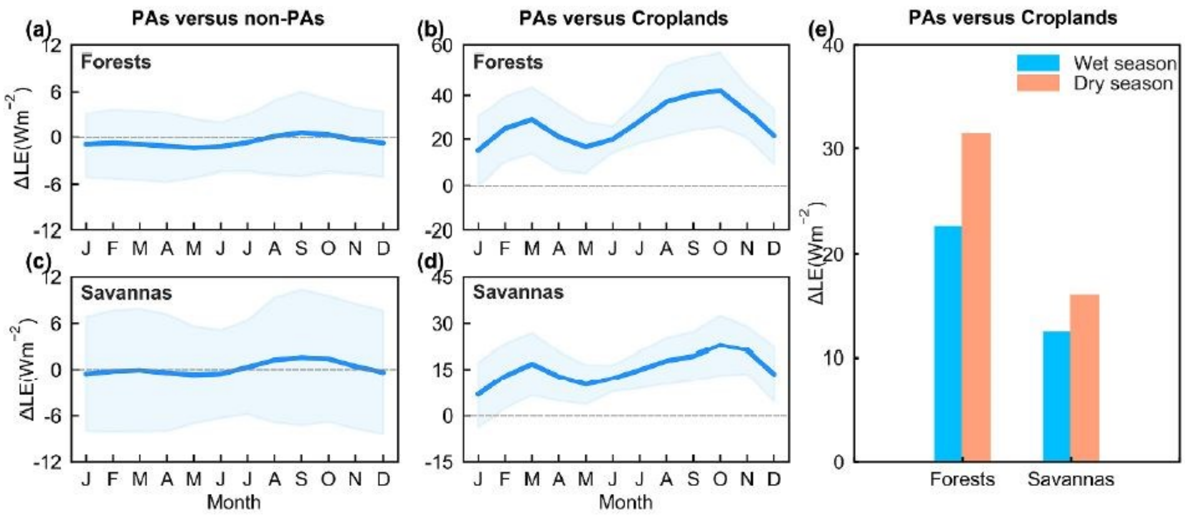
The role of forests in maintaining critical habitat for biodiversity is well known, but new research on extinction confirms the role of forests in maintaining critical climates to support biodiversity. Changes in maximum temperature are driving extinction (not changes in average temperature), and deforestation is associated with an increase in the maximum daily temperature throughout the year in the tropics and during the summer in higher latitudes. The biophysical effects of forests also moderate local and regional temperature extremes such that extremely hot days are significantly more common following deforestation even in the mid- and high latitudes. Forests provide local cooling during the hottest times of the year anywhere on the planet, improving the resilience of cities, agriculture, and conservation areas. Forests are critical for adapting to a warmer world. At the same time, forests also minimize risks due to drought associated with heat extremes. Deep roots, high water use efficiency, and high surface roughness allow trees to continue transpiring during drought conditions and thus to dissipate heat and convey moisture to the atmosphere. In addition to this direct cooling, forest evapotranspiration can influence cloud formation, enhancing albedo and potentially promoting rainfall. Lawrence et al (2022) measure the local temperature changes on global scale due to deforestation and afforestation for tropical, temperate and boreal forests (and other geographic classes) from in-situ measurements, satellite-based land surface temperatures and air temperature measurements [48].

Figure 37: Local average annual temperature change in response to deforestation (black symbols) or afforestation (green symbols) as determined by comparing neighbouring forested and open land (space for time approach) or measuring forest change over time in the tropics, temperate and boreal zones, by (A) in situ or (B) satellite based land surface temperature measurements (0 m, triangles) or air temperature measurements (2 m, circles). [48]



Huang et al (2022) examine the effects of protected areas (PAs) on land surface temperature in the Amazon region. They obtained evidence of the PAs impact on local thermal environment from satellite observations. PAs in Amazon and its surrounding areas can effectively alleviate local warming compared with adjacent croplands, which represent zones with a full anthropogenic land conversion from forests and savannahs to crops, indicating their potential in buffering thermal environment change driven by anthropogenic land uses. Compared with open land (e.g. croplands), Pas are demonstrated to have an asymmetrical cooling impact between the daytime and night time, and between the wet and dry seasons. The reduced diurnal and seasonal temperature ranges within PAs tend to provide suitable habitats for protecting tropical biodiversity because vegetation growth depends on daily and seasonal temperature extremes and variabilities. The asymmetrical diurnal and seasonal cooling impacts of PAs are mainly driven by albedo and evapotranspiration, the two competing biophysical mechanisms to modulate land surface temperatures. Compared to croplands, protected natural vegetation has lower albedo and therefore absorbs more shortwave radiation, leading to a warming effect. However, PAs have higher evapotranspiration than croplands, which causes higher latent heat loss that completely overcomes the warming effect of albedo change and dominates the local cooling effect. However, as restrictions of deforestation are applied within PAs, logging pressure is transferred to their adjacent non-protected forests. Therefore, non-protected forests tend to be exposed to more human disturbances, reducing the ability of forests to buffer its thermal environment from background climate change. Although the buffering effect of non-protected forests is weaker than that of protected forests, the non-protected forests have the potential to serve as a buffer zone for the protected forests to resist external disturbances [49].

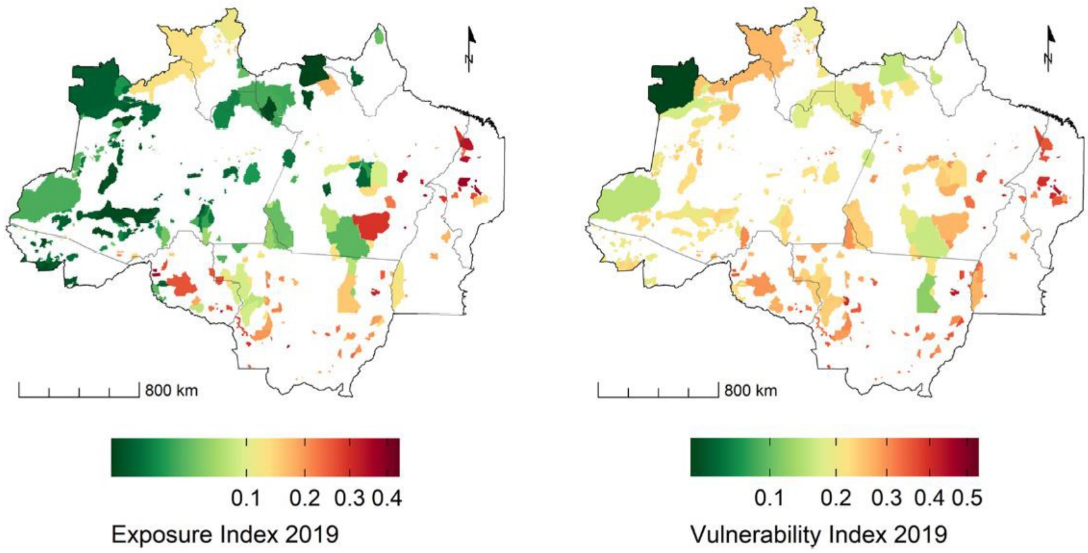
Figure 38: Differences in latent heat changes (ΔLE) between protected areas and non-protected areas or croplands. The mean monthly ΔLE between PAs and non-protected areas (non-PAs) for forests (a) and savannahs (c), and between PAs and croplands for forests (b) and savannahs (d). The shaded areas in (a-d) show the standard deviation of mean monthly for all the compared grid cells. ΔLE between PAs and croplands during wet and dry seasons were calculated for forests and savannahs (e) [49]



Nunes et al (2022) look at the rates of multiple land-use and land-cover transitions (LULCTs) in the Amazon forest and their impact on the ecosystem. In the study, the prevalence and the ecological impacts of 18 types of LULCTs in the Brazilian Amazon were quantified to make a comprehensive assessment of the relative risk of the major LULCTs, in order to get information about the rates of the different LULCTs, to assess the impacts of LULCTs on different ecosystem properties (e.g. biodiversity, carbon, soil) and to find the transition with the greatest magnitude of change on the ecosystem. The clearance of forests for pasture was found to be the most prevalent and high-impact transition, but also other LULCTs with high impact but lower prevalence were identified (e.g., forest to agriculture). The highest rates of LULCTs were from pastures to young secondary forests, followed by transitions from young secondary forests and undisturbed primary forests to pastures. The conversion rate of pastures to agriculture was three times higher than the inverse, while the conversion rate of primary forests to agriculture was 67 times lower than its conversion to agriculture. The species richness of almost all biodiversity groups declined by 18 to 100% with the conversion of primary and secondary forests to pastures or mechanized agriculture. Notable exceptions were the diversity of ants and orchid bees, which did not change after the conversion of undisturbed primary forests and old secondary forests to pastures. Large tree and dung beetle diversity decreased by 25 and 27%, respectively, in response to the transition from undisturbed to logged-and-burned primary forests. The diversity of large trees, small trees, and lianas declined (by 21, 17, and 21%, respectively) when logged primary forests transitioned to logged-and-burned primary forests, and the diversity of ants and birds decreased by 30 and 59%, respectively, when pastures were converted to mechanized agriculture. The diversity of large trees doubled and small tree diversity increased by 55% in response to the transition from young to old secondary forests. The study demonstrates the importance of considering multiple ecosystem components and LULCTs to understand the consequences of human activities in tropical landscapes [50].

Rorato et al (2022) examine the vulnerability of Brazilian Amazon Indigenous Lands (ILs) in terms of exposure, sensitivity and adaptive capacity to threats to the territory, based on expert knowledge. The most exposed ILs are found in the region of the Arc of Deforestation (Southern and Eastern Amazon) and in Roraima State. The ILs most vulnerable to environmental threats are those that present a high potential impact and a low adaptive capacity. In general, vulnerable ILs are most concentrated in the Arc of Deforestation region and below, as well as in the states of Pará, Amazonas, and Roraima. Very high vulnerability is stated for some ILs located in regions of intense environmental degradation, as is the case for the ILs in the state of Maranhão; in fact among 19 ILs in the state of Maranhão (in the Legal Amazon region), 16 are classified with a high vulnerability index. Among them are ILs that shelter isolated Indigenous peoples, i.e. groups that refuse contact with non-indigenous peoples and Indigenous peoples of recent contact, the isolated Indigenous people of the IL Awá, belonging to the Awá Guajá, ethnic group, are considered the most vulnerable Indigenous people in the world[67]. In general, exposure and sensitivity of ILs are increasing; in 2011–2019 around 73.9% of all ILs were more exposed to environmental threats, while 64.8% of all ILs showed to be more sensitive compared to 2001–2010. Furthermore, the study's results demonstrate a strong relationship between the environmental threats that affect Amazonian ILs internally and in their surroundings, illustrating the large pressure exerted on ILs by external processes and the need for policies aimed at control and inspection of the activities in the vicinity of ILs [51].

Figure 39: Indexes of exposure (left) and vulnerability (right) of the Amazonian Indigenous Lands in the Brazilian Legal Amazon [51]

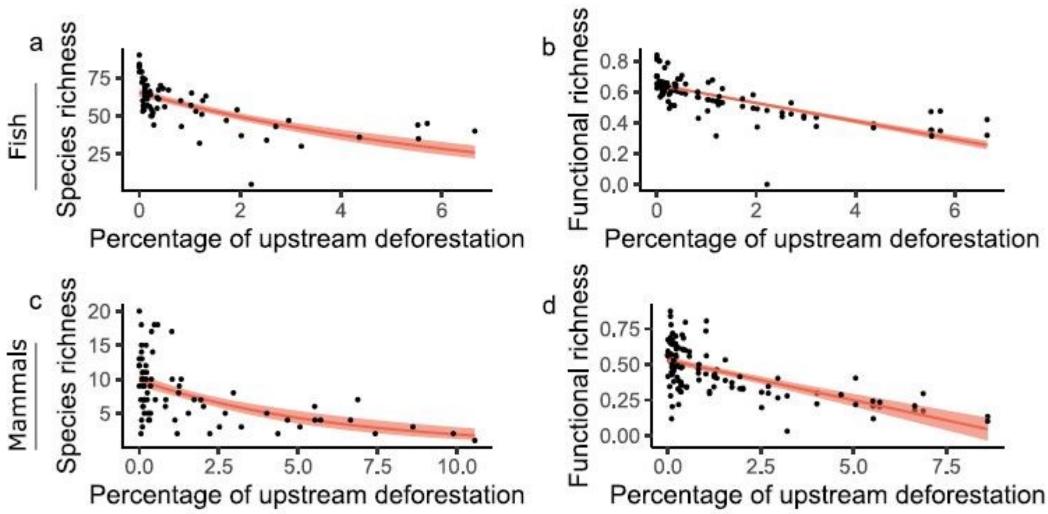


Da Silva et al (2022) state that protecting ~80 % of the Brazilian Amazon within conservation areas is feasible. Achieving this goal would require a mix of three types of interventions: disincentive-based, incentive-based, and enabling instruments. Allocating undesignated public lands to public conservation areas is a disincentive-based strategy. It takes land out of the future market and reduces the incentives for those actors aiming to obtain profits from deforestation and land grabbing. On the other hand, supporting landowners to create and maintain RPPNs is an incentive-based strategy. Local actors receive financial incentives in exchange for protecting a significant portion of their lands in perpetuity. Finally, building an integrated management system to promote synergies among conservation areas across different political levels, from local to national, is a critical enabling instrument that does not exist currently in the region. To implement such interventions requires USD1.7–2.8 billion a year (adjusted for inflation) in management costs in perpetuity plus USD 1.0–1.6 billion in upfront investments over the time needed to establish all new protected areas. This value is more than twice higher than the amount governments (from local to national) have historically spent on forest policies in the region. On the other hand, the estimated values are modest compared to the value of some of the ecosystem services generated by the region's native ecosystems. [52].

[67] https://www.survivalinternational.org/awa

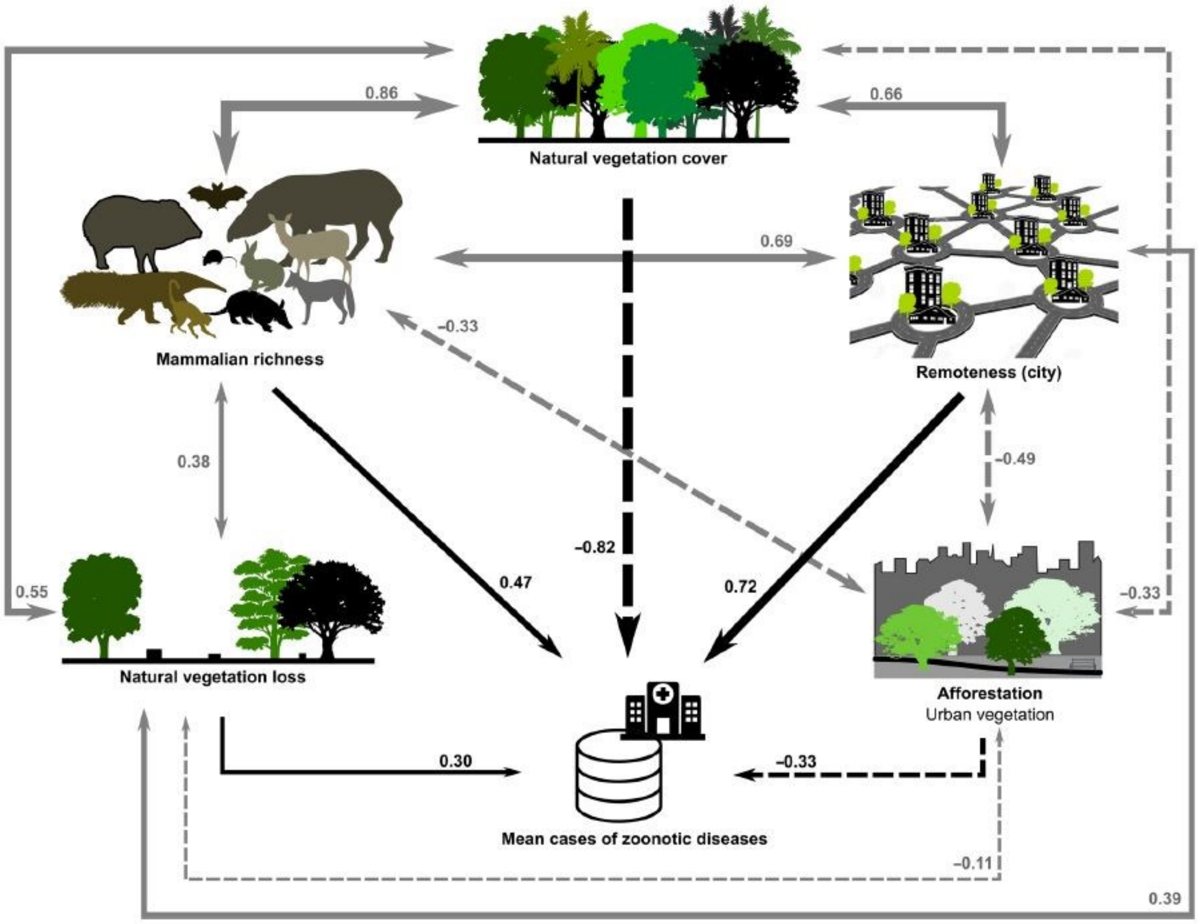
Cantera et al (2022) state that already a low level of anthropization causes vertebrates biodiversity decline in Amazonia. The authors find that remote disturbances may also affect local biodiversity, based on the evaluation of the relationships between vertebrate biodiversity (fish and mammals) and disturbance intensity in two Amazonian rivers. The findings suggest that anthropization had a spatially extended impact on biodiversity. Forest cover losses of <11% in areas up to 30 km upstream from the biodiversity sampling sites were linked to reductions of >22% in taxonomic and functional richness of both terrestrial and aquatic fauna, suggesting that anthropization had a cumulative effect on biodiversity over large spatial extent and underscoring the vulnerability of Amazonian biodiversity even to low anthropization levels. By comparing deforested and non-deforested sites, average rates of spatial decline in mammal and fish species richness of 26% and 41%, respectively, were observed. This accounts for an average loss of 13 fish and 4 mammal species in anthropized sites, compared to non-anthropized sites [53].

Figure 40: Effects of upstream deforestation intensity on biodiversity, with species richness (a, c) and functional richness (b, d) of fish (a, b) and mammal (c, d) communities [53]



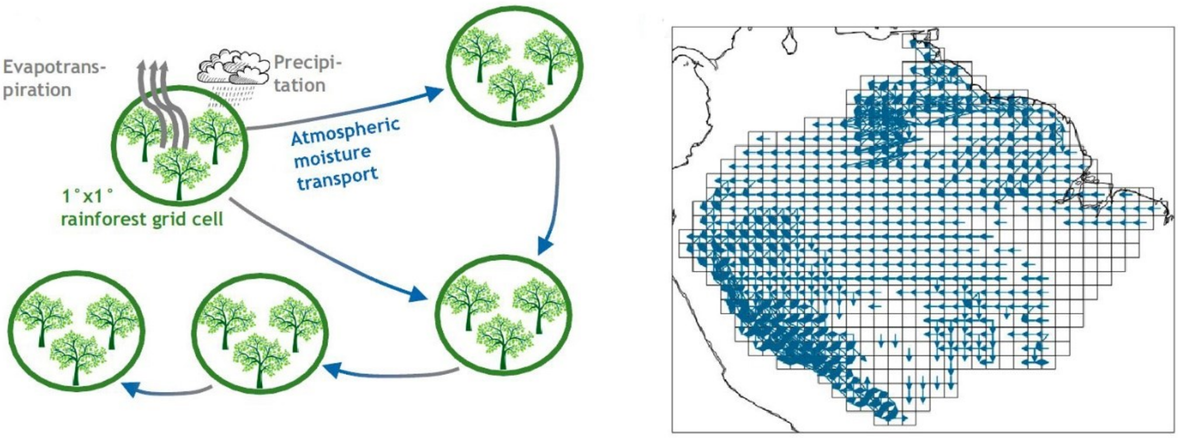
Winck et al (2022) investigate on the connection between the zoonotic disease emergence in Brazil and environmental degradation in combination with socio-ecological vulnerability in the country. Brazil currently combines socioecological vulnerabilities and an ongoing economic and political crisis that make the country a potential incubator of the next pandemic. This current crisis in Brazil is characterized by the disregard for scientific evidence and attacks on conservation organizations, the flexibilization of environmental laws, and the replacement of institutional mechanisms promoting biodiversity conservation by destructive environmental policies. Identifying critical species representing potential zoonotic disease sources requires us to focus on processes that increase the likelihood of human-wildlife contacts, such as deforestation and associated bush meat hunting and consumption. The study's assessment method assigned the higher risk level to six states from the Northern region (Acre, Amapá, Rondônia, Roraima, Amazonas, and Maranhão) and to one state from Central-Western (Mato Grosso). These states are partially or entirely covered by the Amazon rainforest In general, these states show the lowest levels of urban afforestation, the highest mammal richnesses, and the highest levels of city remoteness. The high-risk group also includes states with the highest vegetation cover (Amazonas) and the highest vegetation loss (Mato Grosso) [54].

Figure 41: Path diagram demonstrating the direct and indirect effects of mammalian richness, natural vegetation loss, remoteness, urban afforestation, and natural vegetation cover on mean cases of zoonotic diseases in the 27 Brazilian states, from 2001 to 2019. Arrow width is proportional to the path coefficient. Solid and dashed arrows indicate positive and negative coefficients, respectively [54].



Wunderling et al (2022) examine the recurrent drought increase risk of cascading tipping events by outpacing adaptive capacities in the Amazon rainforest. Tipping elements are nonlinear subsystems of the Earth system that have the potential to abruptly shift to another state if environmental change occurs close to a critical threshold with large consequences for human societies and ecosystems. Among these tipping elements may be the Amazon rainforest, which has been undergoing intensive anthropogenic activities and increasingly frequent droughts. Here, we assess how extreme deviations from climatological rainfall regimes may cause local forest collapse that cascades through the coupled forest–climate system. The authors develop a conceptual dynamic network model to isolate and uncover the role of atmospheric moisture recycling in such tipping cascades. They account for heterogeneity in critical thresholds of the forest caused by adaptation to local climatic conditions. Our results reveal that, despite this adaptation, a future climate characterized by permanent drought conditions could trigger a transition to an open canopy state particularly in the southern Amazon. The loss of atmospheric moisture recycling contributes to one-third of the tipping events. Thus, by exceeding local thresholds in forest adaptive capacity, local climate change impacts may propagate to other regions of the Amazon basin, causing a risk of forest shifts even in regions where critical thresholds have not been crossed locally [55].

Figure 42: left: Exemplary atmospheric moisture recycling network, where each forest circle represents a 1∘× 1∘ grid cell, right: Atmospheric moisture recycling network for the hydrological year 2014 [55]



Forzieri et al (2022) look at emerging signals of declining forest resilience under climate change. Forest ecosystems depend on their capacity to withstand and recover from natural and anthropogenic perturbations (that is, their resilience). Experimental evidence of sudden increases in tree mortality is raising concerns about variation in forest resilience2, yet little is known about how it is evolving in response to climate change. They integrate satellite-based vegetation indices with machine learning to show how forest resilience, quantified in terms of critical slowing down indicators, has changed during the period 2000–2020. They show that tropical, arid and temperate forests are experiencing a significant decline in resilience, probably related to increased water limitations and climate variability. By contrast, boreal forests show divergent local patterns with an average increasing trend in resilience, probably benefiting from warming and CO2 fertilization, which may outweigh the adverse effects of climate change. These patterns emerge consistently in both managed and intact forests, corroborating the existence of common large-scale climate drivers. Reductions in resilience are statistically linked to abrupt declines in forest primary productivity, occurring in response to slow drifting towards a critical resilience threshold. Approximately 23% of intact undisturbed forests, corresponding to 3.32 Pg C of gross primary productivity, have already reached a critical threshold and are experiencing a further degradation in resilience. Together, these signals reveal a widespread decline in the capacity of forests to withstand perturbation that should be accounted for in the design of land-based mitigation and adaptation plans [56].

Vora et al (2022) propose forest protection of tropical and subtropical forests as one of four actions needed to reduce the risk of a virus exchange between animals and people. Various studies show that changes in the way land is used, particularly in tropical and subtropical forest regions, might be the largest driver of emerging infectious diseases of zoonotic origin globally. Wildlife that survives forest clearance or forest degradation tends to include species that can live alongside people, and that often host pathogens capable of infecting humans. Furthermore, the loss of forests is driving climate change. This could in itself aid spillover by pushing animals, such as bats, out of regions that have become inhospitable and into areas where many people live. Actions to prevent spillover in these areas, particularly by reducing deforestation, would also help to mitigate climate change and reduce the loss of biodiversity. For around US$20 billion per year, the likelihood of spillover could be greatly reduced. This is the amount needed to halve global deforestation in hotspots for emerging infectious diseases; drastically curtail and regulate trade in wildlife; and greatly improve the ability to detect and control infectious diseases in farmed animals [57].

Da Silva et al (2022) examined the compliance of deforestation embargoes in the Brazilian Amazon and found forest recovery in only 13.1% (±1.1%) of embargoed polygons, while agriculture and pasture activities were maintained in 86.9% (±1.8%) of the cases between 2008 and 2017. The reason was the limited monitoring of embargoed areas, due to the environmental agents' rare on-the-spot verification of the embargoed lands' status. According to the authors, advances in remote sensing would provide low-cost ways to monitor compliance and should form the basis of concerted efforts to ensure law compliance and prevention of benefits for illegal deforesters [58].

Benzeev et al (2022) look at how local governance influence deforestation in the Brazilian Amazon. Evidence suggests that governance may play a critical role in influencing deforestation, and while a number of studies have demonstrated a clear relationship between national-level governance and deforestation, much remains to be known about the relative importance of subnational governance to deforestation outcomes. The authors compiled a dataset of 22 municipal-level governance variables covering the 2005–2018 period for 457 municipalities in the Brazilian Amazon. Using an econometric approach, we tested the relationship between governance variables and deforestation rates in a fixed-effects panel regression analysis. We found that municipalities with increasing numbers of agricultural companies tended to have higher rates of deforestation, municipalities with an environmental fund tended to have lower rates of deforestation, and municipalities that had previously elected a female mayor tended to have lower rates of deforestation. These results add to the wider conversation on the role of local-level governance, revealing that certain governance variables may contribute to halting deforestation in the Brazilian Amazon [59].

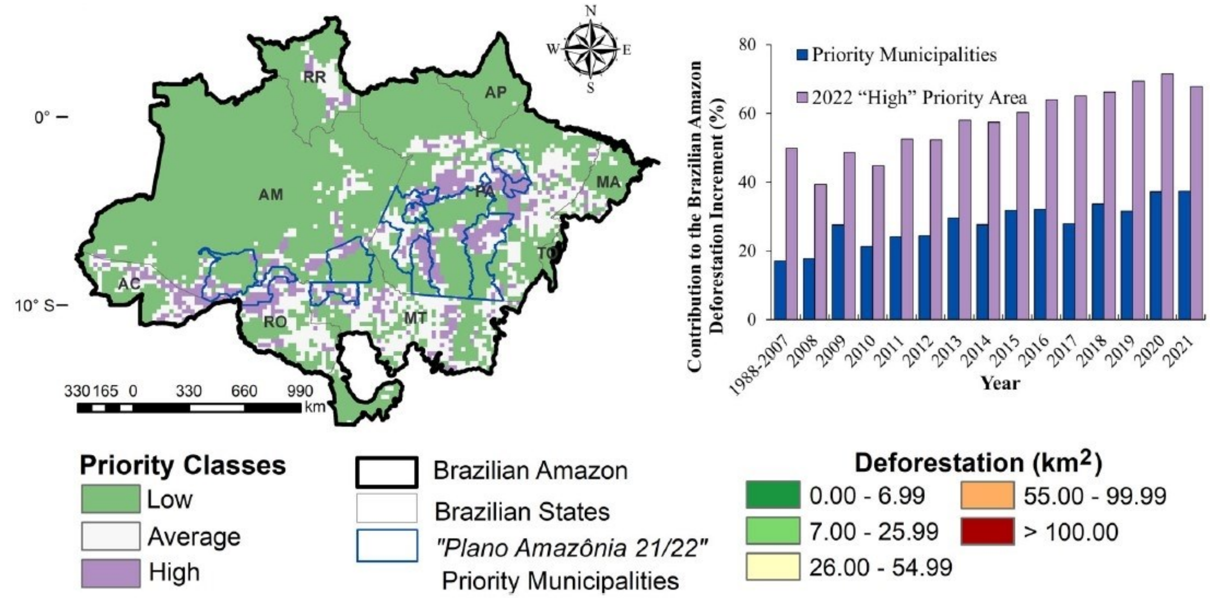
Reis et al (2021) make a point regarding the deforestation legality requirement for commodity trade in Brazil. Consumer countries and blocs, including the UK and the EU, are defining legal measures to tackle deforestation linked to commodity imports. The authors point out that measures aiming to fight illegal deforestation only (i.e. requiring imported goods to comply with the relevant producer countries' land use laws) are insufficient to address global deforestation[68]. Using Brazil's example of a key exporter of forest-risk commodities, it has ~3.25 Mha of natural habitat (storing ~152.8 million tons of potential CO2 emissions) at a high risk of legal deforestation until 2025. Additionally, the country's legal framework is going through modifications to legalize agricultural production in illegally deforested areas. What was illegal may become legal shortly. In Brazil, the legal framework to protect native vegetation has been changing in the recent years to allow more legal deforestation and legalize economic activities carried out in former forests and natural habitat that was illegally cleared. Hence, a legality criterion adopted by consumer countries is insufficient to protect forests and other ecosystems and may worsen deforestation and conversion risks by incentivizing the weakening of social-environmental protection by producer countries [60].

Brouwer et al (2022) analyse the (mostly) Brazilian scientific valuation literature in order to assess the economic value of the Brazilian Amazon's ecosystem services (ES). Economic valuation of ES helps to make the values of nature more visible. Tropical rainforests are among the most valued and threatened ecosystems in the world. Although several studies synthesize the results from forest valuation studies worldwide [e.g. 1–4], none of these studies investigate the economic values of the ES delivered specifically by the Amazon, the largest tropical rainforest in the world, covering some 5.2 million km2 across eight South American countries. The main objective of this study is to assess the economic values of ES provided by the Amazon rainforest in Brazil to local populations, in particular regulating services such as carbon sequestration and water regulation, and cultural ecosystem services such as recreation and eco-tourism, and habitat for species. Insight in these local values is paramount for comparison with the opportunity costs of forest preservation in cost-benefit analysis [61].

[68] The recent EU proposal for a regulation to curb deforestation (that was published in Nov 2021 after the Reis et al paper) goes beyond national frameworks to tackle both illegal and legal deforestation by introducing 'deforestation-free' criteria that will apply equally to all countries, including in the EU.

Mataveli et al (2022) propose to use science-based planning to support law enforcement actions for curbing deforestation in the Brazilian Amazon. While Brazil publicly committed to reduce deforestation in Amazonia at the 26th Conference of the Parties (COP26), the Brazilian parliament is moving toward weakening environmental laws. Deforestation rates continue ascending, reaching in 2021 the highest value since 2006 (13,235 km^2). To overcome this paradox, strategies to curb deforestation are mandatory. The current strategy, “Plano Amazônia 21/22,” prioritizes law enforcement actions to curb illegal deforestation in only 11 Amazonian municipalities. The authors show that this prioritization is likely to be insufficient since these municipalities account for just 37% of the current deforestation rate. This strategy may also be undermined by the leakage of deforestation actions to unmonitored municipalities. Using a set of spatially explicit datasets integrated into a deforestation-prediction modelling approach, they propose a science-based alternative method for ranking deforestation hotspots to be prioritized by law enforcement actions. Our prioritization method accounts for more than 60% of the deforestation, detecting larger deforested areas in both private and public lands, while covering 27% less territory than “Plano Amazônia 21/22.” Optimizing the detection of priority areas for curbing deforestation, as proposed here, is the first step to reducing deforestation rates and comply with the Brazilian legal commitment of 3925 km^2 year^{-1} [62].

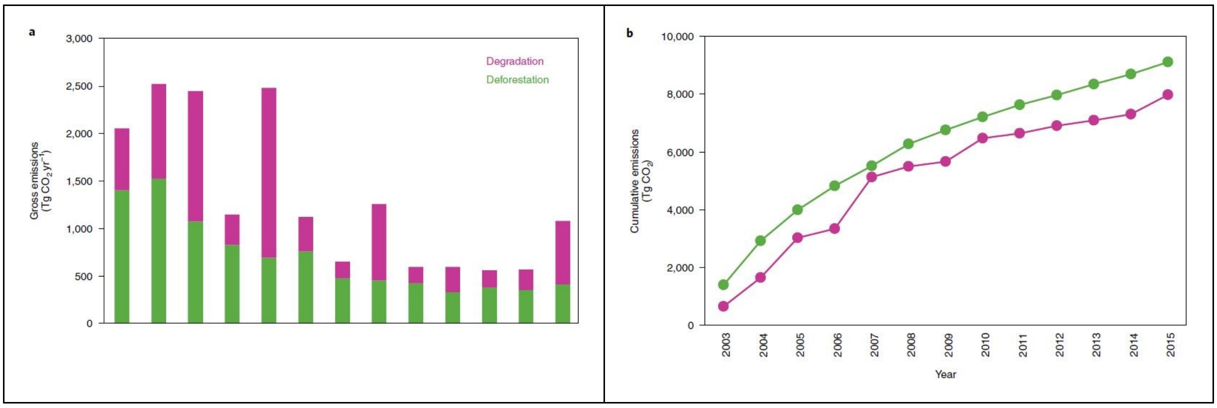
Figure 43: left: Priority classes for combating deforestation in the Brazilian Amazon in 2022 considering the regular grid of 25 X 25 km, Contribution of the “Plano Amazônia 21/22” priority municipalities and the 2022 “High” priority areas to the Brazilian Amazon deforestation rates over time [62]



5.2.2 Forest degradation

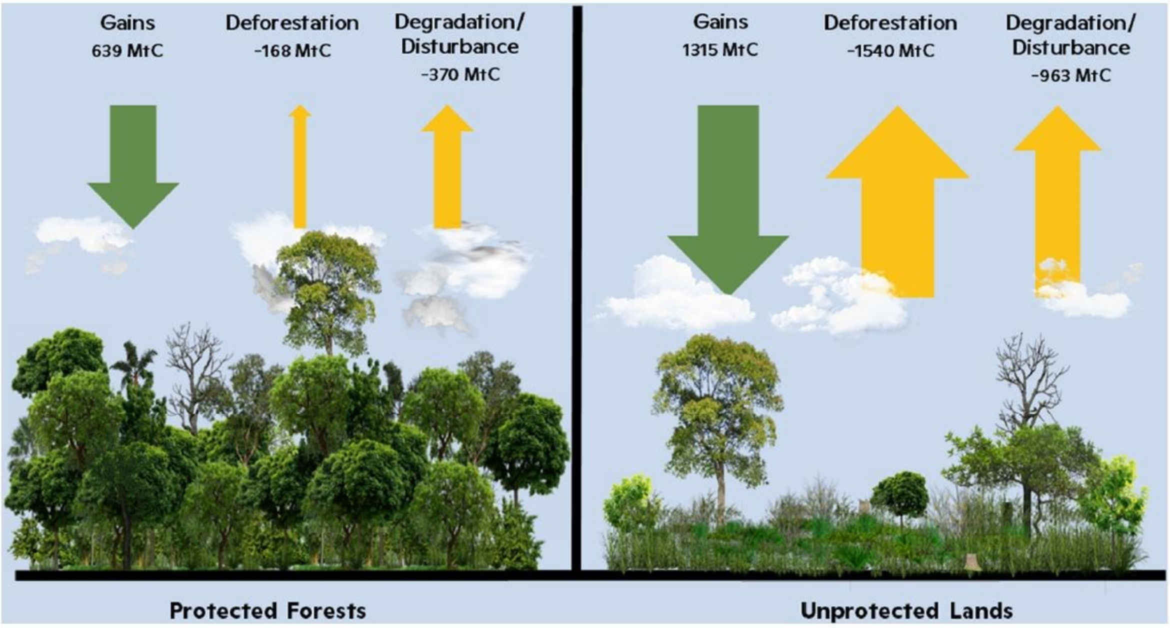
The revision of the national commitments to reducing greenhouse gas (GHG) emissions will play a key role in defining the future of Earth's climate. In the past, the main target of Amazonian nations was to reduce emissions resulting from land-use change and land management by committing to decrease deforestation rates. However, human-induced forest degradation caused by fires, selective logging, and forest edge effects can also result in large carbon dioxide (CO_2) emissions, which are not yet explicitly reported by Amazonian countries. Despite its considerable impact, forest degradation has been largely overlooked in previous policy discussions. It is vital that forest degradation is incorporated into future commitments to reduce GHG emissions. Degraded forests currently occupy a larger area than forest clear-cut areas. During the 2003–2015 period in the Brazilian Amazon, CO_2 committed emissions from forest fires (5,904 Tg) and edge effects (2,068 Tg) reached 88% of the gross deforestation emissions (9,108 Tg) [63].

Figure 44: Carbon dioxide (CO_2) emissions from deforestation and forest degradation from forest fires and edge effects in the Brazilian Amazon, annual emissions (left) and cumulative CO_2 emissions [63]



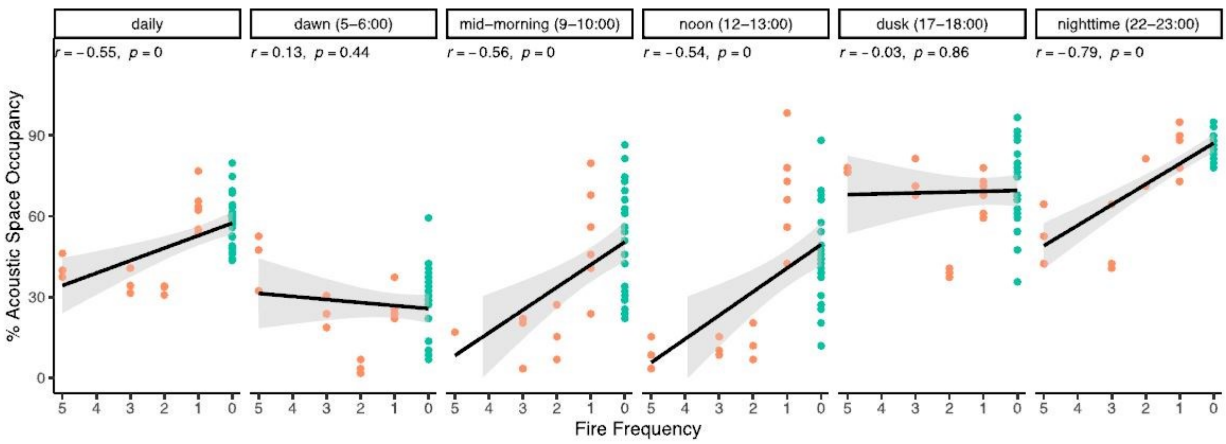
Carbon losses from forest degradation and disturbances are significant and growing sources of emissions in the Brazilian Amazon. Between 2003 and 2019, forest degradation and forest disturbances accounted for 44% of forest carbon losses in the region, compared with 56% from deforestation. Land tenure played a decisive role in explaining these carbon losses, with Undesignated Public Forests and Other Lands (e.g., private properties) accounting for the majority (82%) of losses during the study period. Illegal deforestation and land grabbing in Undesignated Public Forests widespread and increasingly are important drivers of forest carbon emissions from the region. In contrast, Indigenous Territories and Protected Natural Areas had the lowest emissions, demonstrating their effectiveness in preventing deforestation and maintaining carbon stocks. These trends underscore the urgent need to develop reliable systems for monitoring and reporting on carbon losses from forest degradation and disturbance. Together with improved governance, such actions will be crucial for Brazil to reduce pressure on standing forests; strengthen indigenous land rights; and design effective climate mitigation strategies needed to achieve its national and international climate commitments [64].

Figure 45: Cumulative (gross) above-ground carbon fluxes from protected forests (left) and unprotected forests (right) between 2003 and 2019 [64]



Safeguarding tropical forest biodiversity requires solutions for monitoring ecosystem structure over time. In the Amazon, logging and fire reduce forest carbon stocks and alter habitat, but the long-term consequences for wildlife remain unclear. Through a combination of multiday acoustic surveys, airborne lidar, and satellite image time series covering logged and burned forests in the southern Brazilian Amazon, acoustic markers of forest degradation are identified. Aboveground biomass was not a consistent proxy for acoustic biodiversity due to the divergent patterns of "acoustic space occupancy" between logged and burned forests. Ecosystem soundscapes highlighted a stark and sustained reorganization in acoustic community assembly after multiple fires; animal communication networks were quieter, more homogenous, and less acoustically integrated in forests burned multiple times than in logged or once-burned forests. By contrast, soundscape changes after selective logging were subtle and more consistent with acoustic community recovery than reassembly. Research suggests that the effect of selective logging on tropical forest biota is governed less by time since recovery and more by logging intensity [65].

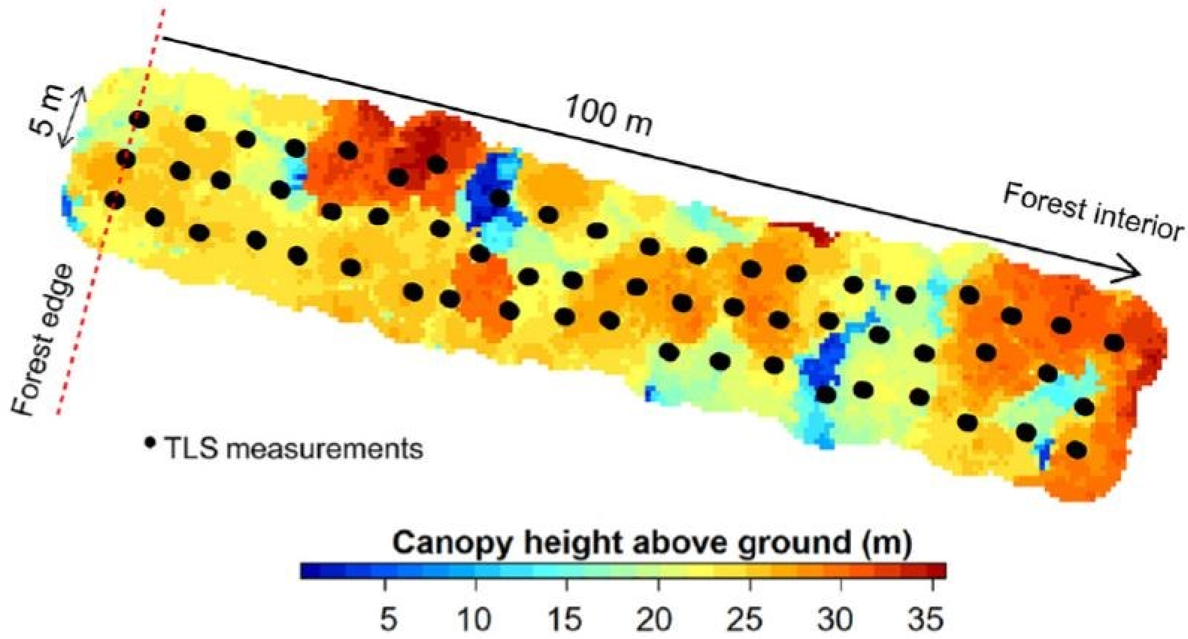
Figure 46: Daily Acoustic Space Occupancy of the animal community in burned and unburned forests (Southern Brazilian Amazon) [65]



5.2.3 Forest edge effects

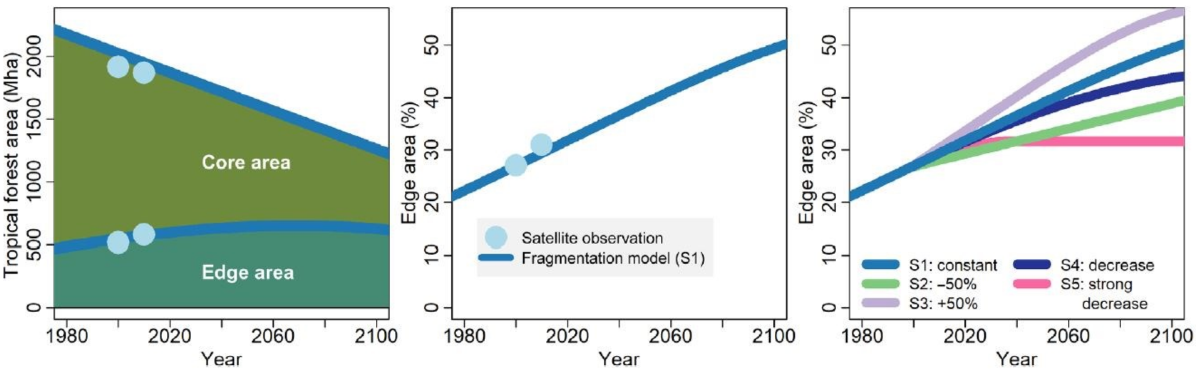
Forest edges are an increasingly common feature of Amazonian landscapes due to human-induced forest fragmentation. Substantial evidence shows that edge effects cause profound changes in forest biodiversity and productivity. Analysis of 600 high-resolution terrestrial laser-scanning (TLS) measurements showed a persistent change in forest structural characteristics along the edges of forest fragments, which resulted in a significantly lower structural diversity, in comparison with the interior of the forest fragments. These structural changes could be observed up to 35 m from the forest edges and are likely to reflect even deeper impacts on other ecosystem variables such as microclimate and biodiversity. The high mortality of large trees in forest edges has been linked to a higher exposure to wind turbulence and greater desiccation stress. Trees larger than 60 cm in diameter were shown to die approximately three times faster near edges than in forest interiors. Changes in the light regime in gaps opened by the death of large trees, added to increased lateral light penetrating near edges, create favourable conditions to the recruitment of new individuals, mainly pioneer trees, as well as accelerated growth rates of trees and lianas. However, the current experiment is established under controlled conditions, i.e., the matrix surrounding the fragments consists of stable secondary vegetation. More commonly, the lands surrounding forest fragments undergo intensive management, which may include, for instance, prescribed fires and cultivation of commodity crops, which can increase the penetration capacity of edge effects. Other studies have shown that surface temperature increase in deforested areas converted to large-scale commodity crops can be up to three-fold higher than in small-scale farms with less intensive management increasing the potential for deeper edge-effects [66].

Figure 47: canopy height model extracted from the TLS data with overlaid sampling scheme [66]



Large areas of global tropical forests have been lost through deforestation, resulting in fragmented forest landscapes. However, the dynamics of forest fragmentation are still unknown, especially the critical forest edge areas, which are sources of carbon emissions due to increased tree mortality. We analysed the changes in forest fragmentation for the entire tropics using high-resolution forest cover maps. We found that forest edge area increased from 27 to 31% of the total forest area in just 10 years. The number of forest fragments increased by 20 million with consequences for connectivity of tropical landscapes. Simulations suggest that ongoing deforestation will further accelerate forest fragmentation. By 2100, 50% of tropical forest area will be at the forest edge, causing additional carbon emissions of up to 500 million MT carbon per year. Thus, efforts to limit fragmentation in the world's tropical forests are important for climate change mitigation [67].

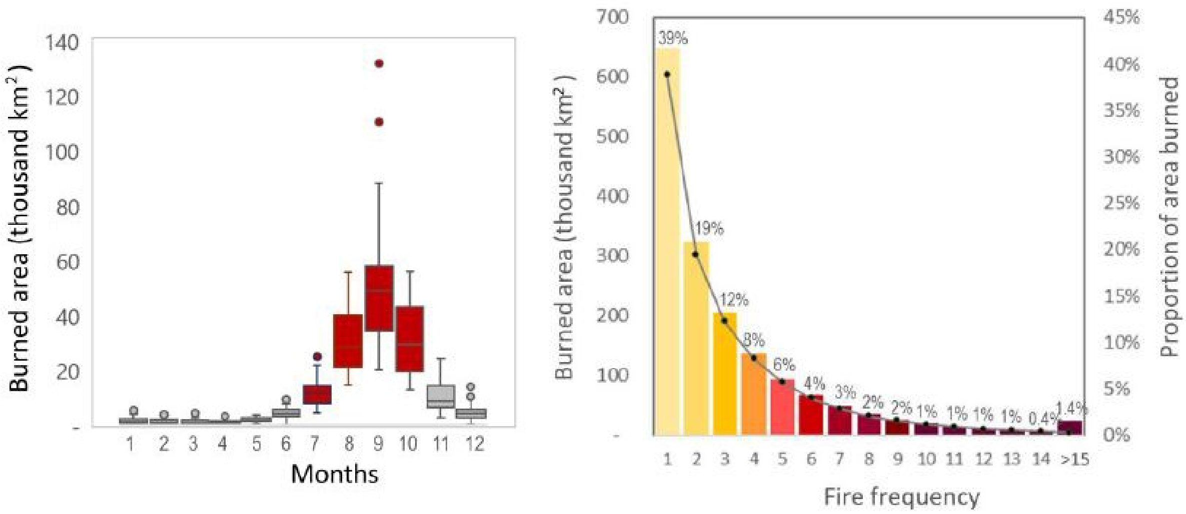
Figure 48: projected global areas of forest edge and forest core areas until year 2100 (left), global forest edge area percentages (centre) and projections of global forest edge area percentages under different scenarios (right) [67]



5.2.4 Forest fires

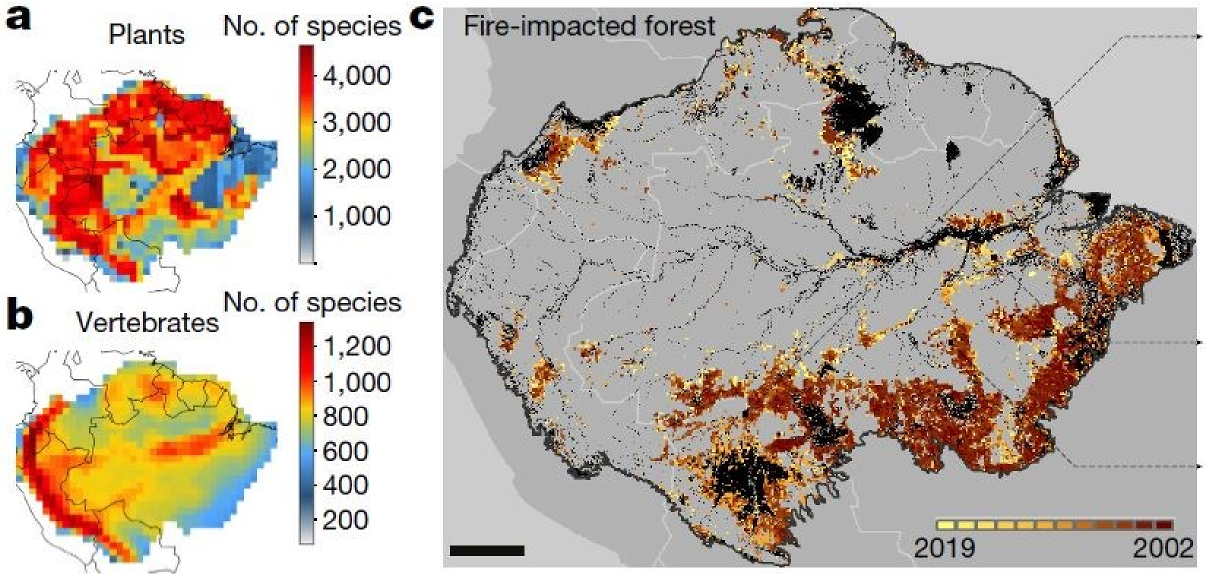
Although fire has long been an intrinsic component of Brazilian biomes, affecting political, economic, social, and even cultural forms of human and nature interactions, its long-term historical dynamics are still poorly understood. Due to the ephemeral and diverse characteristics of Brazilian fires, it has been difficult to address their real extent, as well as identify their historical paths and trends. Remote sensing observations have provided important products, but several challenges remain for capturing the long-term multi-decadal history of burned areas on a large scale and over such diverse ecosystems. These challenges encompass the high levels of spectral heterogeneity of the burned areas in response to seasonality and land use change. The natural seasonality of native vegetation confounds the signals of unburned and burned areas, increasing their spectral similarity, and land cover and land use conversions sometimes also present signatures similar to those of burned areas. The burned area dataset revealed that at least 19.6% of the Brazilian territory was burned at least once from 1985 to 2020. The majority of these areas (61%), burned more than two times in the period of analysis. Most fires in Brazil (83%) are active in the Cerrado and Amazon, but other biomes had important contribution and increases in fire activities and extent of burned area in the past decades. For some of the biomes the higher fire frequencies point to altered fire regimes that are a response to increase in human ignition and climate change. The Amazon is the most alarming of these biomes with a fire frequency distribution similar to that of biomes that are adapted to fire, such as Cerrado and Pantanal. [68].

Figure 49: left: Seasonal patterns of fire events occurred in Brazil, considering the variation of burned area per month in the period (1985–2020), right: burned area and proportion of the burned area by frequency class [68]



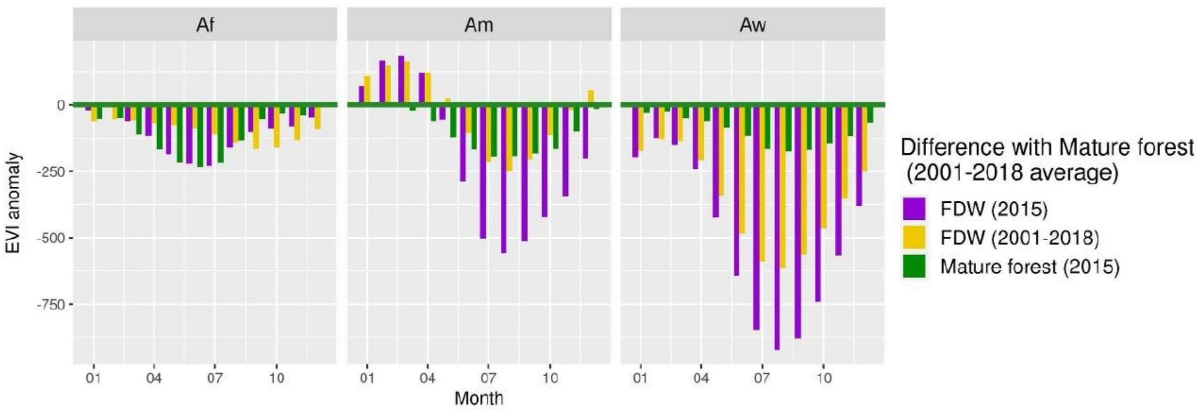
Habitat loss due to deforestation has profound negative impacts on Amazonian biodiversity, and fires can exacerbate these already substantial impacts. There is a tight association between the cumulative amount of forest experiencing fire and the impacts on biodiversity. Over the past two decades, the ranges of the majority of Amazonian species are likely to have been impacted in some way by fires. Many of these impacted species are already considered by the IUCN to be threatened. Since 2001, 103,079–189,755 km^2 of Amazon rainforest has been impacted by fires, potentially impacting the ranges of 77.3–85.2% of species that are listed as threatened in this region. The impacts of fire on the ranges of species in Amazonia could be as high as 64%, and greater impacts are typically associated with species that have restricted ranges. As fires move closer to the heart of the Amazon Basin—which is characterized by greater levels of diversity—the impact of fires on biodiversity will undoubtedly increase, even if the rate of forest burning remains unchanged. Although regulations have been effective in slowing the pace of burning and deforestation, relaxing those regulations—as shown in Brazil in 2019—can quickly erase gains made. Such policy reversals, in combination with more severe droughts, are likely to accelerate the impacts of fire on Amazonian species and destabilize the role of biodiversity in mitigating climate change in the future [69].

Figure 50: Number of plant and vertebrates species in the Amazon region (a,b), fire-impacted Amazon forest (c) [69]



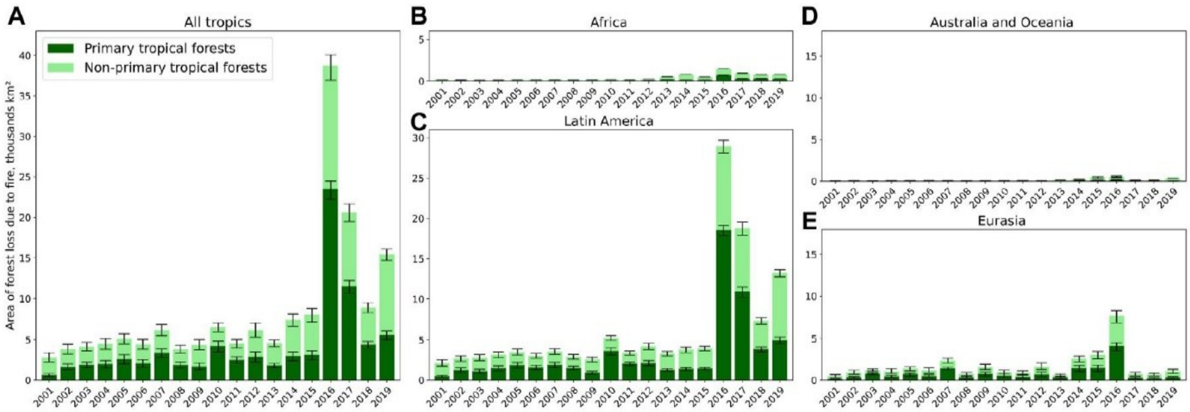
The phenology of tropical forests is tightly related to climate conditions. In the Amazon, the seasonal greening of forests is conditioned by solar radiation and rainfall. Yet, increasing anthropogenic pressures (e.g. logging and wildfires), raise concerns about the impacts of forest degradation on the functioning of forest ecosystems, especially in a climate change context. Assessing the contribution of solar radiation and precipitation to forest greening in mature and fire degraded forests, with a focus on the 2015 drought event, showed that forest greening is more dependent on water resources in degraded forests than in mature forests. As a consequence, the expected increase in drought episodes and associated fire occurrences under climate change could lead to a long-term drying of tropical forests [70].

Figure 51: Anomalies of Enhanced Vegetation Index (EVI) for forest in the three Köppen climate subclasses Af (no dry season), AM (short dry season) and Aw (long dry season). Area of interest: Parà, Mato Grosso and Rondônia States of Brazil. FDW = Forest Disturbed by Wildfires [70]



Tyukavina et al (2022) present a global 30-m resolution satellite-based map of annual forest loss due to fire. Forest fires contribute to global greenhouse gas emissions and can negatively affect public health, economic activity, and provision of ecosystem services. In the humid tropics, fires are largely human induced and lead to forest degradation. An increasing global trend in forest loss due to fire from 2001 to 2019 was found by the analysis, driven by near-uniform increases across the tropics, subtropical, and temperate Australia, and boreal Eurasia. The results quantify the increasing threat of fires to remaining forests globally and may improve modelling of future forest fire loss rates under various climate change and development scenarios [71].

Figure 52: Annual area of forest loss due to fire in primary vs. non–primary tropical forests in (A) all tropics; (B) Africa; (C) Latin America; (D) Australia and Oceania; (E) Eurasia. Area estimates and uncertainty intervals are map-based, within the joint extent of mapped tree cover in 2000 and forest loss from 2001 to 2019 (according to Hansen et al 2013)[69] [71]



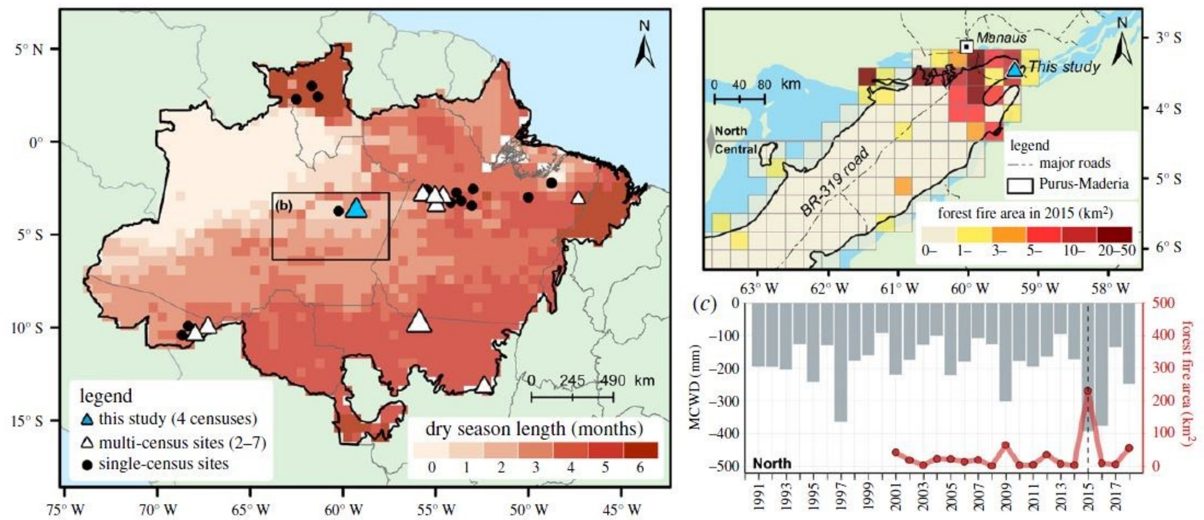
With humanity facing an unprecedented climate crisis, the conservation of tropical forests has never been so important – their vast terrestrial carbon stocks can be turned into emissions by climatic and human disturbances. However, the duration of these effects is poorly understood, and it is unclear whether impacts are amplified in forests with a history of previous human disturbance. The Amazonian epicentre of the 2015–16 El Niño is a region that encompasses 1.2% of the Brazilian Amazon. At high temporal resolution, the impacts of an extreme El Niño (EN) drought and extensive forest fires on plant mortality and carbon loss in undisturbed and human-modified forests are quantified. Mortality remained higher than pre-El Niño levels for 36 months in EN-drought–affected forests and for 30 months in EN-fire–affected forests. In EN-fire–affected forests, human disturbance significantly increased plant mortality. The ecological and physiological predictors of tree mortality showed that trees with lower wood density, bark thickness and leaf nitrogen content, as well as those that experienced greater fire intensity, were more vulnerable. Across the region, the 2015–16 El Niño led to the death of an estimated 2.5 ± 0.3 billion stems, resulting in emissions of 495 ± 94 Tg CO2. Three years after the El Niño, plant growth and recruitment had offset only 37% of emissions [72].

While the climate and human-induced forest degradation is increasing in the Amazon, fire impacts on forest dynamics remain understudied in the wetter regions of the basin, which are susceptible to large wildfires only during extreme droughts. Burned and unburned plots were installed immediately after a wildfire in the northern Purus-Madeira (Central Amazon) during the 2015 El-Niño. Overall, the burned forest lost 27.3% of stem density and 12.8% of biomass, concentrated in small and medium trees. Mortality drove these losses in the first 2 years and recruitment decreased in the third year. The fire increased growth in lower wood density and larger sized trees, Our findings suggest that fire impacts are weaker in the wetter Amazon. Here, trees of greater sizes and higher wood densities may confer a margin of fire resistance; however, this may not extend to higher intensity fires arising from climate change. The resistance of the forest to fire in very humid Amazon forest is

[69] https://www.science.org/doi/10.1126/science.1244693

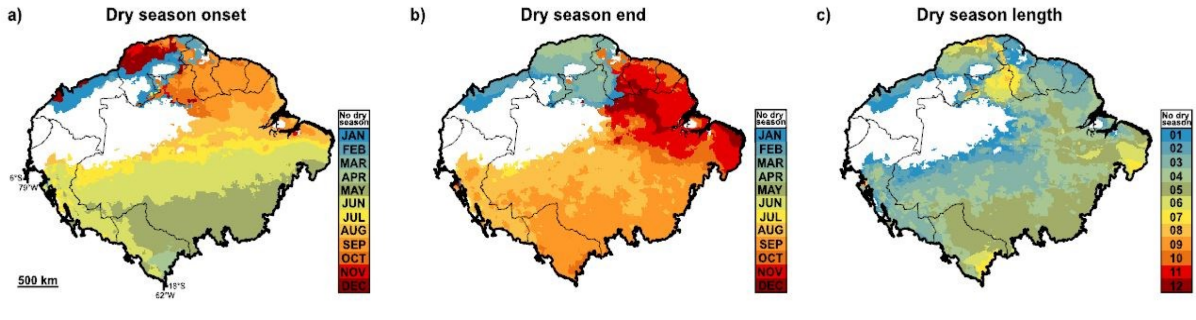
similar to the forest in the phyto-geographic borders of the Amazon, but for different reasons. Trees in highly seasonal phyto-geographic border regions tend to have adaptive protections against fire, in particular thicker bark, while in less seasonal regions higher surface fuel moisture limits fire spread and intensity even during an extreme drought such as the 2015/2016 El Niño period [73].

Figure 53: area of interest (rectangle) in the Central Brazilian Amazon with an indication of dry season length (left), burned forest area 2015 of the Purus-Madeira forest region (top right), annual lowest maximum cumulative water deficit (MCWD) and forest fire area in the Purus-Madeira forest region (lower right) [73]



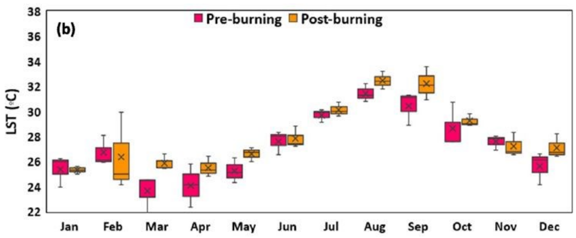
The dry season spatio-temporal variation determines the Amazonian fire calendar. Analysing a monthly time series of active fires from 2003 to 2019 characterizes the fire dynamics throughout the year and identifies the fire peak months. More than 50% (32 246) of the annual mean active fires occurred in the peak dry month. In 52% of the cells, the peaks occurred between August–September and in 48% between October–March, showing well-defined seasonal patterns related to spatio-temporal variation of the dry season. Fire peaks occurred in the last two months of the dry season in 67% of the cells and in 20% in the first month of the rainy season. The shorter the dry season, the more concentrated was the occurrence of active fires in the peak month, with a predominance above 70% in cells with a dry season between one and three months. We defined a Critical Fire Period by identifying the consecutive months that concentrated at least 80% of active fires in the year. This period included two to three months between January and March in the northwest of the Amazon region, and in the far north it lasted up to seven months, ending in March–April. In the south, it varied between two and three months, starting in August. In the northeast, it was three to four months, between August and December [74].

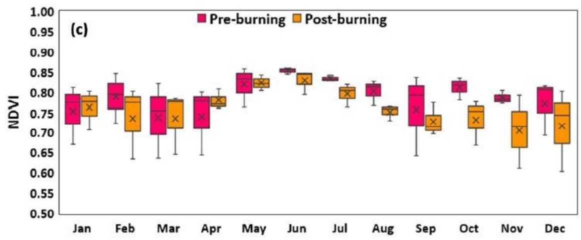
Figure 54: Spatio-temporal patterns of the dry season in the Amazon Basin were calculated using CHIRPS data from 1981 to 2019 at a spatial resolution of 10 km. The dry season includes the months with mean monthly rainfall below 100 mm. The onset/end months of the dry season are shown in figures (a) and (b), respectively. The dry season length is the number of consecutive months of the dry season [74]



The legacy effects following (low intensity) fire on surface energy, water and carbon fluxes in mature Amazonian forests were assessed, based on high temporal and spatial resolution remote sensing and climate reanalysis data. The fire significantly increased Land Surface Temperature (LST) (0.8°C) and air temperature (1.2°C) in the forests over a 3 years interval, comparing pre-burning and post-burning. The fire caused a significant decrease in NDVI (~4%) over the same interval. Three years was enough time for the forests to recover their original states in terms of surface energy availability, and coupling between the carbon and water cycles. However, a high severity fire can alter the canopy characteristics more strongly than a low severity fire such as the one we observed, which means that distinct disturbance regimes can potentially affect the carbon and water cycling after the fire in forested areas quite differently [75].

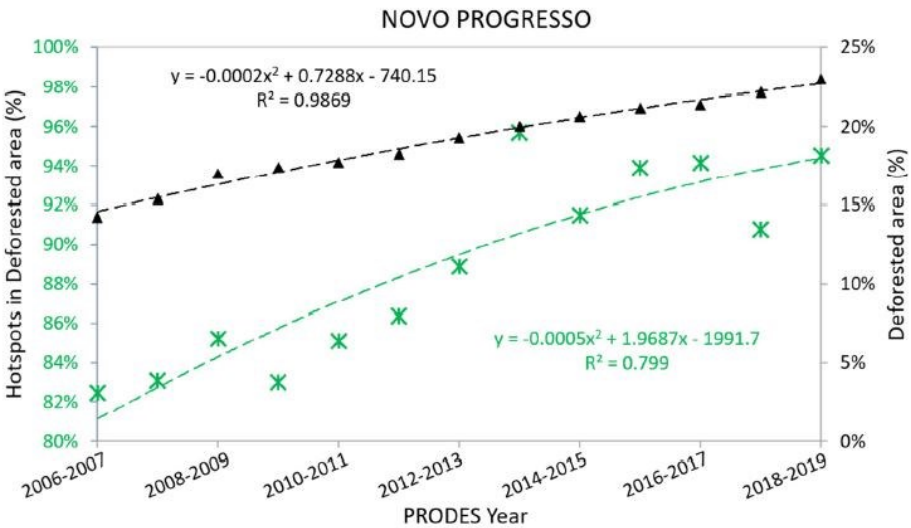
Figure 55: comparison of pre- and post-fire Land Surface Temperature (LST) and Normalised Differentiated Vegetation Index (NDVI) in mature forest fragments in southeastern Parà State in Brazil [75]





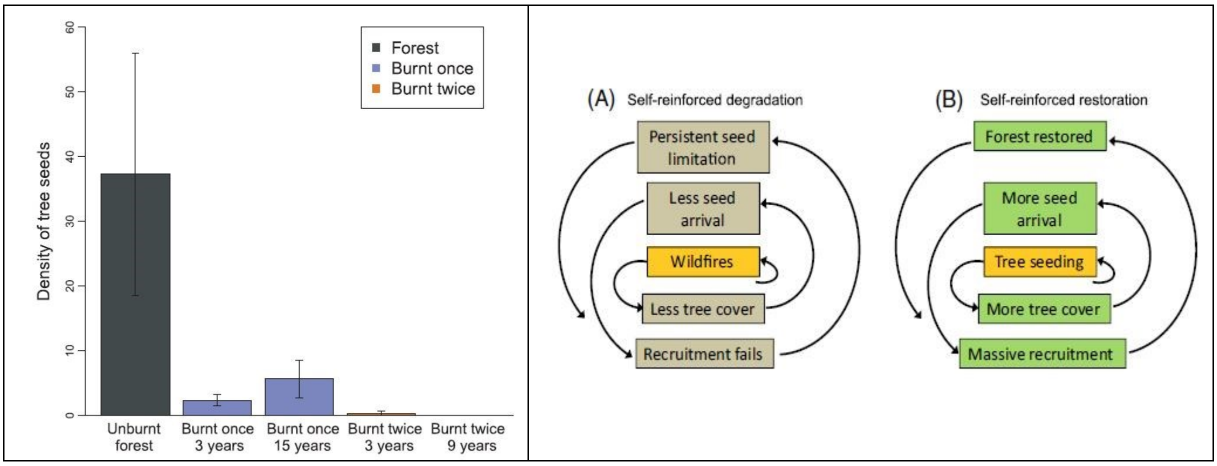
A strong correlation can be observed between active fire hotspots and newly deforested areas in the Brazilian State of Parà over a time period of 14 years (2006-2019), indicating a positive correlation on local and regional scales, while suggesting similar results within the whole Brazilian deforestation arc due to common slash-and-burn practices. Many fire occurrences within the forest near recently deforested areas result in ecosystem degradation, turning the forest more prone to future fire events. The area of old-growth forest is thus negatively influenced by nearby slash-and-burn practices, enlarging the area of forest degradation. The occurrences of fire hotspots in old-growth forest ranges from 5% to 20%, compared to the occurrence in the newly deforested areas [76].

Figure 56: Occurrence of active fires (MODIS) within and outside deforested areas from 2006-2019, (according to INPE-PRODES) in the town of Novo Progresso, Parà State [76]



Comparing planted seed growth of six different native tree species in four different Amazonian floodplain forest areas (unburned, forest edge to burned forest, forest burned once, forest burned twice) shows that the seed emergence was happening in all areas in a similar manner. However, the highest growth rate was found in forest areas that were burned once and (by far) the lowest growth in unburned forest. The reason for the success of (planted) seeds in burned forest is the high availability of light and nutrients. In addition the natural abundance of tree seeds was evaluated for all four forest classes. Here, the picture was very different compared to the planted seeds. The unburned forest has by far the most natural seeds available, while showing very low numbers when looking at once or twice burned forest. Once burned forest shows a slow recovery of natural seeds numbers 15 years after the burning, while twice burned forest never recovers its natural seed availability – and thus never shows signs of forest regrowth. The lack of success is linked to the lack of seed dispersal in burned floodplain forest, as it does not appear attractive to seed dispersing animals like birds, bats or mammals [77].

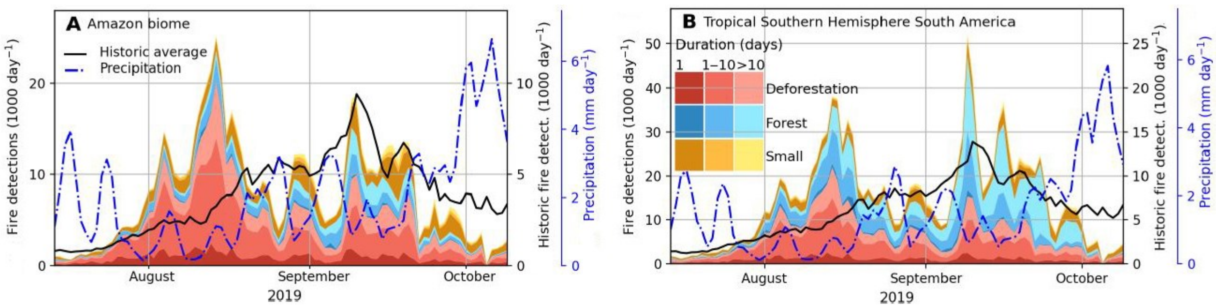
Figure 57: 'natural' density of tree seeds in unburned and burned Amazon floodplain forest (left), positive feedbacks of natural (A) and active seeding (B) of native trees in repeatedly burned forest (right) [77]



Requia et al (2021) quantify the impact of wildfire-related PM2.5 on 2 million hospital admission records due to cardiorespiratory diseases in Brazil between 2008 and 2018. The national analysis shows that wildfire waves are associated with an increase of 23% (95%CI: 12%–33%) in respiratory hospital admissions and an increase of 21% (95%CI: 8%–35%) in circulatory hospital admissions. In the North (where most of the Amazon region is located), we estimate an increase of 38% (95%CI: 30%–47%) in respiratory hospital admissions and 27% (95%CI: 15%–39%) in circulatory hospital admissions. The authors report epidemiological evidence that air pollution emitted by wildfires is significantly associated with a higher risk of cardio-respiratory hospital admissions [78].

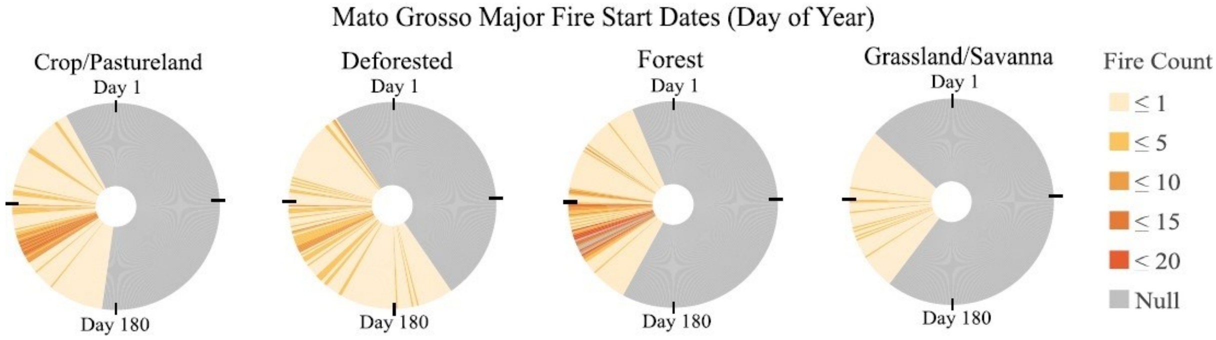
Andela et al (2022) developed a method to track and classify Amazon fire events in near real time in terms of deforestation fires, forest fires, agricultural fires and savannah fires, relate them to burned area size and carbon emissions, and apply the approach to the 2019 fire season in South America. Exceptional fire activity in 2019 sparked concern about Amazon forest conservation. However, the inability to rapidly separate satellite fire detections by fire type hampered fire suppression and assessment of ecosystem and air quality impacts. Across the southern Amazon, 19,700 deforestation fire events accounted for 39% of all satellite active fire detections and the majority of fire carbon emissions (63%; 69 Tg C). Multiday fires accounted for 81% of burned area and 92% of carbon emissions from the Amazon, with many forest fires burning uncontrolled for weeks. Most fire detections from deforestation fires were correctly identified within 2 days (67%), highlighting the potential to improve situational awareness and management outcomes during fire emergencies. Forest fires were the largest fire type, with a mean size of 5.0 km^2 that was about eight times the size of the average deforestation fire event (0.6 km^2). Numerous small clearing and agricultural fires accounted for only 8% of total burned area in the Amazon biome, while savannah and grassland fires accounted for nearly 55% of total burned area. This information on individual fire type and attributes provides important context on the spatiotemporal evolution of Amazon fire activity and fire carbon emissions [79].

Figure 58: Daily fire detections from new fire starts (dark shades) and fires that burned between 1 and 10 days or longer than 10 days (lighter shades) in forest ecosystems classified into three fire types for (A) the southern Amazon and (B) tropical southern hemisphere South America (0° to 25°S). The fire length classification in combination with fire type of B is also valid for A [79]



Walker et al (2022) analyse the fire dynamics in and around indigenous territories and protected areas in a Brazilian agricultural frontier. The study aims to quantify the role of Indigenous Territories and Protected Areas (ITPAs) in characterizing anthropogenic fire regimes over the 2020 fire season in Mato Grosso, Brazil. ITPAs cover 25% of the study area's land and contained approximately 20% of significant recorded fires in 2020. Recently deforested areas, forest, grassland, and cropland fires showed varying seasonality and lower frequencies inside ITPAs, but mean fire start dates for all fire types occurred in mid-September. Results suggest that the overall density of major fires is reduced in ITs. PAs only inhibit the density of crop or pastureland fires, but no major fires occurred past 10 km inside their borders. Burn severity of major fires had a weak relationship to distance from ITPAs for some fire types. This study highlights the advantages of near real-time data for individual fire events, provides further evidence of the effect of ITPAs on fire behaviour, and demonstrates the importance of adequate protection strategies for mitigating fire activity. The proportion of forest fires recorded in the state of Mato Grosso (48.3%) was higher than that recorded in all of Brazil within the Amazon Basin (30.7%), whereas the proportion of recently deforested fires was lower in Mato Grosso (22.6%) than that of the Brazilian Amazon Basin (39.5%). Mato Grosso therefore showed more individual fire activity related to burning undisturbed forest or the escape of other fire types into forest [80].

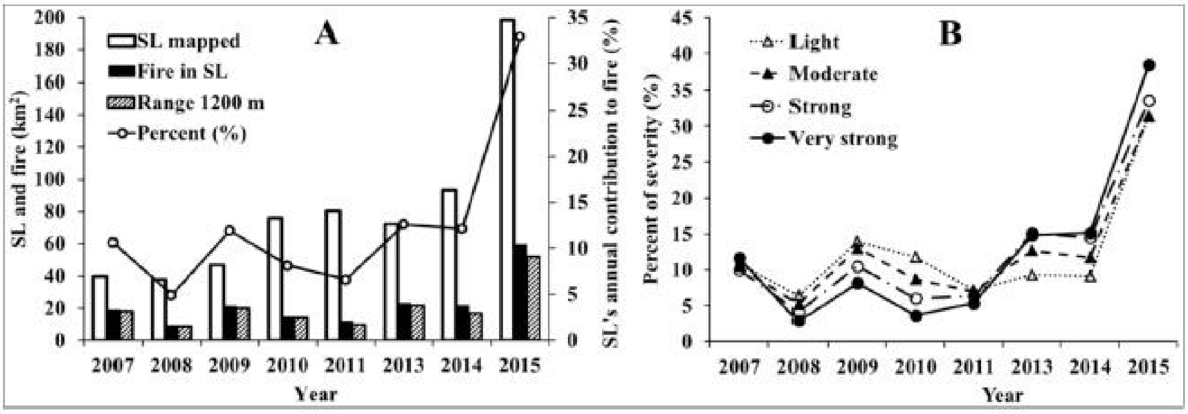
Figure 59: Seasonality of fire type, measured by the date of recorded fire starts [80]



5.2.5 Selective logging

The interrelation between selectively logged forest and burned forest was studied for the Southern part of Roraima State in the North of Brazil. Southern Roraima was, until recently, considered immune to fire; it is characterized by forest types that occur in environments with high natural humidity, but that are now strongly impacted by selective logging. The biomass impacted by fire totalled 26.4 × 106 Mg, representing 9.5% of the total mapped for the study area (277.4 × 106 Mg). The biomass killed by the fire totalled 5.9 × 106 Mg, representing 22.3% of the biomass affected by the fires. The highest level of fire severity (very strong) proportionally affected 84.6% more forest biomass inside than outside selectively logged areas. Forest vulnerability to fires increased by 265.5% in terms of area and by 400.7% in terms of biomass when exposed to selective logging. Logging also increased the severity of fires when they occurred: a hectare of burned forest was 85.9% more likely to have a "very strong" fire if it had been previously logged. Selective logging more than doubled the impact of fire on biomass loss as compared to the impact of the logging itself. In addition to its contribution to carbon emissions and other impacts, the amplifying effect of SL on forest fires indicates that the assumption that authorized forest management projects in Amazonia are sustainable is unwarranted. The future role of this practice should be rethought, existing projects should be subject to close inspection and control, and unauthorized logging should be identified and repressed. The policy of allowing sale of wood from clearcutting projects should be reconsidered, because it provides a loophole for laundering wood from illegal logging [81].

Figure 60: (A) Annual contribution of areas impacted by selective logging that were burned during the 2015/2016 El Niño event in the study area. (B) Gradient of fire severity depending on the year of logging [81]



Romero et al (2021) report on the inventory of commercial tree species in a forest under reduced impact logging (RIL) in Acre State in the south-western Brazilian Amazon and on the amount of removed and remaining biomass after the logging operation. The authors conclude that all Amazonian management operations need to incorporate reduced-impact logging procedures if they are to minimize harvesting impacts and satisfy society's demand for low-impact end products. According to the authors, currently, post-harvest silvicultural treatments (techniques for improving natural regeneration, commercial species enrichment, species composition structuring and management of forest gaps) in south-western Amazonia are not applied, even though they may be required by the POA (Annual Operational Plan). However, these treatments are apparently not mandatory, and their economic return may be considered questionable by the logging concessions. In addition, most entrepreneurs do not take responsibility for maintaining the forest under the same conditions in terms of benefits for future generations. The government needs to adopt regulations that encourage entrepreneurs to carry out silvicultural treatments that favor natural regeneration and the continuity of benefits generated by forests [82].

The issue of illegal selective logging in Brazil is looked at by Kleinschmit et al (2021) from a viewpoint of communication. A strong focus on human threats and humanization to support emotional reporting in the media frames concentrating on technological fixes in the scientific discourse and a more central role of IOs in the

NGOs/IOs discourse, according to the authors. Despite these specific perspectives that give precedence to certain aspects over others, these frames are all embedded in the general master frame of environmental justice. The study's results show the strong national character of the discourse as well as the continued focus on command and control instruments, e.g., pointing toward the enforcement of existing regulations while anticipating the lively and creative debate of new governance mechanisms only to a minor degree. These results might indicate that the internationalization of the legality verification debate has only been taken up to a minor degree when discussing specific national problems like illegal logging in Brazil. The results can also be a reflection of the fact that most of the (illegally) harvested timber remains in the domestic market of Brazil [83].

Figure 61: Dominant, cross-cutting frames and elements of specific frames highlighted in the discourses on illegal selective logging of science, newspapers and NGOs/IOs [83]

FRAME ELEMENTS	Dominant cross-cutting Frame	Scientific Discourse	Newspaper Discourse	NGO/ IO Discourse
DRIVER	Weak governance/ enforcement	Insufficient monitoring		
RESPONSIBLE	Political actors & agencies/ large economic players		Jair Bolsonaro	(International) criminal networks
VICTIM	Forest/ environment/ local communities		Indigenous people	
SOLUTION	National governance	Technological fixes	Informal practices	IO's/ international governance

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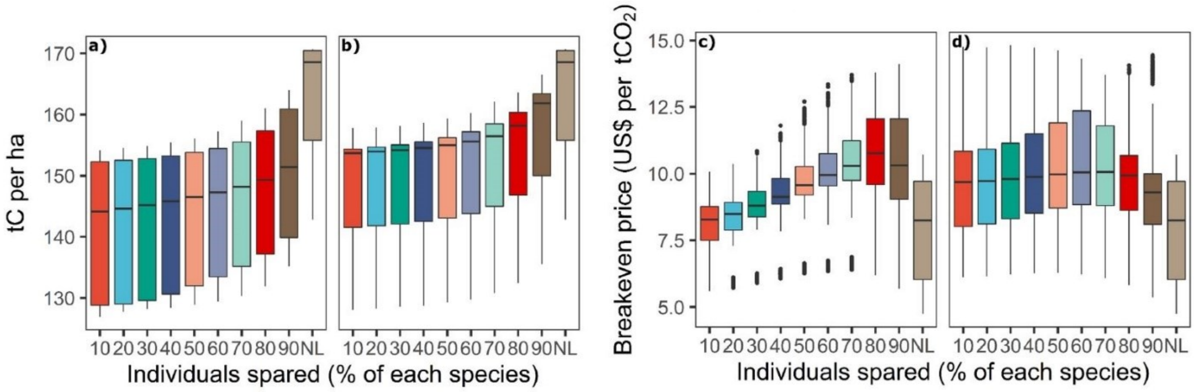
Carbon-based payment for ecosystem service schemes, including REDD+, give economic value to standing forests and can protect them from degradation, but only if the revenue from carbon payments is greater than the opportunity cost of forgone or reduced selective logging. There is a need to understand whether carbon payments are feasible for protecting Amazonian forests from selective logging, despite the Amazon holding the largest unexploited timber reserves and an expanding logging sector. Using financial data and inventories of >660,000 trees covering 52,000 ha of Brazilian forest concessions it is estimated that a carbon price of $7.90 per tCO_2 is sufficient to match the opportunity costs of all selective logging and fund protection of primary forest. Alternatively, improving the sustainability of logging operations by ensuring a greater proportion of trees left uncut requires only slightly higher investments of $7.97–10.45 per tCO_2. These prices fall well below the current compliance market rate and demonstrate a cost-effective opportunity to safeguard large tracts of the Amazon rainforest from further degradation [84].

Figure 62: Remaining carbon stocks (tC per hectare) (a, b) and breakeven carbon price (US$ per tCO2) (c,d) for different levels of forest protection, where logging is restricted to higher-value classes only (I or I and II) whilst sparing from harvest an increasing proportion (10–90%) of individuals from each species in these classes, averaged across the seven concessions examined [84]



Condé et al (2022) describe the different effects on the forest of conventional selective logging (CL) and selective logging operations with applied sustainable forest management (SFM). SFM has been continuously improved in tropical forests around the world through the adoption of sustainable technologies and practices, with reductions of forest degradation, biodiversity losses, and soil erosion. SFM has been practiced to some degree in the Brazilian Amazon since 1978. Currently, SFM programs have been facing questions regarding their true sustainability and the applicability of the legal criteria adopted in Brazilian Amazon related to the timing of cutting cycles (in years) for different species, selective logging intensity, minimum diameter cutting limits minimum cutting diameters, silvicultural treatments, control of remaining forest stocks, conservation versus extinction of forest species, specific volumetric equations, ecology and regeneration requirements, and the need for greater numbers of permanent plots and continuous monitoring of forest inventories that could validate and support current environmental legislation. However, due to wide variations in the effective application of SFM concepts as a result of political and market pressures (in terms of different approaches and techniques for forest harvesting, site specific cultures, and varying levels of access to tools and technologies), its policies and practices are being questioned in regards to their ability to ensure the true sustainability of global forest benefits. During conventional logging without SFM practices, on the other hand, the forest is selectively logged without prior planning of road construction, log storage yards, or vine cutting one to two years before initiating logging. In CL practices, the loggers choose and cut the greatest possible number of commercial trees per hectare, without worrying about ecological consequences, and with no concern about the damage resulting from opening roads or the fall damage from large commercial trees, thus generating significant forest degradation, high carbon emissions and soil erosion, and severe impacts on the structures of the remaining forests. As consequence, twenty years of post-logging monitoring in the Central Amazon supports the claim that where SFM practices are correctly applied, recovery rates for biomass and timber volumes are much faster than after CL, although climatic events and human pressure can alter natural recovery processes [85].

5.2.6 Roads

Three publications report on the BR-319 Highway from Porto Velho to Manaus and the consequences of its consolidation on the forest and the indigenous people[70].

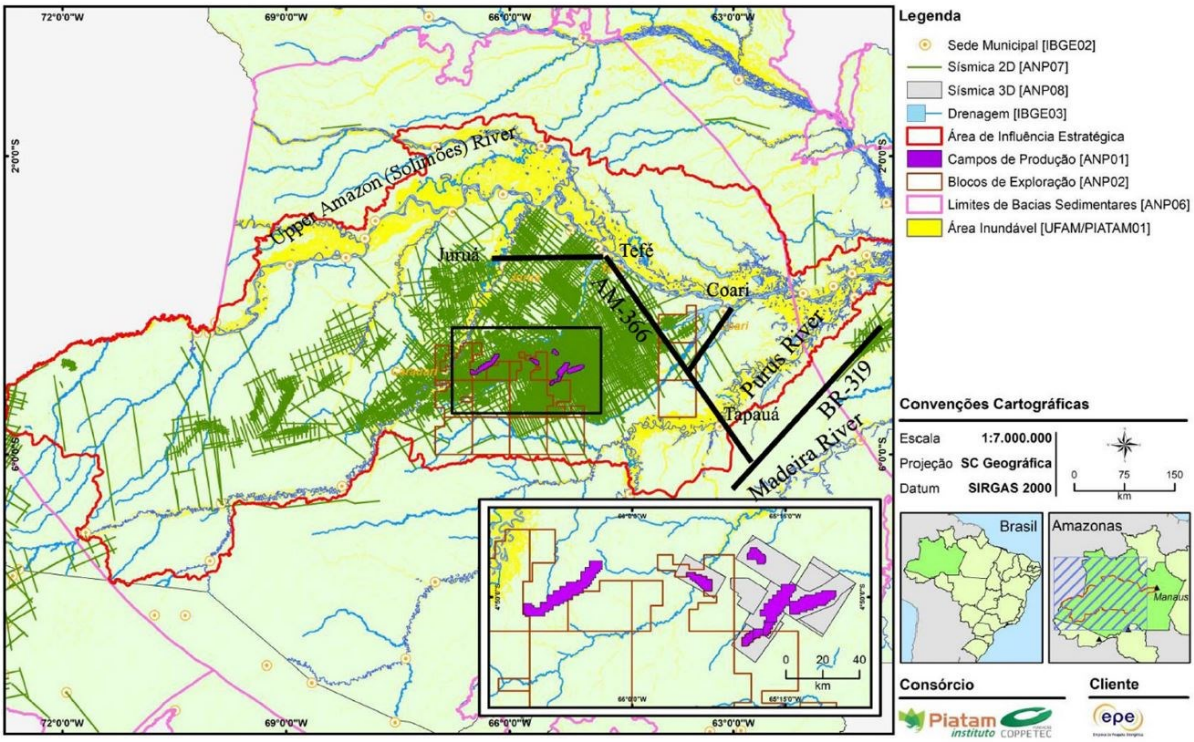
The BR-319 Highway was built in 1972/1973 and officially inaugurated in 1976, but the Ministry of Transport abandoned the road maintenance in 1988 due to its lack of economic viability. Today, the proposed reconstruction of BR-319 (i.e. the asphalting of the existing dirt road, which had been revived in 2015 to be viable in the dry season) is one of the Brazilian government's priority projects. The consolidation of the Highway would inevitably lead to the construction of secondary roads branching off from the main highway and, in consequence, to an estimated deforestation increase of over 1200% by 2100 as compared to the forest area that had been cleared by 2011. Along the existing dirt road of the BR-319 illegal selective logging occurs on a large scale, as well as illegal mining operations. The Highway BR-319 in its current state is already leading to forest degradation along its route and governance in the area is essentially non-existent. Under these circumstances, the reconstruction of BR-319 and the building of planned connecting roads would act as spearheads for deforestation and forest degradation in the western portion of the Brazilian Amazon. The proposed reconstruction project should not be approved until governance is in fact established both in the area along the highway route and in the other areas to which migration would flow [10].

A consolidated BR-319 would link one of the most conserved blocks in the Amazon forest to the "arc of deforestation" on the southern edge of the region, where most forest has already been destroyed. BR-319 and its planned side roads would allow the actors and processes from the arc of deforestation to move into vast areas of unprotected rainforest. In the specific case of this highway, a judicial decision that is not subject to further appeal established, that environmental studies for the first section of the highway to be reconstructed must be carried out before paving. However, the Brazilian Government wants to push the road paving ahead without environmental studies. Economically the BR-319 makes little sense, as the transport of goods on its course to and from São Paulo would be 19% more expensive that using the current system, i.e. the transport by ship from Manaus to Belém, further transport to São Paulo by road. Not coincidentally, the BR-319 reconstruction project is Brazil's only major infrastructure project that does not have an economic feasibility study [11].

One of the main concerns related to the consolidation (i.e. asphalting) of the BR-319 road is the construction of another major highway called AM-366, that would branch off from the BR-319 and run Northwest and West towards the towns of Tefé and Juruá (on the Solimões and Juruá rivers), which can currently only be reached via river transport. The strategic idea behind the plans to install the AM-366 is to be able reach the "Solimões Sedimentary Basin" oil and gas project, stretching from the Purus River to the Peruvian border, by road. The BR-319 and its planned side roads threaten a part of the Amazon that needs to be maintained in forest to generate the environmental services that this biologically diverse habitat provides to the local people, the wider Brazilian population, and the rest of the world [12].

[70] https://news.mongabay.com/2022/05/surge-in-deforestation-as-brazil-pushes-to-pave-a-forgotten-amazon-road/

Figure 63: Map of the planned "Solimões Sedimentary Basin" oil and gas project. The purple areas have wells currently in production. The thin green lines represent locations already surveyed by seismic methods for future drilling [12]

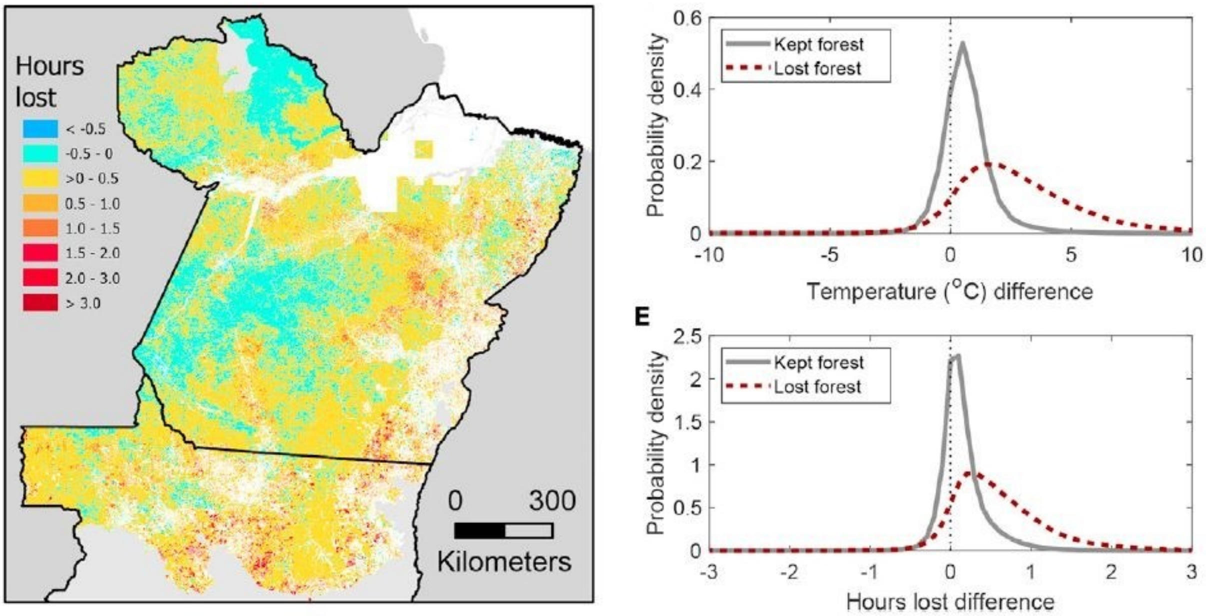


Terrestrial transportation infrastructure, such as roads and railroads, provoke diverse environmental impacts on ecosystems, including the flora and fauna that compose them. Policy and legislation rarely acknowledge the importance of keeping intact ecosystems road- and railroad-free. By modelling Brazil's remaining road-less and railroad-less (RLRL) areas it was found that, although they hold the vast majority of the country's remaining native vegetation (81.5%), because of their limited protection status, only 38% of Brazil's remaining native vegetation is both protected and in RLRL areas. Current Brazilian federal policy aims to develop transportation infrastructure designed with antiquated planning methods that threaten remaining intact ecosystems, while concurrently weakening the country's hallmark environmental protections and commitments. Where Brazil builds its new roads and railroads matters for conservation planning. The occurrence of native vegetation and anthropic land use is associated, at varying degrees, to transportation infrastructure throughout most of Brazil. By pursuing conservation opportunities in RLRL areas, Brazil could instead make impactful steps for conservation, restoration planning, and tangible progress toward achieving national and international environmental and conservation commitments [86].

5.2.7 Deforestation and health

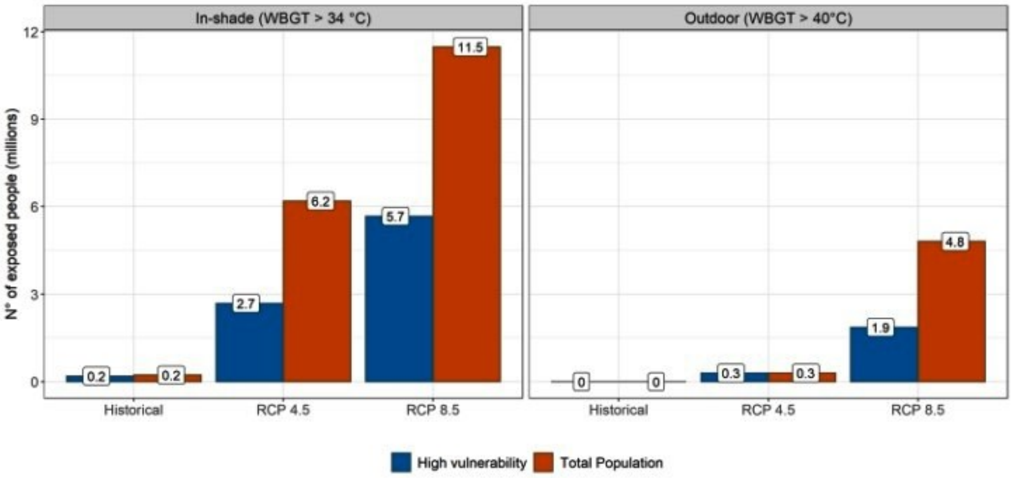
Climate change has increased heat exposure in many parts of the tropics, negatively impacting outdoor worker productivity and health. Although it is known that tropical deforestation is associated with local warming, the extent to which this additional heat exposure affects people across the tropics is unknown. In this modelling study, worker health guidelines are combined with satellite, reanalysis, and population data to investigate how warming associated with recent deforestation (2003–2018) affects outdoor working conditions across low-latitude countries, and how future global climate change will magnify heat exposure for people in deforested areas. Local warming from 15 years of deforestation was associated with losses in safe thermal working conditions for 2.8 million outdoor workers. We also show recent large-scale forest loss was associated with particularly large impacts on populations in the Brazilian states of Mato Grosso and Pará. Future global warming and additional forest loss will magnify these impacts [87].

Figure 64: Lost save work hours change (left) and distribution of temperature changes (upper right) and lost safe work hours difference (lower right) in the Brazilian states of Mato Grosso and Pará [87]



Global warming is causing heat stress conditions that are becoming more frequent and intense in many tropical and subtropical regions of the world. In 2020, the warmest September in history was recorded, with several locations in Europe and South America breaking record-high temperatures, while the high temperatures in Midwestern and Northern Brazil posed a risk for death by hyperthermia. The recent extreme heat exposure in Brazil occurred during a period marked by forest fires and growing deforestation rates in several biomes, especially in the Brazilian Amazon. The results of the Amazon Basin savannization simulations, which examined the worst-case scenario (i.e. the entire Amazon rainforest is replaced with savannah) revealed increased air temperatures and decreased relative humidity and precipitation, especially in the Amazon Basin. In outdoor environments, the most notable effects of savannization and climate change are on the threshold of survivability. In the context of human health impact, the combined effects of global climate change and Amazon rainforest savannization could represent an exposure of more than six to eleven million people (depending on the chosen scenario) to conditions of extreme risk to human health, if the current population in the Amazon was exposed to the projected heat stress distributions. The study reveals that the combined effects of Amazon savannization and climate change are significantly associated with threats to human health and well-being, emphasizing the urgent need for coordinated steps to avoid negative effects on vulnerable populations. The local effects of land-use changes are directly linked to forest sustainability policies and strategies, and changes in these areas are within society's reach. In these areas, the health sector could be an important avenue for proposing integrative policies to mitigate risk and vulnerability [88].

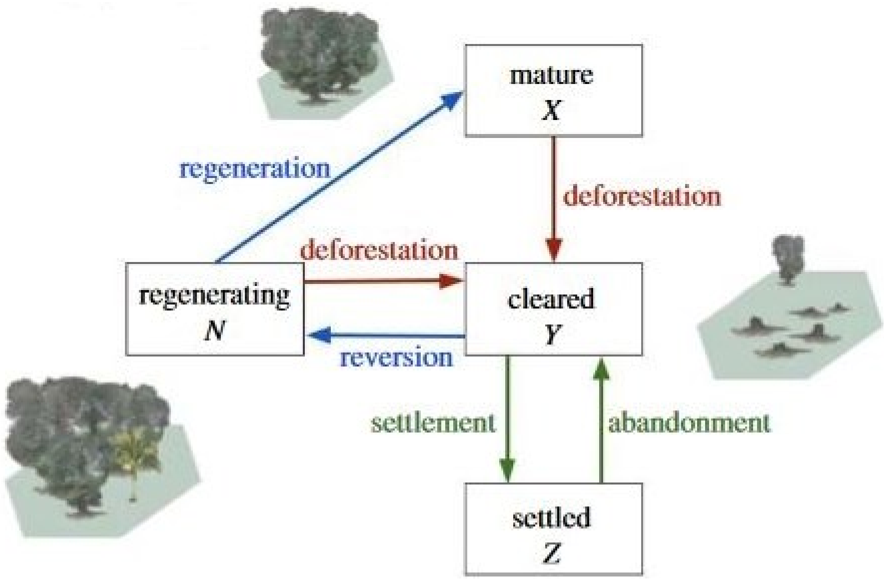
Figure 65: Combined effects of climate change and deforestation on the number of people under heat stress. Additional numbers of people exposed to heat stress above the extreme risk to human health thresholds due to Amazon rainforest deforestation, according to historical period (1980–2010) and global warming scenarios (2073–2100).



Deforestation in the Amazon is a problem of significant national and international environmental interest. There are emerging data on its potential impacts on the interaction dynamics between man, animal, environment and the transmission of infectious pathogenic agents. There are evidences that loss of biodiversity, along with the pollution, destruction, and fragmentation of forest habitats, as well as human intervention in the environment associated with poor sanitation and climate factors, may favour the emergence of numerous infectious diseases of humans, domestic and wild animals, such as leptospirosis. An aggravating factor is that these human populations usually share their peri-domestic and leisure environment eventually with wild animals, specifically in areas with fragmented forests. Moreover, most of the houses did not have fences or walls that could serve as physical barriers, which allowed the animals' free movement. The humans had a direct contact with these animals, possibly related to their limited knowledge about animals as an infection source. This agent may eventually have favoured human-animal-environment infection [89].

Deforestation alters wildlife communities and modifies human–wildlife interactions, often increasing zoonotic spillover potential. When deforested land reverts to forest, species composition differences between primary and regenerating (secondary) forest could alter spillover risk trajectory. The forest regeneration rate, the spillover risk of regenerating forest relative to deforested land, and how rapidly regenerating forest regains attributes of mature forest determine landscape-level spillover risk. Spillover events can occur following changes in human-wildlife contacts, wildlife community competence, and human behaviours, all of which are influenced by changes in the landscape. It is well understood that deforestation can increase spillover risk by altering wildlife communities and increasing human-pathogen contacts However, it remains unknown whether reforestation would then reduce spillover risk, and over what timescale. Land reversion was found to be able to influence short- and long-term spillover risk in opposing ways, depending on attributes of regenerating land (e.g. wildlife community composition) and the rates at which it is created or lost. However, transdisciplinary studies are urgently needed to quantify how sylvatic transmission, human-use and behaviour, and human–wildlife contacts differ between primary and secondary forest, in addition, more detailed studies are needed of how human behaviour results in pathogen exposure in these habitats, as well as the socio-economic drivers of the creation and loss of secondary forests [90].

Figure 66: Compartmental model describing the dynamics of land conversion and reversion. Each box represents a habitat type and arrows represent land transition processes. Red arrows represent the deforestation of mature or regenerating habitat to cleared land. Blue arrows represent the reversion of cleared land to regenerating forest, and subsequent regeneration to mature forest. Green arrows represent the creation or abandonment of settled habitat [90].



Bolton et al (2022) look at the relevance of forest cover for mental health of the population at country level on global scale. According to the authors, the percentage of forestry area in a country is negatively associated with the prevalence of mental health and substance abuse disorders in the same country. The association is maintained after adjusting for poverty, peace, country wealth and urbanization and was replicated in the sensitivity analysis after accounting for access to safe sanitation and food security in fewer countries. The association seems particularly strong on lower-and upper-middle income countries [91].

5.2.8 Mining

Five articles are showing and discussing the risk, scale and impact of mercury exposure to Munduruku indigenous people due to gold mining operations in or near rivers that provide water and nutrition to the indigenous tribe.

The Amazonian indigenous peoples depend on natural resources to live, but human activities' growing impacts threaten their health and livelihoods. The objectives were to present the principal results of an integrated and multidisciplinary analysis of the health parameters are presented and the mercury (Hg) exposure levels in indigenous populations in the Brazilian Amazon are assessed.

Basta et al (2001) [13] examined the socio-economic situation, daily activities, general health status and hair mercury levels of 35 households (with 200 persons) in three Munduruku villages.

De Bakker et al (2001) [14] analysed the economic impact on human health resulting from the use of mercury for illegal gold mining in Brazil, across the mercury release by the mining operation to water, soil and atmosphere, the daily mercury intake by fish to the increase levels of mercury in the hair of indigenous people.

De Vasconcellos et al (2001) [15] looked at the mercury pollution in fish and its consequences through fish consumption by indigenous people as their principal source of animal protein and thus ensuring their nutritional security. He concludes that the artisanal gold mining (also called garimpos) can be considered as one of the most harmful economic activities in the Amazon, because it would cause not only deforestation, river siltation, and soil erosion, but also would release large quantities of mercury into the environment.

Oliveira et al (2001) [16] examined the neurological impacts of chronical mercury (Hg) exposure in Munduruku indigenous adults, concluding that chronic exposure to methylmercury (MeHg), which is transformed from Hg to MeHg in the aquatic environment, can cause memory and learning deficits, motor function anomalies, hearing loss and reduced visual field, and in the extreme, to cellular dysfunction and death.

Kempton et al (2001) [17] examined specifically the methylmercury exposure of and its impact on young Munduruku women and children under 2 years of age. The findings of the study demonstrated that not only women of childbearing age but also their infants have been facing colossal public health challenges. These challenges are consequences of increasing illegal mining activities in their territory and due to historical abandonment by the Federal Government. Among the principal issues illustrated in this study, high levels of methylmercury exposure can be found, as well as stunting, anaemia, poverty, and food insecurity, as well as low vaccination coverage and high infant mortality rates.

Figure 67: Logical line for relating the existence of gold mining to human health outcomes [14].

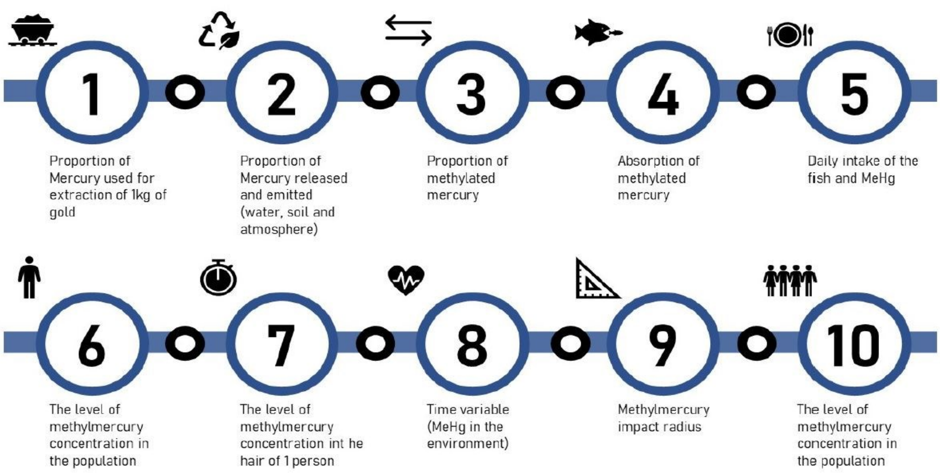


Figure 68: Linear regression between standard length (cm) of predator fish and the concentration of mercury total (µg/g) in the muscle tissue of the fish. The larger the fish, the higher the mercury levels in the fish muscle tissue [15]

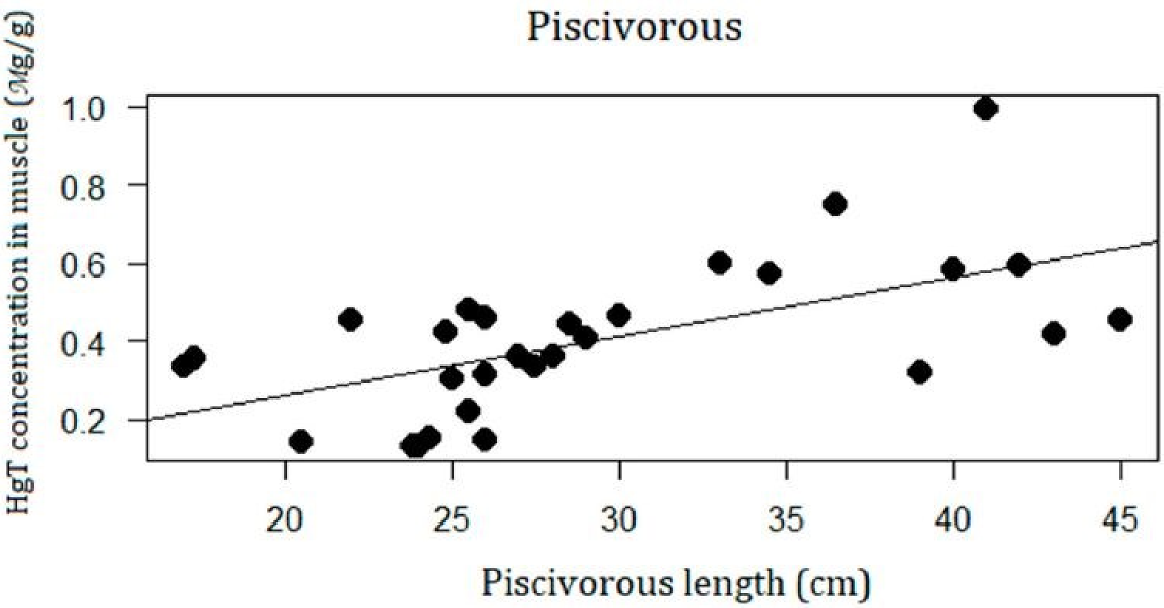
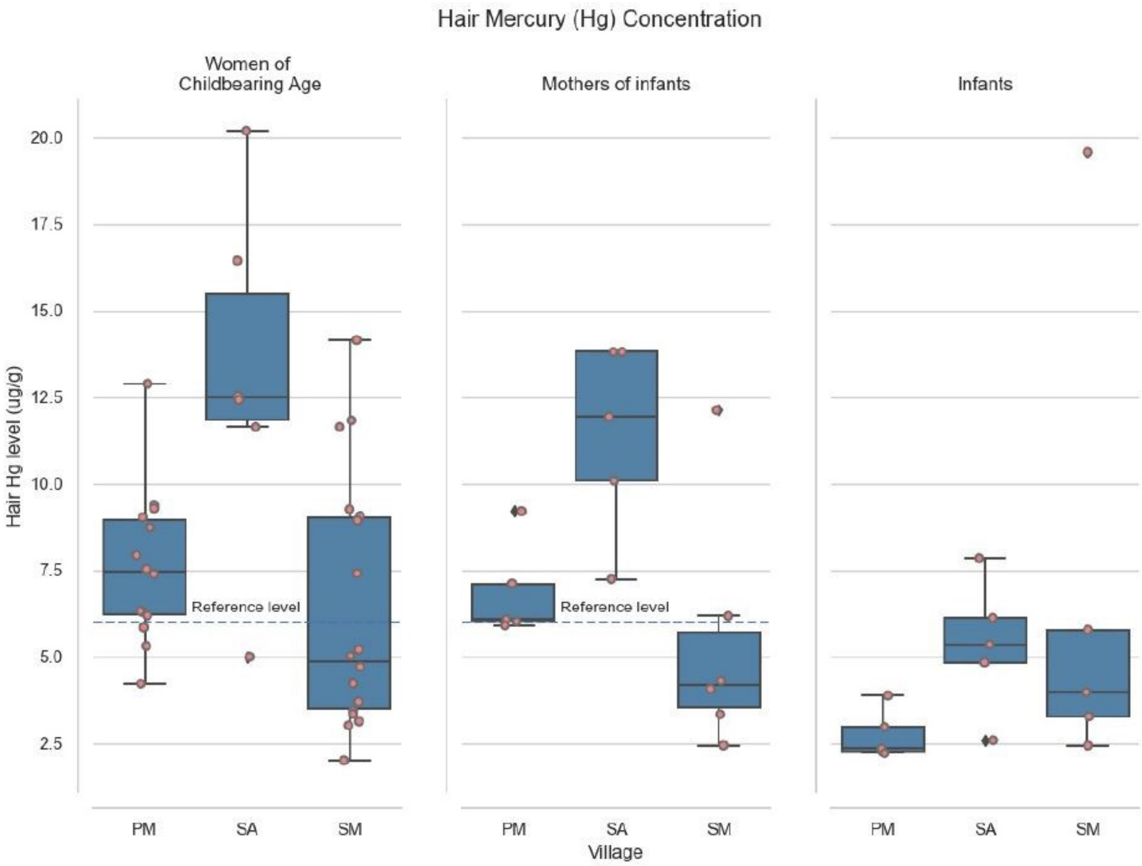


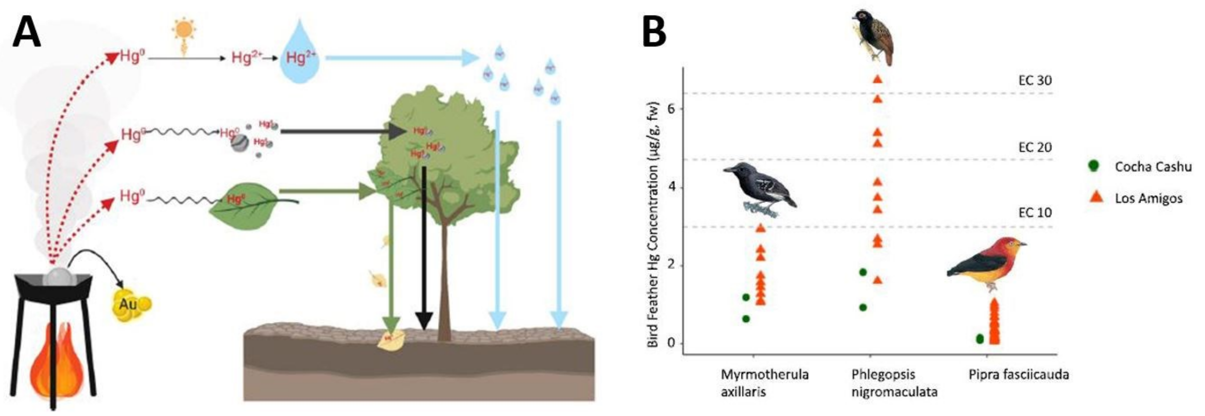
Figure 69: Methylmercury levels split by villages. PM corresponds to *Poxo Muybu* village; SA is *Sawré Aboy* and SM is *Sawré Muybu*. Sawré Muybu Indigenous Land, Pará State, Brazilian Amazon, 2019 [17]



Two publications examined the effects of artisanal small-scale gold mining (ASGM) in the Peruvian Amazon (Madre de Dios region).

According of Gerson et al (2022), gaseous mercury (GEM) – released into the atmosphere during the process of gold purification – is stored in Amazon forest and soil. ASGM activity in the Western Amazon has increased dramatically over the past decade and is expected to continue as gold prices remain high and with increased connectivity to urban centres via the Interoceanic Highway. While GEM concentrations in clearings tracked proximity to mining, total Hg concentrations in throughfall were dependent on both proximity to mining and forest canopy structure. The highest concentrations of mercury were measured in throughfall in the intact mature forest within the mining zone. The continued use of mercury in ASGM could have devastating impacts on wildlife inhabiting these forests. Even if miners eliminated the use of mercury immediately, this contaminant has a legacy in soils that can extend for centuries, with the potential for elevated losses associated with deforestation and forest fires. Mercury contamination from ASGM thus could have long lasting impacts on biota of intact forests near ASGM, with both the current risks and the potential for future contamination through mercury liberation and remobilization maximized in old growth forests with the highest conservation value [92].

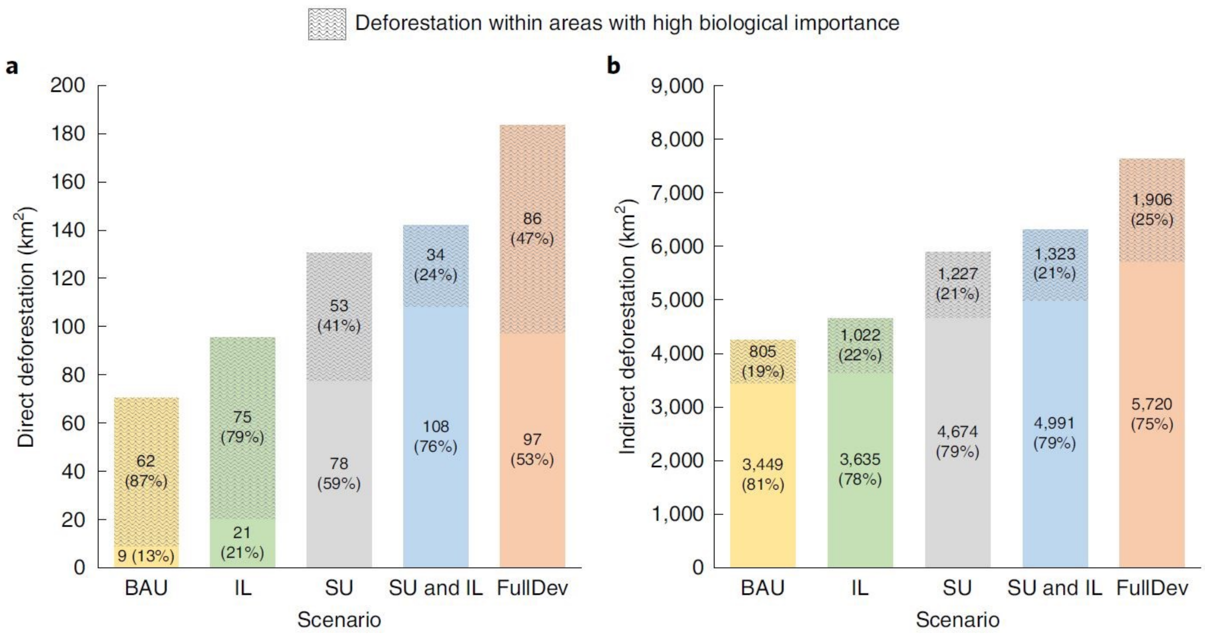
Figure 70: A: Deposition pathways for mercury in the environment in the process of burning a mercury (Hg)–gold (Au) amalgam. B: Total mercury concentrations in tail feathers of bird species in the Peruvian Amazon, the effective concentrations (EC) at which reproductive success is reduced by10, 20, and 30% are shown [92].



Koenigsmark et al (2021) looked at the effects of mercury released by mining operations on population hair mercury content in communities in the Peruvian Amazon (Madre de Dios region). Artisanal small-scale gold mining is a largely unregulated mining technique responsible for over 30% of anthropogenic mercury emissions to the atmosphere and involves the use of liquid elemental mercury, Hg(0)l, to amalgamate and separate gold from excavated soils. In general, population biomonitoring is needed to understand mercury exposure trends near gold mining activities [93].

Siqueira-Gay et al (2022) examine potential strategic planning as a way to mitigate mining impacts on protected areas in the Brazilian Amazon. Growing demand for minerals is increasing the pressure to open protected areas (PAs) for mining. The authors develop spatially explicit models to compare impacts among five policy scenarios to downgrade combinations of PA to allow mining in the Brazilian Amazon. They found downgrading (opening) the region's entire PAs network to develop an additional 242 mineral deposits would cause 183 km^2 of deforestation from mining in the Renca region (at the border between Amapá State and Northern Pará, Brazil), half of this in highly biodiverse regions. This scenario would also require 1,463 km of new roads that facilitate access to the region, causing indirect deforestation (estimated to be 40 times larger than direct mining clearing) and forest fragmentation. Downgrading fewer PAs would halve the impacts of mine expansion but require longer access roads per additional deposit mined to avoid crossing areas still protected. Promoting sustainable development while safeguarding biodiversity in mineral-rich regions requires strategic long-term planning that includes identifying no-go areas critical to conservation and designing policies to reduce infrastructure impact when providing access to new mining areas [94].

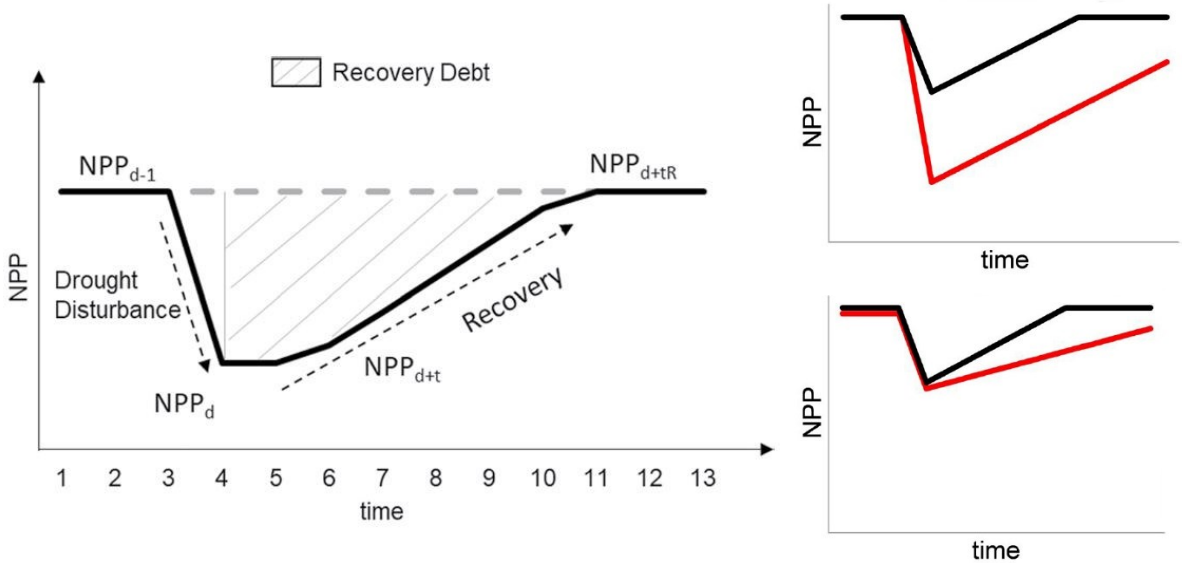
Figure 71: Direct and indirect deforestation and the proportion within areas with high biological importance. a, Direct deforestation—i.e. direct clearing of mining expansion. b, Indirect deforestation—i.e. clearing from other land uses, including roads, resulting from downgrading Protected Areas for mining. BAU = Business As Usual (current protection status), IL = Indigenous Lands, SU = Sustainable Use areas, FullDev = without any restrictions [94]



5.2.9 Forest restoration

Climate change has substantially increased the frequency of extreme droughts in the Amazon basin, generating concern about impacts on the world's largest tropical forest, which contributes about one-seventh of the global vegetation carbon sink. Most research to understand drought impacts has focused on the immediate influences of such events, neglecting post-drought effects on ecosystems recovery. The net primary production (NPP) in the Amazon basin was evaluated from 2003 to 2020, a period in which drought frequency was almost double the decadal incidence of the last century. The NPP does respond to the coupled impacts of individual droughts and the post-drought impacts during ecosystem recovery. In particular, the analysis reveals that the ecosystems undergoing recovery show NPP about 13% lower than reference values based on the pre-drought state or in areas undisturbed by drought. NPP deficits have consistently increased with the extreme droughts of 2005, 2010, and 2015 due to the combined effects of disturbances magnitude and the length of recovery. If the expected increase in drought frequency and intensity does occur, reduced recovery may lead the Amazon Forest to an alternative ecosystem state with lower carbon uptake, contributing to a warming global climate [95].

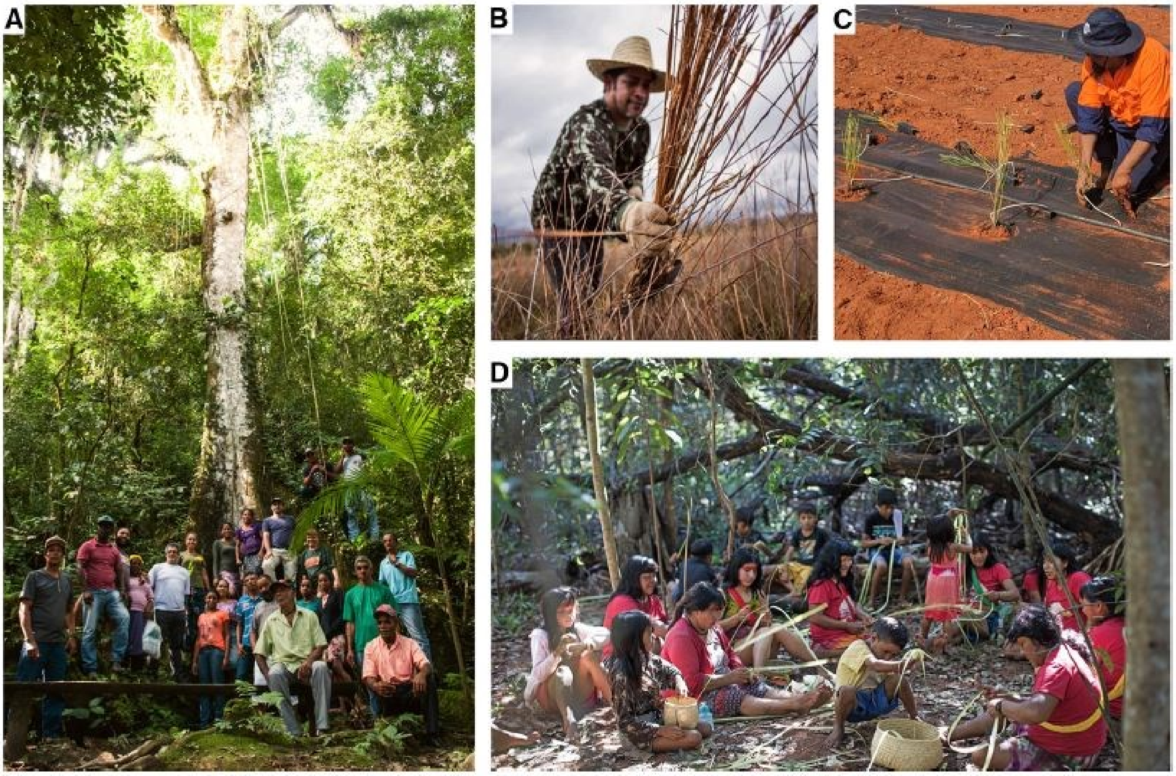
Figure 72: Left: Conceptual model of vegetation net primary productivity (NPP) shaped by dynamics of drought-disturbance and recovery. Hypothetical drought is in time 4 and drought disturbance is the NPP decline from time 3 (NPPd−1) to 4 (NPPd). The dashed grey line represents the reference NPP value existing in the pre-disturbance state (NPPd−1) or in another ecosystem with similar conditions that remained “undisturbed.” Resilience debt (dashed area) is the interim reduction of NPP occurring during ecosystem recovery from time 4 (NPPd) to 11 (NPPd + t). Right: Conceptual model of mechanisms for increasing recovery debts: increase in magnitude of disturbance (top right) and decrease in recovery rates (lower right) [95]



Amazonia is well known for its high natural regeneration capacity; for this reason, passive restoration is normally recommended for the recovery of its degraded forests. However, highly deforested landscapes in southern Amazonia require active restoration. Since restoration methods can shape the quality and speed of early forest recovery, this study aimed to verify how active restoration pushes sites stably covered with exotic grasses towards forest recovery (Vieira et al 2021). 36 active restoration and 31 natural regeneration sites were sampled along the Madeira River, southern Amazonia. Active restoration triggered succession to similar or higher levels of forest structure than sites where natural regeneration was taking place. The most dominant species did not overlap between active restoration and natural regeneration sites. The overall composition of species was different between the two restoration methods. Dominant species and size class distribution show that active restoration is performing successfully. Soil preparation combined with a high availability of seeds of pioneer trees resulted in a high stem density and basal area of facilitative pioneer trees. Planted seedlings added species diversity and increased density of large trees. Interventions to increase the odds of natural regeneration can be effective for non-regenerating sites in resilient landscapes [96].

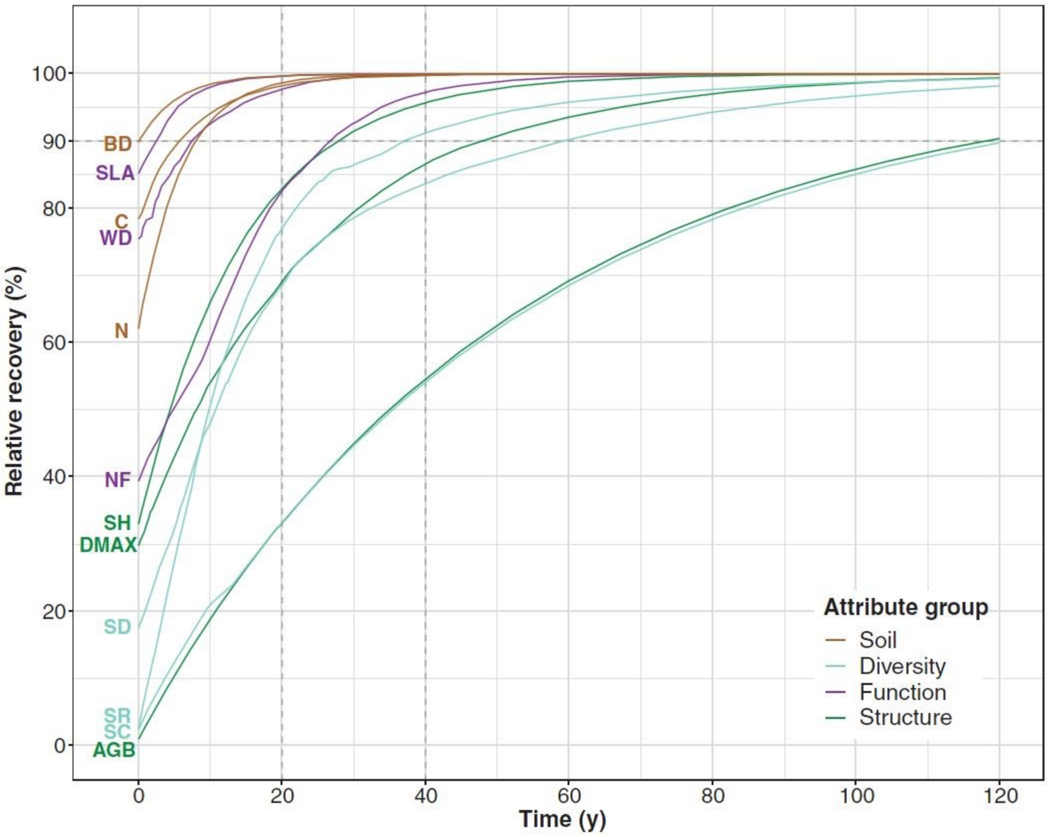
Uderzo et al (2021) propose to use the knowledge of indigenous and local communities to boost the seed supply for ecosystem restoration on global scale. Although local knowledge and engagement are considered key components to achieving successful projects, millions of Indigenous and local communities are commonly left behind in negotiations and planning of large-scale restoration programs across the globe. In order to avoid mere 'tree planting' as the surrogate for 'ecosystem restoration', where species are limited in diversity that focuses on a few, often non-native commercial varieties and where the supply chain is dominated by a few large companies, the authors suggest to improving the availability of diverse native seeds in restoration. While in key restoration markets in Australia and Brazil, for instance, plant material markets are dominated by private companies which create few jobs, poor community engagement with few opportunities for enduring local livelihoods, multilevel restoration policies and financial incentives now need to consider alternative approaches to promote recognition and inclusion of local communities, so that grassroots actions address ongoing social and environmental crises [97].

Figure 73: Community-based native seed supply activities: A: community workshop with seed collectors and practitioners in Vale do Ribeira, Brazil's Atlantic Forest (Claudio Tavares/ISA), B: Native seed grass collection in the Neotropical Savanna of the Central-West region of Brazil (Tui Anandi), C: Installation of an Indigenous owned and operated native seed farm in Morawa, Western Australia (Simone Pedrini), D: Yarang women's movement processing native seed in the Xingu Indigenous Territory, Brazilian Amazon (Carol Quintanilha/ISA) [97]



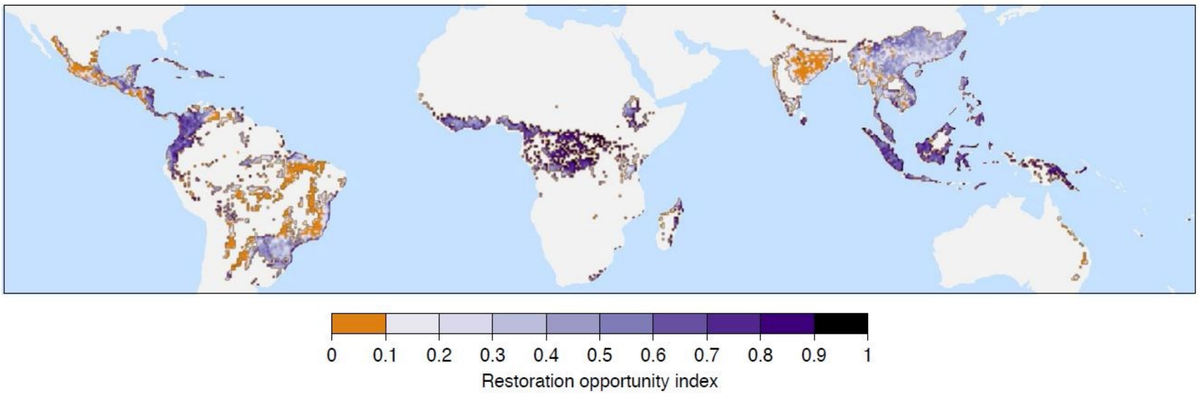
Tropical forests are converted at alarming rates to other land uses, yet they also have the potential to regrow naturally on abandoned agricultural fields and pastures. Widespread land abandonment because of fertility loss, migration, or alternative livelihood options has led to a rapid increase in the extent of regrowing forests. Currently, regrowth covers as much as 28% (2.4 million km^2) of the neo-tropics alone. Regrowing secondary forests (SFs) form a large and important component of human modified tropical landscapes and have the potential to play a key role in biodiversity conservation, climate change mitigation, and landscape restoration. The resilience of 12 forest attributes to recover from agriculture and pasture use. Resilience is the ability of a system to absorb disturbances and return to its previous state. Resilience is driven by two underlying components: the ability to resist disturbance and the ability to recover after disturbance. "Resistance" is the difference between the value of the forest attribute at the start of succession and the average old-growth forest values, which reflects the combined legacies of previous forest and previous land use, and "recovery" as the ability to return to old-growth attribute values after succession. Succession is defined as a change in vegetation structure, species composition, and ecosystem functioning over time after a disturbance. Tropical forests and their soils are highly resilient because all attributes recover within 12 decades after low- to moderate-intensity land use. Recovery of soil attributes (<1 decade) and plant functional attributes (<2.5 decades) is very fast, followed by recovery of structure and diversity (2.5 to 6 decades), and recovery of aboveground biomass and species composition is slowest (12 decades) [98].

Figure 74: Predicted relative recovery trajectories over time for 12 forest attributes. The attributes are related to soil (brown), plant functioning (purple), structure (green), and diversity (turquoise). Relative recovery is expressed for each attribute as the similarity (in percentage) between the predicted age dependent secondary forest value and the old-growth forest value. BD = Bulk Density, C = soil Carbon, N = soil Nitrogen, SLA = specific leaf area (leaf area / leaf mass), WD = wood density, NF = basal area of nitrogen-fixing species, AGB = aboveground biomass, SH = structural heterogeneity, DMAX = maximum tree size, SD = species diversity, SC = species composition, SR = species richness [98]



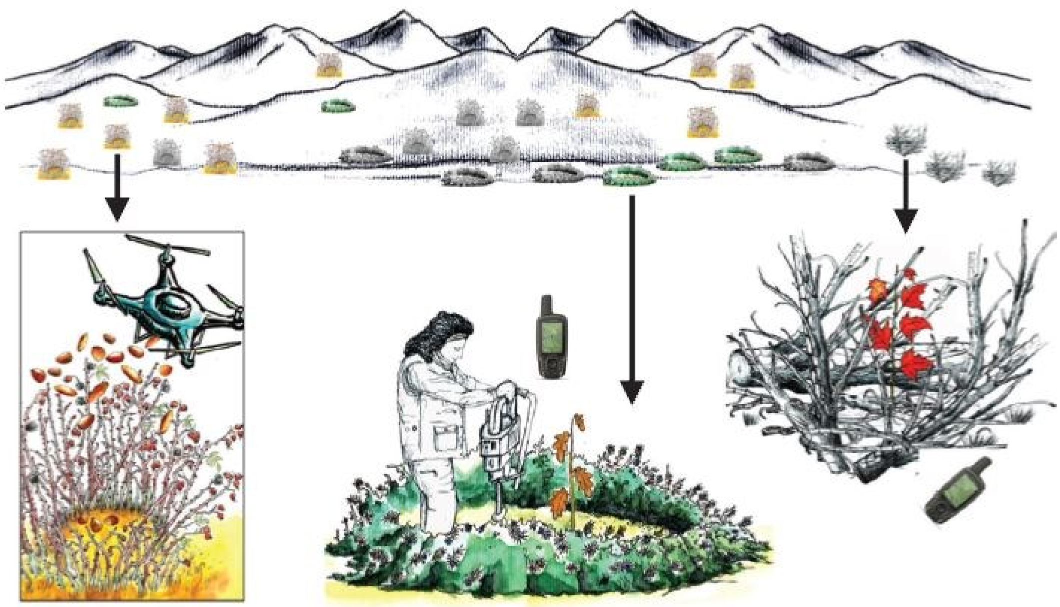
One of the most promising ways to rapidly remove CO_2 from the atmosphere is through the restoration of tropical forests. Ongoing and future climate change may threaten the permanence of carbon stored through restoration. Excessive heat, drought or increased disturbances such as wildfire could all negatively impact the integrity of restored carbon. 221 simulations were performed with a dynamic global vegetation model (LPJ-LMfire), in order to investigate risks to tropical forest restoration, driven by a range of future climate scenarios and eco-physiological responses to CO_2 concentrations. We show that carbon in restored tropical forests is largely preserved under the entire range of potential future climates, regardless of assumptions about the potential for CO_2 fertilization of photosynthesis. Restoring even half of the potential area can account for 56–69% of the carbon storage, depending on whether areas are selected for low cost or high carbon gain [99].

Figure 75: The restoration opportunity index indicates which restoration areas have the most cost-effective long-term (2020–2100) carbon storage potential for all climate change scenarios without additional CO2 fertilization. It is calculated using the rank sum of carbon and opportunity cost, masked to grid cells with a gain in above- and below-ground carbon over 2030–2100, and stable above- and below-ground carbon storage with no reductions in carbon of more than 10% of the de-trended long-term (2030–2100) mean [99]



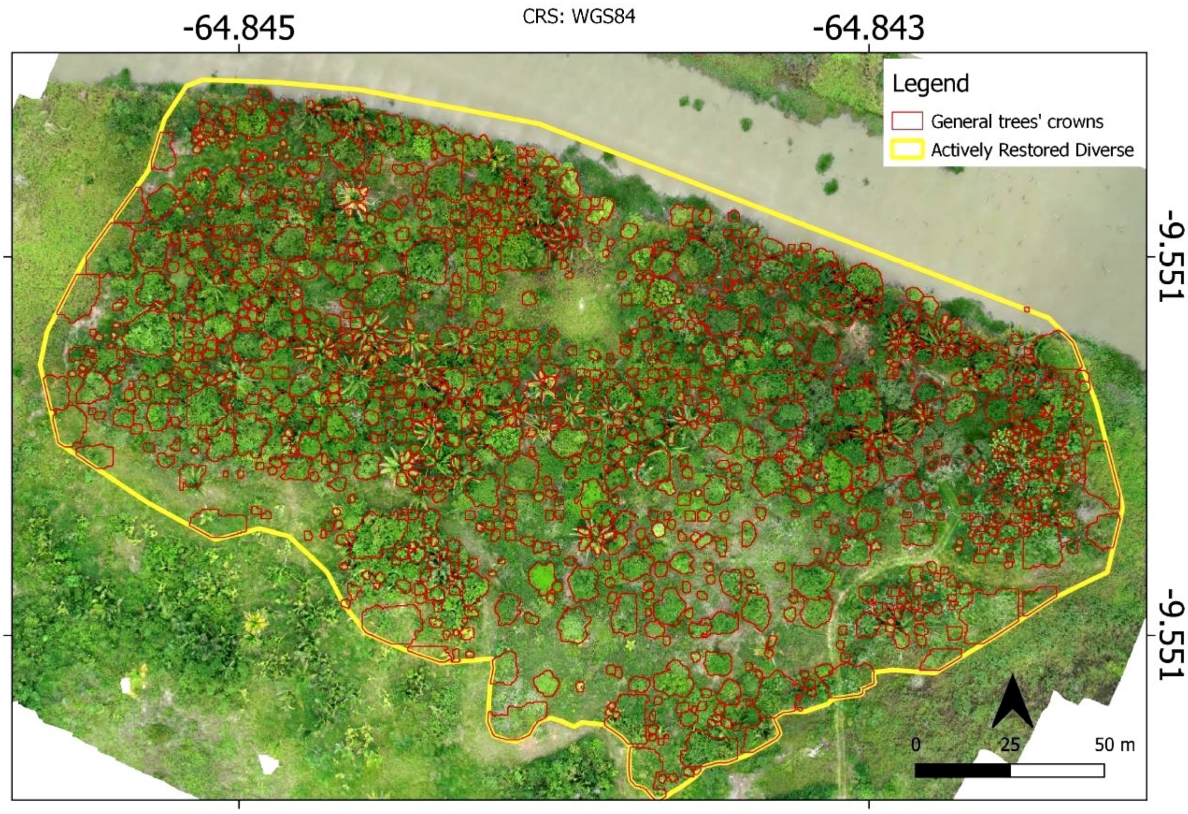
Forest restoration is currently a primary objective in environmental management policies at a global scale, to the extent that impressive initiatives and commitments have been launched to plant billions of trees. However, resources are limited and the success of any restoration effort should be maximized. Thus, restoration programs should seek to guarantee that what is planted today will become an adult tree in the future. There is a need to focus restoration efforts on an individual plant level to increase establishment success while reducing negative side effects by using an approach called "precision forest restoration" (PFR). The objective of PFR will be to ensure that planted seedlings or sowed seeds will become adult trees with the appropriate landscape configuration to create functional and self-regulating forest ecosystems while reducing the negative impacts of traditional massive reforestation actions. PFR can take advantage of ecological knowledge together with technologies and methodologies from the landscape scale to the individual- plant scale, and from the more traditional, low-tech approaches to the latest high-tech ones. PFR may be more expensive at the level of individual plants, but will be more cost-effective in the long term if it allows for the creation of resilient forests able to provide multiple ecosystem services [100].

Figure 76: Performing precise restoration tasks, e.g. instructed workers or sowing drones to place propagules in the centre of the selected spiny shrubs and biological legacies as dead or burnt piles of branches [100]



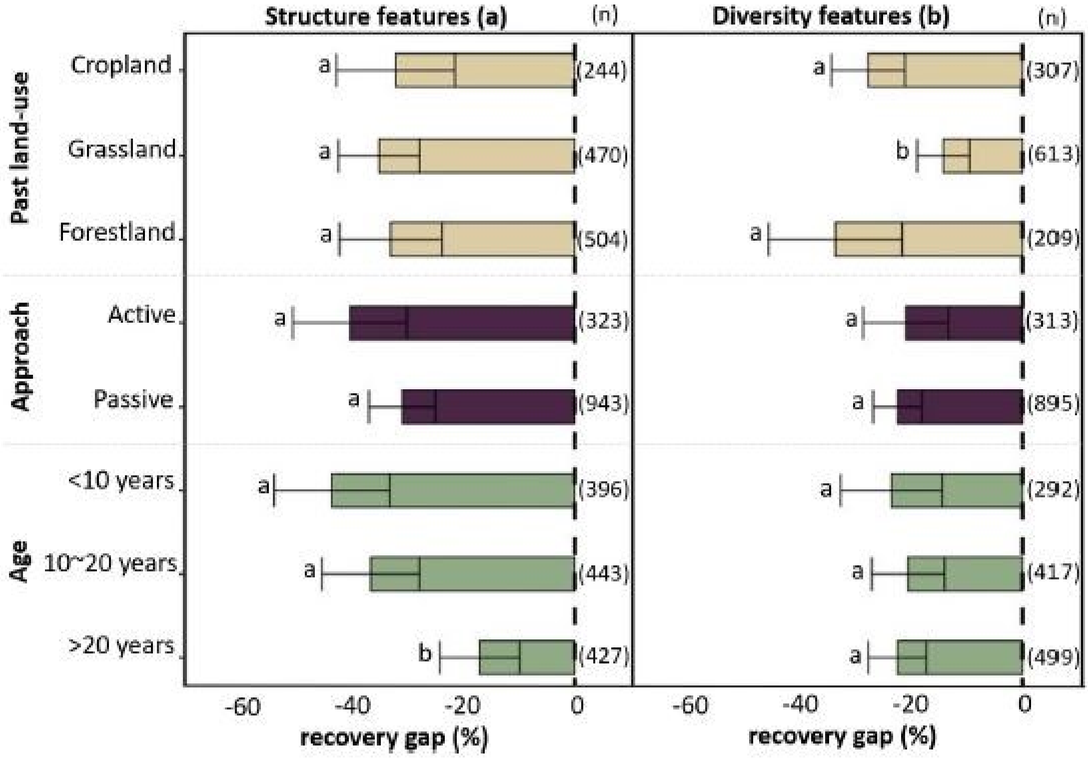
Monitoring the vegetation structure and species composition of forest restoration in the Brazilian Amazon is critical to ensuring its long-term benefits. Since remotely piloted aircrafts (RPAs) associated with deep learning are becoming powerful tools for vegetation monitoring, this study aims to use deep learning to automatically map individual crowns of Vismia (low resilience recovery indicator), Cecropia (fast recovery indicator), and tree crowns in general. Since tree crowns can be accurately mapped, a tree crown heterogeneity index is proposed, which estimates species diversity based on: the heterogeneity attributes/parameters from the RPA image; and the Shannon index measured by traditional fieldwork. The results show that low-cost RPAs have great potential for monitoring forest restoration quality in the Amazon, because Vismia, Cecropia, and tree crowns in general can be automatically mapped. Moreover, the preliminary results of the tree crown heterogeneity index showed high potential in estimating species diversity [101].

Figure 77: automatic RPA tree crown mapping in an actively restored forest site [101]



The UN Decade on Ecosystem Restoration is focussing attention and resources on restoration globally. This is specifically crucial in tropical forests that harbour immense biodiversity, but have also undergone widespread deforestation over the past few decades. A meta-analysis was performed to investigate how biodiversity features respond to forest restoration across the Brazilian Atlantic Forest, one of the most threatened biodiversity hotspots in the world. Different biodiversity metrics of structure and diversity features were assembled of three taxonomic groups (vascular plants, soil microorganisms, and invertebrates), generating a dataset with 2370 observations from 76 primary studies. The incomplete recovery of biodiversity (i.e., the rate of recovery to a pre-disturbance state) was, quantified, occurring during the restoration process, the so-called 'recovery gap'. The results of the study revealed that forests undergoing restoration in the BAF show a recovery gap of 34% for structure features and 22% for diversity features in comparison to reference reforests, considering all taxonomic groups investigated. For vascular plants, soil microorganisms, and invertebrates the recovery gap ranged between 46 and 47%, 16–26%, and 4–7%, respectively. Overall, the recovery gap was influenced by the interaction of restoration actions (i.e., the past land use, restoration age and restoration approach, i.e. active and passive restoration), however, structure features responded more sensitively to the time elapsed since restoration started, while the recovery gap for diversity features depended more on the past land-use [102].

Figure 78: Effects of Brazilian Atlantic Forest restoration actions (past land use/cover types, restoration approaches, and restoration age groups) on recovery gaps percentages in the comparison restoration vs. reference. Bars represent recovery gap percentages and the number of observations is shown in parentheses. Whiskers extending from the bars denote bias-corrected 95% confidence intervals [102]



Forest restoration has attracted the attention of different organizations, investors, and donors with the launch of the UN Decade for Ecosystems Restoration (2021–2030), along with climate and biodiversity commitments. Restoration can address many of mankind's challenges, such as biodiversity loss, climate change, water security, and poverty. In the Brazilian Amazon, the ~28 million inhabitants are among the most vulnerable of the country, and this has only worsened during the COVID-19 pandemic. Meanwhile, millions of hectares are suitable for forest restoration. The growing demand for large-scale forest restoration projects have been prioritizing biophysical objectives (e.g., number of trees, hectares of land, and carbon) while it should be prioritizing the local people's well-being and a fair transition to a sustainable economy based on forest services' recovery. Amazonian states need to control illegality, enforce the existing policies and promote innovative ones to halt deforestation and enable large-scale restoration. Better governance and social engagement are urgently needed but depend upon, recognition of indigenous peoples and local communities' rights, needs, and knowledge. Forest restoration represents an opportunity for the emergence of a more inclusive development paradigm, much needed in the Amazon region, especially in the post COVID-19 world. Forest restoration, as a key element of a broader conservation strategy, is needed to avoid the Amazon collapse tipping point. More than 10 million hectares have been identified as restoration hotspots, where feasibility and benefits are maximized. However, area availability for restoration in the Amazon may be even greater considering the degraded forests that occupy a high proportion in the region. The high potential for natural succession (passive restoration) – considered the most cost-effective method - is a huge opportunity for large-scale restoration projects in the Amazon. Under appropriate conditions, natural regeneration can efficiently promote the restoration of forests and ecosystem services, such as hydrological cycles, local climate regulation, and biodiversity, while active restoration strategies, like tree planting and direct seeding, are required in very degraded landscapes. In both cases, the restoration of ecosystem services along with its economic benefits have a great potential to promote a fair recovery [103].

Protected areas (Conservation Units of Restricted and Sustainable Use – CURU / CUSU), Indigenous Lands (IL) and Quilombo Territories (QT) have shown to play important role in biodiversity conservation in the Brazilian Amazon. These areas do not only reduce deforestation, but contribute significantly to native vegetation regrowth. Diverse governance regimes thus have important contributions to biodiversity conservation, being equal to or even more effective than formal protected areas both in avoiding native vegetation conversion and in promoting forest regrowth. IL and CURU have a higher contribution to curbing native vegetation conversion, but QT and CUSU are also effective in doing so. Regarding native vegetation regrowth, IL, followed by QT and CURU, promoted the higher proportional amount of forest recovery. The high and consistent performance of ILs in avoiding conversion corroborates similar findings from Peru, Bolivia, and Colombia as well as earlier studies in the Brazilian Amazon, particularly within a high-threat agricultural frontier. The mechanisms through which these areas promote positive conservation outcomes, nevertheless, might vary according to different management systems, governances and cosmologies. Different approaches will lead to distinct relations between societies and their territories and promote diverse degrees of biodiversity conservation. Further, the time of creation of each conservation area might also interfere. Some assisted and active forest restoration initiatives are known in and outside Indigenous Lands. Indigenous Peoples in Latin America have been collecting and managing seeds for different purposes and a network of seed programmes are being established to support management of seeds for forest restoration. Even though Quilombo Territories are generally small areas scattered in the territory, they are of considerable efficiency and importance for forest protection and regrowth. The QTs evaluated in this study are the ones formally registered within the Government: however, there are thousands of other QTs still to be registered. In this context, it is important to consider the overall role in conservation systems of relatively small but numerous areas across landscapes and how they can be better recognized and supported by being identified as “other effective area-based conservation measures” [104].

Jakovac et al (2022) examine the floristic composition of early successional forests. While acknowledging the importance of secondary forests for restoring biodiversity and ecosystem services the authors ask if forest regrowth can also preserve the distinct regional tree floras. Using the floristic composition of 1215 early successional forests (≤20 years) in 75 human-modified landscapes across the Neotropic realm, they identified 14 distinct floristic groups. Floristic groups were associated with location, bioregions, soil pH, temperature seasonality, and water availability. Hence, there is large continental-scale variation in the species composition of early successional forests, which is mainly associated with biogeographic and environmental factors, but not with human disturbance indicators. This floristic distinctiveness is partially driven by regionally restricted species belonging to widespread genera. Early secondary forests contribute therefore to restoring and conserving the distinctiveness of bioregions across the Neotropical realm, and forest restoration initiatives should use local species to assure that these distinct floras are maintained. The study’s results indicate that forests that regrow naturally on abandoned agricultural fields can contribute to the restoration and conservation of distinct Neotropical bioregions. Active restoration projects that plant or favour species outside their natural ranges can reduce these broad-scale diversity patterns and contribute to homogenization. The distinctiveness of bioregions should be considered when defining target species in restoration programs. Guaranteeing the regeneration of locally restricted species (especially from these diverse and widespread genera) is therefore crucial for conserving the broad-scale diversity of Neotropical flora. The analysis has shown that soil pH, temperature and climatic water availability are strong determinants of species composition of secondary forests. As land use modifies soil conditions and climate change leads to a global increase in temperature and larger variation in water availability, global changes may induce shifts in species composition, potentially reducing floristic distinctiveness across the continents. Since young secondary forests represent the first step in forest succession and regeneration, this may have large consequences for the functioning of future old-growth forests, potentially leading to biotic homogenization and loss of biodiversity and forest resilience [105].

Piffer et al (2022) look at the persistence of regenerated forest in the Brazilian Atlantic Forest. Even if the region's land cover change dynamics are different from the Amazon forest, lessons can be learned regarding the potentially favourable conditions, the general public and specific conservation policies that promote persistent forest regeneration. The authors used 35 years of detailed land cover maps to quantify forest regeneration and study the drivers of regenerated forest persistence and longevity in the Brazilian Atlantic Forest. Over 4.47 Mha of native forest were mapped, that regenerated in the region between 1985 and 2019, of which two thirds persisted until 2019 (3.1 Mha). The mean age of ephemeral (i.e. cleared before 2019) forest regeneration was only 7.9 years, suggesting a rapid turnover of re-growing forests. Regenerated forests had greater longevity and probability of persistence in steeper slopes, close to rivers and existing forests, near permanent agriculture, and in areas with higher Gross Development Product and agricultural yield, but were less likely to persist in areas with higher rural-urban population ratios. Regeneration occurred predominantly in pasturelands and areas of shifting agriculture, but it was also less likely to persist within these dynamic landscapes. Specific public policies should stimulate forest regeneration in areas of consolidated agriculture, where forest permanence tends to be higher. Second-growth forests in the AF are persisting longer and at higher rates when compared to other regions in Latin America. For example, 38% of mapped regeneration in the Brazilian Amazon and 50% in Costa Rica survived within 35 years, while about 70% persisted in the Brazilian Atlantic Forest within the same period. Furthermore, only 13.5% of the regeneration that persisted until 2019 was younger than five years of age, while very young forests ($\leqslant$5 years) accounted for about 44% of the second-growth forests in the Brazilian Amazon and almost 60% in a Peruvian Amazon region [106].

The new study of Brancalion et al (2022) aims to understand and quantify the job creation potential that lies in Brazilian ecosystem restoration. The authors estimate that restoration activities can generate 0.42 jobs per hectare undergoing restoration, which could potentially create 1.0–2.5 million direct jobs through the implementation of Brazil's target of restoring 12 million hectares – the number being associated with the National Plan for Native Vegetation Recovery, the national pledge to the Bonn Challenge and the Nationally Determined Contribution to the Paris Climate Agreement. The study demonstrates that ecosystem restoration is an emerging economic activity with relevant potential to generate jobs, especially through local organizations. In Brazil, this potential mostly has been leveraged by the financial capacity of states to pay for restoration activities, which highlight the critical role of financial incentives, appropriate policies, and the development of markets for restoration goods and services to create new jobs, especially in less economically developed regions. Successful restoration have a funding commitment longer than 1–2 years and restoration funding, particularly from national and international players, should be expanded and more equitably distributed across regions and biomes [107].

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List of abbreviations and definitions

AGB	Aboveground Biomass
ANVISA	Brazilian Health Regulatory Agency
ASGM	Artisanal Small-scale Gold Mining
BLA	Brazilian Legal Amazon
CI	Confidence Interval
CL	Conventional Selective Logging
COVID-19	Corona Virus Disease 2019
CURU	Conservation Unit of Restricted Use
CUSU	Conservation Unit of Sustainable Use
DETER	Brazilian alert system for deforestation and forest degradation in the Amazonas biome
ES	Ecosystem Services
GAUL	Global Administrative Unit Layer
GFC	Global Forest Change
GWIS	Global Wildfire Information System
IBAMA	Brazilian National Institute for Environment and Renewable Natural Resources
IL	Indigenous Lands
IMAZON	Institute of the People and the Environment of the Amazon
INPE	Brazilian National Space Research Institute
IO	International Organisation
IT	Indigenous Territories
IUCN	International Union for Conservation of Nature
JRC	Joint Research Centre of the European Commission
NDC	Nationally Determined Contribution
NGO	Non-Governmental Organisation
NPP	Net Primary Production
OGD	Old-Growth Deforestation
PA	Protected Areas
PFR	Precision Forest Restoration
PL	Brazilian Law Proposal
PRODES	Brazilian program for monitoring deforestation in the Amazonas and Cerrado biomes
QT	Quilombo Territory
RLRL	Road-less and Railroad-less
SAD	IMAZON's Deforestation Alert System
SFM	Sustainable Forest Management
SFR	Secondary Forest Regrowth
TLS	Terrestrial Laser-Scanning

TMF	Tropical Moist Forest Project at the JRC
UN	United Nations
ZD	Zoonotic Disease

List of figures

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