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Drivers of deforestation and forest degradation between 1990 and 2023 - A global meta-analysis

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ABSTRACT

Deforestation and forest degradation are continuing at alarming rates globally and are thereby contributing to climate change, biodiversity loss, and social inequities. Governments have recognized that without halting deforestation, reaching global climate targets and the Sustainable Development Goals will hardly be possible, and have made respective commitments and developed dedicated policies. However, there has been no recent comprehensive analysis on the proximate causes and underlying drivers of deforestation and forest degradation. We address this gap through a systematic review and meta-analysis of studies on the drivers of deforestation and forest degradation worldwide between 1990 and 2023. We identified 234 relevant articles covering 63 countries, mainly in the tropical biome. Our findings show that deforestation is primarily caused by commercial agriculture including livestock (83 %) and to a lesser extent by wood extraction (52 %) and subsistence farming (50 %). On the other hand, forest degradation is primarily caused by wood extraction (100 %) for subsistence. However, the share of studies with a focus on degradation (n = 23) was very low, revealing that much research is still needed in this field. In most cases, underlying drivers play a key role and consist of a combination of economic, demographic, and political factors. We recommend that deforestation-related policies and commitments account for these driving factors and that they are tackled alongside the direct causes.

1. Introduction

Deforestation remains one of the world's biggest challenges as it is causing biodiversity loss, reducing human well-being and risking the livelihoods of rural communities and Indigenous People, and accelerating climate change. Without halting and reversing deforestation and forest degradation, as set out e.g., in the Global Forest Goals and Targets of the UN Strategic Plan for Forests 2030 (DESA, 2019), in the Glasgow Leaders' Declaration on Forests and Land-Use (COP26) or Paragraph 33 of the Global Stocktake (COP28), global climate and development goals will hardly be achieved. Currently, the world is far off track in reaching specific deforestation-related targets (Forest Declaration Assessment Partners, 2024). The dwindling time for implementing commitments is shifting forests again more in the focus of global efforts such as combating climate change or fostering sustainable development under Agenda 21.

Between 1990 and 2020 alone, 178 million ha of forest have been lost globally (FAO, 2020). Historically, a first comprehensive systematic review on the drivers of deforestation for the years 1880 – 1996 was carried out by Geist and Lambin (2002). They revealed agricultural expansion, infrastructure development and wood extraction as main proximate causes with economic, political, technological, cultural, and demographic factors as underlying drivers. Agricultural expansion from the 1970s onwards mostly referred to small-scale subsistence farming and shifting cultivation, often supported through state-run colonization programs and road-building (Geist and Lambin, 2002; Rudel, 2007).

Later, the early 1990s with the 1992 Rio Earth Summit can be seen as a tipping point for humanity and the environment in several aspects. Globally, the United Nations Agenda 21 (United Nations (UN), 1992) has induced an era of regime shifts in forest and environmental policies as well as funding for the conservation and sustainable management of natural resources. Starting in the 1990s, many governments, through the support of global environmental organizations and development agencies, revised their forest strategies and programmes, which had often been relics from the colonial era (Muthee et al., 2022). These new strategies included aspects of conservation as well as community forestry in many countries but also had the goal of enhancing economic returns.

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While deforestation has accelerated in certain regions and countries, especially in Africa and parts of South America, forest area has remained stable or even increased in others, particularly in Europe and China. In the latter economies, the terms 'displaced' and 'imported' deforestation have received increasing attention (Pendrill et al., 2019a). Agricultural trade has become the main cause of deforestation in the past three decades (Austin et al., 2017; Hosonuma et al., 2012; Leblois et al., 2017; Pendrill et al., 2022), but attribution of deforestation has become more difficult due to the large share of globally traded goods such as palm oil, soy, coffee, cocoa, or rubber. Today it is estimated that 26 % of deforestation in the tropics is attributed to international demand (Pendrill et al., 2019a) and that one third of deforestation emissions are related to international trade (Pendrill et al., 2019b).

In the case of intact forest loss, Scullion et al. (2019) argues that logging was even more important than agriculture between 1970 and 2019. This reflects patterns where infrastructure development and logging potentially lead to degradation and ultimately open areas for agricultural development. However, monitoring forest degradation is challenging and still needs continued methodological developments (Neeff et al., 2024), which is one of the reasons why much fewer studies have looked at degradation compared to deforestation. Betts et al. (2024) suggest that forest degradation should in fact be quantified at bigger scales to account for spatial and temporal dynamics.

Agricultural trade or commodity-driven deforestation and degradation also have an impact on consumer countries, as climate change and the loss of biodiversity ultimately affect the entire world. Aware of the problematic, many private companies have made zero-deforestation commitments in the past twenty years but with limited measurable effect (Lambin and Furumo, 2023). The European Union (EU) recently launched the EU Deforestation Regulation (EUDR, EC, 2023) that excludes particular commodities and products originating in deforested or degraded areas from the European market with the aim to halt commodity-based deforestation and forest degradation. While providing a solution with focus on agricultural commodities (including timber and wood products) is plausible, there has also been much criticism toward the EUDR, as it is not addressing underlying drivers such as contrasting policies and regulations, poverty and other pressures on producers in the Global South (Muradian et al., 2025).

The key challenge is therefore that if underlying causal mechanisms are not tackled alongside direct causes of deforestation and forest degradation, lasting solutions are unlikely. Yet, data on underlying drivers at larger scales is scarce. Since Geist and Lambin (2002), no global systematic review has been done that clearly distinguishes between underlying and proximate drivers and that goes beyond the current focus on agriculture. Therefore, we aim to complement current scholarly literature by expanding on previous work (Geist and Lambin, 2002) and broadening the scope to the global level as well as including the problematic of forest degradation.

By conducting a global systematic review and meta-analysis, this paper investigates the following research question: What are the proximate causes and underlying drivers of deforestation and forest degradation worldwide between 1990 and 2023? After describing the review process and methodology, we present an overview of the included articles and the results of the meta-analysis structured according to deforestation and degradation and the proximate causes and underlying drivers. Finally, we discuss the scientific contributions and political implications of our results and provide recommendations.

2. Methods

2.1. Theoretical framework

This study uses the terms and definitions of the Food and Agricultural Organization of the United Nations for forest and forest change. Accordingly, we understand forest as "land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10 %" that does not include land predominantly under agricultural or urban use (Food and Agricultural Organization of the United Nations FAO, 2020). Deforestation is the "conversion of forest to other land use" (ibid.). While there is no universal definition for forest degradation, in this study, degradation refers to changes within a natural (forest) ecosystem that significantly and negatively affect its species composition or structure and reduces its capacity to provide ecosystem services (Thompson et al., 2013). The conversion of a natural forest to a planted forest would thus represent a form of degradation but not deforestation. We want to point out that articles included in this review sometimes used varying definitions. Conversion of natural forests to tree plantations is by some authors considered deforestation, by others it is considered a form of degradation, while still others do not mention it as a change in forest area. In our study, we considered it as degradation if respective information was available.

We used an adapted framework based on the proximate causes and underlying driving forces of Geist and Lambin (2002). Leaning on Meyfroidt (2016), we use the terms proximate causes for land use activities directly impacting forest cover and underlying drivers for indirect factors for which there is some evidence of a causal association with forest cover change but for which causal effects have not been firmly established. Our framework underwent some minor adaptations to fit better with the current research gaps (Fig. 1). In particular, we make a distinction between commercial and subsistence agriculture and also study mining as a separate category of proximate causes. Regarding underlying drivers, we added natural factors such as soil fertility or annual rainfall, which were referred to in several of the studies.

2.2. Data collection

2.2.1. Study design and article selection process

As a framework for the systematic review process, we followed the general guidelines provided by the Collaboration for Environmental Evidence (Collaboration for Environmental Evidence CEE, 2013). We used the open-source software Cadima (V.2.2.3) as support tool for data management and the systematic review protocol. The article selection process is illustrated in the flow diagram in Fig. 2 and explained in more detail in chapters 2.2.2 and 2.2.3.

2.2.2. Search strategy

On 19 June 2023, we searched two databases, Web of Science and Ovid, using two search strings, one for deforestation (deforestation OR forest loss OR forest conversion OR forest degradation OR tree cover loss) and one for drivers (driver OR cause). We searched specifically for scientific articles in English language. Our search yielded 4207 articles through Web of Science and 4605 articles through Ovid. These were imported into Cadima. We then removed all duplicates, first through automatic removal and then manually, ending up with a total of 5918 articles.

2.2.3. Article screening

The article screening was done by the first author in two steps: First, the screening of title and abstract, and second, the screening of the fulltexts. We used the same basic inclusion criteria consisting of three elements of the standard PICO framework (Population = forests, Intervention = proximate or underlying driver of change, Outcome = tree cover loss) for both steps. Thereby, the type of driver investigated was kept deliberately open. While some articles considered multiple drivers and causes, others were framed around one specific direct causes, e.g., studies investigating the role of oil palm in deforestation. In addition, during title and abstract screening, we removed articles according to exclusion criteria: articles without accessible fulltexts, articles without primary data such as meta-analyses and reviews, framework studies or opinion pieces. We also removed studies that did not explicitly focus on deforestation or forest degradation but rather on carbon or biodiversity loss, studies that focused on the effects of deforestation, and studies that

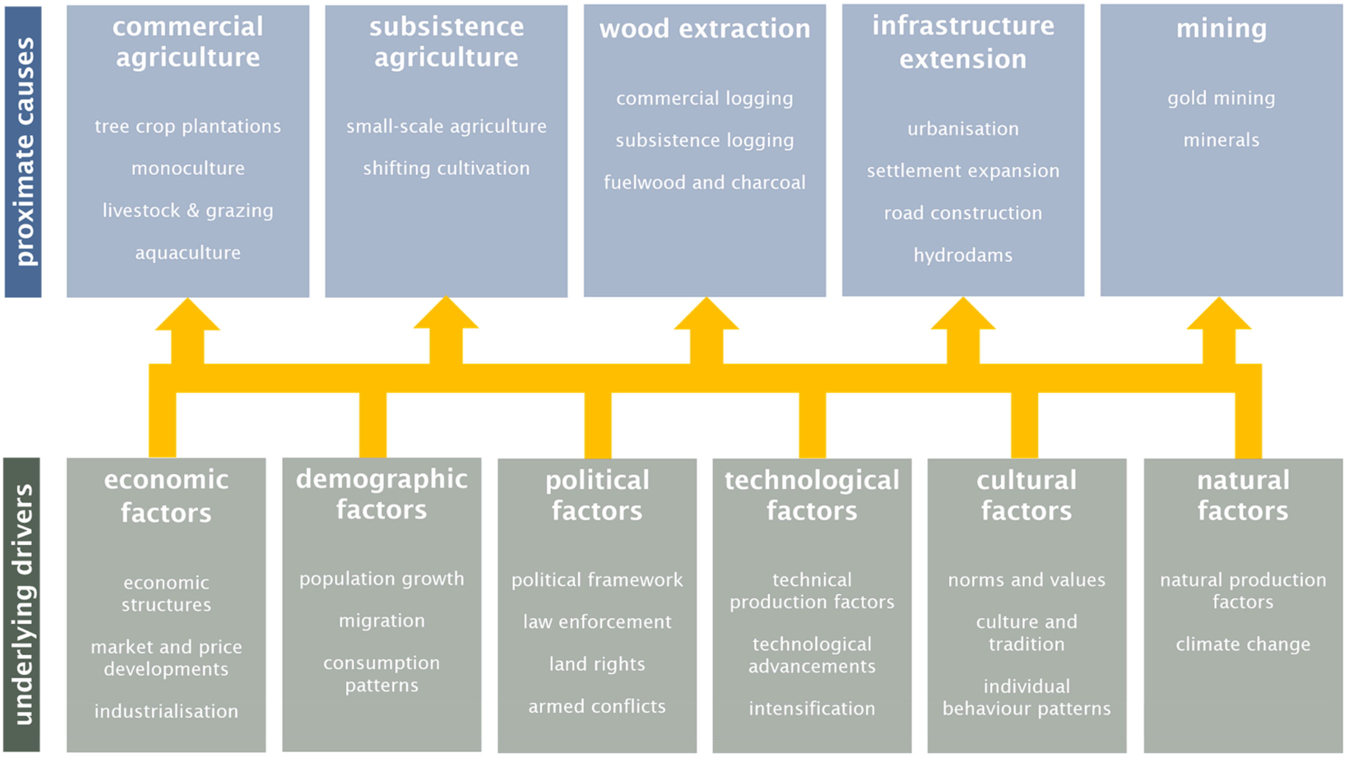

Fig. 1. Theoretical framework showing categories of proximate causes and underlying drivers (factors) of deforestation and forest degradation including sub-categories (adapted from Geist and Lambin 2002).

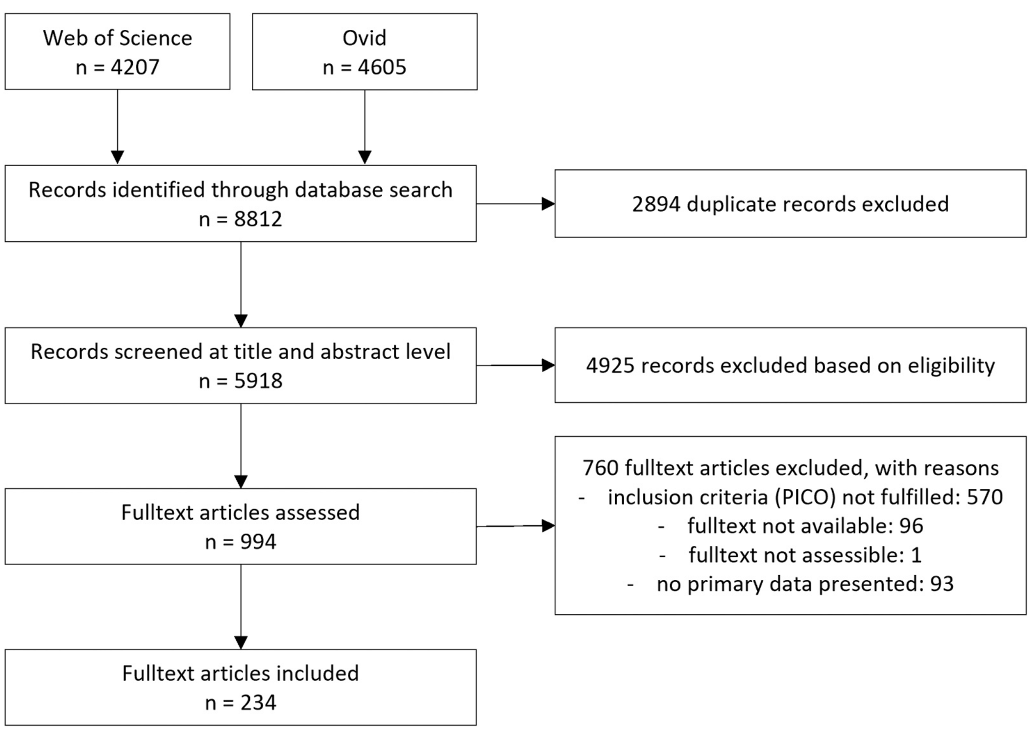

Fig. 2. Flow diagram depicting the study selection process and the studies retrieved for the meta-analysis.

investigated measures to reduce deforestation or enhance conservation. During the title and abstract screening, a total of 4925 articles were excluded from the initial 5918. A fulltext screening was done with the remaining 994 articles. In addition to the basic criteria and in order to stay within the scope of the study, we removed studies considering periods before 1989, studies which modelled deforestation without the use of primary data for past deforestation, and studies that focused on the structural patterns of deforestation such as fragmentation. We finally included a total of 234 fulltexts for analysis (Fig. 2). The complete list of included articles is provided as supplementary material.

2.3. Data analysis

Data extraction and coding was done manually in an excel table. For the meta-analysis, we decided to limit the number of drivers to five per article. Accordingly, we noted the main five proximate causes and/or underlying drivers in the order of importance from most important (driver_1) to least important (driver_5) identified by each article, which was described in the articles either in quantitative terms (e.g. area) or qualitative terms (based on expert opinion). All drivers were first extracted in their original terminology, then in a second step coded into the subcategories and in a third step coded into the main categories of our theoretical framework (Fig. 1). For example, if a study mentioned "swidden agriculture" (uncoded), this was subsequently coded as "shifting agriculture" (code_1) and "subsistence agriculture" (code_2).

Additional data collected about the articles included the country or region of study, the spatial scale (local, subnational, regional, global), the year of publication, the period (years) studied, the forest type (tropical, tropical dry, temperate, boreal, mangrove), the methodology used (quantitative, qualitative, mixed), and whether specific causes were investigated based on their research question and study design. Some studies mentioned links between drivers. These qualitative descriptions were additionally noted in the comment's column.

We used R statistical programme (R Core Team 2023 in Version 2022.07.1) for data analysis and the production of graphs and tables based on the coded excel file (code_2). We did this for both proximate causes and underlying drivers. However, as the categories of underlying drivers were rather evenly distributed across studies and the ranking held very limited certainty, we decided to carry out an additional analysis based on the uncoded drivers. Therefore, we produced word clouds with the Free Word Cloud Generator for the uncoded drivers as mentioned in the articles.

3. Results

3.1. Overview of studies

From the 234 included articles, 4 encompassed a global scale, 5 focused on the tropics, and further 12 considered regions including transboundary issues. All other articles used case studies in one or few countries. Overall, the included studies cover 63 countries (Fig. 3). We found that over 80 % of deforestation and degradation studies focused on tropical and subtropical regions. These were distributed evenly between the three main tropical regions. Considerably less attention was on South and East Asia (n = 17), Europe and Central Asia (n = 11), and the Middle East and North Africa (n = 5). Country-wise, the largest number of studies was done in Brazil (n = 21) with livestock and soy as main causes of deforestation, followed by Indonesia (n = 19) with oil palm as key land use replacing forests. Additional hotspots were Colombia and Myanmar with 17 and 15 studies, respectively. In Colombia, several studies explicitly investigate the impacts of armed conflict and associated emergence of illicit crops on forests (e.g., Clerici et al., 2020; Ganzenmuller et al., 2022). In Myanmar, diverse regions and drivers were studied, including, among others, mangrove deforestation for paddy fields and shrimp production or upland forest degradation and deforestation patterns linked to subsistence and market developments. Our findings in the following chapters usually refer to drivers mentioned in many countries and across continents. In a few cases, a certain driver is demonstrative for a specific region or country and is elucidated accordingly.

Humid and semi-humid tropical forests were the most investigated forest types (n = 159), including 13 studies focusing on the specific case of mangroves. In addition, 31 studies were carried out in tropical dry forests, many of which investigated degradation drivers rather than deforestation, as this is a bigger issue in the semi-arid area of the tropics. As an example, studies in Mexico (n = 11) provided good examples of quantifying degradation (Jiménez-Rodríguez et al., 2022; Morales-Barquero et al., 2015). Overall, 73 % of articles studied only deforestation, 10 % studied forest degradation, and another 17 % included both aspects. We found that the number of relevant articles has increased substantially in the past decade (Fig. 4). A recent increase in forest degradation studies – 8 of the 23 articles were published in 2022 alone – could be explained by methodological advances to quantify and map degradation.

Fig. 4 shows that quantitative studies indeed make up the large majority of papers. This includes both spatial quantification through remote sensing and large surveys. Many studies that used a mixed methodology quantified the proximate causes of deforestation through remote sensing and then carried out focus groups or key informant

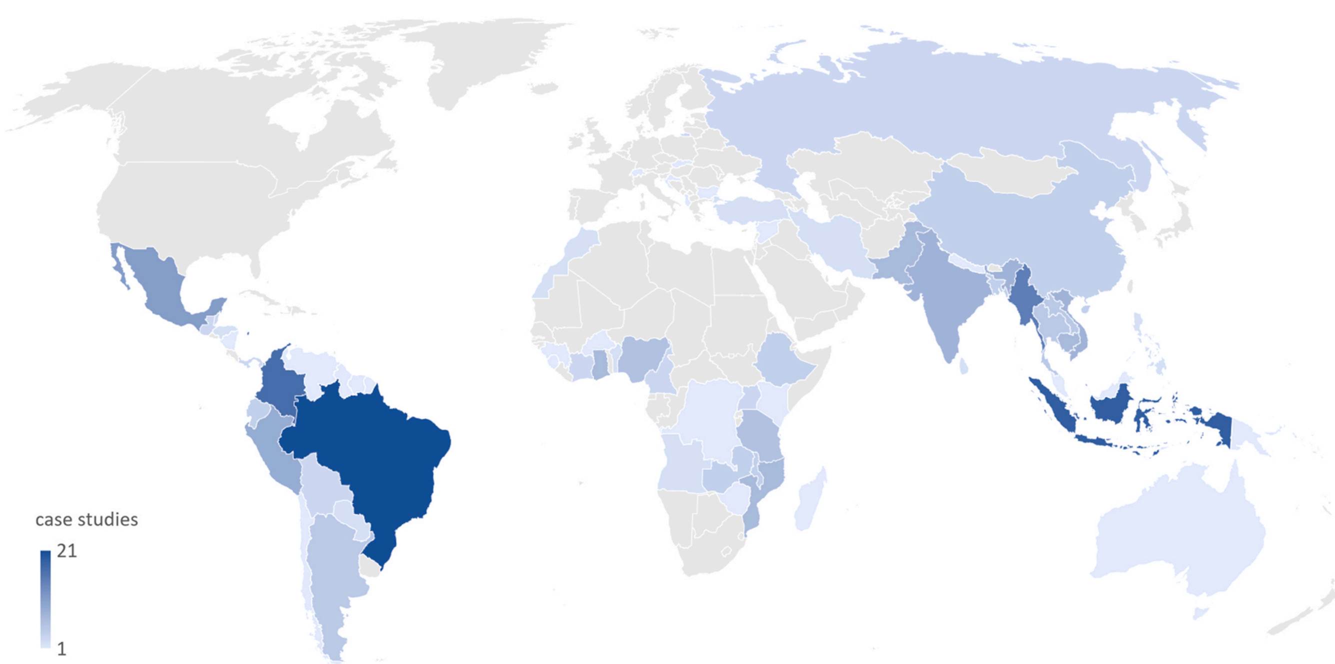

Fig. 3. Global distribution of case studies dealing with the drivers of deforestation and forest degradation between 1990 – 2023 based on 234 articles.

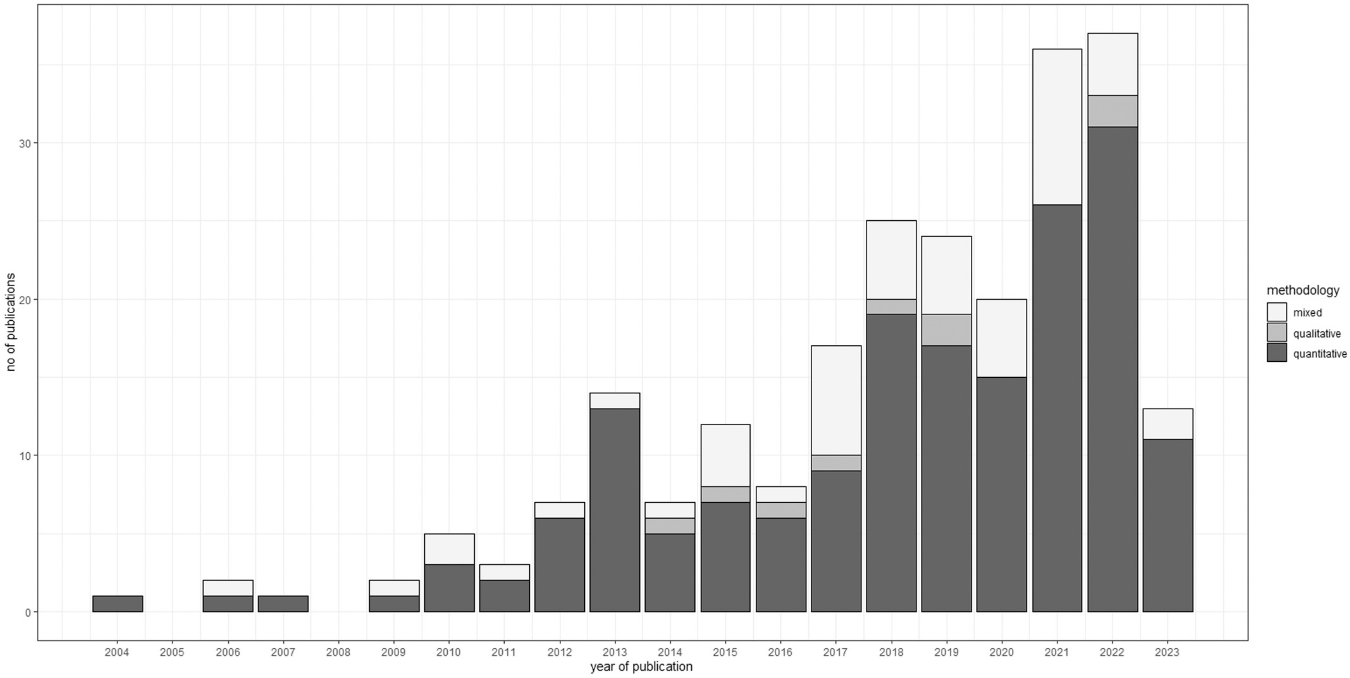

Fig. 4. Number of deforestation and forest degradation driver articles published per year between 1990 – 2023 according to their methodology applied.

interviews to better comprehend the underlying drivers. Good examples of such studies can be found particularly in the African context (Beckline et al., 2018; Ngwira and Watanabe, 2019; Phiri et al., 2023; Zvobgo and Tsoka, 2021).

While the order of importance of proximate causes was generally clearly stated in the studies, this was, however, not the case for the underlying drivers, assumingly due to inherent uncertainties on causal chains and mechanisms (Meyfroidt, 2016). These were often regarded as contributing equally to deforestation and degradation patterns or as being intrinsically linked so that clear statements on their relative contribution could not be made. Additionally, underlying drivers were more often assessed qualitatively compared to proximate causes.

3.2. Deforestation between 1990 – 2023

Deforestation as an outcome was assessed in 211 articles, out of which 177 articles included proximate causes and 184 included underlying drivers in their analysis. While the majority of studies (n = 182) investigated general drivers in a certain area, 26 focused on specific causes including mining (5), illicit crops (4), livestock (4), soy (3), oil palm (3) and infrastructure (3).

3.2.1. Proximate causes of deforestation

Between 1990 and 2023, the expansion of agricultural areas was still by far the main reported cause of deforestation. Across all 177 articles, 94 % found that deforestation was directly caused by the conversion of

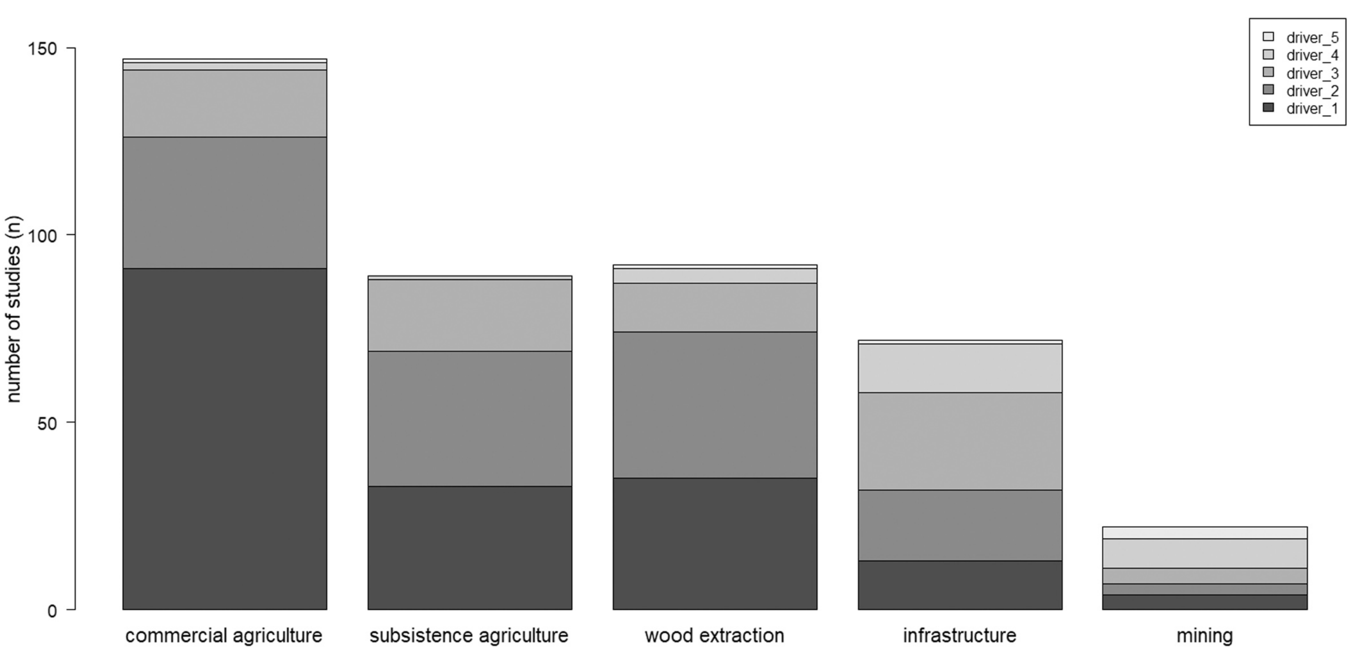

Fig. 5. Proximate causes of deforestation 1990 – 2023 (n = 177) according to their importance in each study (driver_1 to driver_5).

forests for agricultural purposes, whereby **commercial agriculture** was the main driver in 91 studies and a secondary driver in additional 56 studies (Fig. 5). Thus, commercial agriculture was reported in 83 % of studies overall. Commercial agriculture refers mostly to large-scale plantations of internationally traded crops including oil palm, rubber, illicit crops (specific to Colombia), tobacco, rice, and others. For example, studies have identified politically incentivized oil palm as main cause of deforestation since the turn of the millennium in Indonesia and Myanmar (Alban et al., 2018; Cisneros et al., 2021). Rubber is a key issue in Laos (Junquera et al., 2020; Phompila et al., 2017). Cocoa has been found a major driver of deforestation in Ivory Coast (Barima et al., 2016; Renier et al., 2023). In addition, commercial agriculture also entails livestock and pastures, which were responsible for forest clearings in 34 articles but usually as a secondary cause. Particularly in Brazil, cattle ranching and soy production are intertwined causes of deforestation, whereby forest is cleared first for soy and then used for pasture, as described in Gollnow and Lakes (2014). Studies investigating mangrove deforestation found aquaculture to be the main proximate cause in different countries across Asia (Liu et al., 2018a; Rahman et al., 2013; Saw and Kanzaki, 2015; Tinh et al., 2022). Overall, although our results show that commercial agriculture is the main cause for forest loss, it is important to point out that **subsistence and semi-subsistence farming** still plays a key role as it was mentioned as a driver in 89 articles (50 %). Small-scale agriculture as primary cause of deforestation was reported, among others, for dry woodlands of Eastern Africa (Kazungu et al., 2021; Ryan et al., 2014) and tropical rainforests of the Congo Basin (Celine et al., 2013).

Another common driver of deforestation is **wood extraction**, which was reported in 52 % of the articles. Wood extraction includes large-scale commercial logging (Potapov et al., 2017) and small-scale legal or illegal / informal logging as well as the collection of fuelwood. Subsistence use of wood as a driver of deforestation was reported in 74 studies, whereas commercial logging was reported in 57 studies. This indicates that there are a high number of forest-dependent communities in critical rural deforestation hotspots who need small timber and fuelwood for their living. Examples are found in diverse contexts including Sub-Saharan Africa (Adetoy, 2019; Tokura et al., 2020), Eastern Europe (Feranec et al., 2009), and South Asia (Ansari et al., 2022; Devi and Shimrah, 2022).

The role of **infrastructural development**, in particular the expansion of settlements and urbanization, as a driver of deforestation was mentioned in 72 studies (41 %), usually as one of the less important reasons. Out of these, 26 studies specifically mention road construction and 25 refer to hydrodam development. Also, **mining** was mentioned in 22 articles (12 %). However, in terms of area deforested, mining is of much less importance compared to the other proximate causes. As only some of the articles provided a quantitative spatial analysis of drivers, we did not assess the importance of them according to area.

3.2.2. Underlying drivers of deforestation

We found that **demographic** factors, in particular population density and population growth, are among the main reasons behind forest conversion into agricultural areas and settlements. In addition to population dynamics, we considered changing consumption patterns as demographic factors. However, few studies refer specifically to consumption habits. Instead, they rather refer to them as **economic** factors, including as market and price developments (e.g., Dezecache et al., 2017; Zeng et al., 2018) and associated changes in demand for specific goods as underlying drivers of deforestation. Economic causes of deforestation such as economic incentives and product price fluctuations have also been determined in the Brazilian Amazon (Hargrave and Kis-Katos, 2013). As such, globally, economic factors (61 % of studies) have by far overtaken demographic factors (47 %) in their relative importance as a cause for deforestation. We further found a strong emphasis on **political** factors such as forest and land policies, insecure tenure rights, and law enforcement, that enhance deforestation drivers at the local or national level. Interesting examples are provided, e.g., for the effect of policies in Brazil (Gollnow and Lakes, 2014), the link to political parties in power in Turkey (Adiguzel, 2023), the effect of mayoral elections in Indonesia (Cisneros et al., 2021), or the impact of a lack of law enforcement in Cambodia (Ken et al., 2020). Overall, political factors were named by 44 % of the articles. **Technical** (e.g. agricultural aid effects studied by He et al. 2022) and **cultural** (e.g. threat perceptions, attitudes and social norms investigated by Simmons et al. 2021) factors were reported in 30 % and 17 % of articles, respectively. These can therefore be considered as secondary or even site-specific drivers.

We found that many studies considered how spatial variants affect deforestation, e.g. distance to roads, distance to agriculture, or distance to forest. Also site-specific **natural** factors such as accessibility, altitude, climatic or soil suitability for agriculture are well studied (30 %) and used as a means for modelling potential future deforestation patterns. As spatial patterns of deforestation and forest degradation were not within the scope of this study, however, we did not dive deeper into these findings.

3.3. Forest degradation between 1990 – 2023

Forest degradation as an outcome was analysed in 63 articles, whereas 40 of them also looked at deforestation. As it was not possible to extract only data on degradation for those, we only considered the remaining 23 articles for the analysis. Out of these, 22 articles assessed underlying drivers whereas only 17 assessed the proximate causes. It is also noteworthy that not all articles included here specifically refer to forest degradation but that some of them term their outcome as deforestation, however, these were considered degradation studies according to the terms and definitions used in this meta-analysis. This discrepancy was detected for conversions of natural forests into forest plantations and for forest areas that were overused through excessive fuelwood or charcoal collection or overgrazed but remained forests according to definition.

3.3.1. Proximate causes of forest degradation

Compared to deforestation, which is mainly driven by agriculture, our findings reveal that forest degradation that reduces a forest's biomass and capacity to provide ecological functions is in all 17 articles (100 %) caused at least partly by **wood extraction** (Fig. 6). Commercial logging as main cause of forest degradation is thereby mentioned in two studies in Russia (Achard et al., 2006; Uvsh et al., 2020) as well as in one study of the Congo Basin (Cirezi et al., 2022). In all other studies, wood extraction refers to some extent to the extraction of small timber for local construction and to a larger extent to the collection of wood fuels. Commercial charcoal value chains are common around urban areas, particularly in those that are quickly expanding (Ahrends et al., 2010; Sedano et al., 2022)

In terms of **agriculture**, degradation processes rather than complete, permanent removal of forests are primarily caused by shifting cultivation on smaller scales. In Mexico's dry forests, Morales-Barquero et al. (2015) reported that shifting cultivation resulted in a mosaic landscape with low carbon density, while in India, Aditya and Ganesh (2019) identified it as a cause of degradation in buffer zones around a national park. Only four studies (24 %) refer to commercial agriculture as a cause of usually low relative importance. Similarly, **mining** and **infrastructure** were only named in one article each.

3.3.2. Underlying drivers of forest degradation

Similar to deforestation, the underlying drivers of forest degradation can be seen as a mix of factors. A growing population (**demographic**), coupled with poverty (**economic**) and limited alternative income sources leads to excessive fuelwood collection in open forest areas. This is further enhanced through climate change (**natural**) as well as a lack of alternative cooking fuels or energy in rural areas (**technological**).

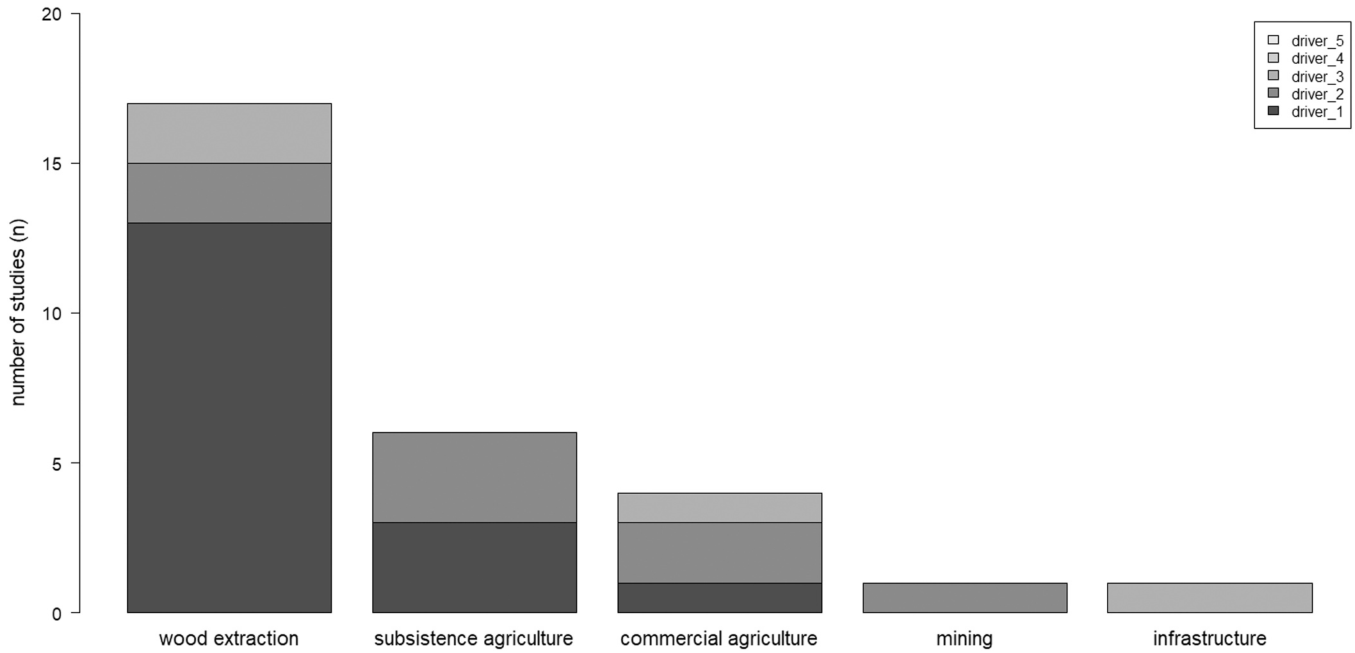

Fig. 6. Proximate causes of forest degradation 1990–2023 (n = 17) according to their importance in each study (driver_1 to driver_5).

Distance, elevation and slopes (natural) further influence the amount of fuelwood collected. Several studies mention that accessible secondary and degraded forests are not sufficiently protected either through respective legislation or by adequate law enforcement (**political**). Furthermore, policy changes related to energy and wood fuels can affect forest and tree cover, as shown in an example in Iran (Heidarlou et al., 2021). Meanwhile, in new settlements and urban areas, a growing population ensures a continuous demand for charcoal. Distance and accessibility to markets therefore also play a role, particularly for the charcoal value chain (Ahrends et al., 2010; Chiteculo et al., 2018). With the exception of **cultural** factors (e.g. traditional land management systems described in Morales-Barquero et al. 2015), which are mentioned by only three articles as having an influence on land use practices leading to degradation, all other factors are of similar importance and have been mentioned between seven to nine times in the articles. Even more prominent than the articles on deforestation, articles on forest degradation also establish that accessibility (or distance) is a major predictor of where overharvesting is taking place as shown by studies in the tropics (Pujiono et al., 2022; Schneibel et al., 2017). It can be assumed that distances play a particular role for carrying fuelwood and less so for charcoal which can be transported more easily to the markets.

4. Discussion

4.1. Global state of research and comparison with earlier reviews

Having set out to investigate deforestation and degradation drivers globally, we came to find that there are a limited number of studies beyond the tropics with fewer than 20 % focusing on Europe, North America or East and Central Asia. This is not surprising as both Europe and parts of Asia have seen a net annual increase in their forest areas between 1990 – 2020 (FAO, 2020). Overall, forest areas in these thirty years have remained more or less stable in temperate and boreal biomes with average deforestation rates of 0.5 and 0.1 million ha per year, respectively, compared to the tropical biome with an annual deforestation rate of 36.8 million ha (ibid.). Our results thus align with the global political emphasis on tropical deforestation and contribute to the understanding of proximate causes and underlying drivers in these regions. Within the tropics, we found a focus on certain regions (humid tropics) and countries, in particular Latin America with Brazil and Southeast Asia with Indonesia as hotspots of deforestation.

Studies on forest degradation are concentrated on fewer countries, including Mexico, which has half of its dry forests in a degraded state (Jiménez-Rodríguez et al., 2022) and where unsustainable forest management practices are investigated (Achard et al., 2006). Across the African continent, no particular country stands out in terms of number of articles included in our analysis, however, countries with drier tropical climates tend to have a stronger focus on degradation compared to those with humid climates. Complementing our results, a remote-sensing study on land uses after deforestation in 30 African countries - published after our article selection process – found highly diverse drivers of deforestation across Africa (Masolele et al., 2024). In addition to well-researched commodities such as cocoa and oil palm, they found that cashew is increasingly responsible for deforestation in drier regions of Africa, e.g. Tanzania or Northern Ivory Coast and Ghana. A high variety of drivers and particularly unequal knowledge about these in different countries is also seen as a main challenge in Southeast Asia (Chen et al., 2024).

Our findings confirm that agriculture remains a key cause of deforestation and hence a key issue related to sustainable development and respective global efforts including the UN Agenda 21. Our result that 94 % of our 177 deforestation cases between 1990 and 2023 are associated with agricultural expansion as a main cause is almost identical to Geist and Lambin (2002) who found this association in 96 % of their 152 cases in previous time periods. However, in contrast to their review, we found commercial agriculture and trade to be substantially more relevant causes of deforestation in these recent decades, which is also supported by other research focusing on the tropics (Austin et al., 2017; Hosonuma et al., 2012; Leblois et al., 2017; Pendrill et al., 2022). Today, it is estimated that 26 % of deforestation in the tropics are attributed to international demand (Pendrill et al., 2019a). Considering the underlying drivers of deforestation, we found a decreased relative importance compared to Geist and Lambin (2002) particularly for the following factors: technical, cultural, and political. All these factors had much fewer mentions in our review. This could point towards progress in global efforts including the Agenda 21 in terms of political and institutional settings (e.g. formal policies, law enforcement, and tenure and property rights), technological advances for more sustainable production intensification, as well as changing attitudes, behaviors and cultural norms.

In addition to earlier studies, we also investigated degradation causes and found that they are highly different from deforestation causes, consisting mainly of fuelwood extraction and charcoal production, whereas agriculture plays only a circumstantial role in degraded forest landscapes. In contrast to deforestation, our meta-analysis thus shows that forest degradation is less affected by global trade and rather driven by poverty and limited alternative income opportunities as well as local or regional dependence on wood fuels. Therefore, degradation patterns and drivers can be assessed at smaller scale and targeted more directly by national policies. In terms of research, case studies are useful as they can inform specific planning mechanisms to reduce degradation a smaller scale. A recent example for this is given by Andoh et al. (2024) who investigated the causes of deforestation and forest degradation at community-level in Northern Ghana to inform a planned emissions reduction project.

4.2. Limitations of the review

While our review was more inclusive than others by a) including degradation and b) setting no geographic boundaries, this also caused challenges in the analysis, particularly concerning the former. Out of 235 included studies, only 23 focused on degradation whereas 40 considered both deforestation and degradation. Upon further examination, we found that studies addressing both aspects more closely conformed to our definition of deforestation, which is why we included them in that analysis. This left the analysis of degradation drivers with only 23 studies and subsequent limitations for our results' robustness. It also shows the need for more targeted research on forest degradation drivers.

We included both qualitative and quantitative studies and were able to present results in terms of the importance of different factors causing deforestation or degradation. However, similar to Geist and Lambin (2002) our data did not allow us to present the area involved in absolute numbers. Such an analysis would be interesting especially at the level of sub-categories of proximate causes, as it could inform policies such as the EUDR on which goods and products are particularly causing deforestation globally. In our analysis, the risk of blowing out of proportion certain drivers is somewhat deflected thanks to our broad coverage of countries and contexts worldwide.

During our selection process of the systematic review, we rejected several articles due to their focus on spatial or structural determinants of deforestation. Even in the remaining studies, we found many that considered geographic factors such as accessibility, terrain, or distance to markets or other infrastructure. But while local to national analyses of spatial deforestation patterns are important for national or regional planning, they do not address the global drivers of deforestation and therefore provide limited guidance on how to reach the Sustainable Development Goals as a collaborative effort under Agenda 21. In this paper, we focused on deforestation and degradation drivers that explain why it is taking place instead of where.

A further challenge we encountered is the distinction between subsistence and commercial farming. While some studies specifically refer to 'commercial farming', 'plantations', 'intensive agriculture' or certain well-known export crops, many also reported on agriculture in very unspecific terms. This could be partly explained by language issues. In those cases, we investigated the main crops of the study area to decide whether subsistence or commercial agriculture were meant. In reality, though, farmers and particularly smallholders usually opt for a combination of both as part of broader livelihood strategies and to keep a certain flexibility and resilience in times of stress (Holmelin, 2021; Isgren et al., 2020; Tibesigwa et al., 2017). We encountered terms such as 'semi-subsistence' or 'subsistence mixed farming' (e.g., Yadeta et al., 2022) that reflect this type of agriculture. Finally, although the lines between subsistence and commercial farming are sometimes blurry, it does not change our finding that agricultural trade has become the main cause of forest loss and is certainly a key lever to address deforestation globally.

4.3. Implications for zero-deforestation commitments and policies on the example of the EUDR

Based on current scientific discourses and our own results, we argue that more important than country-level deforestation causes are commercial relations between countries, particularly between countries of the Global North and countries of the Global South. This is supported by a recent study of food system drivers of deforestation in the tropics (Sylvester et al., 2024). Considering that commercial agriculture is the most important cause of deforestation in the world, it is clear that there is a dire need for more research on evolving consumption patterns and the role of agricultural commodity trade and sustainable practices in global net deforestation.

Our results can contribute to ongoing discussions on zero-deforestation commitments and policies linked to the Agenda 21, efforts towards the achievement of global climate targets, and the European Green Deal, among which is the recent EUDR. We found that commercial agriculture is clearly the number one cause of deforestation and thus we agree that the EUDR can be an important environmental policy approach for tackling deforestation and forest degradation. However, the policy and associated trade requirements cannot tackle deforestation and forest degradation comprehensively but must rather be seen as one part of a whole package of measures to tackle the issue. Other complementary measures need to address the numerous underlying drivers that we identified here.

The EUDR has raised several concerns and questions since its announcement. One of the issues is whether the EUDR tackles the right drivers by focusing on wood, rubber, palm oil, soy, cocoa, coffee, and livestock products. Our findings certainly confirm the important role of wood extraction for forest degradation and of the other goods for deforestation. But we also found additional commercial crops that are driving deforestation in certain regions, e.g. illicit crops in Colombia (Dávalos et al., 2011), cashew in Sub-Saharan Africa (Masolele et al., 2024) and, to a lesser extent, sugarcane, avocado, and cotton. Studies focusing on mangroves, highly important ecosystems for livelihoods, ecosystem services and carbon capture but high exposure to degradation and deforestation pressures, agree on the main causes being aquaculture and rice production (Fauzi et al., 2019; Giri et al., 2015; Richards and Friess, 2016). This ecosystem and respective drivers are not covered by the EUDR, with the exception of countries (Malaysia and Indonesia) where oil palm is also a main cause of mangrove deforestation (Richards and Friess, 2016). While our analysis also highlights the overall significant role of oil palm on forest loss in the tropics, a recent study (not included in our analysis) found devastating effects on forests if palm oil were to be replaced with other vegetable oils and thus also recommends incentivizing deforestation-free palm oil instead (Chiriacò et al., 2024).

The EUDR aims to tackle also forest degradation, which is largely caused by wood extraction. While in part, this refers to excessive timber harvesting and trade (Dudley et al., 2014), our meta-analysis provides a bit of a different picture. We found fuelwood and charcoal either for subsistence or for local markets in producer countries to be the main causes, however, these are not directly tackled by the EUDR. In addition, several studies in the miombo woodlands of Southern and Eastern Africa depicted tobacco cultivation and curing with associated fuelwood needs as a major risk to remaining forests (Jew et al., 2017; Ngwira and Watanabe, 2019; Zvobgo and Tsoka, 2021).

An analysis focusing on Brazil, Colombia and Indonesia as producer countries impacted by the EUDR suggests that the regulation has mostly symbolic effects and does not necessarily reduce deforestation in these countries (Muradian et al., 2025). Their key recommendation is that the regulation should be accompanied by bilateral and multilateral measures addressing underlying and context-specific drivers of deforestation. The fact that 206 of our studies included underlying drivers compared to 195 that assessed proximate causes also points towards a high relevance of these highly complex and context-specific circumstances that cause deforestation and forest degradation. Our results have revealed a gap in the specific integration of evolving consumption patterns as an underlying driver in land use change studies. Sylvester et al. (2024)'s analysis, together with other studies tracing commodity-driven deforestation (Pendrill et al., 2019a, 2019b), makes an important contribution towards better understanding dynamics between supply and demand. To build on that, we argue that interdisciplinary approaches combining the study of social aspects of consumption patterns with the analysis of spatial patterns of deforestation are needed. Thereby, also telecoupling and spill-over effects need to receive more attention (Liu et al., 2018b). Clear frameworks and standardized methodologies are, however, needed in global or regional studies to avoid the trap of a lack of specificity and tendency for unrealistic recommendations (Bernhard et al., 2024).

4.4. Recommendations

Based on our literature review (see chapter 3.1), we identified several avenues for future research. Our review revealed certain geographic hotspots of scientific studies as well as a wide range of applied methodology and terminology. In order to get a more integrated understanding of the deforestation and forest degradation problematic globally and address this review's limitations (chapter 4.2), we recommend that the following research areas are covered more in the future:

- Assessing drivers of deforestation in highly affected regions and countries which are currently not well covered, including Central America (Suriname, Guyana, Nicaragua), Central Asia (Azerbaijan, Uzbekistan) as well as in politically sensitive countries, such as in Sudan, Liberia, or Venezuela
- Intensifying efforts to analyse proximate causes and underlying drivers of forest degradation, including the further development of frameworks and methodological approaches to do so for the application in all forest biomes, especially also in temperate and boreal forest regions
- Spatially quantifying deforestation causes as well as underlying drivers in different regions and at various scales according to purpose
- Contributing towards standardized terminology, frameworks and methodologies
- Mainstreaming interdisciplinary approaches for analyzing the specific role of consumption patterns and agricultural trade in global deforestation patterns
- Studying forest landscape change for a more holistic understanding of causal chains of deforestation and degradation (see also Bürgi et al., 2022)

In terms of global efforts on tackling deforestation and forest degradation, as well as environmental policy efforts including the EUDR, our results point towards the following recommendations:

- Accounting for the underlying drivers of deforestation and forest degradation in global policy commitments for progress towards climate and sustainable development targets
- Introducing complementary measures to address underlying drivers of deforestation and forest degradation relevant to the context of producer countries in environmental policy approaches such as the EUDR
- Extending environmental policy approaches such as the EUDR to additional goods, products and derivates (e.g. cashew, rice or aquaculture produce, but also precious metals) as well as considering financial flows in respective commodities
- Supporting measures that help supply chains not linked to the European market (e.g. charcoal) to become deforestation- and degradation-free

5. Conclusions

Our global review covered a total of 234 articles on deforestation of forest degradation between 1990 and 2023, the majority of which was focused on tropical regions. Our results revealed commercial agriculture as the main cause of deforestation, followed by subsistence agriculture, wood extraction, and infrastructure. Commercial agriculture includes major plantation crops like oil palm or rubber, monocultures like soy or sugarcane, as well as livestock herding and aquaculture. Underlying these forest conversions were primarily economic factors, especially international market developments coupled with limited alternative income sources, as well as demographic and political drivers. Regarding forest degradation, we found wood extraction to be the single most important cause, with agriculture only being mentioned by few studies. Most articles thereby refer to subsistence use of wood and fuelwood rather than commercial timber harvesting. Underlying drivers consist of a mix of demographic, economic, political, and cultural factors. While our meta-analysis confirms the crucial role of agricultural commodities in global forest loss, we recommend that deforestation-related policies and commitments should consider causal chains instead of overly focusing on the proximate causes of deforestation. To this extent, we conclude that, although we have already seen some progress since the initiation of the sustainable development framework Agenda 21, the establishment of complementary measures addressing underlying drivers in both producer and consumer countries is essential. This will allow to effectively tackle global forest and tree cover loss, reversing the trend and restoring affected areas central to the achievement of climate targets and global sustainable development.

CRediT authorship contribution statement

Wolf Oliver: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Feurer Melanie:** Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Markovic Jelena:** Writing – review & editing, Validation, Project administration, Conceptualization. **Starke Michael:** Writing – review & editing, Visualization, Software, Formal analysis, Data curation. **Wilkes-Allemann Jerylee:** Writing – review & editing, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial or other interests that could have appeared to influence the work of this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2025.104242.

Data availability

Data will be made available on request.

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