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A systematic comparison of deforestation drivers and policy effectiveness across the Amazon biome

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Abstract:

The Amazon biome, spanning nine countries, has one of the highest rates of deforestation worldwide. This deforestation contributes to biodiversity loss, climate change, the spread of infectious diseases, and damage to rural and indigenous livelihoods. Hundreds of articles have been published on the topic of deforestation across Amazonia, yet there has been no recent synthesis of deforestation drivers and deforestation-control policy effectiveness in the region. Here we undertook the first systematic review of papers published between 2000 to 2021 that have causally linked proximate and underlying drivers and policies to deforestation outcomes in Amazonia. In the 155 articles that met our inclusion criteria, we find that causal research is concentrated in Brazil, and to a lesser degree Peru, Ecuador, and Bolivia. There has been little study of the Guianas, Venezuela or Colombia. Large- and small-scale agriculture linked to improved market access and high agricultural prices are frequently researched underlying drivers of deforestation across the heavily researched regions. In the Guianas research focuses on mining with little focus on underlying causes. Research on infrastructure expansion, mining, and oil extraction and on technological, sociocultural, and institutional factors remains sparse. Many public and private policies have been found to be effective in controlling deforestation across the biome, with protected areas standing out as particularly successful in slowing deforestation, vis-à-vis supply chain approaches. Frontier age, land tenure, and policy interactions are key moderating factors affecting the outcomes of different underlying causes and policies. Our findings indicate a greater need for research on i) additional deforestation drivers beyond agriculture and economic factors, ii) the complex interactions between different drivers and deforestation control policies, iii) causes underlying deforestation in low or new deforestation areas, and iv) the dynamics between Amazonian subregions and countries.

Understanding the extent and diversity of deforestation drivers and effectiveness of existing deforestation mitigation policies across Amazonia is a necessary first step toward designing policies to further reduce deforestation in the biome.

Keywords: sustainable development, South America, land systems science, policy

1. Introduction

The Amazon biome holds the largest tropical forest in the world and contains more than 10% of known plant and animal species [1]. It is home to 47 million people [1] and spans 6.7 million km^2, divided between Brazil (62%), Peru (11%), Bolivia (8%), Colombia (6%), Venezuela (6%), Guyana (2%), Suriname (2%), Ecuador (2%) and French Guiana (1%) [2]. The biome, also known as Amazonia, is defined by a set of biogeographical criteria and includes the vast lowland rainforest region of the Amazon River basin and several subregions, such as the Guiana shield to the north, the Planalto and Gurupi regions to the south west and east, and a part of the Andes to the west [3].

Although often reduced to one entity, Amazonia holds immense environmental and sociocultural diversity. Its regions are connected through the Amazon river and its tributaries as well as through the transboundary movement of nutrients, animals and people [4,5]. The biome provides its inhabitants with food, raw materials, fresh water and regional climate regulation, estimated to be worth between US$56 to US$737 per hectare per year [6]. It also serves as the foundation for the spiritual and cultural identity of various ethnicities that in turn preserve functions of the biome [7]. Additionally, the forest is also a major global climate regulator through its large and rapid influence on the water cycle, planetary energetics and global atmospheric composition [8].

Since the 1970s, the clearing of Amazonian forests has intensified and over 17% of primary forest cover has been lost [2]. Deforestation in the Amazon biome contributes to widespread biodiversity loss [9], regional and global climate change [10], changes to the hydrological cycle [11–13], the spread of infectious diseases [14], and damage to the livelihoods of indigenous people [15]. Today, the Amazon biome is the most threatened ecoregion in the world in terms of the area cleared each year, accounting for over 3.4 million ha of forest loss per annum [2]. Climate change, forest degradation and deforestation are increasing the likelihood of an irreversible ecosystem dieback across the entire Amazon, with drastic regional and global consequences [16,17].

The number of studies and initiatives providing crucial information on patterns and processes of land use and land cover change has substantially increased over the past decades. As one of the first attempts to synthesize evidence of causes of deforestation across the tropics, Geist and Lambin [18] created a framework of proximate and underlying drivers, which has since been widely adapted in land use science. For example, Armenteras et al. [19] used it to show that deforestation drivers and rates vary substantially across South American countries and forest types. In response to the issue of widespread deforestation, studies on conservation and policies against deforestation have gained relevance. As with research on land use change, large-scale syntheses of policy knowledge provide insightful evidence. Börner et al. [20] for instance found that the effectiveness of conservation policies differs between regions, highlighting the importance of local contexts when assessing policies.

Existing deforestation studies that cover the entire Amazon region have been conducted on the global or macroregional level (e.g., Armenteras et al. [19] for South America), often focusing on land use change mostly due to agriculture [21,22] and sometimes examining links to underlying factors such as global markets [23,24]. Other studies concentrate on analyzing patterns of one direct cause of deforestation [25,26] or the effectiveness of different policy options to reduce deforestation [20,27] across regions.

Several initiatives have produced and connected knowledge on deforestation across the Amazon biome in recent years, such as the MapBiomas Amazonia project [2], the Monitoring of the Andean Amazon Project [28], and the georeferenced socio-environmental information network (RASIG) [29]. Additionally, in 2020, the UN Sustainable Development Solutions Network convened The Science Panel for the Amazon [30], a large interdisciplinary team of researchers, to assess the state of the entire Amazon and give recommendations for improvements in an extensive report. This massive undertaking provided complex, in-depth, expert driven syntheses across a wide range of topics and disciplines relevant to understanding the history and current trajectory of the Amazon biome, across both urban and rural contexts.

Despite these major advancements in monitoring and synthesizing land and policy processes, there is no systematic, concise, multi-region overview of the present-day deforestation drivers and policies, or how these factors vary across Amazonian regions. Older pantropical studies, such as Geist and Lambin [18] and Rudel [31] may no longer reflect the realities of Amazonia in the early 21st century, which has seen exponential growth in global commodities demand and international trade and finance, both of which have exerted significant pressure on the tropics. Specifically, current research on deforestation in the Amazon faces a gap between macroregional or global studies and local case studies. A systematic review is particularly well placed to bridge this gap by gathering existing cases at smaller scales and studying them under a uniform analytical and coding framework [32,33].

The objective of this study is to systematically identify and qualitatively compare current knowledge of the drivers of deforestation and deforestation-control policies (e.g., protected areas, supply chain policies, public regulations) across Amazonian countries and regions, and to point out critical knowledge gaps about these issues, both regionally (i.e., between Amazonian nations) and by topic (i.e., by specific drivers, causes, moderating factors, and policy effectiveness). We build on the framework of proximate and underlying drivers by Geist and Lambin [18], which has been widely adapted and become the gold standard for meta-studies in land use science [33]. Deforestation policy effectiveness is defined as the degree to which the policy successfully reduces deforestation in the target region [34].

Proximate causes are land use changes that directly cause deforestation on the local or regional level. These include specific types of agriculture, mining, and other extractives (oil, timber), and infrastructure that directly replace forests. In our study we also examine drivers that cause deforestation indirectly by displacing other proximate deforestation causes. This would include, for example, crop expansion displacing cattle ranching to a forested place.

Underlying drivers are indirect forces that trigger deforestation through encouraging a proximate cause. These include both socioeconomic and bio-physical underlying drivers. For continuity we use the overall groupings of drivers used by Geist and Lambin [18]: economic, institutional, cultural, demographic, environmental, and technological. Economic drivers include both macroeconomic trends (i.e., employment) and microeconomic household conditions. Institutional drivers relate to formalized rules and land use, including land tenure and policies that directly encouraged deforestation and agricultural settlement. Cultural drivers relate to the shared meanings, norms, and values that actors have around particular land use behaviors. Demographic drivers pertain to both the household composition and broader population trends. Environmental drivers have to do with the climate and soils. Technological drivers are anything that influence the total factor productivity (i.e., output per input). For continuity with Geist and Lambin [18], land quality and farm size is also considered a technological driver.

Ultimately the broad framework depicted in Figure 1 is based on some more specific theoretical models of land use behavior. On the one hand there is the rational actor, income maximization model that suggests an actor will clear land for a particular use (the proximate driver) if the net present value of the expected income less the clearing costs is greater than its value as a standing forest and all other land uses [35]. Aspects like culture extend this model in terms of what constitutes value in a non-monetary sense [36]. Environmental and technological factors influence the overall productivity of a particular land use in a particular place, affecting its profitability [37,38]. Institutions that influence access to land also affect the expected income [39].

When considering smallholder agriculture, the behavioral model is often based around meeting subsistence food, fuel, and housing needs considering leisure-labor tradeoffs, which is why household microeconomic factors are also important, as well as overall demographic pressure in an area [40]. A lack of productive assets is a frequent constraint on behavior [41,42]. Capital availability (to buy land or hire labor or equipment to clear) is one of these key constraints. On the demographic side, labor availability can be another key constraint.

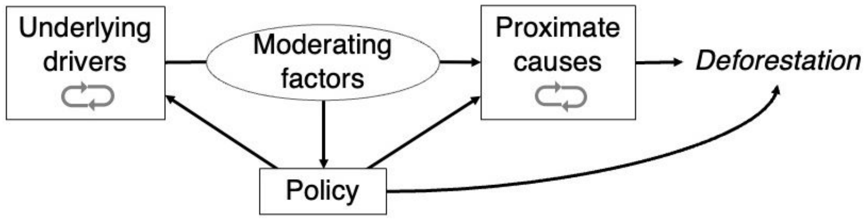

Figure 1: Conceptual model of major mechanisms influencing deforestation

To this framework we added other ***policies*** that directly provide incentives to pursue deforestation via rewards or penalties. Building from the categories used by Börner et al. [20] and Echeverri et al. [43] these types of policy approaches include: area-based conservation (i.e., protected areas, indigenous areas, restricted use areas, mixed conservation areas), public policies (i.e., taxes, quotas), financial instruments (i.e., payments for environmental services), and supply chain policies (e.g., certifications, standards, commitments and pledges). Deforestation policy effectiveness is defined as the degree to which the policy successfully reduces deforestation in the target region. By suggestion of Magliocca et al. [44] and van Vliet et al. [33] we also include ***moderating factors***, as those factors that influence the way in which an underlying driver affects a proximate cause or the implementation and effectiveness of a policy.

Using this framework (Figure 1), we answer the following questions as a means of synthesizing the existing research results: (1) *How do the proximate causes, underlying drivers, and moderating factors of deforestation vary across the Amazon Biome and over time?* (2) *How effective have deforestation control policies been across different regions and over time?*

To assess research gaps and uncertainties to guide further studies we ask: (3) *How does the availability and rigor of evidence vary across regions and topics (i.e., drivers, causes, moderating factors, and policy effectiveness)? (4) How does the evidence generated by case study (i.e., local, state, or national) research differ from regional (Amazon-wide) studies?*

Our findings provide a comprehensive, yet accessible overview on the geographic heterogeneity of deforestation drivers and combined governance effectiveness in Amazonia. Combining drivers, moderating factors, and policies in one synthesis enables us to characterize deforestation pathways and policy effects in more detail and within context and to identify major remaining knowledge gaps.

2. Methods

To answer our research questions, we systematically reviewed the available literature on Amazonian deforestation and deforestation policies published between 2000 and 2021 and coded this evidence base using a framework derived from our theoretical model to identify specific deforestation drivers and policies and to link them to individual Amazonian regions.

Studies were distinguished by whether they were analyzed at administrative level 0 (i.e., national), administrative level 1 (i.e., state/province/department), or administrative level 2 or higher (i.e., municipalities, districts, or individual communities). The journal search started from the year 2000 as the purpose was to provide an updated view since Geist and Lambin [18] and Rudel [31] whose work focused on earlier periods. This was also necessary to constrain the workload and ensure the relevance of our findings. However, we included studies that covered time periods extending before 2000 if they were published since 2000. We coded the drivers and policy outcomes analyzed in these papers using a uniform analytical and coding framework based on the theoretical approach described above (Figure 1), as well as location and time span. Included studies were further divided into *cases*, with an individual case referring to a specific study area, meaning a single study including several study areas was counted as several cases.

Because deforestation processes are highly complex and context-specific, we chose a qualitative approach to adequately review the literature. This also allowed us to carefully navigate the aggregation and generalization of findings, as case studies vary across spatial and temporal scales and methodological spectra. After reviewing selected case studies, we compared this bottom-up synthesis of sub-Amazonia scale work to top-down knowledge from Amazon-wide studies on deforestation drivers and control policies. Qualitative systematic reviews offer an inclusive yet differentiated synthesis of existing literature, while highlighting areas that require more research attention.

We followed recommendations for systematic review best practice, proposed by Haddaway et al. [32] and van Vliet et al. [33], to avoid bias and to improve the transparency and consistency of the analysis. The two largest peer-reviewed article databases “Scopus” and “Web of Science” were used to retrieve peer-review journal articles, as they allowed advanced article searches with complicated search terms (see Table S1 for the search strings). Additionally, we used the platform SciELO to capture articles. We included English as well as Spanish and French, however, we did not identify any French articles that met our selection criteria. We did not do a separate search in Portuguese because our selection already included a vast number of studies in Brazil (where studies in Portuguese were located). We did not use Google Scholar since it only offers simple searches and also contains inconsistently catalogued grey literature in this field, which could lead to biases if included [45]. We did not include grey literature due to the high number of peer-reviewed papers already captured by Scopus, Web of Science, and SciELO and our inability to consistently capture grey literature.

To ensure no relevant paper was missed, a broad search query was defined, using a range of terms to capture deforestation (land cover change, forest loss, forest clearing etc.) and searching all available database sections (title, abstract, keywords). Furthermore, to limit the search to the study area of the Amazon biome while enabling a country-level comparison, all states, departments and provinces (from here on all referred to as states) that are part of the Amazon biome, were included in the query. The border of the Amazon biome was defined according to the MapBiomas Amazonia map [2]. Finally, to ensure papers identified were relevant to current conditions, the search was limited to electronically accessible articles published since 2000 to the time of the search (2021). The search query was then adapted to work identically for the advanced search machines of the two databases.

The search in March 2021 identified 7,401 articles from both platforms combined, of which 5,229 articles were unique. Using the same search term, the search was repeated in December 2021 to include more literature in Spanish and French. The search identified 160 unique articles in Spanish (16 duplicates) and 61 unique articles in French (10 duplicates) from Scopus and Web of Science combined. A different search term consisting of numerous synonyms was used as SciELO does not allow for more elaborate search term formulation like Scopus and Web of Science. The synonyms were translated with the aid of expert native speakers, to include as many terms for deforestation as possible. The search on SciELO in December 2021 yielded 65 Spanish articles, of which 10 were duplicates from Web of Science and Scopus. The evolution of the search term and results is documented in Tables S1 and S2.

The retrieved articles were first filtered by reading the abstract to determine if they fit the overall topic of the review. Those articles that appeared relevant were compared to the following set of criteria to ensure only comparable studies with a rigorous methodological standard were included in the review: i) the study area had to be within the Amazon biome, ii) the study had to include a scale of analysis at the national level or below, and iii) the study had to include a rigorous causal analysis of the impact of at least one driver or policy on actual (i.e., past) deforestation.

For papers on proximate causes of deforestation, we included: i) remotely sensed estimates of land use transitions from forests, ii) correlation studies between deforestation and different land uses (i.e., where a deforestation map is developed first and then deforested areas within a region are assigned to the land uses that are most correlated with forest loss or allocated by another method, such as suitability), and iii) drivers quantified in interviews. While remotely sensed estimates that directly measure transitions from forest to a specific land use within a given pixel provide the strongest certainty that a specific land use is a primary cause of deforestation, we also include studies that look at the correlations between deforestation at higher spatial scales since remotely sensed data on the specific land uses that replace forests are more recent (at the biome scale such data were not available until the development of MapBiomas. We include interview data in addition to remotely sensed or statistical estimates as we believe that farmers' self-reporting of land use provides valid data. While self-reporting is likely to underestimate overall deforestation levels, there is less reason to suspect such bias regarding the specific cause of deforestation where such deforestation is detected.

For underlying drivers and policy impacts where causality is more difficult to assess, a robust econometric analysis that controlled for confounding factors was required. A significant relationship ($p=<0.05$) between the dependent variable (deforestation or deforestation for a specific land use) and the independent variable (i.e., the underlying driver or policy) was necessary for the case to be recorded in the synthesis. The inclusion criteria for policy analyses further required that a sound counterfactual method was used to ascertain what would have happened in the absence of the policy. This could include matching, difference-in-difference, or fixed effects econometric methods. We had intended to include qualitative process-tracing papers as well but identified no papers using this method. Examples and reasons for excluded articles are given in S4. The full coding scheme is presented in S5 in a separate tab from the results.

Each specific geography, proximate driver, underlying cause, and policy analysis is given its own case number. Articles excluded for one part of the conceptual model (i.e., underlying cause, policy effectiveness) can still appear in the coded data for the proximate causes, but the cases pertaining to the underlying cause or policy effectiveness would not be included in the analysis if they did not meet the inclusion criteria. This approach demonstrates not only how many places are studied, but also for a given geography, how many different causes, drivers, and policies have been rigorously examined.

All titles and abstracts were screened by the first author. Before starting the coding process, ten articles were coded independently by the first author and two other authors. The scheme was then adjusted to guarantee future consistency in the coding process. After that only the first author coded the articles. The final coding scheme included fields describing the study region and period, the impact and links of analyzed drivers and policies, and the methodology of the causal analysis. After coding, drivers and policies were aggregated and organized in clusters according to Geist and Lambin [18], the policy mechanism and how they were framed in the studies.

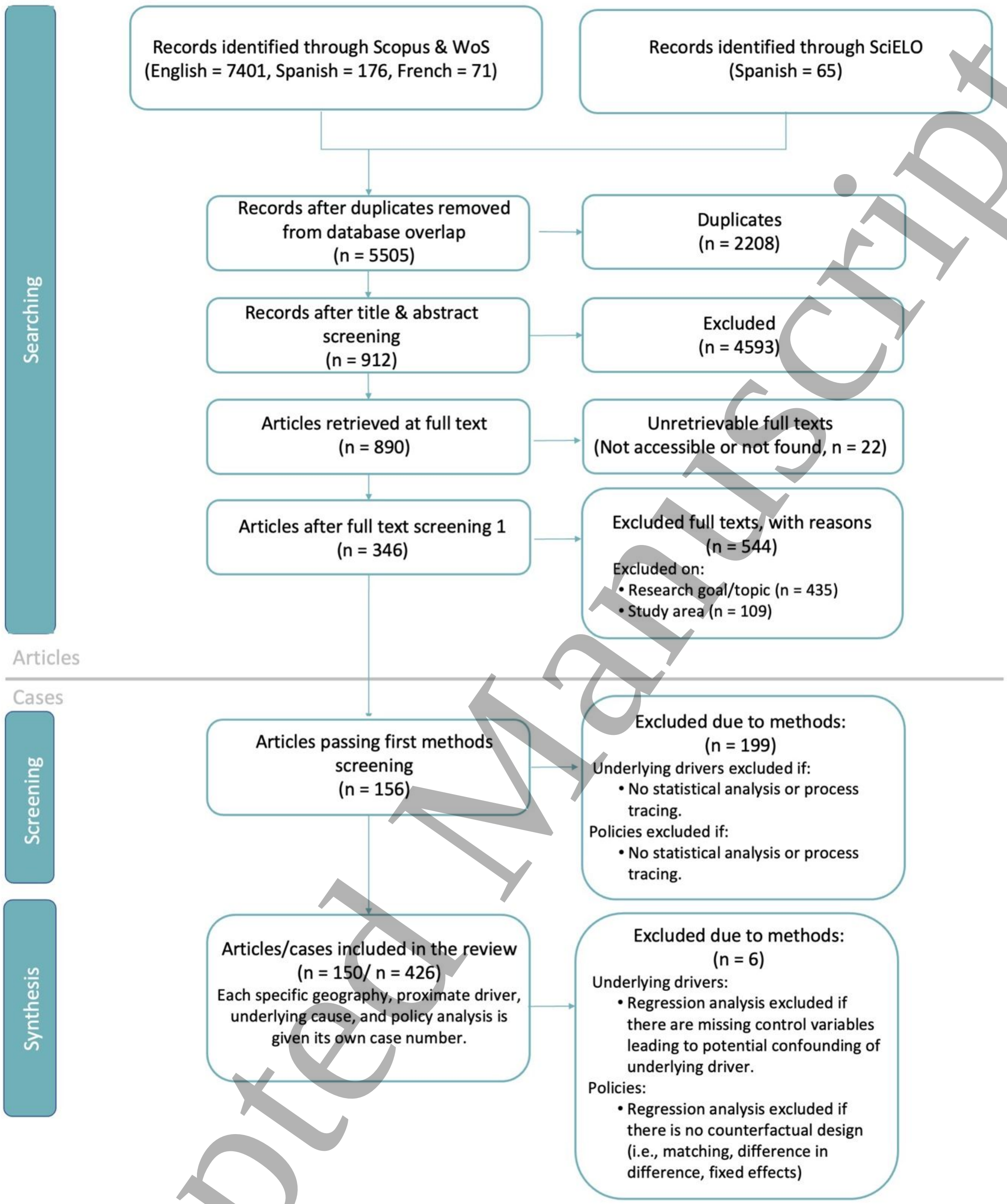

Figure 2: ROSES flow diagram for systematic reviews. Using the template provided by Haddaway et al. [46].

3. Results

Our review methodology identified 150 articles in the literature search. From these articles we identified 426 cases (spreadsheet S5 includes all coded data with separate tabs for cases meeting the methodological criteria and those that did not). The amount of research per year included in the review increased steadily since 2000, with 80% of reviewed studies published after 2010 (see Figure 3a). All papers were published between 2000 and 2021, but the studies have analyzed deforestation and land use data as early as 1970. A majority of the studies focused on the period after 2000. Figure 3b shows the geographic distribution of the 426 analyzed cases (since 1970) and deforestation as estimated in MapBiomas since 1985 (since data is not available before then) across the entire Amazon biome.

(1) How do the proximate causes, underlying drivers, and moderating factors of deforestation vary across the Amazon Biome and over time?

Proximate causes

Agricultural expansion was found to be the main proximate cause of deforestation in all countries except the Guianas. Among studies that examined multiple proximate causes, *large-scale agriculture*, which includes both cattle ranching and commodity crops, was found to have a larger impact on forests compared to other forms of agriculture. *Pasture expansion* was the primary proximate cause of deforestation in the Bolivian, Ecuadorian, Colombian and Brazilian Amazon across the entire period. In Southern Amazonia the rise of *commodity crops* (soy, oil palm) as a driver of deforestation is documented by several cases, especially until the mid-2000s. Studies in the Brazilian Amazon reported a considerable indirect effect of soy expansion displacing pasture into new frontier areas [47,48]. The limited cases show oil palm expansion is linked to deforestation in Peru, especially in Ucayali, but not in Pará, Brazil. *Small-scale or subsistence agriculture* was identified as a small but consistent driver in the Bolivian, Peruvian and Brazilian Amazon and in French Guiana. Regionally, small-scale agriculture caused larger amounts of deforestation in Brazil versus other Amazonian countries, specifically in Roraima and Amapá [49,50], and in Peru in the department of Amazonas [51]. In French Guiana, small-scale agriculture was the main agricultural driver and overall caused intermediate amounts of forest loss [52].

Coca cultivation was found to be a minor and decreasing cause of deforestation in Guaviare, Colombia, and was often replaced with pasture [53,54]. Coca is mostly grown in more accessible territories outside of Amazonia.

Small-scale *gold mining* (including both alluvial and open cast mining) was reported as the main, increasing cause of deforestation in Guyana and Suriname and had an intermediate impact on forest loss in French Guiana and in the Peruvian Amazonia. Mining spread along the gold-bearing greenstone belt of the Guiana Shield and along rivers [55]. In Peru, forest loss was caused equally by small- and large-scale gold mining. Although mining (inclusive of all types) had a very small direct impact on Amazonian forests in Brazil [50], its indirect impact on deforestation was a lot higher through road building that allowed agriculturalists to access new forest areas [56–59]. *Oil exploration* was analyzed as a minor local cause of deforestation in Amazonas, Brazil [60], but was also mentioned by several studies as a pioneer cause opening up areas to development and deforestation in the Colombian [61] and Ecuadorian Amazon [62–65].

Deforestation for *urban areas, settlements, roads and hydropower dams* in the Brazilian, Bolivian, Colombian, and Peruvian Amazon was very small compared to other drivers [50]. Expansion often occurred onto agricultural or other previously cleared areas and therefore avoided direct deforestation [51,66–68]. In contrast, one study found that due to the generally low levels of deforestation in French Guiana, the construction of a hydropower station in 1994 contributed to a large amount of the country's forest loss. Urban expansion however remained a minor driver along the coast [52].

While infrastructure is a proximate driver of deforestation according to the framework, studies mostly treated it as an indirect driver (by enabling other proximate drivers). In the Brazilian Amazon, the construction of large-scale hydropower stations caused considerable local impacts and further induced agricultural and urban expansion in the area, thus indirectly causing more deforestation [69–71]. Several studies observed that during and after the construction of the interoceanic highway (IOH) in Madre de Dios, Peru, deforestation due to agriculture and mining increased in the surrounding areas [72]. Similarly, many studies across the biome linked forest loss to roads, reflected by a distinctive fish-bone pattern of deforestation. In fact, accessibility to markets via roads was identified as an important underlying driver in the Amazon [73–76]. Infrastructure thus acts as a twofold driver, both proximate and underlying, and often dictates the pattern of deforestation.

Only a few studies found that *logging* was associated with complete deforestation (rather than forest degradation). Studies in French Guiana [77], and in the Ecuadorian [65] and Brazilian Amazon [78–80] show that logging had minor direct impacts on deforestation. In Ecuador timber extraction was found to be a byproduct and additional incentive for agricultural expansion, as it provided income to hire labor for clearing [81]. Similarly, *fire* is not necessarily referred to as a proximate cause of deforestation [50]. In the Brazilian and Colombian Amazon, fire was used to clear the remaining or regrowing forest after the logging for agriculture (e.g., in slash-and-burn practices) or for resource extraction. Escaping fires affecting surrounding forests were also reported but their impact was not quantified [53,82–84]. In extractive reserves very small-scale deforestation by extractivists was observed in the 1980s (in patches of up to 1.8 ha) in Acre [80] and in the 1990s and 2000s (in patches up to 4.2 ha) in Amapa [79], both in Brazil. But this deforestation was still deemed be associated with crop production by the extractivists and was replaced by larger-scale ranching and agriculture over time. Besides anthropogenic deforestation, *natural causes* for forest loss such as flooding and wind were observed and quantified as a small impact on Amazonian forests in Peru [72], Bolivia [67] and Brazil [50,56].

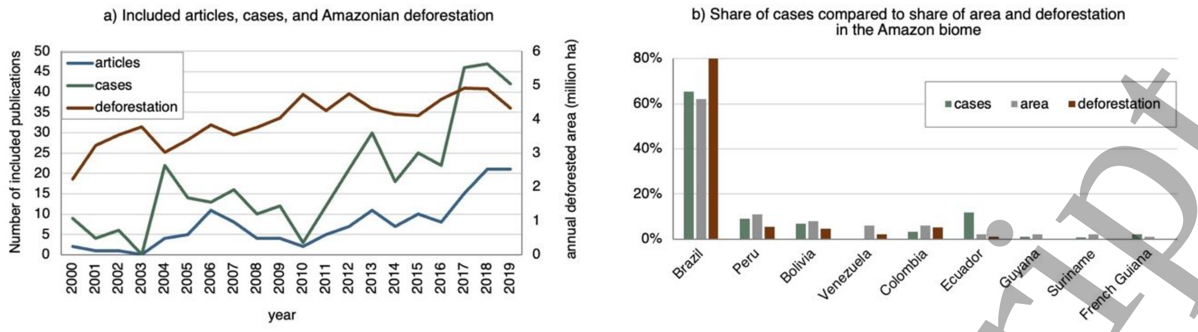

Figure 3: Number of proximate causes (top) and underlying drivers (bottom) identified through causal analyses in the selected studies, including the main drivers per category and the number of links between them (represented also by the thickness of the arrows; not including moderating agents).

Underlying drivers

Economic: The most prominent economic drivers affecting deforestation in the Amazon are related to market conditions that influence the prices that land users receive for the proximate deforestation driver (i.e., agriculture, mining, etc.) (Figure 4). This aligns with the classic net present value model of deforestation behavior (whereby land users are assumed to be motivated by differences in the discount flow of income they can get from different land uses). Studies in Peru [51,73], Bolivia [84,85], Ecuador [76,86] and Brazil [87,88] find that *accessibility via roads* and the resulting *lowered transportation costs to local markets* was associated with increased deforestation, especially due to pasture expansion and small-scale agriculture. Deforestation driven by local market access often spreads in a recognizable fishbone pattern from roads in less remote areas [89–91]. In more remote and less developed areas in the Guianas and earlier in Colombia, Peru and Pará, Brazil, roads had not extended into forests to the same degree and thus deforestation occurred *predominantly along navigable rivers* as this was the primary market access route [55,92].

Since the 1990s, corresponding to the growth in commodity agriculture for export markets, temporal variations in *commodity prices* have increasingly affected deforestation for agriculture and mining, especially in Brazil [93–95]. However, one study suggests that where pasture and cattle ranching are already present, an increase in the relative crop-to-beef price index has been associated with a reduction in deforestation by raising agricultural input prices, driving low productivity cattle ranchers out of agriculture [96]. Conversely, high *wood prices* were correlated with decreased deforestation in the Brazilian Amazon, as forests had investment value and were not fully cleared for agriculture (rather selectively logged) [94,97,98]. In the Ecuadorian Amazon however, extracted timber volume correlated with deforestation, as income from selling timber as a byproduct was often used for further agricultural expansion [81].

Several variables that pertain in one way or another to wealth and capital availability have contradictory results (both positive and negative effects) at the Brazilian Amazon-scale (measured by

GDP per capita) [78,94,99–102] and at the micro-scale (measured by many different proxies for *household income, wealth,* and *off-farm work*) in Brazil, Ecuador, and Peru [97,98,103–109].

The *availability of labor* was consistently linked to small-scale deforestation in the Peruvian [103], Brazilian [104,110], Ecuadorian [65,86] and parts of the Bolivian Amazon [111] during the 1990s. This finding corresponds more closely to subsistence theories of deforestation (whereby decisions are heavily influenced by leisure and labor tradeoffs and overall input scarcity), rather than rational-actor theories.

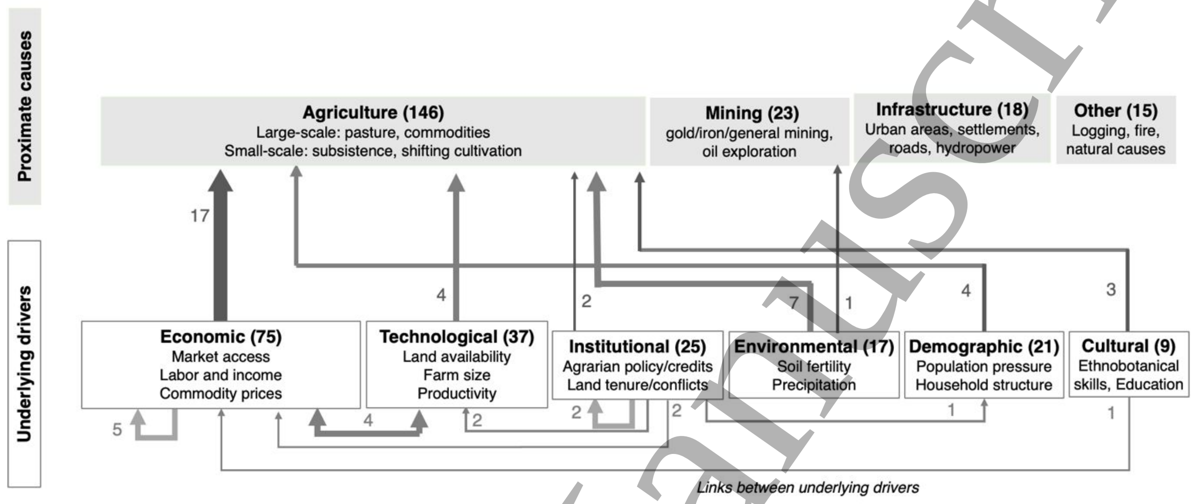

Figure 4: Number of proximate causes (top) and underlying drivers (bottom) identified through causal analyses in the selected studies, including the main drivers per category and the number of links between them (represented also by the thickness of the arrows; not including moderating agents).

Demographic: Population size and growth were found to be important underlying drivers of deforestation at the regional scale in Colombia [92] and Brazil [100]. Yet, at more local scales in Brazil and Ecuador the impact of household size and composition had varied impacts on deforestation with no clear directionality [65,81,86,98,105,112,113].

Technological: Technological drivers were most often studied in the context of agricultural expansion and thus implicitly linked to agriculturally caused deforestation, even where the proximate cause was not directly analyzed. With more forest available there are more opportunities to deforest and the price of land usually lower. This was confirmed by regional and local studies in Ecuador since the 1980s [65,76,81,109] and in more recent cases in the Brazilian Amazon [88,97,114] and in Madre de Dios, Peru [115]. Farm size was also associated with greater deforestation, but in these cases, it was often due to the higher amount of forest available in those farms, rather than farm size itself being a reason for greater deforestation. In the Brazilian Amazon, however, two earlier cases around 1995 found smaller farms deforested more than large ones [104].

The relationship between intensification and deforestation depended on capital availability. In general, farmers with higher agricultural productivity and higher efficiency had higher deforestation. However, very inefficient farmers also had high deforestation because they lacked capital for intensification and thus relied on deforestation to expand production. While higher agricultural productivity often led to more deforestation, agricultural diversification, e.g. , through agroforestry, was found to decrease deforestation in colonization frontiers in Rondônia [106–108,116].

Environmental: Soil quality, precipitation, and slope, were found to be important underlying drivers of deforestation in Brazil, Ecuador, and Bolivia, by determining the environmental suitability for different land uses. However, the importance of different environmental factors depended on the proximate cause in question. Across the Brazilian Amazon, earlier studies noted that deforestation was positively correlated with increased precipitation and low soil fertility, as the ease of initial clearing appeared to be a more significant driver of land clearing than the relative productivity of the following land use. Less fertile, washed-out soil had less vegetation, which facilitated clearing but required more land to achieve the same production [99]. After 1995, however, when commodity agriculture became a more relevant proximate cause of deforestation, lower precipitation, good soil quality, and less drought attracted greater agricultural conversion and more deforestation [76,87,88,94].

Institutional: Institutional drivers focused on agricultural settlement policies and land tenure and conflict. Only one study examined the broader political context as a driver of deforestation. It found that corruption and campaign funding in municipal re-election cycles increased deforestation in Brazil [117].

Land contention has remained an unresolved issue for several decades and was linked repeatedly to increased deforestation in the Brazilian Amazon. Land insecurity, inequality and occupation originating from inconsistencies in the institutional framework for property rights have affected deforestation behaviors. Full property rights are costly to attain and do not protect against encroachment. Consequently, competing landholders and squatters cleared "unproductive" forest to claim the land. Landholders also used preemptive clearing to avoid land occupation movements and expropriation by INCRA [95,97,114,118].

Once secured, land tenure has been shown to have decreased deforestation in the Brazilian Amazon. Where they had the right to clear land, renters and sharecroppers converted more forest to agriculture than land owners, who were usually implementing more long-term activities requiring less land [78,97,116]. However, in the Ecuadorian Amazon the opposite relationship was found. Land titles were required as collateral to acquire credits for cattle ranching in the 1990s, thus deforestation increased when that credit was made available [86].

Cultural: Cultural drivers were mostly assessed in the research hotspot of Beni, Bolivia, regarding the deforestation practices of the Tsimane' indigenous people. Traditionally, Tsimane' practice subsistence shifting cultivation as a secondary livelihood to fishing and hunting and thus only clear very small areas at a time. Generally, it was found that people with good ethnobotanical skills used land more efficiently and cleared less for agriculture [111,119], while those famers and villages that shifted towards more Western values had higher deforestation [90,91].

Finally, greater *education* was consistently associated with increased deforestation, both in the Brazilian [114] and Ecuadorian Amazon, probably due to the need to increased land clearing to generate income in order to fulfill aspirational consumption needs [76,86].

Temporal variance and moderating factors

Pasture-driven expansion is documented in the studies since 1975 [99,100], often encouraged by government-supported colonization programs, whereas commodity agriculture only accelerated in the 1990s and 2000s due to economic liberalization and rising market demand [99,120]. In the Brazilian Amazon, the establishment of agrarian settlements [88,94] and the availability of agricultural credit greatly increased deforestation during the 1990s and 2000s [94,95,104,105,121].

In the Peruvian Amazon, agrarian policy changed with regimes but especially supported cattle ranching and more recently infrastructure projects (e.g. the IOH) for trading, causing more deforestation [89]. Gold mining has been increasing since 1984, especially in Madre do Dios, Peru [122–124]. In Colombia changes in pasture-driven deforestation (in 1985-2001) were linked to changes in demographic pressures [92].

In Brazil both pasture-driven and commodity-driven deforestation peaked in the early 2000s prior to the introduction of improved deforestation-control policies and increases or decreases in rates were associated with similar movements in the price of the relevant in the domestic currency [93–95]. Deforestation only started to rise again in 2019 [2].

The effects of changes in both market access and population density on deforestation over time have been shown to be moderated by the extent of previous deforestation and remaining availability of forest and land. In frontiers with high forest cover, roads lead to greater deforestation, as found in Ecuador [109] and Brazil [75]. In contrast, in areas with less forest remaining, improvements to existing roads were associated with lower deforestation [100] and a higher population density leads to high competition costs associated with obtaining forest land, resulting in lower deforestation [109]. Relatedly, high urbanization, which can be seen as an almost late (or at least later)-frontier stage in development, was associated with decreased coca-related deforestation in the Colombian Amazon [54] and overall deforestation in Brazilian municipalities [114]. Market access and population factors also interact with each other in the context of frontier areas; infrastructure improvements have been found to attract migration and increased demographic pressure on forests.

(2) How effective have deforestation control policies been across different regions and over time?

Area-based conservation: The first legal conservation area in the Amazon basin was established in 1929 in Guyana, but the largest number of legal conservation areas were declared over the last twenty years. Today, about 50% of Amazonian lands are under protection [125]. In the Brazilian Amazon, comparative studies are not entirely conclusive about the most effective type of conservation area. As protected areas technically do not allow for any deforestation and received more regulatory attention, they were deemed most effective, followed by indigenous areas and sustainable use areas [126–129]. But two more recent studies found that indigenous areas faced more deforestation pressure and thus provided greater additionality compared to remotely located protected areas and less stringent sustainable use areas [130,131]. In some places, indigenous and protected areas even caused positive spillovers, by reducing deforestation outside of the area. Sustainable use areas generally had the smallest or no impact on deforestation, as they still allow limited clearing [132].

The additionality of conservation areas also varied depending on the deforestation risk, which in turn was a function of the location of the area. In Bolivia, the impact of conservation areas also depended on the proximate cause of deforestation. Conservation areas appear to have effectively stopped commodity agriculture expansion, but pasture and small-scale agriculture was found within such areas.

A few studies assessed the impact of land titling within indigenous areas. While one Brazilian Amazon study did not find any effect [133], studies in Brazil [134] and Peru [135] found reductions in deforestation after receiving property titles. Titling might have increased the regulatory attention and enforcement power in these areas which made them more effective. In Ecuador, complex tenure forms i.e., indigenous areas overlapping with patrimony or protected forest (restricted-use, public and private lands) showed a higher conservation effect than single tenure forms.

Financial instruments: PES pays participants, compensating them for the deforestation reliant economic activities that are being avoided and often targets additional issues besides forest conservation. PES policies have been rigorously analyzed in Guyana, and in the Brazilian, Peruvian and Ecuadorian Amazon and include both UN facilitated REDD+ (*Reducing Emissions from Deforestation and forest Degradation* in developing countries) projects as well as integrated PES+ICDP (*Integrated Conservation and Development Projects*), which include the Peruvian National Forest Conservation Program and the Ecuadorian Socio Bosque program.

The *Norway-Guyana REDD+ program* resulted in lowered deforestation due to mining in Guyana by 35% between 2010 and 2015, counteracting the influence of rising gold prices [136]. Yet, deforestation rates were still rising during the program and increased rapidly once it had ended. The policy is also suspected to have caused leakage into Suriname, as forest loss was concentrated along the border [136]. In Brazil, twelve *REDD+* projects across the entire Brazilian Amazon focused on agriculturally-driven deforestation did not provide additionality (outcomes beyond business as usual) in 2008-2018 [137]. Similarly, a regional REDD+ project in a previously blacklisted (i.e., cut off from agricultural credit) municipality in Mato Grosso did not find any significant additional effect as deforestation rates were already lowered by the government blacklisting policy as part of PPCDAm (explained below) [138].

The Peruvian *National Forest Conservation Program* PES+ICDP decreased deforestation in other areas, but not within enrolled zones in the same community, as forests with low threats were chosen for enrollment. Furthermore, communities with historically high deforestation rates were underrepresented and the conservation effect was only significant in the first year of the five-year contract [139].

However, a local PES+ ICDP program for the protection of the Moyobamba watershed significantly reduced deforestation by supporting the transition to agroforestry and more sustainable agricultural production [140]. Similarly, the REDD+ Sustainable Settlements Project in Pará, Brazil, reduced deforestation rates by 50% among participating smallholders, at the expense of pasture rather than cropland [141]. Ecuador's *Socio Bosque program* also reduced deforestation [142] and even remained effective when payment to participants was suspended [62]. Yet, participation in the program was more common for more remote and larger properties compared to low-income smallholders for whom forest clearing remained an important economic safety cushion [64].

Public policies: Federal enforcement of environmental policies through fines and embargos in the Brazilian Amazon was found to effectively decrease deforestation [102]. Two studies conclude that these policies have helped to weaken the relationship between global markets and commodity-driven deforestation in the two major hotspots of Pará and Mato Grosso [143].

In 2004 the *PPCDAm* (Action Plan for the Prevention and Control of Deforestation in the Legal Amazon) reversed the steep increase of deforestation in the beginning of the 2000s. After 2008, the blacklisting of municipalities and other mechanisms within the PPCDAM provided significant additionality in decreasing forest loss by up to 60%, likely due to improved law enforcement and monitoring [144–147]. Blacklisting even reduced deforestation in neighboring municipalities, indicating positive spillovers of the policy [148]. The PPCDAm disproportionately targeted cattle ranching and led to intensification of this land use, sparing forests [146]. Supporting the implementation of these policies, the local green municipality program in Pará was partially effective, for example in Paragominas, the initial municipality the policy was implemented in [149], but beyond [150].

Outside of Brazil there are few causal studies of public policies. A broad study covering the entire Guiana Shield [55] found that *militarized repression of mining*, starting in 2002, had significantly reduced deforestation due to gold mining in French Guiana and the neighboring Brazilian Amapá. However, leakage into Suriname is assumed where mining was not regulated. Lack of regional cooperation and strategies and the heavy reliance of local economies on gold mining were considered the main policy challenges in addressing gold mining as the primary driver of deforestation in the Guianas.

Supply chain policies: With the rise of commodity agriculture causing vast deforestation in the Brazilian Amazon, it is also the only place where private policies aiming to eliminate deforestation in supply chains have been fully implemented [151]. As the most effective supply chain policy, the Soy Moratorium reduced soy-related deforestation by 35-55% as it was introduced after 2006 [151,152]. Evidence regarding leakage due to the Soy Moratorium is mixed. One study by Heilmayr et al. [152] finds no leakage, but the most recent study by Villoria et al. (2022) indicates that up to 50% of the avoided deforestation in the Amazon was offset by deforestation leakage to other Brazilian forests. The local Responsible Soy Project in Pará also successfully decreased deforestation among soy-supplying smallholders but was not effective on larger farms [154]. On the contrary, the G4 and TAC cattle ranching agreements did not provide additionality in preventing deforestation. Leakage under the two agreements from properties that enrolled earlier to properties that enrolled later was responsible for the overall zero effect of the policy [155].

Only one study analyzed supply chain policies for other products. A study on the Forest Stewardship Council certification, a *third-party standard,* found it was not effective at reducing deforestation in the Peruvian Amazon, due to low stringency of the certification criteria and low enforcement of compliance to these criteria within certified operations [156].

Policy interactions: Public policies and institutions are key moderating factors for deforestation policy effectiveness. The success of REDD+ and voluntary policies was highly dependent on redundancies, complementarities, and antagonisms between: 1) public deforestation control policies like PPCDAm and 2) the presence of indigenous areas (both of which reduced deforestation, creating a certain redundancy that reduced the additionality of the said program), and 3) the type of land tenure present. Policies also indirectly affect deforestation through underlying drivers. For example, road building linked to deforestation is often an explicit function of public road building investments, making public policy a key underlying driver of infrastructure.

(3) How does the availability and rigor of evidence vary across regions and topics (drivers, causes, moderating agents, and policy effectiveness)?

As shown in Figure 4, agriculture (including cattle ranching), was the most researched proximate cause, with 146 cases covering the entire period of 1970-2019. Mining and infrastructure, and their linkages, were the next most researched proximate causes. There was no literature on large-scale gold mining, despite its presence in the Guiana Shield. There was also no literature specific to other types of mining (e.g., iron ore, copper).

The research hotspots for deforestation from *large-scale (soy) agriculture* are Santa Cruz in Bolivia (5 cases) and the Arc of Deforestation in Brazil (36 cases). Large- and small-scale expansion of *oil palm* is less well researched (8 cases). Subsistence agriculture has received considerably less research (30 cases) and this is mostly in the form of very local case studies. Coca research is largely absent in Amazonia but is more prevalent outside of the Amazon where coca production is also more common.

Economic factors, such as commodity prices, access to markets (e.g., proximity or cost-distance to riverways, urban centers or export terminals), GDP, and income are the most frequently studied underlying drivers (75 cases) and were linked to deforestation driven by large- and small-scale agriculture, as well as mining. Economic factors were analyzed in all countries especially in Brazil (44 cases), but not in Colombia and Venezuela.

Technological aspects were covered in 37 cases, mainly in the Ecuador (8 cases) and Brazil (27 cases). Most studies on these drivers refer to the context of agricultural production, but usually just link technology to overall deforestation instead of a specific proximate deforestation cause.

Institutional factors focused on agricultural settlement policies and land tenure and conflict and were analyzed in 25 cases. Most of these cases (21) were in Brazil where land conflict and tenure were commonly analyzed factors. Environmental factors were discussed in 17 cases, mostly in Brazil and Bolivia. Demographic factors were discussed in 13 cases, limited to the Ecuadorian and Brazilian Amazon. Culture was rarely analyzed (9 cases) and this was predominantly in Beni, Bolivia and various provinces in Ecuador.

Many underlying drivers and policies were linked to general deforestation, but not via a specific proximate cause. Sixty cases examined moderating factors between underlying drivers and proximate causes or policies. Nearly half of these cases (28) had to do with policies or institutions moderating other underlying drivers. Economic factors (mostly market access) and technological ones (relating to the remaining forest area) were the next two largest clusters of moderating factors.

(4) How does the evidence generated by local case study research differ from regional (Amazon-wide) studies?

Commodity agriculture in Brazil and its links to macroeconomic conditions is the leading focus of both types of research in Amazonia

As indicated in global and Amazon-wide analyses [21,22], deforestation, especially at large scales, has become driven mostly by the expansion of commodity agriculture (particularly beef and soy production). Brazil has the largest Amazonian territory and overall highest levels of deforestation, corresponding to the largest cattle herd and soy production areas. Accordingly, existing literature on deforestation drivers and policies follows these broad trends, with 65% of the cases focused on deforestation in Brazil, 31% of which were focused on analyzing agriculture as a proximate cause of deforestation. Bolivia and Peru are the next biggest hotspots of research on agriculturally-caused deforestation.

Global synthesis reports link this commodity expansion to growth in global and regional consumption of these products [1]. Similarly, we observe a shift in the focus of case study research over time from smallholder-driven deforestation and underlying household attributes to commodity-driven deforestation and macroeconomic underlying drivers. This corresponds closely to a shift in tropical deforestation agents described by Rudel [31]. Nevertheless, causal case study research obscures important findings from biome-wide studies on how political narratives about modernization and economic development influence clearing in the Amazon [157]. Such political economy dimensions are inherently more difficult to study at only local scales with causal inference methods. “Chain of explanation” approaches, which evaluate the influence of variables interacting at a number of scales, are a more common approach to understanding the effects of power relations on land use [158].

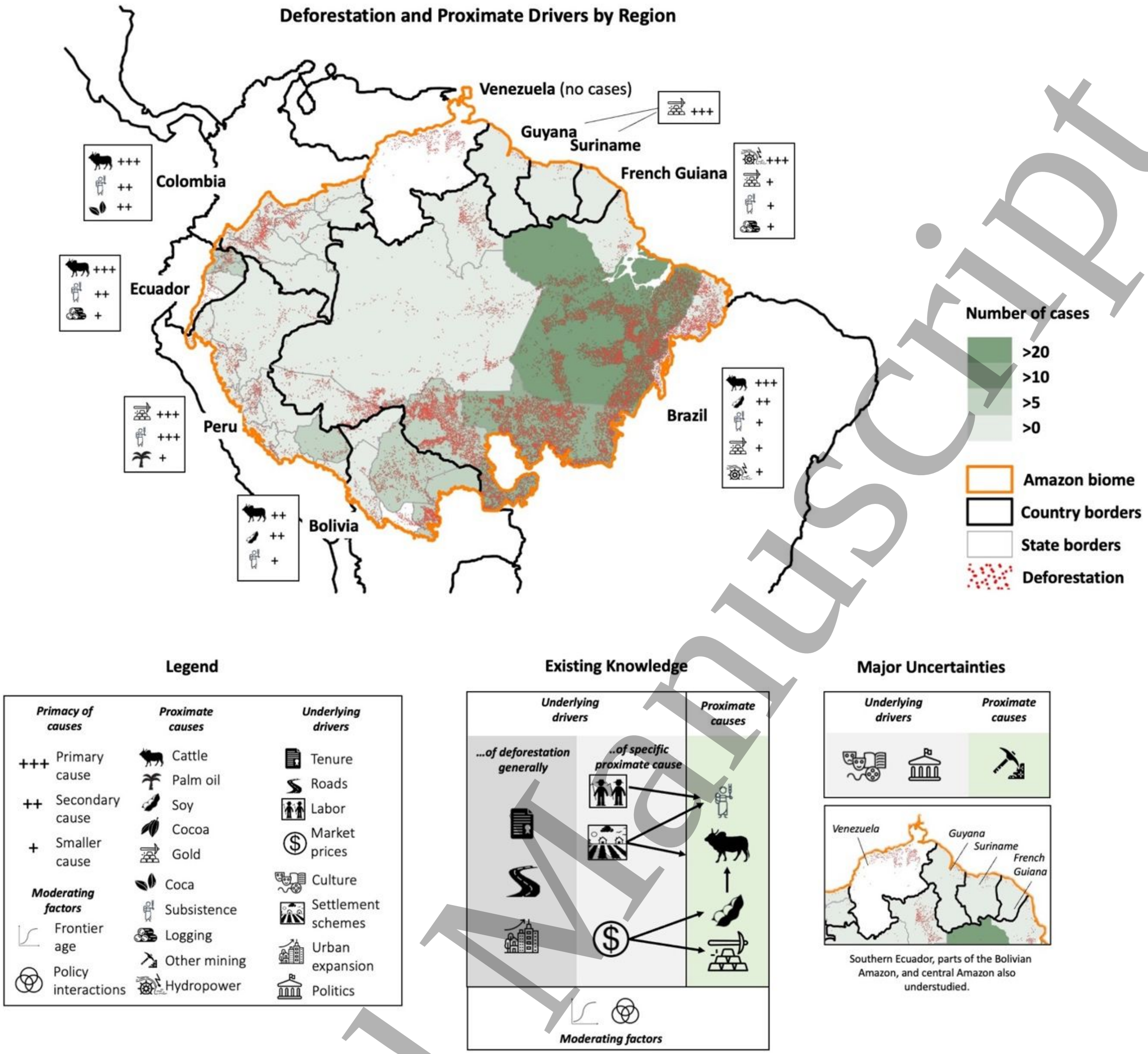

Figure 5: Distribution of cases (since 1970) and cumulative deforestation (since 1985) across the Amazon biome, synthesis of proximate drivers by region, existing knowledge, and major uncertainties. Map of the Amazonian border and deforestation data by MapBiomas Amazonia project (2022).

Despite an increasing focus on commodity agriculture, both Amazon-wide studies and case studies show that smallholder farming is still a relevant driver, especially in the western and northern regions of the Amazon (Figure 5)[21,22]. Kalamandeen et al. [159] found that small-scale clearing has significantly increased in 2008-2014 in all Amazonian countries and has spread with lower density into isolated areas. There is some speculation that large-scale farmers may be attempting to evade policy enforcement by clearing smaller, non-detectable areas [160], but this has not been definitively proven. Regardless of who the agents of change are, our review brings into focus that such small-scale patches of deforestation are relatively poorly studied despite their ongoing importance to deforestation and degradation in the Amazon biome.

Case studies illuminate the importance of mining as a key deforestation cause in Peru and the Guianas

Gold mining has been confirmed as a major cause of deforestation in the Guianas and in Madre de Dios, Peru and comprised 12% of the cases in these two regions. Yet it still shows up as relatively minor overall cause of deforestation [22] and is largely obscured as a subset of commodity-driven deforestation [21] in pan-tropical or Amazon wide studies, with the exception of the very recent study by Giljum et al. [161] focused entirely on industrial mining.

Additionally, our findings point to growing mining hotspots in eastern Venezuela and the Tapajós–Xingu region in Brazil. Forest loss due to gold mining in these regions increased dramatically since 2001 and is moving into remote areas of higher conservation priority that overlap with greenstone areas [25]. Mining activity in official concessions can be small- or large-scale but illegal mining is rife and difficult to police due to accessibility issues and lack of resources by relevant countries. So far, military operations against mining in French Guiana and Madre de Dios (e.g. Operation Mercury) were effective but have displaced the cause to other areas [55,162]. As Alvarez-Berríos and Aide [25] confirm, deforestation due to gold mining is also connected global markets and rising gold prices.

Many areas of Amazonia are completely ignored

On the national Amazon level, the distribution of cases is comparable to the share of deforestation and the share in Amazonian area. Ecuador has a particularly high density of cases while Brazil has the largest amount of forest loss per area and cases (Figure 3b, 4) [2,163]. Within countries, research hotspots are visible. Outside of Brazil, well-studied areas with a high density of local and regional cases include Madre de Dios in Peru (8 cases), Beni (6 cases) and Santa Cruz (5 cases) in Bolivia and Northern Ecuador (12 cases). In Brazil, both forest loss and number of local and regional cases were particularly high in the Pará, Mato Grosso, Rondônia (136 cases collectively). These three states constitute the majority of the Brazilian Arc of Deforestation, a region named for its historically high levels of deforestation. Most of these hotspots have higher rates of forest loss compared to the rest of their respective countries [2,163].

Despite the presence of deforestation in the Venezuelan Amazon, the Southern Ecuadorian Amazon (departments of Zamora Chinchipe and Morona Santiago) and Bolivian Amazon (departments of Cochabamba and La Paz) [2], the reviewed literature entirely misses these areas. In the remaining countries, at least one case study researched the entire Amazon region of the respective country. This could indicate that research is done where most urgently needed. However, areas with high forest cover and low deforestation and research coverage, such as the Guianas or the central Amazon region, should not be neglected. The sparse, small-scale forest loss in this area is not monitored and analyzed with the same attention as deforestation in other parts. Therefore, these regions are at high risk to ineffective or delayed conservation, especially if they are reached by large-scale deforestation (e.g., if existing colonization frontiers develop into commodity frontiers as has occurred in Brazil's Arc of Deforestation to the South). Furthermore, ecological impacts of forest loss on intact, remote forests are unknown given their poor coverage, but may be even more detrimental than in areas that are already degraded or affected to some degree. For example, the 227 "hyperdominant" tree species that make up over half of all Amazonian trees tend to be located in specific regions, whilst over 10,000 trees are rare, poorly known and potentially threatened [164]. In addition, remote areas tend to have high degrees of endemism: for example there are over 40% endemic plant species in the Kaieteur Falls National Park in Guyana [165].

Strengths and shortcomings in forest conservation

As a global review by Börner et al. [20] showed, policy analyses of forest conservation are generally lacking in the Guianas and Venezuela while Brazil has the highest number of studies worldwide. Forest conservation is also frequently studied in Peru and Ecuador. Accordingly, the distribution of policy research in Börner et al. [20] is consistent with the distribution of policy cases in this review.

The meta-analysis by Börner et al. [20], which also considered effect sizes, found that indigenous territories avoid more deforestation than protected areas or any other policy studied, on average. Our synthesis (Figure 4) does not consider effect sizes given the wide differences in the policy types and the spatial scopes they cover. We instead only consider whether they were additional in providing reduced deforestation beyond business as usual within their target areas. As summarized in Figure 6, we find that indigenous areas, restricted use areas, protected areas, PPCDAm (a suite of deforestation control policies in Brazil), militarized repression of mining in the Guiana Shield, and Socio Bosque (a national integrated conservation and development program in Ecuador) were all, on average, effective in providing reduced deforestation beyond business as usual. Several interventions (indigenous areas, mixed use areas, and ZDCs had cases of negative spillovers, while only protected areas and ICDPs included only positive spillovers.

Global reviews indicate that PES schemes have been moderately effective in reducing forest loss in Latin America but have struggled to be impactful in terms of coverage area, in the absence of deforestation risks, and when confronted with insecure land tenure and weak governance. This was confirmed by our review in the Peruvian and Ecuadorian Amazon. As PES are voluntary and used for compensating opportunity costs of avoided deforestation, their effectiveness also depends on the global willingness to pay for these schemes and institutional settings such as the level of market integration, an important underlying driver in this review, and who receives the payment (governments or steward populations). The effectiveness of ICDP approaches generally seems to have improved over the past years, as newer reviews now indicate their increased additionality [166–169]. Overall, the diversity of outcomes and range of spillovers across different policy types calls into question any clear "best" single policy approach, instead supporting calls for broader conservation and development policy mixes [170,171].

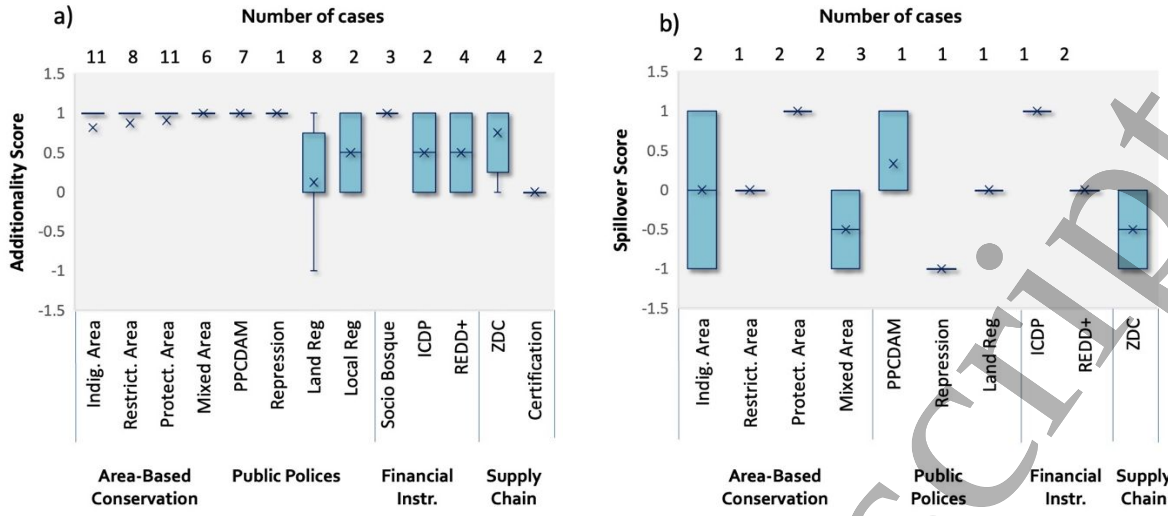

Figure 6: Comparison of the additionality (a) and spillovers (b) of different deforestation control policies in the Amazon. *Box plots show the mean and distribution of additionality scores (1=positive additionality/spillover, 0=no additionality/spillover, -1=negative additionality/spillover). The number of cases per policy is listed at the top. Notes: Indig. = indigenous, restrict. = restricted use, protec. = protected, PPCDAm = the Plan for the Prevention and Control of Deforestation, repression = militarized repression of mining, land reg = land registration, Green muni = the green municipality program, ICDP = integrated conservation and development programs, Socio Bosque = a national ICDP in Ecuador, REDD+ = reducing emissions from deforestation and degradation programs, ZDC = zero-deforestation commitments.*

6. Conclusion

This review combines and synthesizes an analysis of deforestation drivers and the impacts of policies targeting deforestation in Amazonia while providing a comprehensive, yet accessible overview on the topic. It demonstrates the geographic (and temporal) heterogeneity and complexity of deforestation drivers and governance issues and concludes that not all drivers are equally at play across the region. The various policy instruments and their successes also vary. The review therefore shows the importance of understanding local context and regional differences to better devise appropriate governance options.

Our results show that the distribution of case study research parallels rates of deforestation across the biome. This focus on deforestation hotspots results in a lack of research in regions with lower, but significant rates of deforestation and areas where new drivers such as mining and infrastructure expansion are emerging. There is no causal research of drivers or policies on Venezuela, southern Ecuador and parts of the Bolivian Amazon, and very little in the Guianas or the central Amazon region.

Besides large-scale agricultural expansion and economic underlying factors, other drivers have received comparatively little research attention. Mining, smallholder farming and infrastructure expansion as well as logging and fires may have a smaller direct impact on forests but are also less understood in today's evidence base. Given the emerging importance of critical minerals for electric batteries [172] and increasing extent of forest degradation in Amazonia [173], the large blind spots regarding drivers and impacts of mining, logging, and fire in Amazonia are very worrying.

As research is concentrated in deforestation hotspots and where forest loss occurred, areas with low deforestation rates and high forest cover such as the Guianas, are less researched. However, these regions are still at risk of increased forest loss, especially as new drivers like mining and infrastructure emerge without suitable control policies.

Research on sociocultural, behavioral, institutional, and technological factors as underlying causes is scarce, and concentrated in either Brazil or certain research hotspots. Very few studies connect proximate and underlying drivers and policies, via moderating factors. This reduces the understanding of how drivers and policies affect each other and how their interactions affect deforestation. For example, analyzing which drivers are impacted by a policy is essential to understand how its effectiveness can be improved. More interlinked research that focuses on the complex pathways and networks of deforestation processes, particularly indirect land use change, is needed.

Finally, only few studies compare or connect specific regions of the Amazon. As the biome is integrated in many ways, effects of a local policy or driver on forests may carry across borders to other countries and biomes. Studying these dynamics and comparing local contexts may provide essential knowledge for conservation in the Amazon.

Based on our review and the comparison of our results to additional literature, we define the following main areas in need of more research in the Amazon:

i. proximate causes of deforestation that are not agricultural, such as mining and infrastructure,
ii. links between forest degradation and deforestation,
iii. deforestation in areas with low deforestation rates and high forest cover,
iv. cultural, institutional, and technological underlying drivers of deforestation,
v. research on the politics and policy pathways underlying deforestation increases and reductions, and
vi. comparative studies between Amazonian subregions and countries.

These findings may help to guide future research and conservation in the Amazon, for instance by providing a basis for improving the design of future conservation policies in the region, moving beyond existing approaches that are not suited to the local context or miss key drivers.

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Author contributions

AH, SL, and RG designed the research. AH and RG analysed the data with support from SL. AH wrote the original draft. AH and RG created the figures. SL, RG, JB, XR, IB, and DA all helped develop this draft and contributed to writing, reviewing, and editing. RG, AH and SL undertook the major revisions with review and edits from all other co-authors. RG finalised the manuscript.

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