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Amazon Deforestation: Drivers, damages, and policies

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Amazon Deforestation:
Drivers, damages, and policies

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Abstract

This chapter 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.

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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 stunning 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 through the centuries. But besides the biodiversity, the natural beauty, the water, and the 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 other countries, such as Colombia and Bolivia, deforestation is also connected to coca crops and the drug industry, but they have not achieved the scale of Brazilian deforestation. Despite policies trying to prevent farmers from destroying the forest, regulatory compliance is still an unsolved issue. Unclear property rights, understaffed enforcement agencies, and cumbersome judicial systems stand in the way of enforcing the law. Section 2 of this chapter discusses the economics of Amazon deforestation, particularly in Brazil, and the theoretical solutions that economists have proposed to the problem.

The Amazon Rainforest hosts the richest biodiversity in all of Earth's biomes, helps regulate the rainy 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 negative effects and summarizes the scientific literature measuring them.

Section 4 presents the historical experience with conservation policy in the Brazilian Amazon forest. Mainly focused on command and control, Brazil has successfully brought deforestation rates down by 70% from their high levels in the early 2000s. Enforcement improvements play an important role in forest conservation, but price incentives and industry arrangements also contribute. In recent years, however, deforestation has accelerated again. Finally, section **??** concludes by proposing some ways forward in terms of new policy instruments.

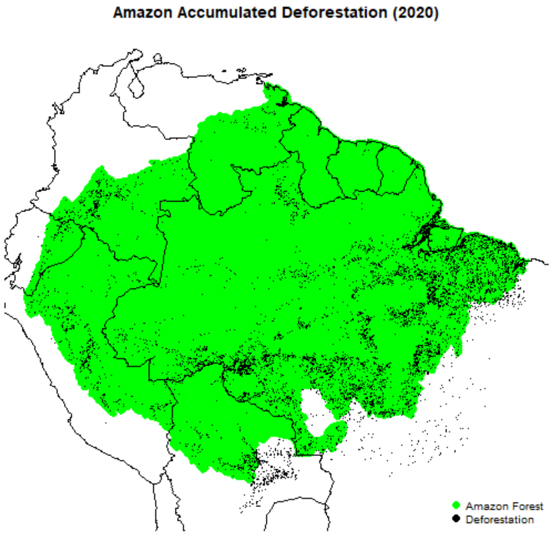
2 The economic drivers of Amazon deforestation

Historically, economic development in South America mainly occurred in coastal cities, either the Atlantic or the Pacific Ocean. Consequently, the forest remained largely intact until large-scale deforestation started in the 1970s. As a result, the Amazon Forest has lost 15% of its original forest cover.

The South and Southeastern frontiers of the Amazon Forest in Brazil are critical hotspots of deforestation. Brazilian farmers have been expanding northwards into the forest since the 1970s, converting the forest into crop fields and pastures. Brazil has lost 21% of its original forest cover, by far the largest share of all nine countries. Bolivia, 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. Table 1 summarizes the status of the Amazon Forest cover by country.

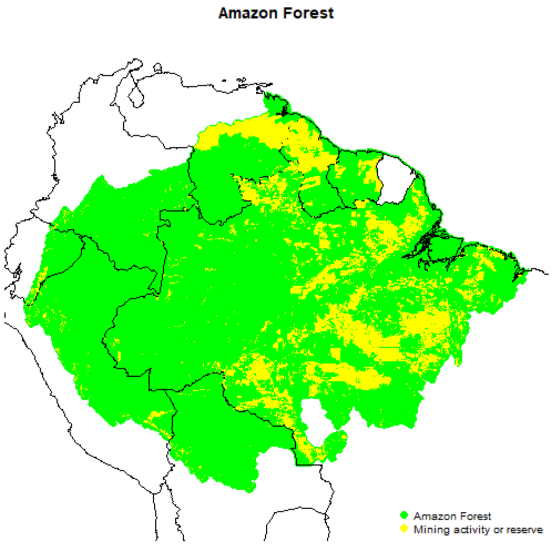
Deforestation is damaging to the environment and, ultimately, to humans. However, the forest is also a source of valuable resources such as fruits, timber, gold, and land. The leading cause of large-scale forest destruction is agriculture and pasture. Farmers augment their cultivation and pasture area by clearing vegetation and, when possible, taking possession of new land. Moreover, land value encourages farmers to take control of public forests and manufactured land ownership to sell it afterward.

Figure 1: The Amazon Forest Spans Across Nine Countries



Source: RAISG

Figure 2: Mining activities and reserves in the Amazon Forest



Source: RAISG (no information for French Guiana)

Agriculture in the Amazon Forest mainly produces soy, corn, and pastures for cattle grazing. Additionally, to a smaller extent, coca and palm oil. In the 1990s and 2000s, the expansion of soy agriculture into the forest was the main driver of deforestation in Brazil, leading to large destroyed areas. In the 2000s, the main driver of deforestation became cattle-grazing and, ultimately, 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. Finally, palm oil is developing rapidly in Ecuador.[1]

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 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 important gold reserves, such as Venezuela, Guyana, Suriname, and French Guyana.

Deforestation is the destruction of biomass, typically intended to convert the area into economic

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[1] In line with this explanation, deforestation seems to accelerate when expected profits from cattle-grazing or soy production increases. In the 2000s, the correlation between deforestation and crop prices was strong and graphically visible, as shown in figure 13 by Assunção et al. (2019), where the authors have weighted prices by the area in Amazon municipalities used for each crop culture and cattle-grazing. However, this correlation seems to have weakened in later years, particularly after two major policy events in 2004 and 2008, explained later.

activity. Destruction of biomass can be total or partial, when 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 process of deforestation consists of logging an area using mechanical tools and labor, and extracting valuable woods for sale. Much of the biomass is useless for sale and 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.

The best available estimate 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 deforestation expenditure is barely recovered by the sale of valuable timber: the average returns per hectare is only around 4 USD per hectare because only specific types of wood have economic value (Santana et al. 2012).

On the benefits side, the average soy productivity is 3.5 ton/hectare, with an average export value of 0.4 USD/kg, meaning that the gross revenues from one hectare of soy are 1400 USD/hectare.[2] Using a profit rate of 25%, each average profits per hectare are 350 USD per hectare.[3] Similarly, the productivity of meat is approximately 70 kg per hectare, and the export price of a kilogram of frozen meat was around 5 USD/kg in 2020, meaning gross revenues of 350 USD per hectare.[4] Assuming a 25% profit rate, these values imply profits of roughly 80 USD per hectare.[5]

The overwhelming majority of deforested areas become pastures for cattle. However, the land use change varies a lot by country as indicated in Table 1. Moreover, for environmental reasons, Amazon deforestation is tighly regulated in most countries. Therefore, virtually all deforesta-

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[2] 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

[3] Figures computed using the exchange rage 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/

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

[5] 25% is a “generous” profit rate, higher than the 20% found in a 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/

tion is illegal. The illegality of deforestation partly makes it hard to have detailed information on the type of people who engage in this activity. However, it also makes it harder for large corporations and farms to engage in it. Deforestation is mostly carried out by small and medium farmers, land grabbers, and small miners. More than half of the deforestation in Brazil, for example, is due to deforested areas smaller than 50 hectares, though in recent years large deforestation plots are on the rise (see Figure 12 in the Appendix). Often these activities are linked to larger legal or illegal networks, as is the case of coca plantations in Colombia and Peru, connected to narco-trafficking (Prem, Saavedra, and Vargas 2020, Tozzi 2022).[6] In Brazil, where 66% of recent deforestation became pastures (see Table 4 in the Appendix), 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). The decision-making farmers decide to convert forest into an economic activity if it is profitable. They compare expected revenues from sales to production costs, deforestation costs, and regulatory compliance costs. However, deforestation generates damages 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 damages also constitute the economic costs of deforestation. However, unlike labor and capital, there is neither a market nor a price for them.

In practice, someone else is paying the price of these damages, and for this reason they are called negative externalities. However, since the decision maker does not have to pay these costs, deforestation may happen even when its social net benefits are negative, even though private net benefits are positive. In such cases, deforestation is an economically harmful decision and, therefore, a market failure.

Externalities arise because prices only reflect the costs of goods traded in markets, such as commodities and labor, and not those goods not traded in markets, such as the climate, air quality, and biodiversity. The absence of these markets stems from the difficulty of establishing property rights or economic measures that one can easily convert into a monetary amount. For example, it is hard to establish property rights for the climate, so harmed parties cannot require compensation for harmful activities. Consequently, market prices fail to encourage agents to make economically efficient decisions. The solution to this inefficiency is to make the decision-making agent face these costs directly or indirectly.

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[6] 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.

Government policy can improve market failure situations by making agents face the total costs of their actions. Tax or quantity regulations are the two most common interventions to deal with externalities. However, there are several other policy instruments, which I will discuss in section 4. Indeed, several factors constrain the ability to use policy instruments, such as institutional quality, compliance, and political considerations. In practice, policies often take mixed features and complicated designs.

The nature and magnitude of the externality dictate the appropriate corrective policy. Quantifying externalities is a tremendous scientific challenge requiring theoretical knowledge about forest systems and state-of-the-art measurement technologies. Furthermore, as already mentioned, deforestation generates global, regional, and local damages, depending on the type of economic activity. In section 3, I discuss these different externalities and what activities give rise to them.

Table 1: Summary Amazon deforestation by country

Country	**Area Amazon forest**	**% Preserved as primary forest**[1]	**Main drivers of deforestation**[2]
All countries	6.4 million km^2	85%	Cattle, timber, coca, palm oil, mining
Bolivia	6.9% (of the Amazon forest)	92%	Cattle-ranching, soy
Brazil	60.3%	79%	Cattle-ranching, soy
Colombia	6.9%	88%	Cattle-ranching, coca
Ecuador	1.5%	90%	Palm oil
French Guyana	1.1%	97%	Gold mining
Guyana	3%	99%	Timber, gold mining
Peru	11.3%	92%	Coca, palm oil, cocoa
Suriname	2.1%	96%	Gold mining
Venezuela	6.7%	96%	Gold mining

Sources: [1]Own computation using GlobalForestWatch data, and PRODES data for Brazil, [2]Compilation by Costa (2020, February 18th), and Crime and Institute (2021)
Obs: palm oil is a generic designation, and in South America one typically refers to *dendê* oil.

The destruction of the Amazon Forest is a threat to the environment, but at what rate is it happening? The wide availability of satellite images allows researchers to compute the areas of deforestation based on observed forest cover loss. Satellite-measured deforestation is the primary indicator of greenhouse gas emissions for the Amazon Forest. 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.[7] To measure deforestation, researchers rely on color-based measures of forest cover, such as the normalized difference vegetation index (NDVI).[8] Since it is a continuous measure, the NDVI can be used to measure forest degradation. Conversely, satellite imagery is useful to compute carbon capture due to forest growth. However, the interpretation of satellite imagery is prone to errors and requires continuous finetuning.[9]

Probably the most widely used dataset for tree cover loss is the Global Land Analysis & Discovery (GLAD) of the University of Maryland (Hansen et al. 2013). Figures 3 and 4 show the deforestation area and rate (as a share of forest cover in 2000) for the Amazon countries except Guyana, Suriname, and French Guiana. The figures show that Brazil destroyed more forest as a share of forest area in the last twenty years. However, Bolivia, Colombia, and Peru display accelerating deforestation patterns. Venezuela has kept deforestation rates low, slightly increasing in the last few years.[10]

Brazil has an official program since the 1980s to measure deforestation in the Amazon Forest, led by the Brazilian Institute for Spatial Research (INPE). The program, called PRODES, calculates the loss of primary forests only and has documented a successful reduction of deforestation rates in the early 2000s and a rapid acceleration in the last ten years (see Figure 11 in the Appendix). Finally, another source of information in Brazil is the initiative MapBiomas. This network of researchers has been using satellite imagery to measure deforestation, reforestation, forest degradation, and other patterns of land use in the whole country.

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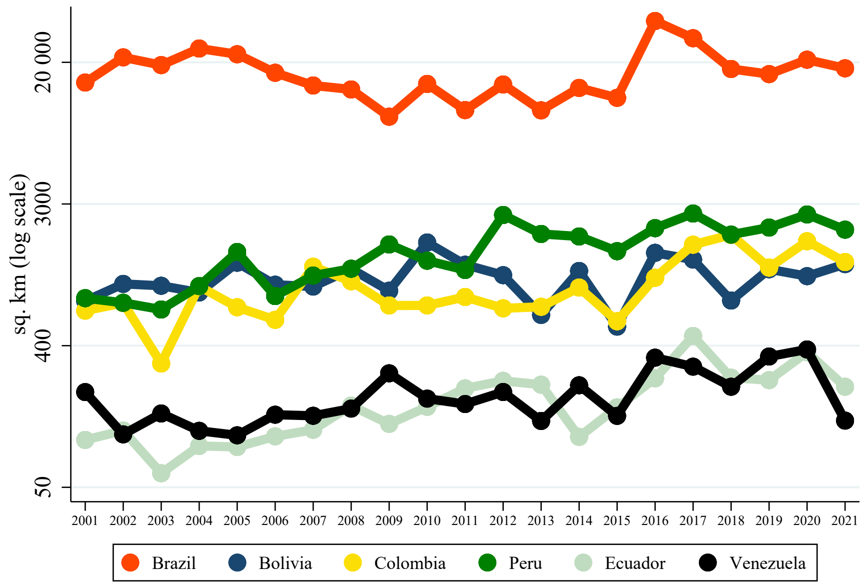
[7] The first satellite of the Landsat program was launched in 1972 by NASA. In 2021, NASA launched Landsat 9, the ninth satellite of the program. More information about the program can be accessed in its website: https://landsat.gsfc.nasa.gov/

[8] 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, both of which are 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/

[9] See Alix-Garcia and Millimet 2023 for a discussion of measurement error of deforestation. Different institutes may present different numbers for deforestation, even if they use the same images. These discrepancies happen because of differences in the criteria to declare an area as deforested.

[10] The deforestation series in Figures 3 and 4 has suffered a methodological adjustment in 2015. This adjustment explains the sudden rise in deforestation for Brazil in 2016.

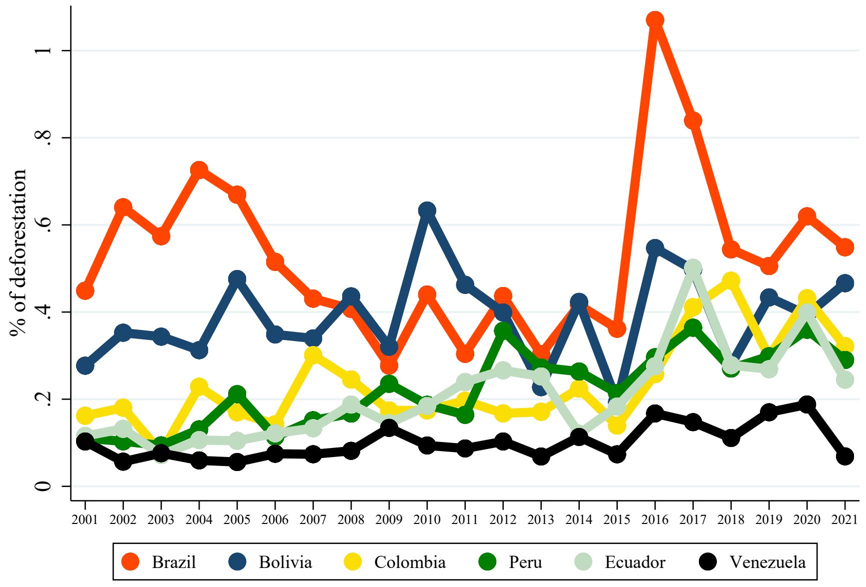
Figure 3: Deforestation Area by Country



Obs: areas with more than 75% tree cover loss. The series suffered a methodological change in 2015.

Source: Global Forest Watch (Hansen et al. 2013)

Figure 4: Deforestation Rate by Country



Obs: areas with more than 75% tree cover loss. The series suffered a methodological change in 2015.

Source: Global Forest Watch (Hansen et al. 2013)

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, at a more local level, deforestation disturbs local ecosystems causing biodiversity loss. Moreover, mining activities pollute water bodies with heavy metals, contaminating the water and fish. Below I sketch how the natural sciences literature has described and quantified these damages.[11]

3.1 The global externality: climate change

Deforestation affects the global climate because trees are carbon stocks. The carbon stock of forests' biomass and soils represents an entire century of emissions from burning fossil fuels, and roughly half that stock is in aboveground biomass.[12] Furthermore, the Amazon Forest has the largest carbon stock of all forests in the world because of its area and dense vegetation (Pan et al. 2011). For this reason, Amazon deforestation can affect the density of carbon in the atmosphere and the planet's climate.

Trees are carbon stock because they 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. As trees die, their organic matter is decomposed, liberating carbon and methane into the atmosphere. Moreover, trees release carbon during the process of cellular respiration. Indeed, when forests reach an equilibrium state in which they do not grow further, they become essentially carbon neutral with respect to their carbon flows (Mitchard 2018). 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.[13] 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.

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[11] This section does not discuss other damages caused by deforestation: the acceleration of malaria spread (MacDonald and Mordecai 2019, Ellwanger et al. 2020), the existence or "non-use value" of its natural beauties (see Chan et al. 2011 for a broad discussion), violence associated with resource extraction (Pereira and Pucci 2021), and the threat that deforestation poses to indigenous peoples.

[12] As calculated by the World Resources Institute, accessed in July 2022 here: https://research.wri.org/gfr/biodiversity-ecological-services-indicators/forest-carbon-stocks

[13] 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.

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). Tropical forests growth contributed to a quarter to a third of this global sink, absorbing 15% of anthropogenic emissions (Hubau et al. 2020), and by far outperforming other biomes such as boreal or temperate forests (Pan et al. 2011). Moreover, some scientists argue that preserved forests are natural carbon sinks even without net growth 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, the leading reason why deforestation is a climate concern is the stock, whereas the net flows of mature forests tend to be small and noisily estimated.

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, and 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 seen as the target to keep global warming below 2 degrees Celsius (see Appendix B for details).

To compute emissions from deforestation, scientists have estimated the carbon density of the Amazon Forest. These computations rely on a combination of vegetation density observed via satellite images and field measures of tree size. A simple way to estimate emissions from deforestation is to impute average values. For example, the Emissions Modeling by the Brazilian Spatial Institute (INPE) estimates the carbon density in the Amazon Forest at roughly 500 tons of CO2 per hectare.[14] However, more sophisticated procedures rely on maps of carbon stock that assign carbon densities to each area, such as Baccini et al. (2012). Though there is much uncertainty about the actual carbon density values, as discussed in Fearnside (2018), carbon emissions from deforestation are sizable. Brazil, Ecuador, and Colombia explicitly committed to reducing deforestation as a contribution to lower emissions in their Nationally Defined Contributions of the Paris Agreement.[15]

Estimates of carbon emissions that only use deforested areas underestimate the full scope of emissions from deforestation. This underestimation happens because, as already mentioned, forest fires used to clear biomass spread far beyond the site initially intended for deforestation.

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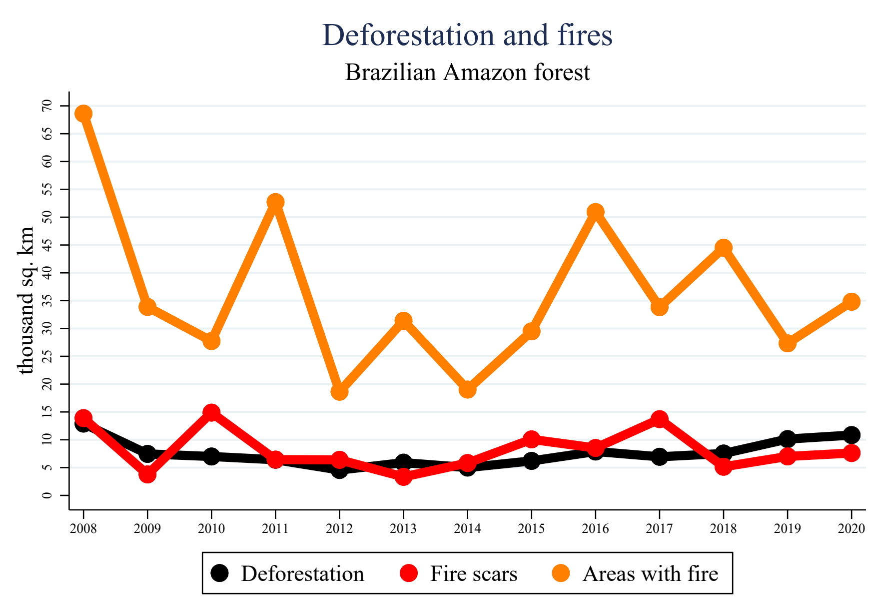
[14] The data is available at http://inpe-em.ccst.inpe.br/en/estimates-for-the-amazon/

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

Most fire events captures by satellite data do not completely destroy the forest and do not leave clear traces, known as “fire scars”. The areas of fire scars, computed by MapBiomas, are roughly the same as the yearly deforestation areas, but the areas affected by fires events are much larger, as shown in Figure 5. The large extent of fire events which damage, but do not destroy the forest, suggests that forest degradation is a problem of large dimensions. The Brazilian Spatial Research Institute (INPE) has a program to measure forest degradation, and the computed data shows that degraded areas every year are almost twice as large as deforested areas, and mostly 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 fires in the Brazilian Amazon Forest caused enough forest degradation to increase emissions by 50% than estimates based only on deforestation would imply.

Figure 5: Degradation by fires



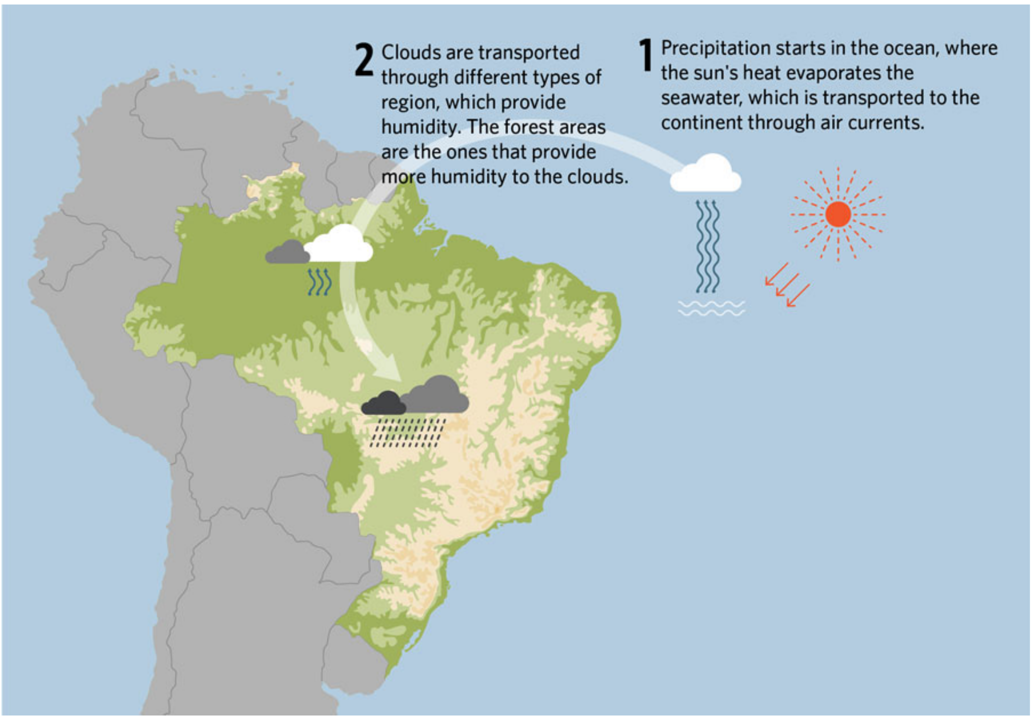
Source: Deforestation by PRODES/INPE, fire scars by MapBiomas, fire areas from INPE (Terra/Aqua)

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 rainfall. 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 basin, centered on the river Amazonas and its hundreds of tributaries, is the largest in the world. Receiving air currents from the Atlantic Ocean, the Amazon Forest retains large amounts of water in its water bodies and vegetation, as shown in Figure 6. As a result, 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).[16] 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 rain for the forest and these neighboring regions. For example, rainfall in the Brazilian state of Mato Grosso, a large soy producer, depends directly on the flying rivers that come from the Amazon Forest (Araujo 2021). Moreover, the area of water surface in the Amazon Forest has fallen by 8% relative to the early 2000s (see Appendix D).

Figure 6: Water cycle in the Amazon Forest



Source: Climate Policy Initiative and Araujo (2021)

A reduction in precipitation rates 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, Lovejoy and Nobre 2018, Lovejoy and Nobre 2019), though forest regeneration and global climate conditions may affect it. In any case, recent studies have provided evidence that areas with large levels of deforestation are linked to

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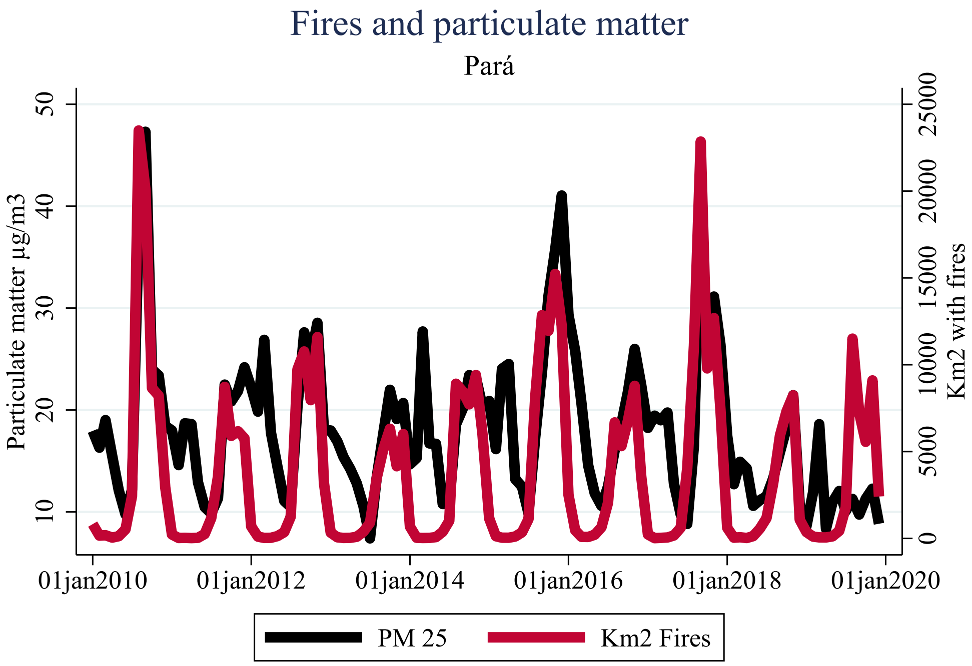
[16] Medvigy et al. (2013) show with simulations of a weather model that minor disturbances to the Amazon Forest's evaporation may have significant effects on the snow peaks of the Sierra Nevada and, therefore, on freshwater supply in the American Northwest.

longer dry seasons (Leite-Filho, Sousa Pontes, and Costa 2019) and lower levels of precipitation (Xu et al. 2022), including in areas with agricultural activity (Leite-Filho et al. 2021).

In the context of Amazon forest fires, the onset of the fire season, during the "dry season", coincides with increases in the concentration of particulate matter. The correlation between the two is strikingly visual, as illustrated by figure 7, and has already been documented elsewhere Sá et al. (2019). Since air pollution travels with the wind, its effects are felt in areas beyond where the fire occurred.

The level of particulate matter 2.5 in the state of Pará, averaged across measurement stations in the state, went above 40 micrograms per cubic meter in 2010 and 2016, and almost reached 30 micrograms in several years. These levels are still low compared to a highly polluted city, but increases above 12 already trigger undesirable health effects in vulnerable groups. Air quality above this level is already considered "moderate" by the Environmental Protection Agency of the U.S., for example.[17] 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).

Figure 7: Fires are highly correlated with concentration of PM



Source: own calculations from SISAM and Queimadas

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[17] Source: Standards on air quality of the Environmental Protection Agency, available at: https://www.epa.gov/criteria-air-pollutants/naaqs-table

3.3 Local externalities: biodiversity services and water pollution

The most local types of externalities are impacts on biodiversity services and, in the case of mining, water quality. Deforestation and forest degradation are direct threats to biodiversity because, by definition, they kill biomass and replace it with other land uses. As a result, the flora is destroyed, and the fauna is killed or displaced.

The Amazon Forest is home to the richest biodiversity of all existing biomes on Earth (IPBES 2018), and the countries covered by it make it to the top of biodiversity rankings. 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).

The most common quantitative indicator for biodiversity is the count of known species.[18] According to this indicator, tropical forest rank first among all other biomes as cradles of biodiversity, and the Amazon Forest on top of tropical forests. 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 for two reasons. First, extinction is, by definition, irreversible. Second, 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). In short, preserving primary forests has an irreplaceable value in terms of biodiversity.

The other local externality is water pollution caused by mining activities. Water pollution is particularly pronounced in the search for gold, which can often be found under or close to water bodies. Miners throw mercury into the water to extract gold, thereby polluting the 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 local population, particularly miners themselves (see Torres and Torre 2022 for a review). Though it could be objectionable to call damages to miners as "externality", it is not immediately obvious that workers are aware of the health damages derived from mercury contamination, or that their salaries reflect these health hazards. In this sense, water pollution is still an externality because its cost is not reflected in any price.

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

4 Policy interventions

Negative externalities imply that deforestation is more costly than farmers realize. 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 resulting rise in temperature in the form of excess storms, floods, heatwaves, and ocean levels. The net present value of these damages is the "social cost of carbon", estimated at 50 to 100 USD per ton of CO2. Consequently, the climate externality of destroying one hectare of forest ranges between 25 and 50 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 probably much lower. Indeed, there is anecdotal evidence that land value in the Amazon forest can be as low as one thousand USD per hectare.[19]

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 a decision that generates more overall damage than benefit and, therefore, a market failure.

Policies can solve the market failure by including environmental damage in the costs of deforestation, directly or indirectly. However, policy design depends on the externality it is trying to

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[19] 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 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)

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 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 command conservation areas or make it costly to deforest via taxes or regulation. Both these instruments, quantities or prices, can achieve lower deforestation. However, there is uncertainty regarding how to adjust the policy parameters of each to meet a specific conservation target. Quantity regulation is preferable to price regulation wherever the damage from forest destruction increases steeply with deforestation, which would happen in the case of “tipping points”. On the other hand, price instruments are more likely to be cost-effective because they discourage low-productivity farmers from deforestation more than high-productivity farmers. Finally, policies can also target practices or technologies, inducing economic agents to mitigate the externalities from deforestation. This approach can be particularly useful to reduce air and water pollution stemming from forest fires and mining. The use of fires and mercury are convenient, but their effects can be mitigated and even eliminated.

To achieve these different policy objectives, governments have a toolbox of policy instruments. Some of them directly affect the ability or willingness of farmers to deforest. They are the bans on deforestation and financial incentives for conservation. Bans on deforestation can be partial or total, and usually go by the name of “command and control” policies. Financial incentives are carbon taxes, payments for ecosystem services, or any type of conditional loan or cash transfer based on conservation targets. 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. In addition, policymaking is potentially very costly because of enforcement challenges. An enforcement apparatus is needed for whatever policy type, but each policy may encourage different compliance behaviors.

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 2022, Ferreira 2022, 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 Historical overview

Amazon countries' environmental legislation is strict against deforestation, 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 to this day. Finally, Congress passed a law in 1998 instituting "environmental crimes", punishable by jail, including deforestation and forest fires. The legislation bans deforestation in most imaginable cases, and only about 3-4% of yearly deforestation has legal permission to occur (Valdiones et al. 2021).

4.2 Command and control and enforcement

Brazil relies heavily on command and control to protect the Amazon. In private farms, approximately 20% of the territory, the law requires farmers to protect 80% of the surface, as already mentioned. Moreover, deforestation is banned in indigenous land and conservation units, which cover half the territory. The remaining 30% are public forests 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. Despite having 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.

The strengthening of the federal enforcement agency IBAMA and the systematic remote sensing became key elements of a major policy overhaul that took place in the 2000s. 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. The most prominent aspects of this policy toolkit were the rapid expansion of protected land (i.e. indigenous territory or conservation units) and the creation of a real-time monitoring system using remote sensing data, named DETER, to support enforcement action. Since then, PPCDAm has had other phases in which new policies were enacted with focus on enforcement strategies, such as the policy of "priority municipalities" of 2008, in which municipalities receive more intensive inspection efforts. Moreover, a presidential decree in 2008 increased the penalty rates for most infractions related to deforestation and forest fires. In short, strengthening monitoring and enforcement has been the main focus of conservation policy in the Amazon forest in the last decades.

When IBAMA inspectors meet an offender, three things happen. The inspectors hand the offender a fine proportional to the deforested or degraded area, which is increase if deforestation is in protected land and if the offender used fire. The standard fine rate is one thousand USD per hectare of deforestation on private property (above the 20% farmers area allowed to deforest). The fine rate is increased under several hypotheses, such as if deforestation takes place on protected areas, indigenous land, public forest. Other aggravating situations are the use of fire, which increases the fine by 50%, and the illegal commercialization of wood. The current fine rates are determined in a presidential decree of 2008 which substantially increased the penalties for deforestation, but the effective rates may depend on situations on the ground.[20]

Three major issues limit the ability to enforce the Brazilian conservation law effectively: the low execution of fines, the lack of clarity on land tenure, and the limited capacity of IBAMA. It is indeed major issue with the Brazilian enforcement system that offenders seldom pay the fines they received for illegal deforestation. On average, only 2% of the nominal fines gets paid to the government, while most offenders default on these payments (Schmitt 2015). The lack of a correct enforcement of the fines is a severe limitation of Brazilian environmental law, which has sparked a debate about the effectiveness of inspections at all. However, the low payment rate should not be interpreted as the true cost to offenders. Indeed, fines impose administrative burdens on offenders, and defaulting on them limits their ability to obtain loans, for example. Moreover, the enforcement agency relies on two other forms of punishment to inflict direct costs on offenders: land embargos and equipment seizure. On top of giving a fine to the offender, the deforested land is banned from economic use, and the equipment used for deforestation is either destroyed or auctioned. Therefore, inspections are potentially very costly to offenders, even if the fine's value does not perfectly reflect this cost.

Figure 8 shows the heterogeneity in enforcement intensity in the Brazilian Amazon Forest. The red dots represent the offices of IBAMA in the region, and the color palette reflects the share of Amazon deforestation that was punished by IBAMA in the decade 2010-2020. Indeed, the areas with the highest probability of a sanction are also the areas with most deforestation, located in the Southern Amazon border, also known as the "Arc of Deforestation". The positive correlation between enforcement intensity and deforestation (see Appendix Figure **??**) does not mean that enforcement causes deforestation, but rather that enforcement effort is targeting the hotspots. Indeed, disentangling causation from correlation is one of the main challenges in the econometric analysis of environmental enforcement.

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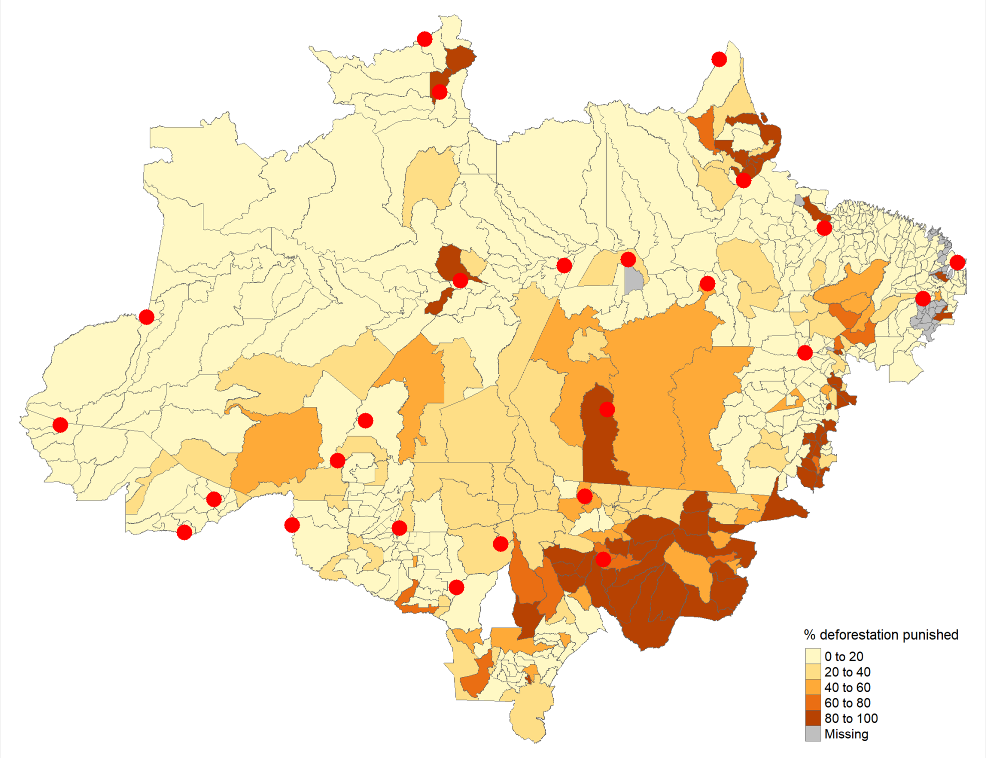
[20] Appendix Figure 19 shows that just after the decree, the effective penalty rate per hectare doubled, but has fallen to previous levels since, partly for lack of inflation adjustments.

Figure 8: Share of punished deforestation in 2010-2020 by municipality



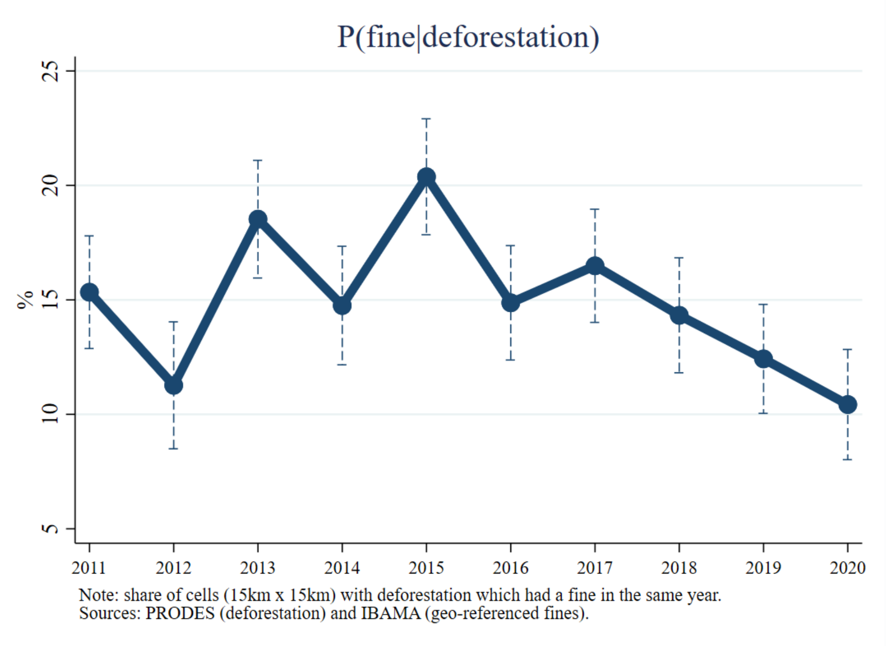
Source: IBAMA and INPE

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 2022). 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 2022). 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 on behavioral responses to changes in inspection rates.

Another important issue with enforcement regard the uncertain land tenure in the Brazilian Amazon forest. Most deforestation activity happens in public forests, and in such cases enforcement agents cannot identify the offender only based on satellite imagery. Enforcement operations involve trips from the city to the exact locality of the infraction using trucks or helicopters, and agents deliver a fine in person to the offenders. For this reason, real-time information from satellites is instrumental to target inspections and catch the offenders. 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.[21]

Finally, the third issue is the limited capacity of IBAMA. The limited capacity of the federal enforcement agency to punish deforestation in the Amazon forest is suggested by the probability of a fine. Ferreira (2022) merged geo-referenced fines with maps of deforestation to compute the probability that a 15km x 15km area with deforestation receives a fine. This probability was on average only 13% in the last decade, with a steady decline in the last couple of years, as shown in figure 9. IBAMA does target areas with larger deforestation incidence, so that approximately 25-30% of the total deforestation areas get fined. However, the conclusion remains that most deforestation in the Brazilian Amazon Forest goes unpunished.

Figure 9: Fine probability in the Brazilian Amazon forest



Note: share of cells (15km x 15km) with deforestation which had a fine in the same year.
Sources: PRODES (deforestation) and IBAMA (geo-referenced fines).

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

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[21] 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/

forest plummeted by 40% (see Appendix figure 18). The number of environmental agents is also relatively small, with only about 200 agents allocated in the states of the Amazon Forest.[22] 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.

4.3 Financial incentives

Financial incentives may take the form of conditional payments or loans that require recipients to help preserve the forest. Direct price incentives have also been shown to induce farmers to conserve forest in Africa (Jayachandran et al. 2017), but few large scale programs have been enacted with this objective. In Brazil, a conditional cash transfer for low income farmers (Bolsa Verde) has had some modest impact on conservation (Cisneros et al. 2022). Currently, many organizations and governments are experimenting with payments for ecosystem services in Latin America. However, there are still severe challenges involving the impact assessment of these programs. Some issues in evaluating these programs are sample size and self-selection into the program.

Rural credit in Brazil is granted by public institutions and subsidized. In the scope of the PPCDAm policies of 2008, the Brazilian Central Bank issued a resolution that restricted access to rural credit in the Amazon Forest to farmers that are compliant with conservation law. Given that rural credit finances approximately one third of agricultural expenses, such restrictions should represent an important incentive to comply with conservation legislation. That is exactly what Assunção et al. (2020) find by comparing Amazon municipalities to neighboring municipalities that were not affected by the regulation. After the introduction of the constraint, municipalities within the Amazon biome presented much lower levels of deforestation than their neighboring ones in the Cerrado biome. This result suggests that direct price incentives may have an important effect on farmers' conservation behavior in Brazil. However, this program is limited to formalized farmers who take subsidized loans.

4.4 Other policies: land tenure regulation and market access

In addition to command-and-control and financial incentives, there are several indirect ways of discouraging farmers from destroying the forest. These policies are land tenure regulation, incentives for sustainable practices, and labels for market access.

Land tenure is an important piece in understanding deforestation. Command and control regulation is tied to the type of land tenure. In Brazil, private farms must protect 80% of

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

their area, whereas conservation parks and indigenous territories are 100% protected. The non-designated forests are object of land grabbing by farmers that hope to obtain property rights via amnesties or false documents. The knowledge of who owns each piece of land in the Amazon Forest is far from ideal even on private lands, making enforcement action difficult.

In recent years, the federal government has been expanding a digital dataset of rural properties called CAR.[23] 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 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 land that was occupied illegally, generating other types of challenges for enforcement. In general, however, clarity about land ownership makes law enforcement more effective.

Delimiting areas as indigenous land or units of conservation is a way to preclude the possibility of private farmers claiming the land as their own. It is unclear whether these demarcations have a causal effect on conservation because of weak enforcement. However, studies have found clear conservation gains at the borders of these reserves (BenYishay et al. 2017, Baragwanath and Bayi 2020). Indeed, indigenous land demarcations and units of conservation are ubiquitous in the Amazon Forest, covering half of the whole territory, as shown in Figure 10.

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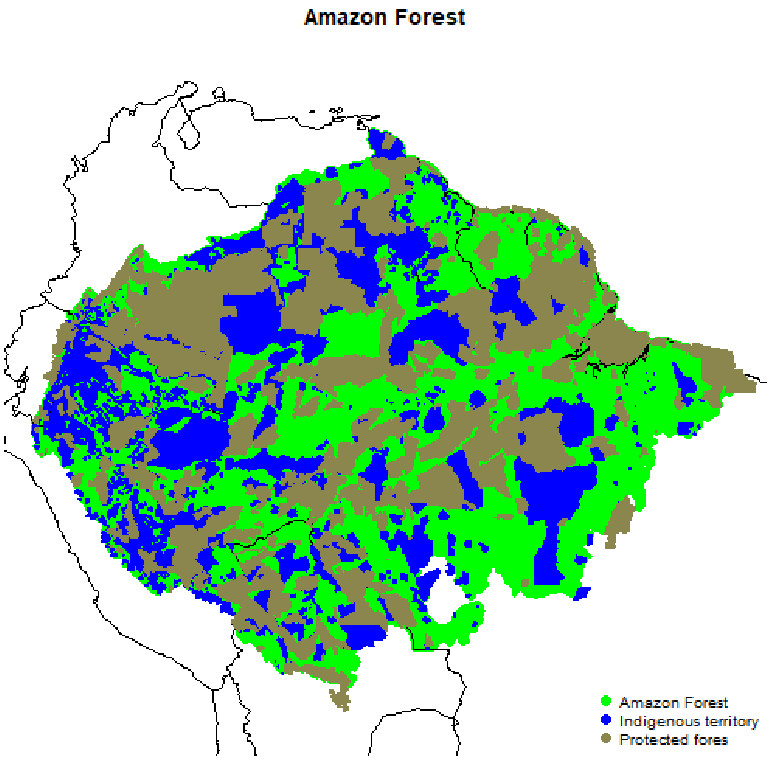
[23] Shapefiles of the declared properties are available online for free on a special website: `https://www.car.gov.br/publico/imoveis/index`

Figure 10: Indigenous Territories and Protected Forests



Source: RAISG

Another seemingly successful initiative was 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). 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.

5 Conclusion

Amazon deforestation is a complex topic. It is driven by the legitimate urge to obtain economic gains from resource exploitation, upon which households' livelihoods depend. However, it generates damage on local, regional, and global scales. The debate around Amazon Forest protection is a stage of scientific and ideological confrontation. Consequently, we have a myriad of initiatives from the public and private sectors, each trying to contribute to forest protection.

More and more is known about what works and what does not work for forest protection. For example, researchers have documented the central role of enforcement efforts for whatever proposed initiative. Reductions in enforcement efforts, far from being compensated by smarter policies, seem to undermine all policy instruments.

However, much is still to be discovered about the effects of current policies. For example, why is the execution of fines so low in the Brazilian Amazon Forest? What are the optimal criteria to target enforcement practices? Beyond enforcement, several other policy-relevant questions deserve research. What policies discourage farmers from using fire in deforestation? Is it conceivable to protect the forest and guarantee the livelihoods of local households only with sustainable extraction of fruits and nuts?

On a more macro-policy level, there is room to debate ambitious ideas that could help tackle the environmental problems that originate from Amazon deforestation. 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? More generally, is it possible (or desirable) to move slightly away from command and control regulation, and closer to financial incentives for Amazonian landholders? For example, Souza-Rodrigues (2019) estimates large efficiency gains from such a shift for the same levels of forest protection.

Amazon deforestation is already a topic of global concern, and researchers of several disciplines are thinking about its consequences and potential solutions. The severity of problem is felt as much in the Amazon countries as it is felt globally. The international community cannot expect Amazon countries to internalize deforestation's climate change impact without compensation. At the same time, Amazon countries cannot make the mistake of underestimating the regional impacts of deforestation due to reduced rainfall, biodiversity loss, and pollution.

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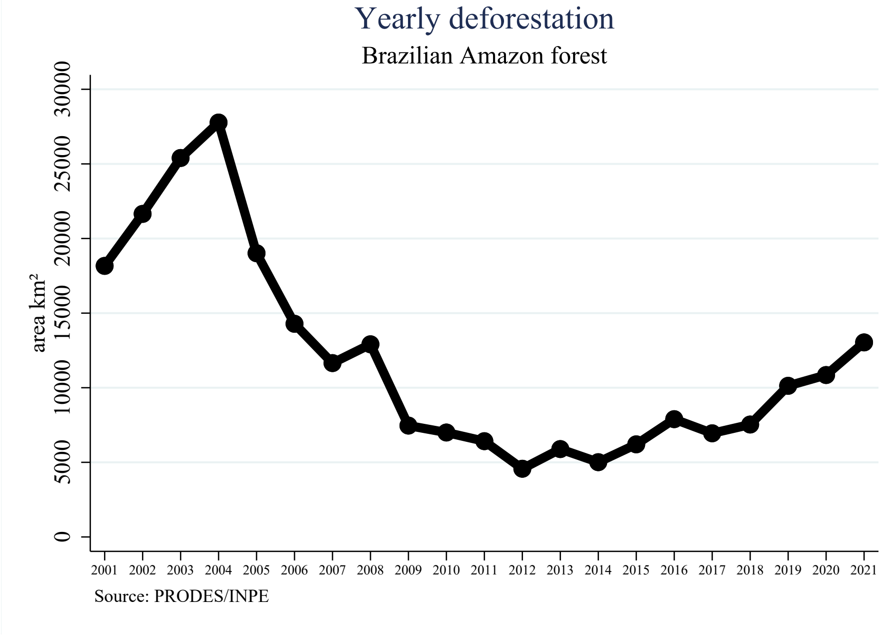
Appendices

A Brazil deforestation

Figure 11: After slowing down, deforestation of primary forest is accelerating again



Source: PRODES/INPE

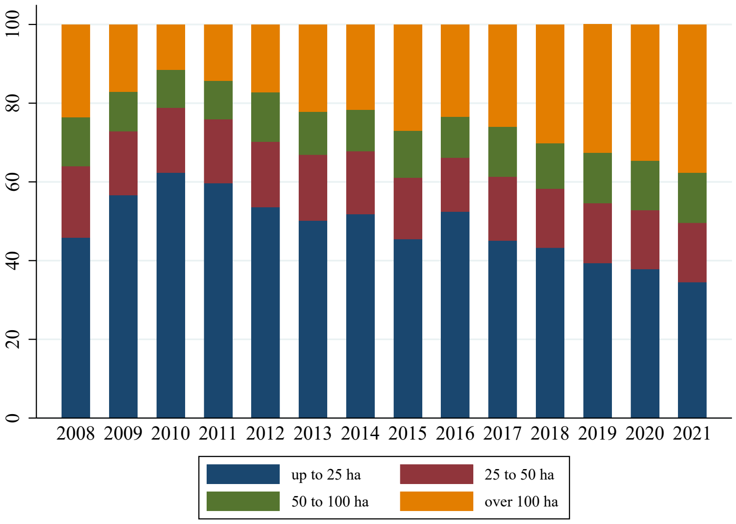
Table 4: Summary Amazon Forest

Summary statistics of the Brazilian Amazon forest

Total Area	6.4 million km^2
Area in Brazil	4.2 million km^2
% covered by primary forest	78% (2021, PRODES)
% of deforested area covered by secondary vegetation	24% (2014, TerraClass)
% of deforested area covered by pasture	66% (2014, TerraClass)
% of deforested area covered by crops	6% (2014, TerraClass)

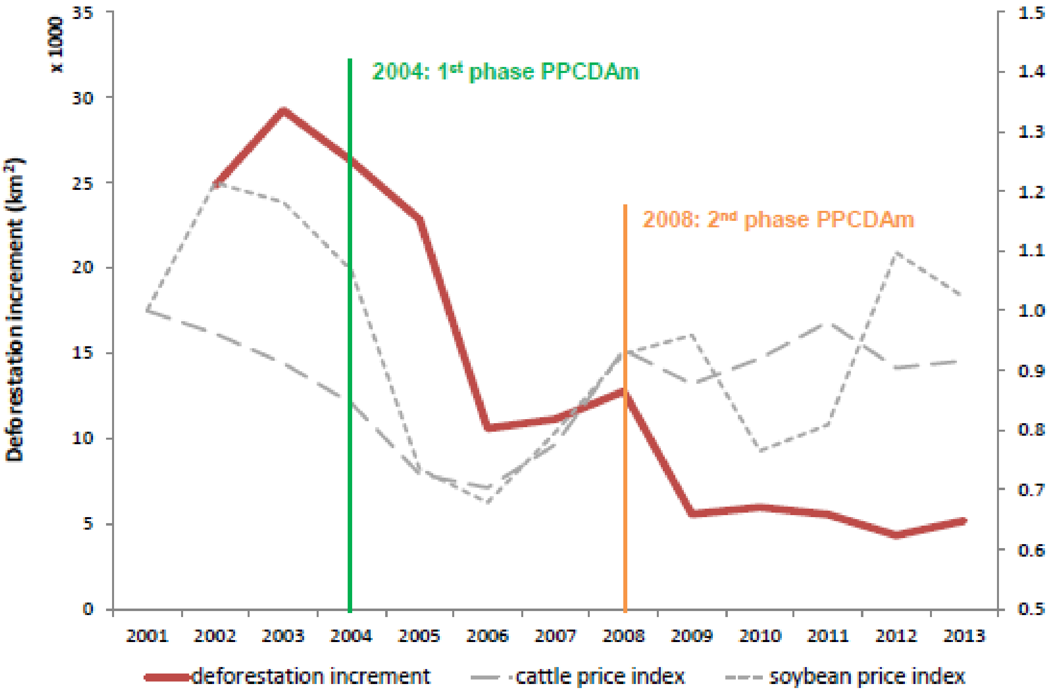
Source: TerraClass and PRODES (INPE, EMBRAPA)

Figure 12: Share of total deforestation area by size of deforestation polygons



Obs: The graph above depicts the share of total yearly deforestation that is composed of polygons of each size category.

Figure 13: Correlation between commodity prices and deforestation



Source: Assunção et al. (2019)

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.

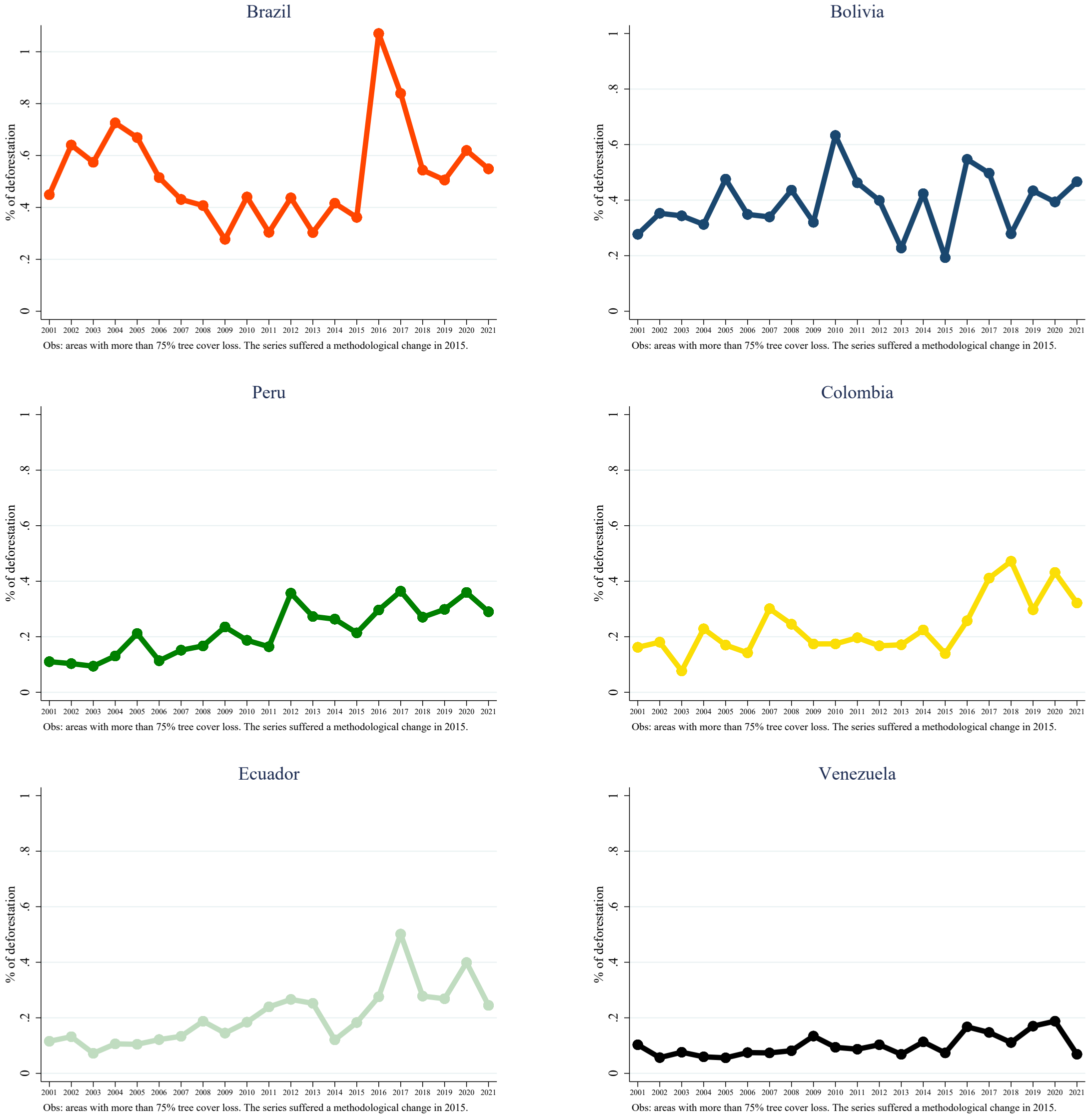
Table 5: CO2 concentrations and global warming

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)

C Deforestation by country

Figure 14: Deforestation Rate as a Share of Original Forest Area by Country

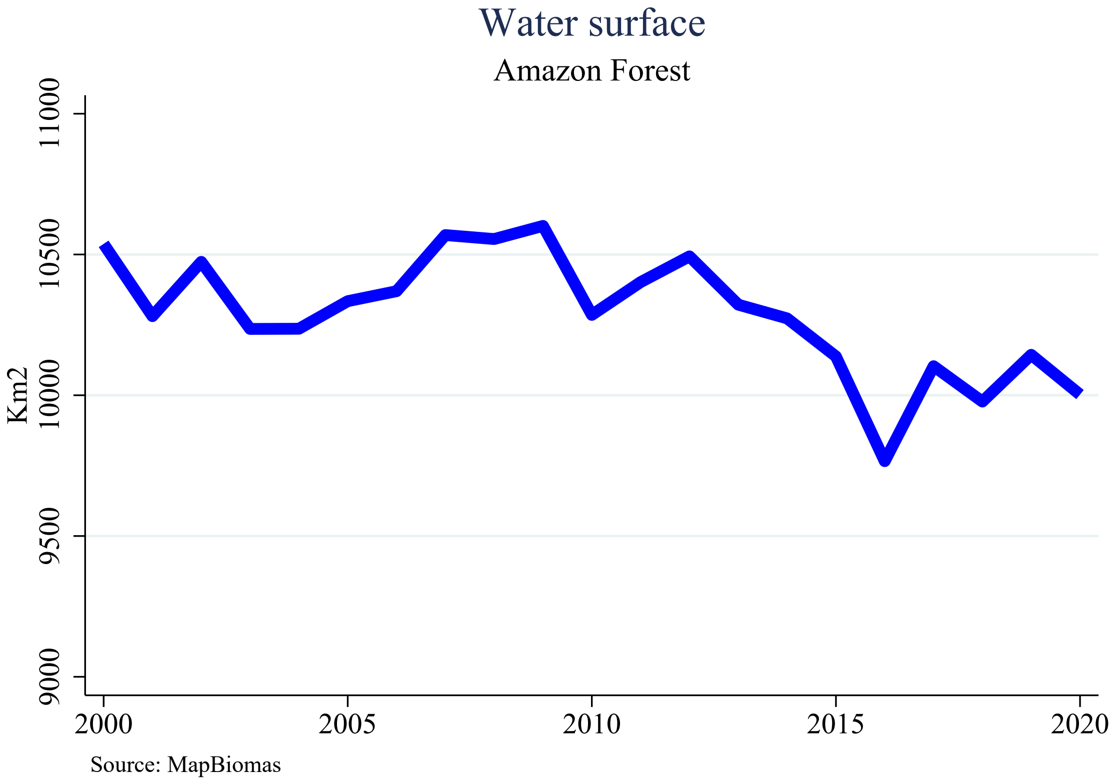


Source: Global Forest Watch (Hansen et al. 2013)

D Water surfaces

One worrying aspect of the increased dryness of the Amazon forest is the loss of its water surface. Satellite data allows measurement of these surfaces, and current levels are as much as 8% lower than the average in the early 2000s. The loss of water surfaces is related to more droughts and deforestation (Souza Jr et al. 2019).

Figure 15: Water surface is 8% lower than the average pre-2010

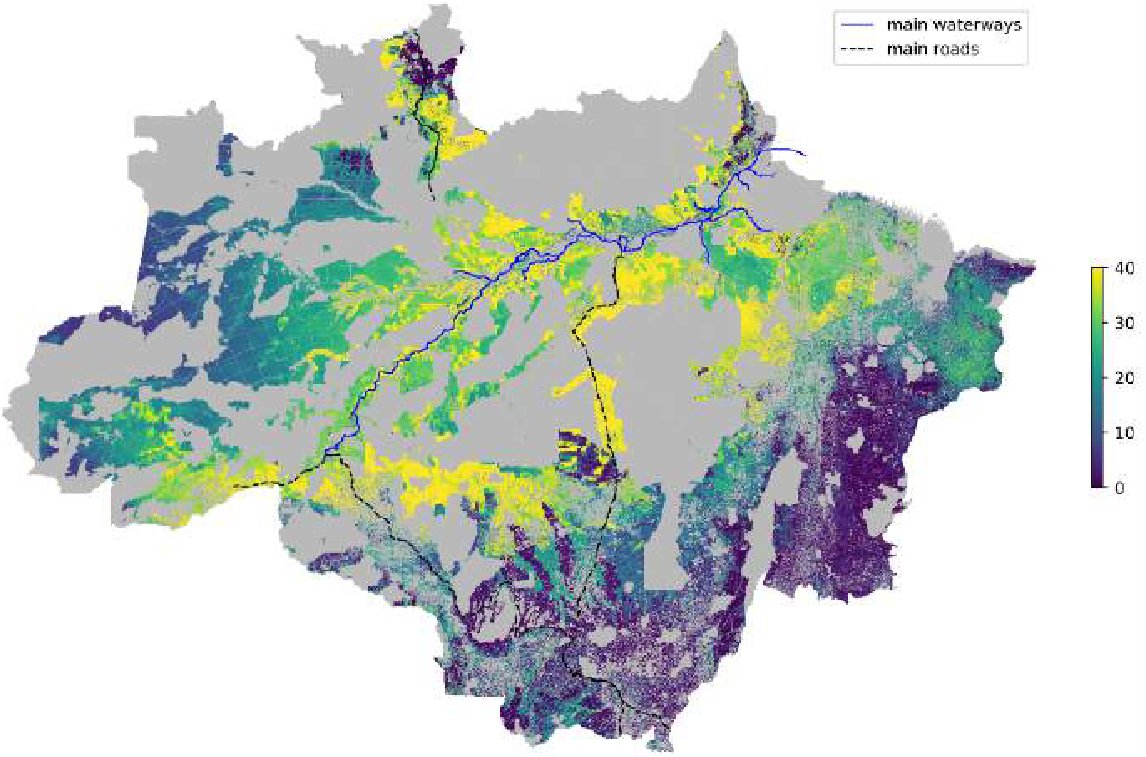


Source: MapBiomas

E Spatial heterogeneity in environmental damage and economic gains

The values of economic benefits and carbon content vary a lot from region to region in the Amazon forest. Exploring these two levels of heterogeneity with rich datasets, Araujo, Costa, and Sant'Anna (2022) managed to compute the areas in which deforestation would occur "inefficiently" from a climate change point of view, leading to figure 16. The study excludes protected conservation areas and indigenous land from the analysis.

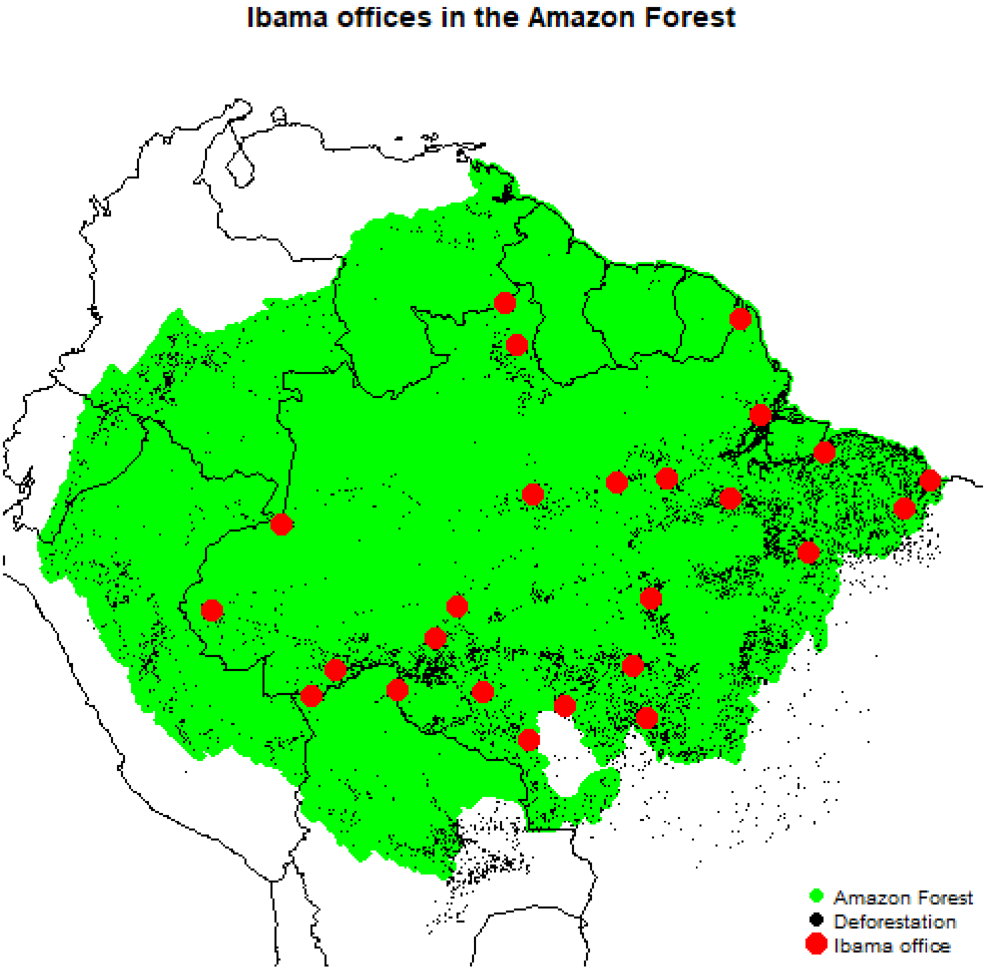
Figure 16: Areas where environmental costs are larger than economic benefits



Source: Araujo, Costa, and Sant'Anna (2022)

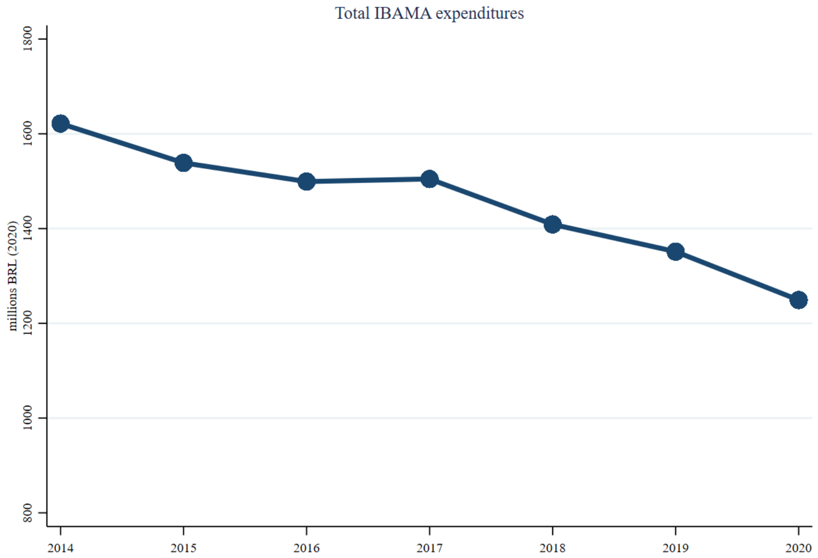
F Enforcement in Brazil

Figure 17: IBAMA offices and deforestation in the Brazilian Amazon Forest

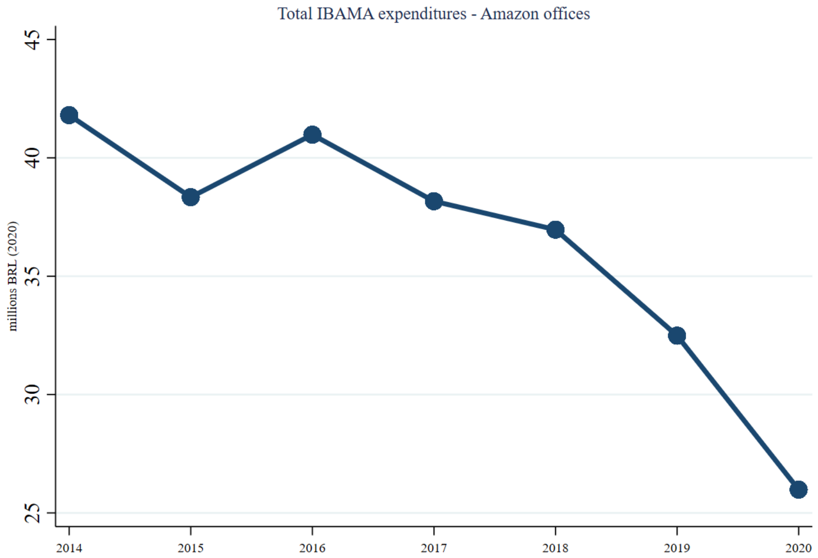


Source: IBAMA

Figure 18: IBAMA budget evolution since 2014 in real terms

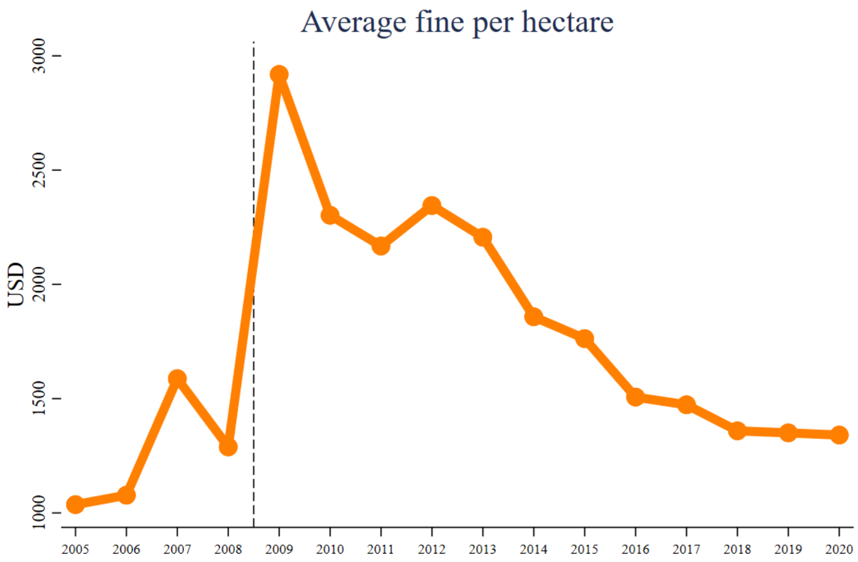


Source: Budget execution federal government, Portal da Transparência.



Source: Budget execution federal government, Portal da Transparência. Amounts do not include wages.

Figure 19: Fines for deforestation in the Brazilian Amazon Forest



Source: IBAMA.
Obs: Deforestation areas and fines as recorded in audit reports. Fines were censored at top 1% for fine amounts and size of area.
Year t is defined from August of t-1 to July of t, since deforestation is measured by PRODES (INPE) at the beginning of August.