Amazon Deforestation:
Drivers, damages, and policies

Alipio Ferreira*

July 25, 2024

Abstract

This review discusses the economic drivers, the environmental damages, and the policies enacted to fight Amazon deforestation. It provides key statistics about conservation in the nine Amazon countries, and discusses the underlying causes leading to forest destruction in the region. Economic exploitation of the forest generates profits, but forest destruction creates harms on global, regional, and local levels. The global harm is the impact of greenhouse gas emissions on climate change. Regional damage is due to the impact of deforestation on rainfall, and the impact of forest fires on air pollution. On a local level, deforestation destroys ecosystem services, and mining activities pollute water bodies. The chapter proposes a typology of conservation policies: bans on deforestation, financial incentives, land tenure regulations, market access, sustainable practices, and indirect instruments. It discusses examples of policies and reviews impact evaluations.

---

*alipioferreira@smu.edu, Southern Methodist University. I thank Maria Florencia Buccari, Ricardo Estrada, Carlos Federico Juncosa, and Dan Millimet for their support and feedback. I also thank the audiences at the CAF Environmental Workshop in August 2022 in Buenos Aires and at the 2022 LACEA-LAMES Annual Meeting in Lima for their comments. This paper received the financial support of the Corporación Andina de Fomento (CAF).

1 Introduction

The Amazon Rainforest sprawls over 6.7 million square kilometers in nine countries of South America. The forest is home to the biodiversity hotspot Yasuní National Park in Ecuador, the Autana Mountain in Venezuela, and the Amazon River, which flows from Peru to the Atlantic Ocean in Brazil. In addition, the forest is the source of culture and pride for millions of people, particularly the hundreds of indigenous tribes that have inhabited it for centuries. Besides biodiversity, natural beauty, water, and culture, the Amazon Forest also contains valuable resources whose exploitation leads to deforestation. The adverse effects of deforestation are felt locally, regionally, and even globally. This paper discusses the economic drivers, environmental damages, and conservation policies related to Amazon deforestation.

Since the 1970s, Brazilian agriculture has advanced rapidly into the Amazon Forest, first converting forest into soy crops and, more recently, into pasture for cattle grazing. In Bolivia, Colombia, and Peru, deforestation is also connected to coca crops and the drug industry. However, deforestation in these countries has not achieved the scale it has in Brazil. Despite policies trying to prevent farmers from destroying the forest, regulatory compliance remains low. Unclear property rights, understaffed enforcement agencies, and cumbersome judicial systems hinder law enforcement. Section 2 of this chapter discusses the economics of Amazon deforestation, particularly in Brazil, and the theoretical solutions that economists have proposed to this problem.

The Amazon Rainforest hosts the richest biodiversity in all of Earth's biomes, regulates the rain seasons in the region, and holds an enormous stock of carbon. Therefore, the destruction of the forest creates imbalances in the biome's ecosystems, affects regional rainfall precipitation, and generates greenhouse gas emissions. In addition, using fires for deforestation creates air pollution, and chemicals used in mining pollute the water with heavy metals. Section 3 discusses these adverse effects and summarizes the scientific literature measuring them.

This review contributes to the literature on deforestation by organizing results from economics that are relevant to the context of the Amazon forest. Balboni et al. (2023) provide reviews of deforestation more generally, and Busch and Ferretti-Gallon (2017) propose a meta-analysis of results of forest conservation policies. However, the size of the Amazon forest (the world's largest rainforest) and its institutional settings warrant a specific review of studies focused on this biome.

Section 4 presents the historical experience with conservation policy with a focus on the Brazilian Amazon forest. Besides enforcement efforts, infrastructure, commodity prices, and industrial practices contribute to deforestation rates. Finally, section 5 concludes by proposing some ways forward in terms of new policy instruments.

2 The economic drivers of Amazon deforestation

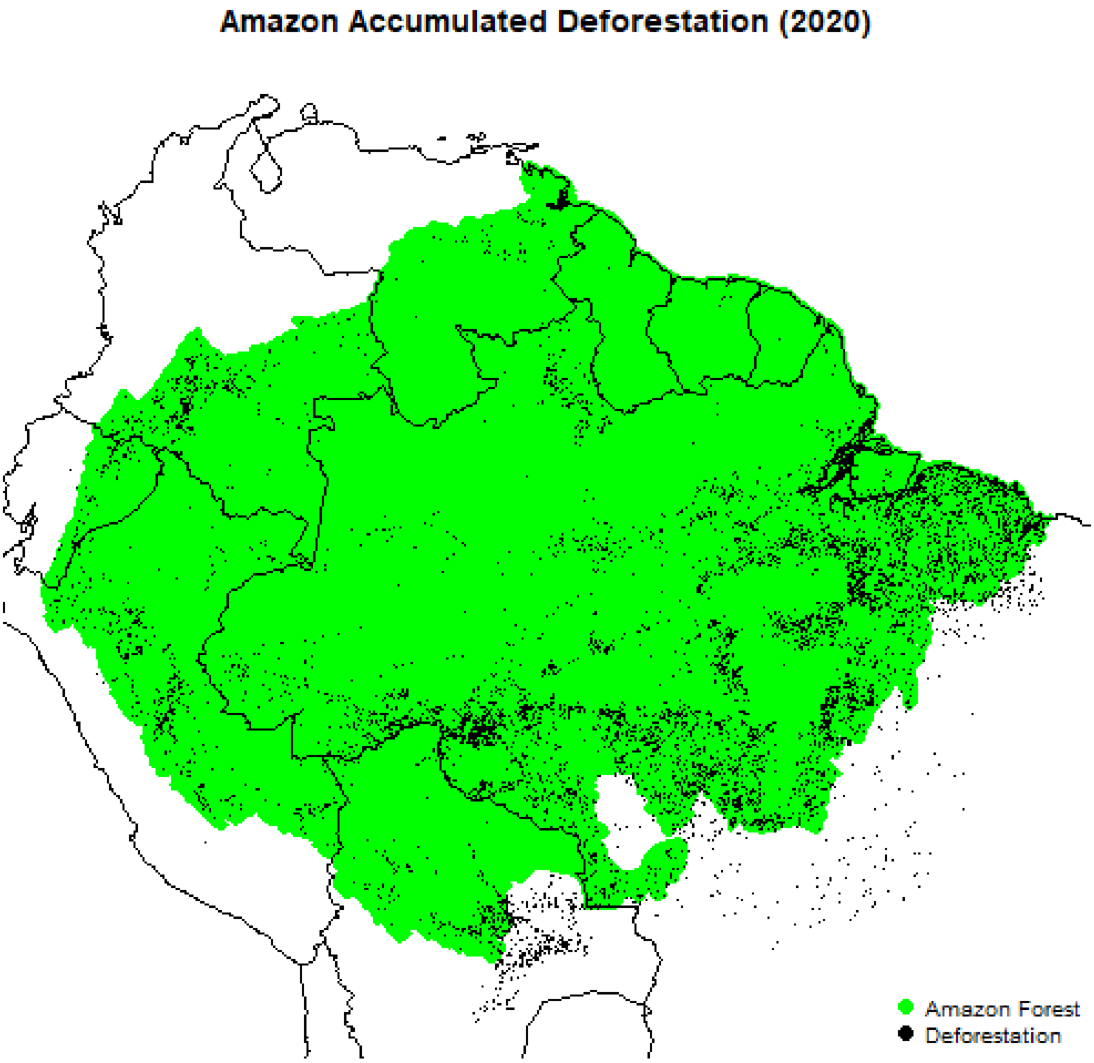
Historically, economic development in South America mainly occurred in coastal cities of the Atlantic and the Pacific. Consequently, the forest remained largely intact until large-scale deforestation started in the 1970s. Since then, the Amazon Forest has lost 11 to 15% of its original forest cover.

It is believed that humans have been present in the Amazon forest for more than 11 thousand years (Roosevelt et al. 1996), and that the population of Indigenous groups in the Amazon reached 5 to 6 million people at the start of European colonization in the late 1400s (Denevan 2003, Denevan 2014). Despite colonization efforts for economic exploitation and missionary activity in the region, it remained peripheral during the Portuguese and Spanish colonial phase and after the Amazon countries gained independence from their colonial powers in the early 19th century. The main economic activities during the colonial era were exploiting nuts, fruits, fish, and cacao. In the late 19th century, the Southwestern region of the Amazon saw an economic and demographic boom due to the exploitation of rubber trees. This activity died out in the early 20th century, except for a short-lived boom during the Second World War (see Souza 1994 and Cleary 2001 for a history of the Amazon).

Economic booms and busts notwithstanding, the Amazon area remained almost entirely covered by forest, as none of the activities mentioned above required the deforestation of large areas. This reality changed with the expansion of agriculture into the Amazon forest, starting in the 1970s in its South and Southeastern frontier. Brazilian farmers started claiming land and expanding cropland areas northwards, converting the forest into crop fields and pastures, often with government support. Historical estimates of deforestation using agricultural census data put deforested areas at about 1% in the 1940s Brazil and 3% in 1975, when the earliest satellite-based measures became available (Barsanetti and Ferreira 2024).

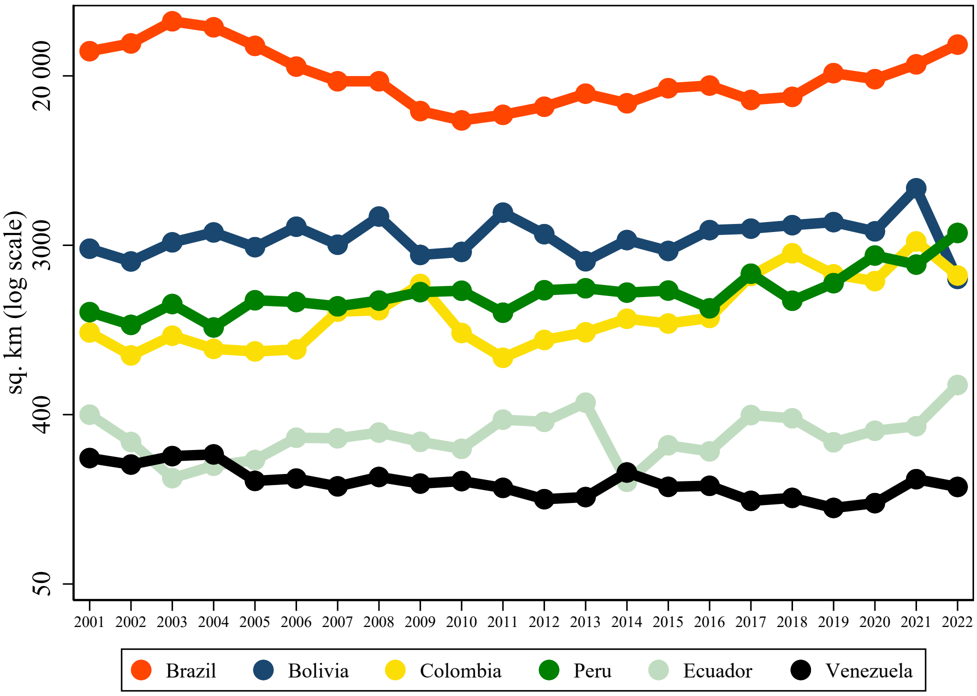
Since then until 2020, the Brazilian Amazon had lost between 17% and 21% of its original forest cover depending on the methodology, by far the largest share of all nine countries. Bolivia comes second, with around 17% of deforestation. Colombia, Ecuador, and Peru have lost approximately 10% each. The Northern part of the Amazon forest, which covers Venezuela, Suriname, Guyana, and French Guyana, is almost entirely preserved. Figure 1 shows the accumulated deforestation in the Amazon Forest by the year 2020, and Figure 2 shows the evolution of deforestation by country (except for Guyana, Suriname, and French Guyana), since 2001, in hectares (panel a) and percentage of forest cover in 1985 (panel b).

Figure 1: Accumulated Amazon Deforestation Across the Nine Countries

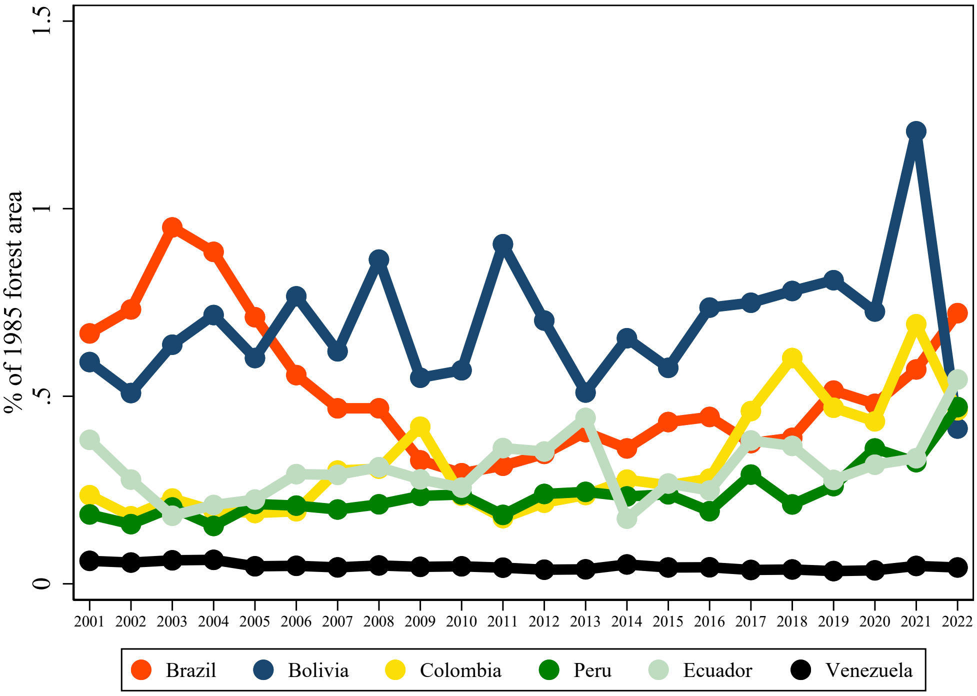


Source: RAISG

Figure 2: Deforestation by Country



(a) Deforestation Area by Country



(b) Deforestation Area by Country

Source: MapBiomas (Amazon Transitions Statistics)

Researchers and government organizations have been measuring deforestation since the early 1970s, especially using high-resolution optical images from the satellites of the Landsat program.[1] To measure deforestation, researchers often rely on optical-based measures of forest cover, such as the normalized difference vegetation index (NDVI), which also measures forest degradation.[2] The most widely used dataset for tree cover loss worldwide is the Global Land Analysis & Discovery (GLAD) of the University of Maryland (Hansen et al. 2013), mainly based on 30-meter resolution Landsat imagery. The Brazilian Institute for Spatial Research (INPE) also has its program to measure deforestation based on Landsat imagery, relying on visual validation of polygons instead of a fully automated algorithm. Alternatively, the network MapBiomas has its measures of land cover for the Amazon Forest, which they update regularly retroactively with models trained on new data, including field inspections. I use MapBiomas information throughout this paper as the primary land-use reference measure. Newer methods of measuring deforestation rely on radar images (based on the relief on the surface) or higher resolution optical images, such as the ones provided by the Sentinel satellites (10 meters).

Deforestation is the destruction of biomass, typically intended to convert the area into economic activity. Destruction of biomass can be total or partial, in which case one refers to it as forest degradation. In the Amazon Forest, as discussed in section 2, people deforest to exploit the land for crops or pasture or to extract timber and minerals. The typical process of deforestation consists of logging an area using mechanical tools and labor and extracting valuable wood for sale. Much of the biomass has no sale value is destroyed, usually with fire. At the end of the process, farmers sow seeds of crops or pasture (Nepstad, Moreira, and Alencar 1999, INPE 2008). In the case of mining, additional investments are necessary to start the mineral extraction.

Agriculture in the Amazon Forest mainly produces soy, corn, meat, and, to a smaller extent, coca and palm oil. In the early 2000s, the expansion of soy agriculture into the forest was the main driver of deforestation in Brazil, leading to large deforested areas. Later in the 2000s and into the 2010s, deforestation became increasingly “decoupled” from the expansion of soy (Macedo et al. 2012) and the main driver of deforestation became cattle grazing for meat production. Deforestation for cattle grazing is also important in Bolivia, Peru, and Colombia. However, in these countries, deforestation is often connected to the expansion of coca plantations (Dávalos, Sanchez, and Armenteras 2016). Finally, palm oil is rapidly replacing

---

[1] The first satellite of the Landsat program was launched in 1972 by NASA. In 2021, NASA launched Landsat 9, the ninth satellite of the program. More information about the program is available on the website: https://landsat.gsfc.nasa.gov/

[2] The NDVI measure is pervasive in studies of forest cover. It is a normalized variable from -1 to 1 based on the near-infrared and red light measured by multispectral optical sensors installed in satellites such as Landsat. For a technical explanation of NDVI, see the GIS Geography website: https://gisgeography.com/ndvi-normalized-difference-vegetation-index/

forest in Ecuador and Peru (Vijay et al. 2016).

Timber and mineral exploitation also cause deforestation, but typically on a smaller scale since they depend on local resource availability. Logging for timber concentrates on tree species such as mahogany (*mogno*) and *ipê*. In contrast, most Amazon trees and plants have no economic value as timber. Similarly, gold mining is an important economic activity in parts of the Northern Amazon Forest. However, these activities tend to deforest small areas, as suggested by the low deforestation rates in countries with substantial gold reserves, such as Venezuela, Guyana, Suriname, and French Guyana (See Appendix Figure 6).

Based on MapBiomas data, 11% of the Amazon Biome's forest in 1985 was deforested by 2022, representing roughly 640 thousand square kilometers of deforestation. Accounting for reforestation brings this number down to 10%. The rate of deforestation is evenly split between the periods 1985-2000 and 2000-2022, indicating a slight acceleration in the last decades. Of the deforested area since 1985, 95% was converted into agricultural use, mostly pasture (77%), crops (12%), and a mosaic of uses between crops and pasture (6%). Forest conversion to cropland accelerated in the 2000s and slowed in the 2010s. Table 1 summarizes the statistics by country.

The best available estimates for the cost of converting forest to cropland varies from 300 USD to 600 USD (3000 BRL) per hectare, as reported by specialized reports (Bispo and Coelho 2021, October 10th, Ramos September 22nd, 2021, Conservancy 2019) and one econometric study (Araujo, Costa, and Sant'Anna 2022), with the caveat that this figure depends on local labor and capital costs. Converting forest to pasture, or pasture to cropland, is slightly cheaper, according to the same sources. The sale of valuable timber barely recovers the deforestation expenditure: the average return per hectare is only around 4 USD per hectare because only a few types of wood have economic value (Santana et al. 2012).

The economic benefits of deforestation include the one-off sale of valuable timber and the value of agricultural production on the land over time. The sale of valuable timber barely recovers the deforestation expenditure: the average return per hectare is only around 4 USD per hectare because only a few types of wood have economic value (Santana et al. 2012). The average yearly soy productivity in the Brazilian Amazon is 3.5 metric tons per hectare, with an average export value of 400 USD per metric ton, meaning that the gross revenues from one hectare of soy are 1400 USD per hectare.[3] Assuming a profit rate of 25%, yearly average profits per hectare are

---

[3] These figures refer to the state of Mato Grosso. The numbers of productivity per hectare and average export price refer to 2020 and were extracted from EMBRAPA's website: https://www.embrapa.br/web/portal/soja/cultivos/soja1/dados-economicos These figures are similar to the ones obtained from IBGE's monthly agricultural survey LSPA https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9201-levantamento-sistematico-da-producao-agricola.html?=&t=destaques

350 USD.[4] The productivity of meat is approximately 0.07 metric ton per hectare, and the export price of a kilogram of frozen beef was around 5,000 USD per ton in 2020, meaning gross revenues of 350 USD per hectare.[5] Assuming a 25% profit rate, these values imply profits of roughly 80 USD per hectare.[6]

Coca plantations (common in Bolivia, Colombia, and Peru), have a much higher gross productivity rate, with a productivity of 4 to 10 kg of cocaine per hectare of coca cultivation according to the White House Office of National Drug Control Policy.[7] These levels of production represent a gross productivity of over 2 thousand USD per hectare, before labor and processing costs. However, coca cultivation is not suitable to all areas of the Amazon and face much stronger regulatory risks.

Similarly, gold extraction has a much higher return per hectare than agriculture. Since 2015, the international price of one kilogram of gold went from 38 thousand to 80 thousand USD. To benchmark this value, Gasparinnetti et al. (2024) estimate the productivity of gold in the Tapajós Basin, Brazil, at around 1.7 kg per hectare based on surveys with artisanal miners. However, mining is geographically restricted to areas with gold availability, and both exploration and extraction can be costly.

The overwhelming majority of deforested areas happened in Brazil, where Amazon deforestation is tightly regulated, as it is in most Amazon countries. Virtually all deforestation in the Brazilian Amazon is deemed illegal (Valdiones et al. 2021, MapBiomas 2024). The illegality of deforestation partly makes it hard to gather detailed information on the type of people who engage in this activity. What can be known based on satellite data is that deforestation is mostly carried out by small and medium farmers, land grabbers, and miners. For example, more than half of the deforestation in Brazil is done in areas smaller than 50 hectares. The illegality also makes loggers organize in illegal networks, as is often the case with illegal timber extraction in Brazil and coca plantations in Bolivia, Colombia, and Peru (Prem, Saavedra, and Vargas 2020, Tozzi 2022).[8] In Brazil, where 81% of deforestation became pastures (see Table

---

[4] Figures computed using the exchange rate 1 USD = 5 BRL. Profit rate values refer to the Centro-Oeste region, as reported by the software company Siagri. Article available here: https://www.siagri.com.br/lucro-por-hectare-nas-lavouras/

[5] Data on beef productivity is summarized in the French report on the EU-Mercosur trade agreement (Ambec 2020), and average export prices are obtained from the Brazilian Ministry of Trade.

[6] 25% is in the ballpark of the profit rate of 20% found in the case study by Mecca, Vergani, and Eckert (2022). This value seems in line with recent cases cited in an interview by the specialized websites MinutoRural, available here: https://www.minutorural.com.br/noticia/6229/pecuaria-de-corte-encerra-2021-lucrativa-mesmo-com-o-aumento-dos-insumos , and GirodoBoi https://www.girodoboi.com.br/destaques/mais-de-80-das-fazendas-de-pecuaria-do-brasil-nao-conseguem-apurar-o-proprio-lucro/

[7] Latest press release available here: https://www.whitehouse.gov/ondcp/briefing-room/2022/07/14/ondcp-releases-data-on-coca-cultivation-and-production-in-the-andean-region/

[8] Although coca plantations also caused deforestation in Colombia, Prem, Saavedra, and Vargas (2020) argue that the conflict between the state and paramilitary guerrillas prevented large-scale deforestation from spreading in the Amazon Forest.

1), illegal farmers sell their cattle to legal farms, which then sell them to slaughterhouses as if they had come from the legal farms (Abreu 2022, July).

The profitability of these activities can explain why many farmers and land grabbers are willing to deforest despite the relatively high expenditures (300 to 600 USD per hectare). However, agricultural activities require farmers to have a relatively long time horizon to compensate for the costs of deforestation, including regulatory compliance costs. Given the large areas of yearly deforestation in the Amazon, it is safe to conclude that the benefits can easily outweigh the costs from the farmers' or miners' perspective.

Several studies have documented factors that contribute to accelerating deforestation by making it more economically attractive. Pfaff (1999) identified several of them, highlighting the strong correlation between deforestation and proximity to roads. Using a structural model, Souza-Rodrigues (2019) highlights the role of transportation costs in the demand for deforestation. Another important factor is commodity prices: Assunção, Gandour, Rocha, et al. 2015 show that almost 40% of the variation in deforestation rates in the Brazilian Amazon can be explained by changes in international commodity prices. In contrast, increases in agricultural productivity in Brazil, which enabled a boom in the soy production, are not associated with increases in deforested areas (Da Mata, Dotta, and Lobo 2023), in accordance with the "Borlaug hypothesis."

On the other side of the coin, deforestation generates costs for which farmers do not have to pay: greenhouse gas emissions from biomass destruction, particulate matter emissions from forest fires, reduction in water evaporation and rainfall, water pollution from mining activities, and ecosystem disturbances. These external costs, or "externalities", are not reflected in market prices, unlike labor and capital. In practice, these damages are paid diffusely by people who do not take part in the economic decision to deforest. It is theoretically possible and empirically plausible that many instances of deforestation would yield negative economic value if these external costs were taken into account. In such cases, deforestation is an economically harmful decision and, therefore, a market failure. The nature and magnitude of the externalities dictate the appropriate corrective policies. The next section discusses these externalities and recent advances in measuring them.

Table 1: Summary Amazon deforestation by country

				Forest transitions 1985-2022			
Country	**Share Amazon forest**	**% Deforested (2022)**[1]	**Main drivers**[2]	**% pasture**	**% crops**	**% palm**	**% mining**
All countries	6.4 million km^2	11%	Cattle, timber, coca, palm oil, mining	80%	14%	1%	1%
Bolivia	6.9%	14%	Cattle, soy	30%	51%	0	9%
Brazil	60.3%	17%	Cattle, soy	81%	15%	0	2%
Colombia	6.9%	8%	Cattle, coca	71%	19%	0	0
Ecuador	1.5%	9%	Palm oil	26%	56%	10%	1%
French Guyana	1.1%	1%	Gold mining	12%	13%	0	7%
Guyana	3%	1%	Timber, gold	7%	13%	0	24%
Peru	11.3%	6%	Cattle, coca	37%	48%	3%	2%
Suriname	2.1%	1%	Gold mining	11%	19%	0	30%
Venezuela	6.7%	1%	Cattle, gold	39%	22%	0	9%

Sources: Own computations using MapBiomas Amazon transitions data. Deforestation (2022) assumes that agriculture area in 1985 used to be forest, and does not include reforestation. Transition shares refer to deforestation between 1985 and 2022. List of main drivers compiled from Costa (2020, February 18th), and Crime and Institute (2021)

3 Environmental damages from Amazon deforestation

Deforestation causes global, regional, and local externalities. The global externality of deforestation is its impact on climate change through greenhouse gas emissions. At the regional level, deforestation reduces water evaporation and rainfall, affecting water availability for crops in the whole region. In addition, forest fires generate particulate matter, which pollutes the air far beyond the ignition area. Finally, deforestation disturbs local ecosystems at a local level, potentially causing biodiversity loss and the interruption of ecosystem services. Moreover, artisanal mining activities pollute water bodies with heavy metals, contaminating the soil, water, and fish. These are the main externalities of deforestation discussed in this section. However, researchers have also highlighted the adverse effects of deforestation in other dimensions, such as the acceleration of malaria spread (MacDonald and Mordecai 2019, Ellwanger et al. 2020), the destruction of "non-use value" of natural heritage (see Chan et al. 2011 for a broad discussion), violence associated with mineral extraction (Pereira and Pucci 2021), and the threat that deforestation poses to indigenous peoples (Barsanetti and Ferreira 2024).

3.1 The global externality: climate change

Forests are carbon stocks because plants and trees absorb carbon from the atmosphere via photosynthesis and store it as wood and leaves. Therefore, tree growth is an effective natural carbon sequestration device. Forests are also sources of carbon emissions through the natural decomposition of organic matter and cellular respiration. When forests reach an equilibrium state where they do not grow further, they become essentially carbon neutral concerning their carbon flows (Mitchard 2018). However, some studies argue that forests remain net carbon absorbers even when mature because part of the absorbed carbon remains in the soil when trees die (D'Amore and Kane 2016). The mature areas of the Amazon Forest still operated as a net carbon sink from the 1980s into the 2000s (Phillips and Brienen 2017, Hubau et al. 2020).

However, their sudden destruction may release the carbon stocks accumulated during the growth phase, affecting the atmosphere's carbon concentration and aggravating the greenhouse effect.[9] Therefore, whether forests are net carbon sources, net sinks, or carbon neutral is a function of biological, climatic, and anthropogenic processes that alter the carbon fluxes of a forest. Tropical forests, where deforestation has accelerated the most in recent decades, are biomes with an exceptionally high carbon density. The Amazon Forest has the largest carbon stock of all forests worldwide because of its vast area and dense vegetation (Pan et al. 2011).

---

[9] On top of its impact on the atmosphere's carbon concentration, the net contribution of forests to the oxygen cycle in the atmosphere is also roughly zero. The Amazon forest has often been called the "lungs of the Earth" to reference its presumed oxygen-generating capacity. However, due to the oxygen consumption needs of the forest itself, its net contribution to the atmosphere is zero.

Table 2: Environmental damages from Amazon deforestation

Level	**Damage**	**Description**	**Reversibility**
Global externality	1. Climate change	Deforestation and degradation liberates carbon stored in biomass into atmosphere.	High: reforestation can rapidly sequester carbon and help mitigate climate change.
Regional externality	2. Rain cycle	Forests store and evaporate large quantities of water, regulating rain patterns in the forest and neighboring regions.	Medium: deforestation may trigger self-reinforcing dynamics of dryness above a "tipping point". Regeneration may have avoided this scenario up to now.
Regional externality	3. Air quality	Use of fires in deforestation liberates large amounts of particulate matter and other toxic gases that harm human health.	High: control of use of fires would entirely eliminate the problem.
Local externality	4. Biodiversity services	Deforestation actively kills plants, putting some at extinction risk. Deforestation and degradation also disturb ecosystems, reducing the biodiversity in them.	Low: regenerated forest have lower biodiversity, and deforestation triggers rapid loss of biodiversity above certain thresholds.
Local externality	5. Water quality	Throwing mercury into the water for mining purposes contaminates potable sources of water, fish, and the atmosphere.	Medium: heavy metal contamination can contaminate sources for a long time.

Tropical forest growth contributed to a quarter to a third of this global sink, absorbing 15% of anthropogenic emissions from fossil fuels (Hubau et al. 2020), outperforming other biomes such as boreal or temperate forests (Pan et al. 2011).[10] Conversely, deforestation and forest degradation turn forests into net carbon emitters. Forest regeneration could capture these carbon emissions, but it rarely happens because other land uses, such as crops or pastures, replace the forest. The spread of forest fires can increase greenhouse gas emissions by causing forest degradation beyond the deforested areas. In the Amazon Forest, those fires cause persistent and irreversible effects on the vegetation, often failing to regrow to its previous state (Nepstad, Moreira, and Alencar 1999). These irreversible damages happen because fires are not natural

---

[10] Oceans and forests have absorbed as much as 55% of the additional CO2 emitted by burning fossil fuels, attenuating the effect of human-made emissions on climate change (Hansen 2010, Mitchard 2018).

in the Amazon Forest, and its vegetation cannot naturally resist them, unlike in the Cerrado biome (Nepstad, Moreira, and Alencar 1999, Nepstad et al. 1999). Therefore, forest regrowth and regeneration is an imperfect replacement for deforestation and degradation.

Deforestation and forest degradation turn forests into net sources of carbon. Forest regeneration could capture these carbon emissions, but it rarely happens because the forest is replaced by other land uses, such as crops or pastures. Moreover, forest fires used in deforestation spread to neighboring areas causing forest degradation, which is also an important source of emissions. In the Amazon Forest, those fires cause persistent and irreversible effects on the vegetation, often failing to regrow to its previous state (Nepstad, Moreira, and Alencar 1999). These irreversible damages happen because fires are not natural in the Amazon Forest, and its vegetation cannot naturally resist them, unlike in the Cerrado biome (Nepstad, Moreira, and Alencar 1999, Nepstad et al. 1999). Therefore, deforestation and forest degradation are significant sources of greenhouse gas emissions without compensation via forest regeneration.

Greenhouse gas emissions from the Amazon Forest receive enhanced attention because it is the largest tropical forest in the world. The Amazon Forest contains a stock of carbon of approximately 90 Gigatons of Carbon (GtC), of which 54 GtC are in Brazil (Baccini et al. 2012). This stock makes Brazil the country with the most extensive aboveground carbon stock, followed by the Democratic Republic of Congo and Indonesia. The Amazon Forest's stock of 90 GtC represents nine years of CO2 equivalent emissions from fossil fuel burning. If deforestation wiped out the Amazon Forest entirely, the concentration of carbon in the atmosphere would increase from its current 410 ppm to 450 ppm, usually associated with a 2 degrees Celsius increase in average temperature relative to the pre-industrial era. (see Appendix B for details).

To compute emissions from deforestation, scientists rely on estimates of the carbon density of the Amazon Forest based on satellite images and field measures of tree size and vegetation density. A simple way to estimate emissions from deforestation is to impute average values. For example, the emission modeling by the Brazilian Spatial Institute (INPE) estimates the carbon density in the Amazon Forest to be roughly 500 tons of CO2 per hectare.[11] However, more sophisticated procedures rely on maps of carbon stock that assign carbon densities to each area, such as Baccini et al. (2012). Carbon emissions from deforestation are sizable and among the top sources of greenhouse gas emissions in the Amazon countries. Brazil, Ecuador, and Colombia explicitly committed to reducing deforestation as a contribution to lower emissions in their Nationally Defined Contributions of the Paris Agreement.[12]

Estimates of carbon emissions that only use deforested areas underestimate the full scope of emissions from deforestation. This underestimation happens because forest fires spread far

---

[11] The data is available at http://inpe-em.ccst.inpe.br/en/estimates-for-the-amazon/

[12] The Nationally Defined Contributions are found in the UNFCCC website: https://unfccc.int/NDCREG

beyond the site initially intended for deforestation. Most fire events do not obliterate the forest but often leave “fire scars.” The areas of fire scars, computed by MapBiomas, are roughly the same as the yearly deforestation areas. However, the areas affected by fire events are potentially much larger, as shown in Appendix Figure 7. The large extent of fire events suggests that forest degradation is a problem of large dimensions. According to data by the Brazilian Spatial Research Institute (INPE), degraded areas every year are almost twice as large as deforested areas and are primarily associated with fires (Pucci et al. 2021). Researchers have been trying to compute the area of forest degradation and its associated emissions by using models or measuring emissions in air samples (Gatti et al. 2021). Aragão et al. (2018) estimate that forest degradation from forest fires in the Brazilian Amazon Forest increases emissions by 50% than estimates based only on deforestation would imply.

3.2 Regional externalities: rain fall and air quality

Amazon deforestation generates regional damage in two ways. First, deforestation reduces water evaporation and transpiration, consequently reducing aerial water transportation to neighboring areas. Second, forest fires emit particulate matter, polluting the air. Both effects cause damage in areas beyond the exact site of deforestation since vapor and air pollution spread in the air following the wind.

The Amazon Forest retains large amounts of water in leaves and water bodies. Evaporation from rivers and plants releases large quantities of water into the atmosphere, generating clouds that produce rain in the whole region and beyond (Spracklen, Arnold, and Taylor 2012).[13] The water vapor moves according to air currents, forming the so-called “flying rivers” that transport water from the forest to agricultural regions South of the Amazon. Reduced vegetation implies less water transportation, reducing vegetation health in downwind regions and amplifying the adverse effects of deforestation via additional degradation (Araujo et al. 2023). Moreover, reduced rainfall may also harm agricultural productivity in downwind regions (Araujo 2021) and water availability for hydroelectric dams (Araujo 2024). Recent studies have provided evidence that areas with large levels of deforestation are linked to longer dry seasons (Leite-Filho, Sousa Pontes, and Costa 2019) and lower levels of precipitation (Xu et al. 2022). It is possible that deforestation may be responsible for the 8% reduction already detected in water body areas in the Amazon, relative to the early 2000s (see Appendix Figure 9).[14]

---

[13] Medvigy et al. (2013) show with simulations of a weather model that minor disturbances to the Amazon Forest’s evaporation may have significant effects on the snow peaks of the Sierra Nevada and, therefore, on freshwater supply in the American Northwest.

[14] A reduction in precipitation rates also makes the forest more vulnerable to fires and forest regeneration more difficult (Spracklen et al. 2018). In addition, feedback mechanisms may imply the existence of deforestation “tipping points”, after which the forest becomes so dry that it starts dying out by itself. Advocates of the tipping point theory argue that it lies between 25% and 40% of forest cover loss (Nobre and Borma 2009,

The second regional externality of deforestation is associated with the methods used to clear forests. As mentioned, the typical method includes logging and burning biomass, the latter being a cheap way to clear biomass and fertilize the soil. Besides often running out of control and spreading to standing forests, deforestation fires generate particulate matter that pollutes the air in neighboring areas. This problem is visible in the dry season of the Amazon Forest (May through September), where fires are more likely to survive and spread, leading to a significant deterioration of air quality in regions more prone to deforestation Sá et al. (2019). For example, in the Brazilian state of Pará, the correlation between fires and particulate matter concentrations 2.5 is striking, as illustrated by Appendix Figure 8. Consequently, despite being a sparsely populated area, air pollution stemming from deforestation has detectable effects on mortality and human health in the Amazon region (Reddington et al. 2015, Requia et al. 2021 Butt et al. 2021).

3.3 Local externalities: biodiversity services and water pollution

The most local externalities of deforestation are the impacts on ecosystem services and pollution. The Amazon Forest is home to the richest biodiversity of all existing biomes on Earth (IPBES 2018), often measured by the number of species in a biome.[15] The importance of biodiversity is hard to assess but easy to understate. For example, the forest's biodiversity provides the livelihoods of households that extract fish and fruits. Moreover, the Amazon Forest's biodiversity gives rise to continuous biological research that can help understand diseases and find their cure. The intrinsic value of biodiversity comes from its direct services to humans and the diffuse benefits it has on life because of scientific research (Fearnside 1999, Fearnside 2021). Deforestation directly reduces the number of species by killing vegetation, potentially at a large scale, putting species of plants at risk of extinction (Barlow et al. 2016), and by disturbing ecosystems, leaving forests more fragmented and sparse, which makes it harder for species of animals and plants to reproduce (Ochoa-Quintero et al. 2015). Finally, deforestation and degradation cause irreversible damage to biodiversity because forest regeneration fails to retrieve the density of biodiversity of primary forests decades after reforestation has taken place (Catterrall et al. 2004, Brockerhoff et al. 2008, Gibson et al. 2011).

The other local externalities are soil and water pollution, primarily caused by artisanal mining activities. Water pollution is particularly pronounced in the search for gold, often found under or close to water bodies. Miners use mercury, a toxic heavy metal, to separate gold from other minerals. Gold separation involves heating the mix with mercury, which evaporates and

---

Lovejoy and Nobre 2018, Lovejoy and Nobre 2019), though forest regeneration and global climate conditions may affect it.

[15] See a table with the number of species of fauna and flora compiled by Mongabay: https://rainforests.mongabay.com/03highest_biodiversity.htm

contaminates nearby soil and water through the rain. Moreover, mercury is often handled without protection and spills on the soil and nearby water. Researchers have documented elevated mercury levels in water, vegetation, fish, and air in the proximity of gold mining activities in Peru (Gerson et al. 2022), with noticeable effects on the mercury concentration of the local population and the miners themselves (see Torres and Torre 2022 for a review).

4 Policy interventions

Negative externalities imply that deforestation is more costly than farmers realize when they decide to clear an area of forest. To illustrate a market failure, let us solely consider the problem of climate change. Deforestation contributes to global warming via greenhouse gas emissions, and each hectare of deforestation is a marginal contribution to the increase in global temperatures. According to Emissions Modeling by the Brazilian Spatial Institute (INPE), the carbon density in the Amazon Forest is 150 tons per hectare, meaning that clearing this one hectare emits approximately 500 tons of CO2. The damage from one extra ton of carbon emissions is the net present value of the global economic damage caused by the rise in temperature, namely excess storms, floods, heat waves, and higher ocean levels. The estimates of the net present value of these damages, or the social cost of carbon, typically range from 50 USD to 300 USD (Barrage and Nordhaus 2024, EPA n.d.) per ton of CO2, depending on modelling parameters and on the discount rate used. The U.S. Environmental Protection Agency's estimate of the social cost of carbon at a 2% discount rate is 190 USD per ton of CO2. Consequently, using 50 and 190 USD as lower and upper bounds for the social cost of carbon, the climate externality of destroying one hectare of the Amazon forest ranges between 25 and 95 thousand USD.

As discussed in section 2, the average costs of deforesting one hectare of the Amazon forest depend on local labor and capital costs, such as the rental price of a tractor, and range between 300 and 600 USD. The profits from economic activity depend on labor, capital, transportation costs, commodity prices, and the farm's productivity. As mentioned, cattle grazing generates average gross profits of 300 to 400 USD per hectare per year, whereas soy generates 800 USD. All these figures are approximate, but they give us a sense of the magnitude of the actual values and allow us to understand the problem of market failure. The net present value of agricultural activities, using a discount rate of 2%, is around 20 thousand USD for pasture and 40 thousand USD for soy. These values do not discount taxes or the farmers' opportunity costs. Therefore, the net present value is potentially much lower in practice. Indeed, there is anecdotal evidence that land value in the Amazon forest can be as low as one thousand USD per hectare.[16]

---

[16] I computed the net discounted value as the infinite discounted sum of a constant profit flow using a discount rate of 2%, i.e. $NPV = \sum_{i=0}^{\infty}(1-r)^i\pi$, where r is the discount rate and π is the profit flow. For Brazilian standards, 2% is a low real interest rate. Moreover, soils may wear out after some time, losing productivity and profitability. For the average value of hectares in the Amazon Forest, news reports in 2015

The total economic cost of deforestation, reflected in the social cost of carbon, is much larger than the net present value of agricultural activities and land value. However, the lack of a market that makes this cost explicit prevents farmers from incorporating it in the economic decision to deforest. The result is that deforestation may end up generating more economic damage than benefits.

Policies can solve this market failure by inducing economic agents to incorporate the environmental damage, directly or indirectly, in their decisions regarding deforestation. However, policy design should depend on the externality it is trying to address. For example, from a climate change perspective, the objective is to reduce emissions regardless of where they originate. From a biodiversity perspective, however, the location of deforestation matters because some areas are more crucial than others for ecosystemic balance. Therefore, policies that only target overall deforestation without accounting for geographic heterogeneity may fail to prevent disastrous outcomes in terms of biodiversity. Likewise, forest areas may have more effect than others on rainfall in crop areas in the South of the Forest. Spatial heterogeneity in the production of externalities calls for targeted conservation policies.

Policy interventions may ban deforestation in certain areas or make deforestation costlier through taxes or regulation. Quantity limits and prices can achieve lower deforestation, and the appropriate instrument depends on enforcement costs and the uncertainty around the costs and benefits of deforestation. Price regulation, such as a well-enforced tax on deforestation or a product thereof, would incentivize farmers to deforest only as long as their benefits outweigh the tax, naturally inducing low-productivity farmers to conserve. Therefore, price regulation tends to be the preferred approach of economists to environmental policy as it allows to achieve environmental goals at the lowest possible economic cost. Examples of price regulation are carbon taxes, payments for ecosystem services, or any type of conditional loan or cash transfer based on conservation targets.

However, quantity regulation, such as bans, can be easier to design and enforce than taxes. The reason is that violations of quantity regulations are easier to observe and can be assessed by virtually anyone. In contrast, violations to the tax code require more detailed audits and give rise to more complex forms of noncompliance (Glaeser and Shleifer 2001). The simplicity of enforcement of command-and-control, quantity-based rules, partly accounts for its wide adoption in land use regulation. For similar reasons, it is easier to enforce place-specific quantity regulations than place-specific deforestation taxes. Examples are conservation units that place deforestation bans in areas of rich biodiversity or high carbon density.

---

mentioned that land was being traded at 2500 BRL per hectare, which at the time meant approximately 1000 USD. See https://epoca.oglobo.globo.com/colunas-e-blogs/blog-do-planeta/amazonia/noticia/2015/07/terras-na-amazonia-estao-uma-pechincha.html)

Another reason to choose quantity regulation instead of price regulation can be uncertainty about environmental damages and conservation costs. Under uncertainty, quantity regulation allows policymakers to establish a maximum level of environmental damage, risking to impose potentially very large costs of compliance, that is, conservation. In contrast, price regulation would encourage farmers to deforest as long as the marginal economic benefits of deforesting one hectare beats the cost of the tax. The risk of price regulation under uncertainty is that the amount of deforestation is endogenous to the productivity of farmers' technology and their land, and could potentially be larger than what is advised to avoid catastrophic scenarios. Indeed, quantity regulation is preferable to price regulation whenever the damage from forest destruction increases more steeply with deforestation than the costs of conservation decrease, which would probably happen in the existence of "tipping points" and runaway effects.[17]

Other policies include the regulation of permissible production practices or technologies that are less damaging to the environment. Imposing high sanctions on the use of fire, or requiring protective measures, can reduce the environmental impact of deforestation. Similarly, encouraging or mandating the use of mercury-free technologies of gold mining can help reduce water pollution stemming from that activity. Similarly, interventions on the demand side can theoretically induce producers to adopt sustainable practices, such as labels, certifications and campaigns for sustainable consumption. Some other tools operate through less direct mechanisms. Such indirect tools are hurdles and regulations that make deforestation costly to farmers. Examples include certification for market access, land tenure regulations, incentives for sustainable resource exploitation, and indirect taxes. Table 3 summarizes this typology of policies.

---

[17] This paragraph applies the theoretical results of Weitzman (1974) to the problem of forest conservation policy.

Table 3: Typology of Conservation Policies and Examples

Type of policy	**Description**	**Examples and References**
Command and control	Direct regulation banning or limiting deforestation for land holders, with enforcement efforts.	1) Enforcement with field inspections in Brazil (Assunção, Gandour, and Rocha 2023, Ferreira 2024, Assunção, Gandour, and Souza-Rodrigues 2019); 2) target municipalities in Brazil (Assunção et al. 2019)
Payments for Ecosystem Services	Financial incentives for land holders to preserve or restore forest.	1) Conditional subsidized rural credit in Brazil (Assunção et al. 2020); 2) Conditional cash transfers in Brazil (Cisneros et al. 2022); 3) Conditional cash trasnfers in Uganda (Jayachandran et al. 2017)
Land tenure	Definition of who owns the land and which rules apply.	1) indigenous reserves in Brazil (BenYishay et al. 2017, Baragwanath and Bayi 2020); 2) land titling programs in Brazil (Probst et al. 2020)
Sustainable practices	Foster economic activities that exploit the forest without destroying it.	1) forest concessions in Peru (Rico et al. 2022) 2) eco-tourism; 3) sustainable use of forest resources
Labels and market access	Condition access to (international) markets on proofs of good environmental practices, such as taxes and regulations.	1) Soy Moratorium, 2) Sustainable wood labels
Indirect instruments	Mechanisms that indirectly affect the incentives to deforest.	1) taxes to affect commodity prices; 2) control the sales of motor saws and other equipment

4.1 Overview of conservation policies in the Brazilian Amazon

Brazil has strict laws against deforestation in the Amazon, but enforcement is weak. The current legislation is the outcome of a long process of environmental lawmaking in Brazil that started in the early 20th century with the Forest Codes of 1934 and 1967, the latter creating the command and control rule that obliges farmers to protect a share of their property's area as native vegetation ("Reserva Legal"), depending on the biome. In the 1990s, the Brazilian Congress passed an amendment to the Forest Code, increasing the Amazon biome's conservation requirement to 80% of the property's area. This amendment reflected a rising concern about the preservation of the Amazon Forest, given the high rates of deforestation pushed by agricultural expansion. In the 1970s, the Brazilian government encouraged the occupation and development of the Amazon region with tax incentives and infrastructure projects such as the immense (and unfinished) “Transamazônica” road.

During the 1980s and 1990s, the government instituted or strengthened environmental organizations that enabled the execution of environmental policy, such as the federal environmental enforcement agency IBAMA, created in 1989, and the Ministry for the Environment, founded in 1990. In 1988, the Brazilian Institute for Space Research started systematically measuring Amazon deforestation using remote sensing data in a program that continues today. In 1998, Congress passed a law instituting “environmental crimes”, punishable by jail, including deforestation and forest fires. Currently, virtually all deforestation in the Brazilian Amazon is illegal. Studies overlaying remote-sensed deforestation areas with protected areas concluded that only about 5% of yearly deforestation has legal permission to occur (see Valdiones et al. 2021 and MapBiomas 2024 for two such analyses).

4.2 Quantity regulations (command and control)

Brazil relies heavily on quantity regulations, or command-and-control, to protect the Amazon. The regulation varies by the land tenure status. In privately owned properties, which comprise 20 to 25% of the Amazon’s territory, farmers must have 80% of the property’s surface covered by native vegetation. This protected area is called a “Legal Reserve” (Reserva Legal). Any deforestation, even outside the “Legal Reserve,” must have prior authorization by the environmental authorities.

Approximately half of the Brazilian Amazon’s territory is designated as Indigenous territory and conservation units, where deforestation is generally banned. The remaining forest area (approximately 25 to 30%) is owned by the federal, state, or municipal governments, often called “non-designated” forests. Deforestation is illegal in these areas, but land grabbers covet them, counting on the weak enforcement presence and the perspective of securing land rights in the future. Despite strict bans against deforestation, Brazil has a weak enforcement system in the Amazon forest, and much of the policy discussions focus on how to improve it.

Despite the legislative progress of the preceding decades, Amazon deforestation continued to hit records, prompting the government to act decisively by launching a multi-ministerial task force called PPCDAm in 2004. Critical elements of the PPCDAm were strengthening the federal enforcement agency IBAMA, creating a quasi-real-time satellite-based monitoring system (called “DETER”), and expanding protected land (i.e., Indigenous territory or conservation units). In 2008, the government enacted new policies focusing on enforcement, such as the increase in penalty rates for most infractions (particularly forest fires) and the policy of “priority municipalities,” in which municipalities receive more intensive inspection efforts.

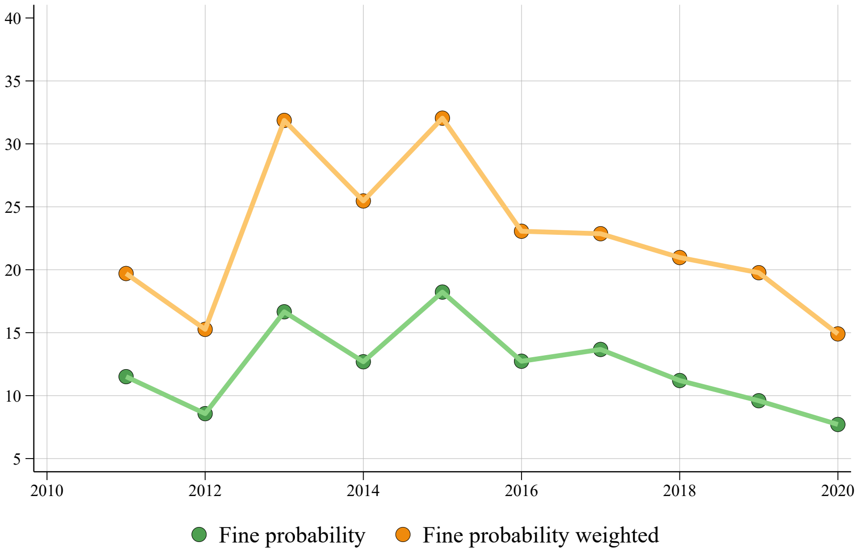
An enforcement action by IBAMA typically comprises a field visit, and in case of a presumed infraction, officials hand the offender a fine. The fines are proportional to the deforested or degraded area, which can be increased if deforestation is in the property's "Legal Reserve," in protected territory, or in publicly owned forests. There can also be aggravating circumstances that increase the fines, such as using fire for deforestation or transporting illegally extracted wood. The standard fine rate, set by a 2008 presidential decree, is approximately 1 thousand USD per hectare of deforestation on private property.

Three major issues limit the ability to enforce the Brazilian conservation law effectively: the low execution of fines, the limited capacity to conduct inspections, and the lack of clarity on land tenure. On average, only 2% of the nominal fines get paid to the government (Schmitt 2015). The lack of enforcement of fines is a severe limitation of Brazilian environmental law, which has sparked a debate about whether inspections offer any deterrence at all. However, inspections impose costs on offenders beyond the nominal fine. First, fines impose administrative burdens on offenders, and defaulting on them limits their ability to obtain loans. Second, the property with deforestation is embargoed and cannot sell its produce legally. Finally, whenever possible, inspectors seize the equipment used for deforestation. The equipment is later auctioned or destroyed. Therefore, inspections are potentially costly to offenders, even if the fine's value does not perfectly reflect this cost.

Despite the shortcomings of fine execution and the econometric challenges regarding the interpretation of the data, there is strong empirical evidence that IBAMA's inspections deter deforestation in the Brazilian Amazon Forest. The real-time monitoring system DETER has allowed IBAMA to target inspections more quickly, and areas with better satellite visibility have shown lower levels of deforestation (Ferreira 2024). Municipalities that received fines thanks to DETER information presented a substantially lower level of deforestation one year after IBAMA's intervention (Assunção, Gandour, and Rocha 2023). Moreover, increases in the inspection rates of "priority municipalities" reduced deforestation rates relative to non-priority municipalities (Assunção and Rocha 2019, Assunção et al. 2019). Finally, enforcement action also had a positive effect on regeneration rates in targeted areas (Assunção, Gandour, and Souza-Rodrigues 2019, Oliveira Filho 2020). In summary, despite the deficiencies of the Brazilian enforcement system, there is abundant empirical evidence of behavioral responses to changes in inspection rates.

The second issue is the limited capacity of IBAMA. The limited capacity of the federal enforcement agency to punish deforestation in the Amazon forest is reflected in the probability of fines in areas with deforestation. Using geo-referenced fines, Ferreira (2024) computes the probability of a fine happening in the same year of deforestation at around 13% in the decade from 2011-2020, with a steady decline in the last couple of years, as shown in figure 3. Adjusting for the size of deforestation areas, the share of deforestation area that was fined by IBAMA is around 25-30%. These numbers reveal a strikingly low probability of enforcement in the Amazon.

Figure 3: Fine probability in the Brazilian Amazon forest



Obs: This figure depicts the probability of receiving a fine in a given year in which deforestation is detected. The analysis is doing by dividing the Brazilian Forest in a grid cells of 4 km x 4 km in which there is positive deforestation (based on PRODES data), and computing the share of these grid cells that had a fine (based on geo-referenced IBAMA fines). The lower, green line depicts the probability of a fine per year conditional on positive deforestation within the grid cell. The higher, orange line, weighs the observation by the area of deforestation within the grid cell. This exercise is based on Ferreira (2024).

The situation has worsened since 2013, when Brazil started facing an economic crisis that led to budget cuts in several agencies, including IBAMA. The overall budget of the institution fell by 20% in real values from 2014 to 2020, and the operational expenditures in the Amazon forest plummeted by 40% in real terms. The number of environmental agents is also relatively small, with only about 200 agents allocated in the states of the Amazon Forest.[18] The recent fall in IBAMA's capacity, along with the visible reduction in the fine probability and increase in deforestation rates, is an eloquent indication of the importance of enforcement efforts in the control of deforestation in Brazil.

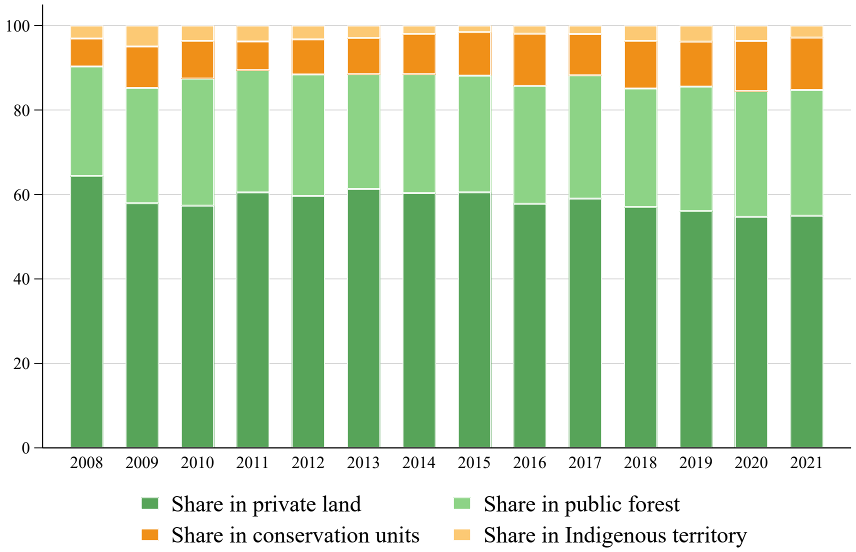
Finally, important enforcement issue regards the various types of land tenure in the Amazon forest. In the Brazilian part of the forst, approximately half the deforestation happens within private properties or government-sponsored land distribution projects ("assentamentos"). However, this share has been dropping in recent years, with deforestation in conservation units and

---

[18] Source: human resources spreadsheet of environmental agents of IBAMA, requested by the author.

public forests rising (see Figure 4). Outside of publicly registered farms, enforcement agents cannot identify the offender only by knowing where deforestation is; instead, they need to be more ostensibly present in the field. Enforcement operations involve trips from the agency's offices to the locality of the presumed infraction using cars, trucks, or helicopters. For this reason, real-time information from satellites is instrumental to target inspections and catch offenders.[19]

Figure 4: Share of deforestation by land tenure in the Brazilian Amazon



Obs: This figure depicts the share of yearly deforestation by land tenure using four categories: private land, public forest, conservation units, and Indigenous territory. Private land is based on the data of CAR, SIGEF, and INCRA, and includes government-sponsored land distribution projects ("assentamentos"). Maps of Conservation Units are obtained from INPE. Maps of Indigenous territories are obtained from FUNAI and refer to those territories that were registered ("homologated") by the year 2020. Public forest is the residual share of these other land tenures, after correcting for overlaps using the following hierarchy: Indigenous territory trumps conservation units, which trump private land. Deforestation data is obtained from PRODES.

In recent years, the federal government has been expanding a digital dataset of rural properties called CAR.[20] Farmers can declare their properties on CAR, with the geographical coordinates, which are eventually verified and confirmed by authorities. The clarification of land ownership in the Brazilian Amazon Forest clearly helps the task of enforcement agents, since it enables

---

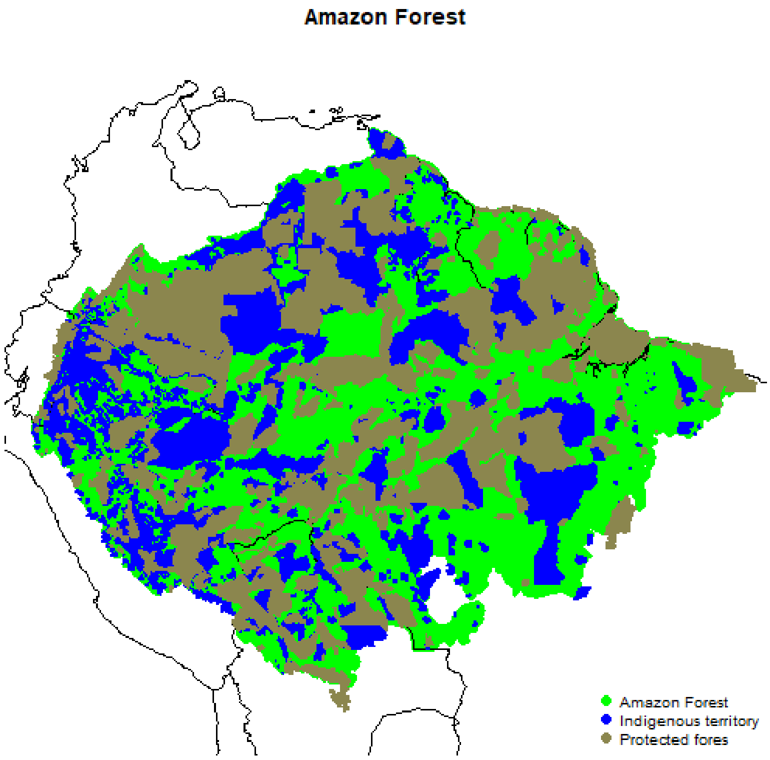
[19] Moreover, even when satellites detect deforestation on private land, IBAMA's agents must go in person to carry out the inspection and fine the farmers. Only in recent years did IBAMA start sending fines to farmers based exclusively on satellite images, and will probably expand this practice in the future in the absence of legal obstacles. More information on IBAMA's webpage: http://www.ibama.gov.br/ultimas-3/1795-nova-ferramenta-aprimora-controle-do-desmatamento-ilegal Some legal disputes over this practice already exist, as reported here: https://oeco.org.br/reportagens/ibama-muda-regras-para-aplicacao-de-multas-e-dificulta-ainda-mais-punicao-a-desmatadores/

[20] Shapefiles of the declared properties are available online for free on a special website: `https://www.car.gov.br/publico/imoveis/index`

them to assign responsibility more easily to offenders. Alix-Garcia et al. (2018) see evidence of reduced deforestation due to the rolling out of CAR. However, CAR has also been exploited by land-grabbers who claim illegally occupied land, generating other types of enforcement challenges.

Defining protected areas is a common policy throughout the Amazon Forest. as shown in Figure 5. However, there is mixed evidence on their impact on conservation. Indigenous lands in Brazil have modestly positive conservation effects on their borders (Baragwanath and Bayi 2020), but null overall effects (BenYishay et al. 2017). Similarly, protected conservation areas seem to present only modest positive effects on conservation (Pfaff et al. 2015), if any (Joppa and Pfaff 2011). A recent study in Peru found positive effects of protected areas in Peru, with no difference for areas that allow for resource extraction (Rico, Wang, and Pfaff 2023).

Figure 5: Indigenous Territories and Protected Forests



Source: RAISG

4.3 Price regulation and financial incentives

Although Brazil and the other Amazon countries have no specific tax on deforestation, small-scale initiatives resemble price regulation by giving conditional financial incentives to preserve forests in the form of “payments for ecosystem services” (PES). Such programs present a trade-off between cost-effectiveness and participation since large payments would likely make the cost of conservation too expensive by attracting participants who would conserve their forest regardless of the program. Moreover, PES becomes particularly difficult to design in environments with unclear land tenure or when deforestation happens on public land, as is often the case in the Amazon. Finally, PES still requires monitoring efforts to ensure compliance with the conditional payment.

Few large-scale PES programs exist in the Amazon Forest (see Pagiola, Von Glehn, and Taffarello 2013 for a few case studies). One example is the “Bosques” program in Peru, which gives payments to Indigenous communities in proportion to conserved forests. Another example is the Brazilian “Bolsa Verde”, which gives a conditional cash transfer for low-income farmers and has had modest impacts on conservation (Cisneros et al. 2022). Despite their large geographic scope, these programs have difficulties obtaining participants and are still small in relation with the potential targeted population. Despite the issues with takeup and design, direct price incentives have also been cost-effective in inducing forest conservation in Africa (Jayachandran et al. 2017). Currently, many organizations and governments are experimenting with payments for ecosystem services in Latin America.

Another way to provide financial incentives for conservation is through the financial system. In the scope of the 2008 PPCDAm policies, the Brazilian Central Bank restricted access to subsidized rural credit to farmers compliant with conservation law in the Amazon Forest. Given that rural credit finances approximately one third of agricultural expenses, such restrictions should represent an important incentive to comply with conservation legislation. Comparing Amazon municipalities to neighboring municipalities unaffected by the regulation, Assunção et al. (2020) find sizable conservation effects of this policy. The limitation of this program is that it can only directly affect the incentives of formalized farmers who take subsidized loans. In short, informality and lack of clear property rights have been obstacles in designing price regulations for conservation in the Amazon.

4.4 Market access and labels

In addition to quantity and price regulations, there are several indirect ways to discourage farmers from destroying the forest. Common approaches involve demand interventions, such as sustainable labels, market access rules, and indirect taxation. Labels and market access rules are related to corporate or individual social reponsibility, meaning that corporations or individuals take it upon themselves to reward sustainable suppliers. The result is a price premium on sustainable practices that works similar to a price incentive on conservation (Bénabou and Tirole 2010).

One prominent initiative in Brazil is the so-called “Soy Moratorium”, which is an industry arrangement brokered by farmers, traders, and the organization GreenPeace. According to this arrangement, traders would only buy soy from farmers that had not deforested after July 2006. The compliance with the Soy Moratorium would be enforced via airplane inspections at first, and later satellite-based remote sensing. The Moratorium severely limited the incentives of farmers to expand soy fields, since they could not have access to export markets, and successfully reduced the pressure of soy on deforestation (Nepstad et al. 2014, Nepstad et al. 2009, Heilmayr et al. 2020). A similar initiative was attempted with meat production, but has so far failed to come through because of the lack of a reliable traceability system for cattle. As described in Abreu (2022, July), cattle raised on illegally deforested land is easily mixed with cattle raised on regular farms and then sent to slaughterhouses. Indeed, since the Soy Moratorium, expansion of pastures for cattle-grazing is the main driver of Amazon deforestation in Brazil. Despite the apparent success of the Soy Moratorium, corporate pledges to reduce deforestation do not systematically present positive results in terms of conservation, suffering from low credibility and leakage problems (Lambin et al. 2018).

Corporations also may signal to consumers and stakeholders their commitment to environmental causes through ecological certification. However, researchers have not found additional conservation outcomes from certified forests or farms in logging concessions in the Peruvian Amazon (Rico-Straffon et al. 2023). Similarly, Blackman, Goff, and Planter (2018) find no effect of FSC certification on conservation in Mexican forests. These disappointing results mean that the certification allows producers to specialize into different markets, supplying environmentally-minded consumers, but without affecting the behavior of producers.

One potential cause for the small effect of such supply-side interventions is that the size of the market for sustainable products is limited by the demand. For this reason, environmental organizations often invest in interventions to awareness about environmental causes among consumers, hoping to affect their preferences and steer consumers’ behavior. In this regard, the behavioral literature has provided some insights in understanding which messaging tools have impact on people’s consumption choices and preferences (Banerjee et al. 2023a, Banerjee et al. 2023b) and conservation preferences (Ferreira and Banerjee 2024).

5 Conclusion

Amazon deforestation is a complex issue where the legitimate urge to deforest for economic gain conflicts with the externalities generated on local, regional, and global scales. More and more, social sciences research reveals what works and does not work for forest protection. This review aimed to provide a review of the main statistics, drivers, and policies related to forest protection in this biome. As explained throughout the text, Amazon deforestation started in the 1970s, accelerated in the last two decades, and shows no signs of receding. Some policy solutions have effectively reduced deforestation rates, but they often fall short of halting deforestation rates due to a lack of state capacity and the complex land tenure structure in the forest.

However, much is still to be discovered about the effects of current policies. What is the role of poverty and inequality in forest protection, and what is the incidence of costs of conservation policies? Relatedly, what are the optimal criteria for targeting enforcement practices? Beyond enforcement, several other policy-relevant questions deserve research. What policies discourage farmers from using fire in deforestation? Is it realistic to posit that sustainable extraction activities are a solution that may protect the forest and guarantee households' livelihoods? On a more macro-policy level, deforestation has been debated in the context of international trade deals. For example, the lack of guarantees to reduce Amazon deforestation was one of the arguments that led the EU-Mercosur trade into a deadlock. Is it possible to create multi-block mechanisms of financial incentives for conservation and regeneration inside the European Emissions Trading Scheme? These are research topics with the potential to help design better policies and achieve conservation cost-effectively.

References

Abreu, Allan de (2022, July). “A Lavagem da Boiada”. In: *Piauí* 190.

Alix-Garcia, Jennifer, Lisa L Rausch, Jessica L’Roe, Holly K Gibbs, and Jacob Munger (2018). “Avoided deforestation linked to environmental registration of properties in the Brazilian Amazon”. In: *Conservation Letters* 11.3, e12414.

Ambec, Comission (2020). “Dispositions et Effets Potentiels de la Partie Commerciale de l’Accord d’Association entre l’Union Europeenne et le Mercosur en matiere de developpement durable”. In: *Rapport au Premier Ministre.*

Aragão, Luiz EOC, Liana O Anderson, Marisa G Fonseca, Thais M Rosan, Laura B Vedovato, Fabien H Wagner, Camila VJ Silva, Celso HL Silva Junior, Egidio Arai, Ana P Aguiar, et al. (2018). “21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions”. In: *Nature communications* 9.1, pp. 1–12.

Araujo, Rafael (2021). “Mapping the Effect of Deforestation on Rainfall: A Case Study from the State of Mato Grosso”. In: *Climate Policy Initiative Rio de Janeiro.*

– (2024). “The value of tropical forests to hydropower”. In: *Energy Economics* 129, p. 107205.

Araujo, Rafael, Juliano Assunção, Marina Hirota, and José A Scheinkman (2023). “Estimating the spatial amplification of damage caused by degradation in the Amazon”. In: *Proceedings of the National Academy of Sciences* 120.46, e2312451120.

Araujo, Rafael, Francisco Costa, and Marcelo Sant’Anna (2022). “Efficient forestation in the Brazilian Amazon: Evidence from a dynamic model”. In: *Working Paper.*

Assunção, Juliano, Clarissa Gandour, and Romero Rocha (2023). “DETERring deforestation in the Brazilian Amazon: environmental monitoring and law enforcement”. In: *American Economic Journal: Applied Economics.*

Assunção, Juliano, Clarissa Gandour, Romero Rocha, and Rudi Rocha (2020). “The effect of rural credit on deforestation: evidence from the Brazilian Amazon”. In: *The Economic Journal* 130.626, pp. 290–330.

Assunção, Juliano, Clarissa Gandour, Rudi Rocha, et al. (2015). “Deforestation slowdown in the Brazilian Amazon: prices or policies”. In: *Environment and Development Economics* 20.6, pp. 697–722.

Assunção, Juliano, Clarissa Gandour, and Eduardo Souza-Rodrigues (2019). “The Forest Awakens: Amazon Regeneration and Policy Spillover”. In: *CPI Working Paper.*

Assunção, Juliano, Robert McMillan, Joshua Murphy, and Eduardo Souza-Rodrigues (2019). “Optimal environmental targeting in the amazon rainforest”. In: *National Bureau of Economic Research.*

Assunção, Juliano and Romero Rocha (2019). "Getting greener by going black: the effect of blacklisting municipalities on Amazon deforestation". In: *Environment and Development Economics* 24.2, pp. 115–137.

Baccini, AGSJ, SJ Goetz, WS Walker, NT Laporte, Mindy Sun, Damien Sulla-Menashe, Joe Hackler, PSA Beck, Ralph Dubayah, MA Friedl, et al. (2012). "Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps". In: *Nature climate change* 2.3, pp. 182–185.

Balboni, Clare, Aaron Berman, Robin Burgess, and Benjamin A Olken (2023). "The economics of tropical deforestation". In: *Annual Review of Economics* 15.1, pp. 723–754.

Banerjee, Sanchayan, Matteo M Galizzi, Peter John, and Susana Mourato (2023a). "Immediate backfire? Nudging sustainable food choices and psychological reactance". In: *Food Quality and Preference* 109, p. 104923.

– (2023b). "Sustainable dietary choices improved by reflection before a nudge in an online experiment". In: *Nature Sustainability* 6.12, pp. 1632–1642.

Baragwanath, Kathryn and Ella Bayi (2020). "Collective property rights reduce deforestation in the Brazilian Amazon". In: *Proceedings of the National Academy of Sciences* 117.34, pp. 20495–20502.

Barlow, Jos, Gareth D Lennox, Joice Ferreira, Erika Berenguer, Alexander C Lees, Ralph Mac Nally, James R Thomson, Silvio Frosini de Barros Ferraz, Julio Louzada, Victor Hugo Fonseca Oliveira, et al. (2016). "Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation". In: *Nature* 535.7610, pp. 144–147.

Barrage, Lint and William Nordhaus (2024). "Policies, projections, and the social cost of carbon: Results from the DICE-2023 model". In: *Proceedings of the National Academy of Sciences* 121.13, e2312030121.

Barsanetti, Bruno and Alipio Ferreira (2024). "Historical Indigenous Extinctions and Modern Deforestation in the Amazon". In: *Working Paper.*

Bénabou, Roland and Jean Tirole (2010). "Individual and corporate social responsibility". In: *Economica* 77.305, pp. 1–19.

BenYishay, Ariel, Silke Heuser, Daniel Runfola, and Rachel Trichler (2017). "Indigenous land rights and deforestation: Evidence from the Brazilian Amazon". In: *Journal of Environmental Economics and Management* 86, pp. 29–47.

Bispo, Fabio and Anderson Coelho (2021, October 10th). "Agro desmatara um milhao de hectares por ano na Amazonia para atender demanda por carne ate 2030". In: *O Joio e o Trigo: https://ojoioeotrigo.com.br/2021/10/agro-vai-desmatar-um-milhao-de-hectares-por-ano-na-amazonia-para-atender-demanda-por-carne-ate-2030/.*

Blackman, Allen, Leonard Goff, and Marisol Rivera Planter (2018). "Does eco-certification stem tropical deforestation? Forest Stewardship Council certification in Mexico". In: *Journal of Environmental Economics and Management* 89, pp. 306–333.

Brockerhoff, Eckehard G, Hervé Jactel, John A Parrotta, Christopher P Quine, and Jeffrey Sayer (2008). "Plantation forests and biodiversity: oxymoron or opportunity?" In: *Biodiversity and Conservation* 17.5, pp. 925–951.

Busch, Jonah and Kalifi Ferretti-Gallon (2017). "What drives deforestation and what stops it? A meta-analysis". In: *Review of Environmental Economics and Policy.*

Butt, Edward W, Luke Conibear, Christoph Knote, and Dominick V Spracklen (2021). "Large air quality and public health impacts due to Amazonian deforestation fires in 2019". In: *GeoHealth* 5.7, e2021GH000429.

Carraro, Carlo and Emanuele Massetti (2009, September 3rd). "The improbable 2C global warming target". In: *CEPR, available at https://cepr.org/voxeu/columns/improbable-2degc-global-warming-target.*

Catterrall, C, John Kanowski, Grant Wardell-Johnson, Heather Proctor, T Rels, Debra Harrison, and N Tucker (2004). "Quantifying the biodiversity values of reforestation: perspectives, design issues and outcomes in Australian rainforest landscapes". In: *Conservation of Australia? s Forest Fauna.* Royal Zoological Society of New South Wales, pp. 359–393.

Chan, Kai MA, Joshua Goldstein, Terre Satterfield, Neil Hannahs, Kekuewa Kikiloi, Robin Naidoo, Nathan Vadeboncoeur, Ulalia Woodside, et al. (2011). "Cultural services and non-use values". In: *Natural capital: Theory and practice of mapping ecosystem services*, pp. 206–228.

Cisneros, Elias, Jan Borner, Stefano Pagiola, and Sven Wunder (2022). "Impacts of conservation incentives in protected areas: The case of Bolsa Floresta, Brazil". In: *Journal of Environmental Economics and Management.*

Cleary, David (2001). "Towards an environmental history of the Amazon: from prehistory to the nineteenth century". In: *Latin American Research Review*, pp. 65–96.

Conservancy, The Nature (2019). "Incentives for Sustainable Soy in the Cerrado". In: *Technical Report.*

Costa, Camilla (2020, February 18th). "Amazônia: o que ameaça a floresta em cada um de seus 9 países?" In: *BBC News Brasil, https://www.bbc.com/portuguese/brasil-51377232.*

Crime, InSight and Igarapé Institute (2021). "The Roots of Environmental Crime in the Colombian Amazon". In: *Report.*

Da Mata, Daniel, Mario Dotta, and Thiago Lobo (2023). "Technological progress and climate change: Evidence from the agricultural sector". In: *Available at SSRN 4358828.*

Dávalos, Liliana M, Karina M Sanchez, and Dolors Armenteras (2016). “Deforestation and coca cultivation rooted in twentieth-century development projects”. In: *BioScience* 66.11, pp. 974–982.

Denevan, William M. (2003). “The native population of Amazonia in 1492 reconsidered”. In: *Revista de Indias* 63.227, pp. 175–188.

– (2014). “Estimating Amazonian Indian numbers in 1492”. In: *Journal of Latin American Geography*, pp. 207–221.

D’Amore, David and Evans Kane (2016). “Climate Change and Forest Soil Carbon”. In: *U.S. Department of Agriculture, Forest Service, Climate Change Resource Center. www.fs.usda.gov/ccrc/topic soil-carbon.*

Ellwanger, Joel Henrique, Bruna Kulmann-Leal, Valéria L Kaminski, JACQUELINE Valverde-Villegas, ANA BEATRIZ G VEIGA, Fernando R Spilki, Philip M Fearnside, Lílian Caesar, Leandro Luiz Giatti, Gabriel L Wallau, et al. (2020). “Beyond diversity loss and climate change: Impacts of Amazon deforestation on infectious diseases and public health”. In: *Anais da Academia Brasileira de Ciências* 92.

EPA (n.d.). “EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances”. In: *U.S. Environmental Protection Agency* ().

Fearnside, Philip M (1999). “Biodiversity as an environmental service in Brazil’s Amazonian forests: risks, value and conservation”. In: *Environmental conservation* 26.4, pp. 305–321.

– (2021). “The intrinsic value of Amazon biodiversity”. In: *Biodiversity and Conservation* 30.4, pp. 1199–1202.

Ferreira, Alipio (2024). “Satellites and Fines: Using Real-Time Monitoring to Target Inspections of Deforestation”. In: *Working Paper.*

Ferreira, Alipio and Sanchayan Banerjee (2024). “Virtual Reality and Forest Conservation Behaviours: Evidence from a Field Experiment in Brazil”. In: *Working Paper.*

Gasparinnetti, Pedro, Leonardo Barcellos Bakker, Julia Mello Queiroz, and Thais Vilela (2024). “Economic valuation of artisanal small-scale gold mining impacts: A framework for value transfer application”. In: *Resources Policy* 88, p. 104259.

Gatti, Luciana V, Luana S Basso, John B Miller, Manuel Gloor, Lucas Gatti Domingues, Henrique LG Cassol, Graciela Tejada, Luiz EOC Aragão, Carlos Nobre, Wouter Peters, et al. (2021). “Amazonia as a carbon source linked to deforestation and climate change”. In: *Nature* 595.7867, pp. 388–393.

Gerson, Jacqueline R, Natalie Szponar, Angelica Almeyda Zambrano, Bridget Bergquist, Eben Broadbent, Charles T Driscoll, Gideon Erkenswick, David C Evers, Luis E Fernandez, Heileen Hsu-Kim, et al. (2022). “Amazon forests capture high levels of atmospheric mercury pollution from artisanal gold mining”. In: *Nature communications* 13.1, pp. 1–10.

Gibson, Luke, Tien Ming Lee, Lian Pin Koh, Barry W Brook, Toby A Gardner, Jos Barlow, Carlos A Peres, Corey JA Bradshaw, William F Laurance, Thomas E Lovejoy, et al. (2011). "Primary forests are irreplaceable for sustaining tropical biodiversity". In: *Nature* 478.7369, pp. 378–381.

Glaeser, Edward L and Andrei Shleifer (2001). "A reason for quantity regulation". In: *American Economic Review* 91.2, pp. 431–435.

Hansen, James (2010). *Storms of my grandchildren: The truth about the coming climate catastrophe and our last chance to save humanity.* Bloomsbury Publishing USA.

Hansen, Matthew C, Peter V Potapov, Rebecca Moore, Matt Hancher, Svetlana A Turubanova, Alexandra Tyukavina, David Thau, Stephen V Stehman, Scott J Goetz, Thomas R Loveland, et al. (2013). "High-resolution global maps of 21st-century forest cover change". In: *science* 342.6160, pp. 850–853.

Heilmayr, Robert, Lisa L Rausch, Jacob Munger, and Holly K Gibbs (2020). "Brazil's Amazon soy moratorium reduced deforestation". In: *Nature Food* 1.12, pp. 801–810.

Hubau, Wannes, Simon L Lewis, Oliver L Phillips, Kofi Affum-Baffoe, Hans Beeckman, Aida Cuní-Sanchez, Armandu K Daniels, Corneille EN Ewango, Sophie Fauset, Jacques M Mukinzi, et al. (2020). "Asynchronous carbon sink saturation in African and Amazonian tropical forests". In: *Nature* 579.7797, pp. 80–87.

INPE (2008). "Monitoramento da Cobertura Florestal da Amazônia por Satélites". In: *INPE report, by Antonio Miguel Vieira Monteiro, Camilo Daleles Rennó, Claudio A Almeida, Dalton de Morisson Valeriano, Joao Vianei Soares, Luis Eduardo Maurano, Maria Isabel Sobral Escada, Silvana Amaral and Taise Farias Pinheiro.*

IPBES (2018). "Regional Assessment Report on Biodiversity and Ecosystem Services for the Americas". In: *IPBES reports.*

IPCC (2007). "Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change". In: *Solomon, S. and Qin, D. and Manning,M. and Chen, Z. and Marquis, M. and Averyt, K.B. and Tignor, M. and Miller, H.L.*

– (2014). "Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change". In: *Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

– (2016). "Chapter 2: Emissions Trends and Drivers of the Intergovernmental Panel on Climate Change Report". In: *Dhakal, Shobhakar and Minx, Jan Christoph and Toth, Ferenc L. (eds.*

Jayachandran, Seema, Joost De Laat, Eric F Lambin, Charlotte Y Stanton, Robin Audy, and Nancy E Thomas (2017). "Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation". In: *Science* 357.6348, pp. 267–273.

Joppa, Lucas N and Alexander Pfaff (2011). "Global protected area impacts". In: *Proceedings of the Royal Society B: Biological Sciences* 278.1712, pp. 1633–1638.

Lambin, Eric F, Holly K Gibbs, Robert Heilmayr, Kimberly M Carlson, Leonardo C Fleck, Rachael D Garrett, Yann Le Polain de Waroux, Constance L McDermott, David McLaughlin, Peter Newton, et al. (2018). "The role of supply-chain initiatives in reducing deforestation". In: *Nature Climate Change* 8.2, pp. 109–116.

Leite-Filho, Argemiro Teixeira, Veronica Yamee de Sousa Pontes, and Marcos Heil Costa (2019). "Effects of deforestation on the onset of the rainy season and the duration of dry spells in southern Amazonia". In: *Journal of Geophysical Research: Atmospheres* 124.10, pp. 5268–5281.

Lovejoy, Thomas E and Carlos Nobre (2018). "Amazon tipping point". In: *Science Advances.*

– (2019). "Amazon tipping point: Last chance for action". In: *Science Advances.*

MacDonald, Andrew J and Erin A Mordecai (2019). "Amazon deforestation drives malaria transmission, and malaria burden reduces forest clearing". In: *Proceedings of the National Academy of Sciences* 116.44, pp. 22212–22218.

Macedo, Marcia N, Ruth S DeFries, Douglas C Morton, Claudia M Stickler, Gillian L Galford, and Yosio E Shimabukuro (2012). "Decoupling of deforestation and soy production in the southern Amazon during the late 2000s". In: *Proceedings of the National Academy of Sciences* 109.4, pp. 1341–1346.

MapBiomas (2024). "RAD2023: Relatorio Anual do Desmatamento no Brasil 2023". In: *MapBiomas.*

Mecca, Marlei Salete, Daiane Cristina Bonatto Vergani, and Alex Eckert (2022). "Custos de Produção pecuária: análise da lucratividade na criação de gato extensivo e em confinamento de uma empresa produtora rural." In: *Revista Valore* 7, p. 7039.

Medvigy, David, Robert L Walko, Martin J Otte, and Roni Avissar (2013). "Simulated changes in northwest US climate in response to Amazon deforestation". In: *Journal of Climate* 26.22, pp. 9115–9136.

Mitchard, Edward TA (2018). "The tropical forest carbon cycle and climate change". In: *Nature* 559.7715, pp. 527–534.

Nepstad, Daniel, David McGrath, Claudia Stickler, Ane Alencar, Andrea Azevedo, Briana Swette, Tathiana Bezerra, Maria DiGiano, João Shimada, Ronaldo Seroa da Motta, et al. (2014). "Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains". In: *science* 344.6188, pp. 1118–1123.

Nepstad, Daniel, Adriana Moreira, and Ane Alencar (1999). *Flames in the rain forest: origins, impacts and alternatives to Amazonian fires.* World Bank, Pilot Program to Conserve the Brazilian Rain Forest.

Nepstad, Daniel, Britaldo S Soares-Filho, Frank Merry, André Lima, Paulo Moutinho, John Carter, Maria Bowman, Andrea Cattaneo, Hermann Rodrigues, Stephan Schwartzman, et al. (2009). "The end of deforestation in the Brazilian Amazon". In: *Science* 326.5958, pp. 1350–1351.

Nepstad, Daniel C, Adalberto Verssimo, Ane Alencar, Carlos Nobre, Eirivelthon Lima, Paul Lefebvre, Peter Schlesinger, Christopher Potter, Paulo Moutinho, Elsa Mendoza, et al. (1999). "Large-scale impoverishment of Amazonian forests by logging and fire". In: *Nature* 398.6727, pp. 505–508.

Nobre, Carlos Afonso and Laura De Simone Borma (2009). "'Tipping points' for the Amazon forest". In: *Current Opinion in Environmental Sustainability* 1.1, pp. 28–36.

Ochoa-Quintero, Jose Manuel, Toby A Gardner, Isabel Rosa, Silvio Frosini de Barros Ferraz, and William J Sutherland (2015). "Thresholds of species loss in Amazonian deforestation frontier landscapes". In: *Conservation Biology* 29.2, pp. 440–451.

Oliveira Filho, Antonio Barbosa de (2020). "Impact of environmental law enforcement on deforestation, land use and natural regeneration in the Brazilian Amazon". In: *PhD Thesis Geography, Cambridge University.*

Pagiola, Stefano, H Carrascosa Von Glehn, and Denise Taffarello (2013). "Experiências de pagamentos por serviços ambientais no Brasil". In: *São Paulo: SMA/CBRN* 86494, pp. 1–338.

Pan, Yude, Richard A Birdsey, Jingyun Fang, Richard Houghton, Pekka E Kauppi, Werner A Kurz, Oliver L Phillips, Anatoly Shvidenko, Simon L Lewis, Josep G Canadell, et al. (2011). "A large and persistent carbon sink in the world's forests". In: *science* 333.6045, pp. 988–993.

Pereira, Leila and Rafael Pucci (2021). "A Tale of Gold and Blood: The Unintended Consequences of Market Regulation on Local Violence." In: *Climate Policy Initiative, Working Paper* 5.

Pfaff, Alexander, Juan Robalino, Diego Herrera, and Catalina Sandoval (2015). "Protected areas' impacts on Brazilian Amazon deforestation: examining conservation–development interactions to inform planning". In: *PloS one* 10.7, e0129460.

Pfaff, Alexander SP (1999). "What drives deforestation in the Brazilian Amazon?: Evidence from satellite and socioeconomic data". In: *Journal of environmental economics and management* 37.1, pp. 26–43.

Phillips, Oliver L and Roel JW Brienen (2017). "Carbon uptake by mature Amazon forests has mitigated Amazon nations' carbon emissions". In: *Carbon Balance and Management* 12.1, pp. 1–9.

Prem, Mounu, Santiago Saavedra, and Juan F Vargas (2020). “End-of-conflict deforestation: Evidence from Colombia’s peace agreement”. In: *World Development* 129, p. 104852.

Probst, Benedict, Ariel BenYishay, Andreas Kontoleon, and Tiago NP dos Reis (2020). “Impacts of a large-scale titling initiative on deforestation in the Brazilian Amazon”. In: *Nature Sustainability* 3.12, pp. 1019–1026.

Pucci, Rafael, Diego Menezes, João Mourão, and Clarissa Gandour (2021). “Through DETER’s Lens: The Relationship Between Degradation and Deforestation in the Amazon”. In: *Rio de Janeiro: Climate Policy Initiative*.

Ramos, Camila Souza (September 22nd, 2021). “Recuperar pastos pode custar ate RS250 bi”. In: *Valor, available at https://valor.globo.com/um-so-planeta/noticia/2021/09/22/recuperar-pastos-pode-custar-ate-r-250-bi.ghtml*.

Reddington, CL, EW Butt, DA Ridley, P Artaxo, WT Morgan, H Coe, and DV Spracklen (2015). “Air quality and human health improvements from reductions in deforestation-related fire in Brazil”. In: *Nature Geoscience* 8.10, pp. 768–771.

Requia, Weeberb J, Heresh Amini, Rajarshi Mukherjee, Diane R Gold, and Joel D Schwartz (2021). “Health impacts of wildfire-related air pollution in Brazil: a nationwide study of more than 2 million hospital admissions between 2008 and 2018”. In: *Nature communications* 12.1, pp. 1–9.

Rico, Jimena, Zhenhua Wang, Stephanie Panlasigui, Colby J Loucks, Jennifer Swenson, and Alexander Pfaff (2022). “Forest Concessions & Eco-Certifications in the Peruvian Amazon: Deforestation Impacts of Logging Rights and Restrictions”. In: *SSRN Working Paper*.

Rico, Jimena, Zhenhua Wang, and Alexander Pfaff (2023). “Comparing Protection Types in the Peruvian Amazon Multiple-Use Protected Areas Did No Worse for Forests”. In: *Available at SSRN 4540784*.

Rico-Straffon, Jimena, Zhenhua Wang, Stephanie Panlasigui, Colby J Loucks, Jennifer Swenson, and Alexander Pfaff (2023). “Forest concessions and eco-certifications in the Peruvian Amazon: Deforestation impacts of logging rights and logging restrictions”. In: *Journal of Environmental Economics and Management* 118, p. 102780.

Roosevelt, Anna C, Marcondes Lima da Costa, C Lopes Machado, Mostafa Michab, Norbert Mercier, Hélène Valladas, James Feathers, William Barnett, M Imazio da Silveira, Anne Henderson, et al. (1996). “Paleoindian cave dwellers in the Amazon: the peopling of the Americas”. In: *Science* 272.5260, pp. 373–384.

Sá, Suzane S de, Luciana V Rizzo, Brett B Palm, Pedro Campuzano-Jost, Douglas A Day, Lindsay D Yee, Rebecca Wernis, Gabriel Isaacman-VanWertz, Joel Brito, Samara Carbone, et al. (2019). “Contributions of biomass-burning, urban, and biogenic emissions to the concentrations and light-absorbing properties of particulate matter in central Amazonia during the dry season”. In: *Atmospheric Chemistry and Physics* 19.12, pp. 7973–8001.

Santana, Antônio Cordeiro de, Marcos Antônio Souza dos Santos, Ádamo Lima de Santana, and Jorge Alberto Gazel Yared (2012). "O valor econômico da extração manejada de madeira no Baixo Amazonas, Estado do Pará". In: *Revista Árvore* 36, pp. 527–536.

Schmitt, Jair (2015). "Crime sem castigo: a efetividade da fiscalização ambiental para o controle do desmatamento ilegal na Amazônia". In.

Souza, Márcio (1994). *Breve História da Amazônia.* São Paulo: Marco Zero.

Souza-Rodrigues, Eduardo (2019). "Deforestation in the Amazon: A unified framework for estimation and policy analysis". In: *The Review of Economic Studies* 86.6, pp. 2713–2744.

Spracklen, Dominick V, Steve R Arnold, and CM Taylor (2012). "Observations of increased tropical rainfall preceded by air passage over forests". In: *Nature* 489.7415, pp. 282–285.

Spracklen, DV, JCA Baker, L Garcia-Carreras, JH Marsham, et al. (2018). "The effects of tropical vegetation on rainfall". In: *Annual Review of Environment and Resources* 43.1, pp. 193–218.

Torres, Fernando G and Gabriel E De-la Torre (2022). "Mercury pollution in Peru: geographic distribution, health hazards, and sustainable removal technologies". In: *Environmental Science and Pollution Research*, pp. 1–15.

Tozzi, Giulia (2022). "Narco-Deforestation: The Environmental Effects of Coca Cultivation". In: *mimeo.*

Valdiones, Ana Paula, Paula Bernasconi, Vinícius Silgueiro, Vinícius Guidotti, Frederico Miranda, Julia Costa, Raoni Rajão, and Bruno Manzolli (2021). "Desmatamento Ilegal na Amazônia e no Matopiba: falta transparência e acesso à informação". In: *https://www.icv.org.br/website/ content/uploads/2021/05/icv-relatorio-f.pdf.*

Vijay, Varsha, Stuart L Pimm, Clinton N Jenkins, and Sharon J Smith (2016). "The impacts of oil palm on recent deforestation and biodiversity loss". In: *PloS one* 11.7, e0159668.

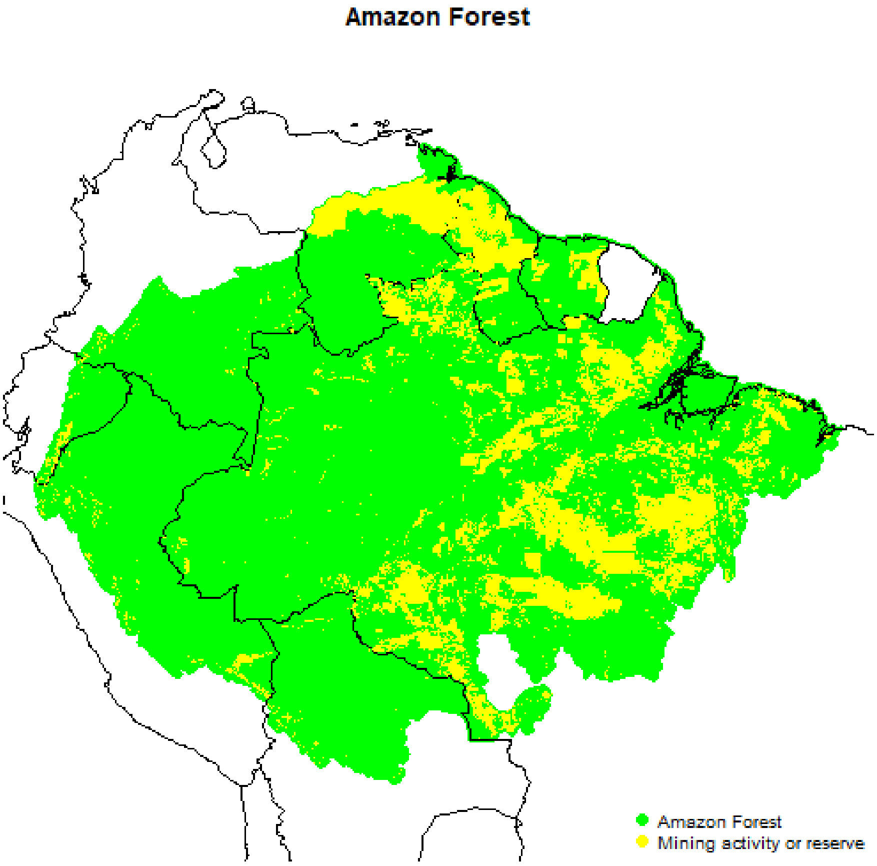
Weitzman, Martin (1974). "Prices vs. quantities". In: *Review of Economics Studies* 41, pp. 477–491.

Xu, Xiyan, Xiaoyan Zhang, William J Riley, Ying Xue, Carlos A Nobre, Thomas E Lovejoy, and Gensuo Jia (2022). "Deforestation triggering irreversible transition in Amazon hydrological cycle". In: *Environmental Research Letters* 17.3, p. 034037.

Appendices

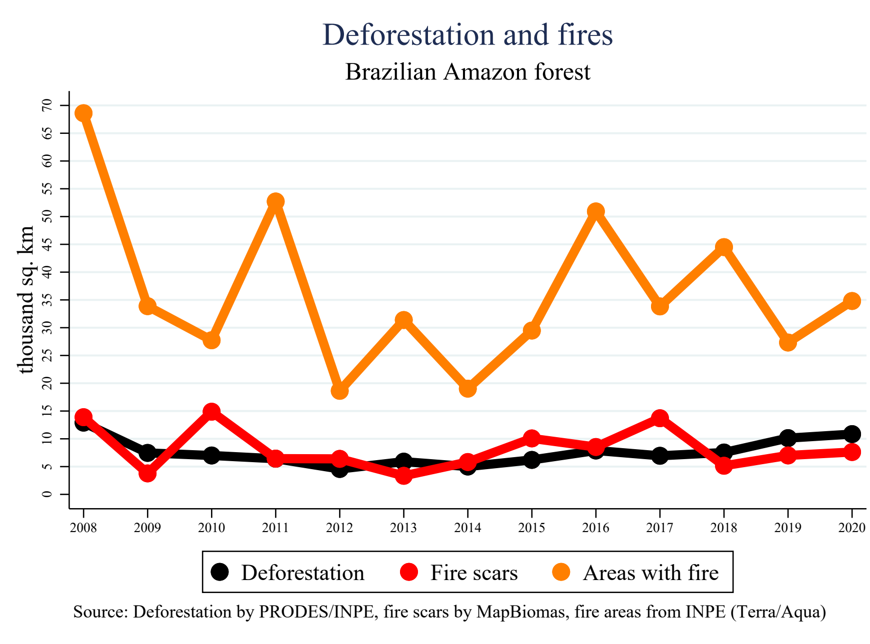
A Figures

Figure 6: Mineral Reserves and Mining Activities in the Amazon Forest



Source: RAISG (no data for French Guyana)

Figure 7: Degradation by fires

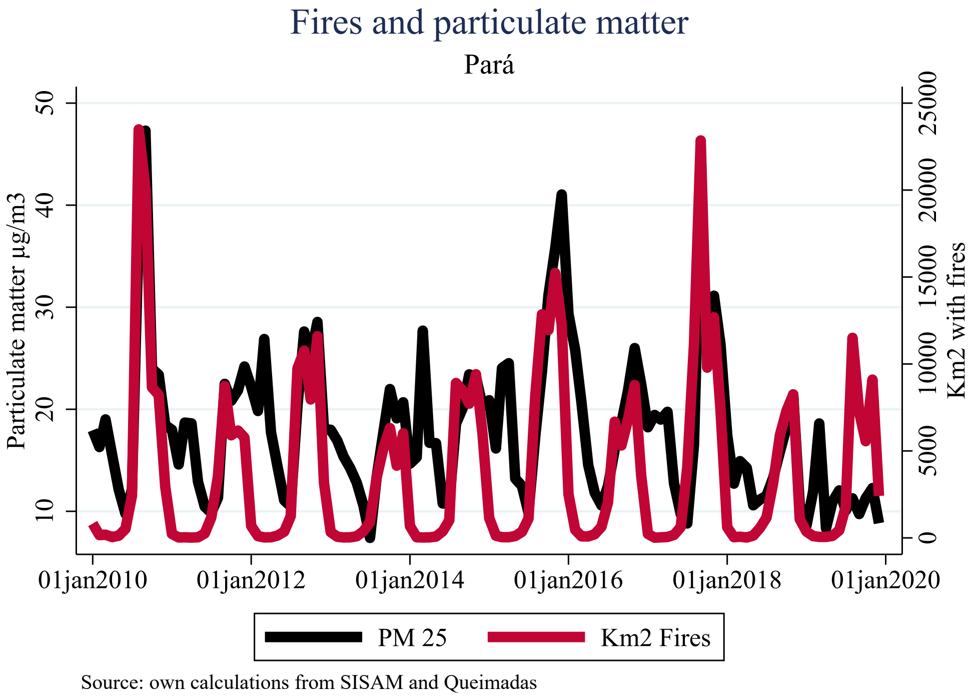

Deforestation and fires

Brazilian Amazon forest

Source: Deforestation by PRODES/INPE, fire scars by MapBiomas, fire areas from INPE (Terra/Aqua)

Obs: The figure plots three quantities measured in thousand of square kilometers. The black line depicts yearly deforestation based on PRODES. The red line depicts the area of fire scars based on MapBiomas. The orange line depicts the area of 1 km pixels that showed at least one fire event in the year, as measured by the satellites Terra and Aqua and downloaded from INPE.

Figure 8: Fires are highly correlated with concentration of PM

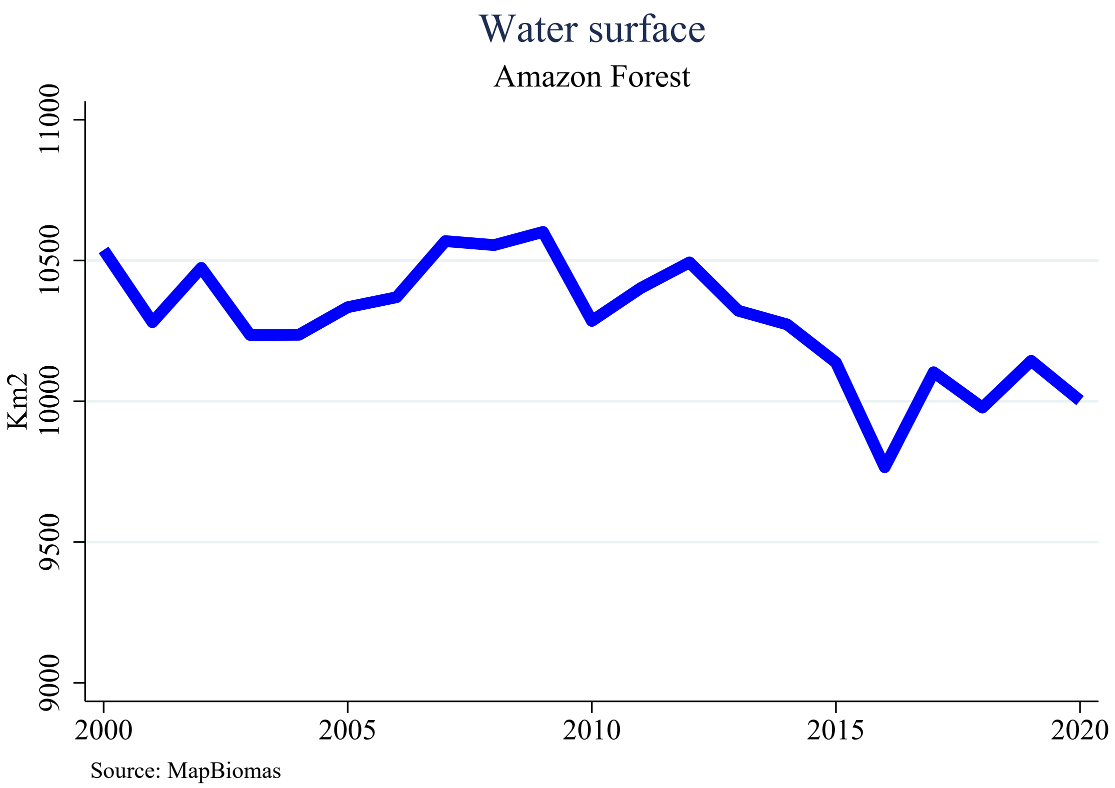

Fires and particulate matter

Pará

Source: own calculations from SISAM and Queimadas

Obs: The figure plots the correlation of PM 2.5 averaged across measurement stations in the state, showing that the average measure rose above 40 micrograms per cubic meter in 2010 and 2016 and almost reached 30 micrograms in several years, levels which are considered moderate or unsafe for human health, particularly for vulnerable groups. Source: Standards on air quality of the Environmental Protection Agency, available at: https://www.epa.gov/criteria-air-pollutants/naaqs-table

Figure 9: Water surface is 8% lower than the average pre-2010



B Calculation of greenhouse gas emissions

Table 2.1 of Chapter 2 in the 2016 IPCC report (IPCC 2016) states that the average emissions from fossil fuel combustion and industrial processs was 36 Gigatonnes of CO2 equivalent emissions per year in the years 2000-2009. Using the conversion rate 1gC = 3.67gCO2, this quantity is equivalent to burning approximately 10 Gigatonnes of carbon every year. Since the Amazon Forest contains 90 Gigatonnes of carbon stock, this stock represents nine years of fossil fuel and industrial emissions.

A Gigaton is equivalent to 10^9 tons and is sometimes referred to as a Petagram (Pg). Emitting 1GtC into the atmosphere increases the concentration of CO2 by 0.45 ppm (particles per million). Therefore, emitting 90 Gigatones of carbon would increase the concentration of CO2 in the atmosphere by 40.5 ppm. The conversion tables are extracted from the Carbon Dioxide Information Analysis Center, and can be accessed here: https://cdiac.ess-dive.lbl.gov/pns/convert.html

The current level of CO2 in the atmosphere, as measured in 2021 in the Mauna Loa Observatory in Hawaii, is 414.72 ppm. More information can be accessed on the NOAA's website: https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

The Fourth IPCC report (IPCC 2007) produced the following table containing the approximate mapping between CO2 ppm concentrations and temperature increases.

Table 4: CO2 concentrations and global warming

Greenhouse gas concentration (ppm CO2-equivalent)	**Most likely**	**Very likely above (>90%)**	**Likely in the range (>66%)**
350	1.0	0.5	0.6 - 1.4
450	2.1	1.0	1.4 - 3.1
550	2.9	1.5	1.9 - 4.4
650	3.6	1.8	2.4 - 5.5
750	4.3	2.1	2.8 - 6.4
1000	5.5	2.8	3.7 - 8.3
1200	6.3	3.1	4.2 - 9.4

Source: IPCC (2014) reproduced in Carraro and Massetti (2009, September 3rd)