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REVIEW PAPER

Drivers of tropical deforestation: a global review of methodological approaches and analytical scales

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Abstract
Recent studies identifying underlying and proximate drivers of tropical deforestation and forest degradation have applied a multitude of methodologies, with varying and sometimes conflicting results. Divergent results can have implications for evidence-informed programs, policy action, and land use planning since these differences can lead to controversy as to which drivers should be addressed by deforestation and emissions-reduction or conservation programs, in addition to mismatch between the scale of study results and the scale of policy and program implementation. To identify and reconcile divergences between results among different scales and methodological approaches, we systematically reviewed 231 articles in the drivers of deforestation literature and found inconsistency in scale applied within studies (e.g., differences between the stated scale of analysis and scale of article recommendations), and variation in the number and type of drivers identified between studies by methodology. Additionally, global and regional studies tended to feature recommendations that would be difficult to implement, or that targeted large-scale problems lacking specificity. This study clarifies common themes in driver identification and what is needed for drawing contextualized, scale-appropriate conclusions relevant to forest conservation policy and sustainable land use planning. We suggest improvements to recommendations drawn from drivers of deforestation studies and avenues to reconcile divergences in approaches and results, which will support efforts to advance forest conservation and sustainable forest management outcomes.

Keywords Drivers of deforestation · Forest degradation · Forest conversion · Methodology · Scale · Global

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Introduction

Anthropogenic disturbance such as land use change for agriculture and other natural resource extraction is responsible for significant recent losses in biodiversity and tropical forest cover and quality (Steffen et al. 2015; Winkler et al., 2021; Pereira et al. 2010). Since 1990 alone, "approximately 420 million hectares of forest have been lost through land conversion uses" (FAO 2020, p. xvi). A well-developed body of scholarly literature identifies the specific underlying and proximate drivers of tropical deforestation and forest degradation at various global, regional, national, and local scales. In the tropics, common drivers of deforestation and degradation include but are not limited to smallholder and industrial agriculture, mining, fires, road and other infrastructure development, and armed conflicts (Fritz et al. 2022; Giljum et al. 2022; Pendrill et al. 2019; Pacheco et al., 2021; Hosonuma et al. 2012; Meyfroidt and Lambin 2009; Geist and Lambin 2002, 2001). To better characterize underlying and proximate drivers of deforestation and forest degradation, recent advancements in remote sensing and big data analytics have resulted in a proliferation of research incorporating cutting-edge algorithmic, statistical modeling, and remote sensing methods (Cardille et al. 2024; Branthomme et al. 2023; Oshan et al. 2022; Pendrill et al. 2022; Laso Bayas et al. 2022; Vieilledent et al. 2022; Shapiro et al. 2023, 2021; Tyukavina et al. 2018; Meyfroidt 2016; Hansen et al., 2013; Hosonuma et al. 2012). Despite the many benefits of these methodological advancements, the abundance of methodologies, datasets, and tools to assess drivers of deforestation has led to divergent and sometimes conflicting results (Scrieciu 2007; Busch Ferretti-Gallon 2017; Mayer 2019).

The diversification of methodological approaches to deforestation research has also resulted in a greater range of treatment of the concept of scale (Oshan et al. 2022). As Oshan et al. (2022) describe, scale can refer to the level at which data collection or physical processes take place, or even "the range over which spatial processes vary" (p. 294). These numerous concepts of scale are considered *type 1 scale multiplicity,* which involves different notions of scale. *Type II scale multiplicity* involves the simultaneous use of multiple scales. Scale, by either of these definitions, as well as context dependencies, are important factors that directly influence the conclusions of any given analysis, including those that identify specific human activities as drivers of deforestation (Fig. 1) (Ferrer Velasco et al. 2020). While there are several consistently identified pantropical drivers of deforestation (e.g., population pressure and agriculture), when studies are conducted at subnational or even finer scale levels, heterogeneity across the findings results from context dependencies and spillover effects (DeFries et al., 2010; Kuschnig et al., 2021; Keenan et al., 2015). Alternatively, coarse global and regional scale studies that neatly identify underlying and proximate drivers can fail to capture the more complex stories at more local levels (Mayer 2019).

The heterogeneity and overlap of potential drivers of deforestation and forest degradation seen in scholarly literature inhibits both our consensus and understanding as well as effective conservation decision-making. The conflicting views in the literature resulting from diverse methodologies and treatments of scale have implications for evidence-informed programs and policy action (Zu Ermgassen et al. 2023; Mauser 2013; Brandt et al. 2013; Margules et al. 2020; Reyers et al. 2010; Bele et al. 2015; Oliveira Meyfroidt 2021). When results are divergent, there may be lack of clarity and consistency regarding whether, for instance, deforestation and emissions-reduction programs should be designed to address drivers identified by regional remote sensing analysis or those identified in local socioeconomic surveys (Harris et al., 2021).

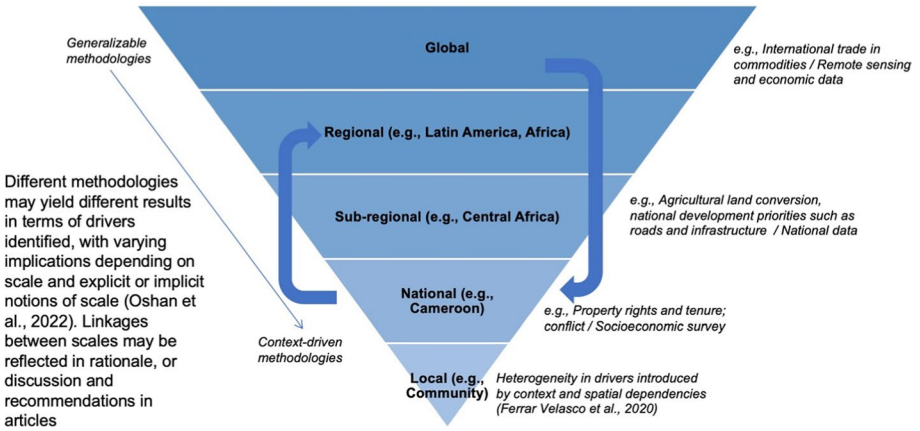

Fig. 1 Conceptual illustration of relationships between scale and evidence on underlying and proximate drivers of deforestation and forest degradation

Problem statement and research questions

This study addresses the need to identify and reconcile divergences between results at different scales and methods, to establish a more cohesive understanding of drivers of deforestation. Linking to transdisciplinary and practice-oriented research, the study further highlights improvements that can be made to recommendations drawn from drivers of deforestation studies to advance implementation (Reyers et al. 2010). This study asks two overarching research questions. First, *how does methodological approach and scale of analysis influence the quantity and type of drivers of tropical deforestation and forest degradation identified?* Second, *what are the implications for conservation policy and program action in specific regional contexts?*

This study elaborates these overarching questions with several specific research questions that are addressed with respect to those above:

- RQ1—Scale Integration: What can the literature on drivers of tropical deforestation and forest degradation tell us about actions to be taken across scale levels?
- RQ2—Driver Identification: What is the range and diversity of tropical deforestation and forest degradation drivers identified in the literature?
- RQ3—Methods: What is the range and diversity methodological approaches used to assess drivers of forest change, and how do results vary by approach?
- RQ4—Action and Implementation: What are the actionable tools that can be designed based on a synthetic understanding of the suite of methodological approaches and treatment of scale for diagnosing and addressing deforestation and forest?
- RQ5—Future Research: What are the priority research gaps that can be identified from this systematic review?

To address these research questions, a global systematic literature review was undertaken focusing on methods used to derive findings and recommendations for underlying and proximate drivers of deforestation and forest degradation at and between analytical and process scales. As described in the Methods and Limitations sections, this study was

conceived within a broader project focused on Central African drivers of deforestation, which informed the sampling of articles for this review. Although a global analysis, the review included regionally specific databases for African contexts to overcome the disproportionately low inclusion of Sub-Saharan African papers in many global systematic reviews, and overall disparities in understanding of drivers of deforestation between Sub-Saharan Africa and other global regions (Pendrill et al. 2022, p. 8). Addressing the knowledge disparity between global regions is important because drivers of deforestation vary between major tropical forest regions, as emphasized by our second overarching research question (RQ2). For example, small-scale agriculture remains the primary driver of deforestation in Sub-Saharan Africa, while the role of global commodity chain and industrial agricultural drivers have become increasingly central in other major regions such as Latin America and Southeast Asia (Pendrill et al. 2022; Branthomme et al. 2023).

Background

Common drivers of tropical deforestation and forest degradation

The literature has established that scholarly treatment of drivers of deforestation should begin by defining and differentiating underlying and proximate causes and drivers, as ambiguity of terms and concepts is a well-documented challenge in the study of drivers of deforestation and forest degradation (Meyfroidt 2016; Geist and Lambin 2002). To provide initial conceptual clarity around the terminology used in this article, we incorporate terminology as defined by Meyfroidt (2016) in Table 1. Conceptual clarity regarding causality, and the use of a "precise vocabulary and harnessing our tools with the clear purpose of establishing both causal effects and causal mechanisms" is critical for strengthening causal explanations in study of drivers of deforestation and forest degradation, as well as drivers of change in broader socio-ecological systems (Meyfroidt 2016, p. 501). Establishing conceptual clarity holds further importance as methodologies described throughout the literature can often be readily classified by their quantitative, qualitative, and mixed methods nature, but not necessarily by application of causal inference techniques (Atmadja Verchot 2012).

Having clarified what is or is not an underlying or proximate driver of deforestation, we can proceed to review the drivers most frequently cited in the literature. In recent years, the drivers of deforestation and degradation literature has advanced not only in terms of better understanding underlying and proximate drivers of forest loss and degradation in Sub-Saharan Africa and other major regions, but also in terms of identifying temporal and spatial scales at which impacts of drivers are enacted, and the actors that are involved (Hänggli et al. 2023; Balboni et al. 2023; Garrett et al. 2021; Pendrill et al. 2022; Pendrill et al. 2019; Lambin et al. 2018; Hosonuma et al. 2012). Systematic reviews such as those by Pendrill et al. (2022), Hängli et al. (2023), and Garrett et al. (2021) have identified drivers and explored policy effectiveness. Theoretical developments in the literature have also shifted from identifying the primary agent of deforestation as an individual actor (Indarto and Mutaqin, 2016; Angelsen and Kaimowitz 1999; Angelsen 2010; Angelsen et al. 2014; Rudel 2007; Barbier et al. 2010; Geist and Lambin 2002) to considering the wider lens of collective or institutional drivers that result in deforestation dynamics driven by influences across scales (Indarto and Mutaqin, 2016; Meyfroidt 2016; Ferrer Velasco et al. 2020; Meyfroidt and Lambin 2009). The increased study of collective and institutional drivers

Table 1 Terminology definitions in identification of deforestation drivers adapted from Meyfroidt (2016, p. 506)

Term	Proposed definition (Meyfroidt 2016, p. 506)
Outcome	Any event, fact or variable for which one wants to explain why and how it occurred
Factor	Any event, fact or variable mobilized in an explanation
Cause	A factor that produces a causal effect on an outcome through a chain of mechanisms
Causal effect	The change in an outcome variable brought about by change in the value of an explanatory variable (the cause)
Causal mechanism	The processes through which a factor produces its effect
Causal chain	A series of causal mechanisms which links an underlying cause to the final outcome of interest
Causal explanation	To identify the causes of an outcome
Driver/driving force	Factors that are typical or hypothetical causes of land or environmental change and have some evidence of association with the outcome, but for which the evidence or knowledge is not sufficient to firmly establish the causal effects and explain the causal mechanisms
Proximate cause	A factor which constitutes a direct cause of the phenomenon to be explained
Underlying cause (of land cover change or environmental change)	A factor which causes the proximate causes of land cover or environmental change
(Spatial) Determinant	A factor contributing to statistical explanation of (the location of) an outcome (or other spatial characteristics such as spatial pattern or structure)
Contextual factor	A factor which constitutes an element of an INUS cause (insufficient but necessary part of a combination of causes), typically being a stable or slowly changing factor or a factor that is largely present within a given place, and which explains the location, timing or prevalence of an event

has also been supported by increasing focus on scale and complexity within the landscape ecology literature (Sayer et al. 2013; Millington 2022; Newman et al. 2019).

Despite literature demonstrating that industrialized agriculture driven by global commodity chains and consumer demand is replacing small-scale agriculture as a key driver of deforestation in many regions, literature suggests that a distinct situation exists in Sub-Saharan Africa (Pendrill et al. 2022; Fritz et al. 2022). Smallholder agriculture and other subsistence extraction activities (e.g., timber collection for charcoal and fuelwood) remain the most important drivers of deforestation and forest degradation in terms of area affected – even in areas where forests are protected (Curtis et al. 2018; Tyukavina et al. 2018; Green et al 2013; Ferrer Velasco, 2020; Mayer 2019). Infrastructure development (e.g., roads and urban expansion), small scale and industrial mining, and fires are other commonly cited drivers of deforestation and forest degradation (Pendrill et al. 2022; Giljum et al. 2022). Many of these drivers, however, are commonly found together; for example, roads often accompany agriculture, and fires are commonly associated with forest conversion to agriculture or industrial mining (Tyukavina et al. 2018; Giljum et al. 2022; Molinario et al. 2015, 2020). Drivers can thus be studied or understood individually, or within archetypal clusters or groupings of drivers that are commonly found together, such as the

"rural complex," which includes small-scale artisanal agriculture in addition to other land cover types including subsequent roads and settlements that accompany agricultural conversion and expansion (Shapiro et al. 2023; Molinario et al. 2015, 2020). Linking the concepts of scale multiplicity, archetypes, and multilevel complexity, the combinations and type and number of drivers included in archetypal groupings can vary depending on scale, specifically implying both *type I* and *type II scale multiplicity* as defined by Oshan et al. (2022). As we describe in this article, the drivers identified at various scales and common archetypal groupings may vary depending on the method used to identify and conceptualize drivers, and can thus be sensitive to the formality and explicitness of treatment of scale within that method.

Underlying conditions at various scales, or ranges over which spatial processes occur – local, landscape, national, regional, global – are also critical for understanding deforestation and forest degradation dynamics in the tropics (Oshan et al. 2022; Sayer et al. 2013; Millington 2022; Newman et al. 2019; Ferrer Velasco, 2020). For instance, at pantropical scales Morpurgo et al. (2021) found that elections can have spillover effects which influence environmental governance and thus impact forest cover through inconsistent application of environmental policy. In the Amazon and Latin American contexts, global commodity markets including demand for soybean and beef in the Global North are an underlying driver of forest conversion to commercial agriculture (Fehlenberg et al. 2017; Fritz et al. 2022). In Central Africa and its Congo Basin forests, other scholars have determined that conflict can be an underlying driver of deforestation and forest degradation depending on conflict dynamics (Burgess et al. 2015). Internal displacement and migration can result in forest regrowth, while conflict occurring in or near forests can result in forest cover loss and degradation (de Merode et al. 2007; Butsic et al. 2015; Shapiro et al. 2021). Similar multi-directional dynamics resulting from conflict have been identified in Latin American contexts such as Colombia (Landholm et al. 2019; Clerici et al. 2020). Collectively, these results reinforce the need for contextualized understanding of socio-political dynamics that influence underlying and proximate drivers and causes of forest cover change and degradation.

Integrating scale and landscape considerations

As described by Ferrar Velasco et al. (2020), scale dependency is defined as the association between scale and heterogeneity of drivers (p. 21), an association also noted by Scrieciu (2007), Newman et al. (2019), Busch and Ferretti-Gallon (2017), and Liu et al. (2007). As the scale of analysis becomes increasingly local, the complexity and number of potential drivers of deforestation and forest degradation increases (Busch Ferretti-Gallon 2017; Newman et al. 2019; Ferrar Velasco et al. 2020). At local scales there may be additional or compounding diverse drivers influencing rates of deforestation and degradation such as local land tenure regimes (Mayer 2019; Müller & Munroe, 2015; Blum et al. 2022), presence or absence of protected areas (Green et al. 2013; Linkie et al. 2010; Songer et al. 2009), intensity of agriculture (Goulart et al. 2023), and even locals' inclusion in forest policy and decision-making (Twongyirwe et al. 2018; Newman et al. 2019; Millington 2022; Ferrer Velasco, 2020; Cuaresma and Heger, 2019; Dalla-Nora et al. 2014). Global and regional level studies (e.g., those with continental scale levels) are often able to capture generalized conditions driving deforestation and forest degradation such as land use change and conversion to agriculture (Pendrill et al. 2022), or even macroeconomic conditions like international commodity markets (Fehlenberg

et al. 2017). However, there are often interlinked and overlapping forces at lower scales that fuel deforestation and degradation (Hoang & Kanemoto, 2021; Scrieciu 2007). Ferrer Velasco et al. (2020), for example, found a "higher and more diverse number of significant determinants of forest cover" at smaller scales (p. 24). Additionally, "certain deforestation forces occur independently of the existing *de jure* governance boundaries (Ferrer Velasco, 2020, p. 1). As one example, Mayer (2019) described how smallholder management and tenure security can play a key role at local levels, as forested landscapes are increasingly "split into smaller managed segments with more owners" in many countries (p. 4). As Mayer (2019) indicates, this tenure and management fragmentation can interact with global-scale processes such as migration and international commodity market forces. For small-scale management, such interactions of multiscale processes can influence land use planning and decision making to result in forest conversion to cash crops and agricultural products of commercial interest.

With recent advances in spatial econometrics and other techniques of causal inference that account for spatial considerations, context and scale are being treated with increasing nuance in on-the-ground land use planning (Cuaresma Heger, 2019; Busch Ferretti-Gallon 2017; Ferraro Pressey 2015; Ferrer Velasco et al. 2020; Scrieciu 2007; Oliveira Meyfroidt 2021). This heightened sensitivity to scale and context is particularly notable in the literature on protected area effectiveness, which has increasingly identified the need to consider the broader landscape in conservation of critical ecosystems (Ferraro Pressey 2015; Sayer et al. 2013; Matthews Selman 2006; Du et al. 2015; Gu Subramanian 2014; Millington 2022; Newman et al. 2019). The landscape approach (Sayer et al. 2013) considers protected or unprotected forests not as "pristine" or as "islands" distinct from their surroundings, but as socio-ecological systems connected bio-geophysically and through social and human geographical landscapes (Cumming Allen 2017). However, despite increasing attention to scale across drivers of deforestation and protected areas effectiveness literatures, there remains need for conceptual clarity and use of "methods capable of making explicitly multiscale inferences about the scale of processes," rather than methods that informally examine process scale (Oshan et al. 2022, p. 311).

This study contributes to these literatures by highlighting: 1) the potential mismatch of analytical scale and methodology with the conclusions drawn from the associated research identifying drivers of deforestation, and 2) the implications of this mismatch for evidence-based conservation implementation and sustainable resource management. Other systematic literature reviews and meta-analyses have synthesized the substantial number of research findings globally regarding underlying and proximate drivers of deforestation (Hängli et al. 2023; Garrett et al. 2021; Busch Ferretti-Gallon 2017; Atmadja Verchot 2012), yet our study provides a unique contribution to this growing body of literature by providing concrete implementation strategies and next steps. Following the prescriptions of Oliveira and Meyfroidt (2021), this research focuses on the "(i) land tenure–planning nexus, (ii) streamlining plan-implementation, and (iii) transdisciplinary planning processes, intended to expand further the importance of the strategic approach in land-use planning in terms of governing tropical landscapes" (p. 1). The study carries Oliveira and Meyfroidt's (2021) recommendation forward with synthesis and recommendations for implementation. Further, the study links and contributes to the transdisciplinary research literature by highlighting challenges and possible solutions to advance evidence-based implementation in forest conservation contexts (Mauser 2013; Brandt et al. 2013; Margules et al. 2020; Reyers et al. 2010).

Methods

This systematic literature review assesses differences in deforestation drivers as identified by studies conducted at different scales and using different methodologies. To develop a protocol for the systematic literature review, we adapted elements of the Collaboration for Environmental Evidence (CEE) guidelines for systematic literature reviews and systematic mapping (CEE, 2020; Haddaway et al. 2018). Terminology definitions (e.g., underlying vs. proximate, see Table 1) were followed by determining the categorization methodology. Adapting the procedures outlined by Atmadja Verchot (2012), we developed the workflow presented in the Supplementary Materials (Appendix I Figure I).

Keyword search was used to identify articles from several databases: Google Scholar, Scopus, Science Direct, Web of Knowledge, FAO, and UNREDD for the 2010–2022 period. Keyword searches in these databases were undertaken in English, though some articles in French and Spanish also appeared in search results (generally because they featured English translations). Examples of specific keywords searches used are presented in Appendix I (B) of the Supplementary Materials. It is important to note that, because this study was conceived in the context of a broader project focused on Central Africa (described by Shapiro et al. 2023), sampling of databases initially focused on Sub-Saharan Africa literature, but was then expanded to be inclusive of other global regions. As such, two FAO literature databases specific to West Africa (43 regionally specific articles) and Central Africa (40 regionally specific articles) were included in the analysis, following screening of article titles and abstracts for relevance. In expanding the review to include articles from other global regions, maintaining articles from these Africa-specific FAO databases essentially constituted purposive "oversampling" of articles from Sub-Saharan Africa, which enabled our literature review to achieve a greater degree of regional balance to address systematic disparities in understanding of drivers of deforestation between Latin America and Africa (Pendrill et al. 2022, p. 8).

In total, 270 articles were collected and screened for analysis. Data aggregation was undertaken in Zotero, where articles were screened for relevance by manual, visual screening, to remove any articles included in error. From Zotero, aggregated data was exported to Excel and followed by an additional eligibility screening of each article (e.g., CEE, 2020). This involved screening of each article manually and inputting data for 16 variables of interest based on values provided in the codebook developed a priori following Ferrer Velasco (2020) and as illustrated in the workflow figure in the Supplementary Materials (Appendix I Figure I), along with a complete list of articles reviewed (Appendix II). Following the removal of duplicates, 231 articles were included in the final review.

Following the export of the Zotero library to Excel, data coding and analysis was undertaken (see sample in Table 2). Articles were coded for their primary scale of analysis, including global, regional (e.g., Africa or Latin America), subregional (e.g., Congo Basin or Amazon), national, local. They were also coded for their *reflection scale*, an indication of whether results in the article conclusions, such as the scale at which drivers are enacted, are generalized to a wider scale (e.g., a national scale article with conclusions reflecting on the regional context), or a narrower scale (e.g., national scale that reflects on local issues within-country, as in Table 2). The codes applied were "upward" and "downward" reflections, respectively. To capture all possible reflection "directions," an additional variable was coded that included consistent reflections, where an article at national scale, for instance, also featured reflections at this same scale. However, even articles that featured some consistent reflections (n = 61) also included upward or downward reflections.

Table 2 Examples of coding for primary and reflection scales to identify "upward" or "downward" reflections, an indication of whether results in the article conclusions, such as the scale at which drivers are enacted, are generalized to a wider scale (e.g., a national scale article) with conclusions reflecting on the subregional context, or a narrower scale (e.g., national scale that reflects on local issues within-country

Scale code	Title	Authors	Year
"Upward" reflections Primary scale: National Reflection scale: Sub-regional and Regional	Conservation and conflict in the Democratic Republic of Congo: The impacts of warfare, mining, and protected areas on deforestation	Butsic, V; Baumann, M; Shortland, A; Walker, S; Kuemmerle, T	2015
	National and regional determinants of tropical deforestation in Colombia	Armenteras, D; Cabrera, E; Rodríguez, N; Retana, J	2013
"Upward" reflections Primary scale: Sub-regional and Regional Reflection scale: Regional and Global	Unveiling Drivers of Deforestation: Evidence from the Brazilian Amazon	Kuschnig, N; Cuaresma, C; Krisztin, T	2019
"Downward" reflections Primary scale: Global Reflection scale: Local	Family forest owners and landscape-scale interactions: a review	Mayer, A.L	2019

We therefore focus on the "upward" and "downward" reflections variable. Next, following Breiman's (2001) approach delineating statistical and algorithmic modeling cultures, methods in the articles reviewed were coded as either "quantitative," with separate categories for "statistical" (e.g., implying a statistical approach like econometric modeling) and "algorithmic" (e.g., remote sensing applying an algorithmic model such as random forest for image classification) analyses, "qualitative" (e.g., thematic coding), or mixed methods (e.g., any combination of quantitative and qualitative, including data collected versus analysis technique) (Ardoin et al. 2015). These were then specifically coded to include the actual methods used to arrive at the results (Atmadja Verchot 2012). Examples of analysis techniques include the following:

- *Quantitative—algorithmic* (e.g., Remote sensing—random forest algorithm)
- *Quantitative—statistical* (e.g., Regression—economic model; Regression—spatial model; Econometric; Material flow analysis; Review—literature review; Review—meta-analysis)
- *Qualitative* (e.g., Thematic coding; Text analysis)

From the above examples, an article was coded as mixed methods if, for example, the data collected were qualitative (e.g., from focus group discussion or interview) but quantitatively analyzed, such as Makunga Misana 2017). Articles were also coded for the types of drivers identified within the article (e.g., underlying, proximate, or both), with articles that lacked explicit labeling of proximate versus underlying or other conceptual clarity reviewed on a case-by-case basis (following Table 1). The "both" category referred to articles that explicitly featured both proximate and underlying drivers, in addition to articles that were not explicit but included reference to drivers that were at times proximate and at other times underlying within the context of the article. Then, to ensure that this category could be further disaggregated as needed, the articles were also coded according to the actual drivers within and total number of drivers identified. Examples include:

- *Underlying* (e.g., Nonspecific agriculture (ag); Nonspecific land conversion; Global supply chain; Global North commodity demand; Governance—general; Elections; Conflict)
- *Proximate* (e.g., Specific commodity land conversion—maize, timber, rubber, cocoa, palm oil; Logging; Illegal logging; Fire; Mining; Infrastructure – roads)
- *Both – not specified* (e.g., Land tenure; Institutions—general; Infrastructure—general; Anthropogenic—not specific)

Next, articles were coded for "good practices" in research for identifying drivers. These included replicability difficulty on a 1–5 Likert scale following Vaske (2019) (e.g., 1—Very difficult; 2—Difficult; 3—Neutral; 4—Easy; 5—Very easy) based on the methods description in the article. To counter potential subjectivity of replicability as a measure, the Likert scale was based on clarity of steps outlined in methods section, rather than the coder's experience with the analysis technique described. Online availability of data was coded binary yes/no (0 or 1), and whether the data and methods enabled regular updating was coded binary yes/no (0 or 1). This component considered recent efforts to improve the openness and availability of forest data (de Lima et al. 2022). Importantly, these replicability measures are not necessarily a reflection of methodological "weakness," though papers included in this review may vary in terms of execution strength. Some methods are, by

nature, less replicable than others (e.g., ethnographic methods versus remote sensing-based methods), and each method carries with it its own weaknesses and limitations, even when well-executed.

The ease of implementation of the recommendations was coded by difficulty on a 1–5 Likert scale (e.g., 1—Very difficult; 2—Difficult; 3—Neutral; 4—Easy; 5—Very easy). Good practices for implementation and specificity of recommendations were based on literature emphasizing the importance of implementation and evaluation in conservation programs, and recommendations from transdisciplinary conservation research literature (Reyers et al. 2010; Börner et al. 2020; Knight et al. 2019). Based on the implementation and evaluation literature, the Likert scale determinations of "difficult" to "easy" included the identification of recommendations in the first place (e.g., does the article make policy or program recommendations?) and whether they could be implemented as described. Again, to counter the potential subjectivity of "ease of implementation" as a measure, the Likert scale was based on clarity of steps for implementation of the recommendations outlined in the article, rather than the coder's experience with implementing such recommendations. For example, as discussed in the findings section, articles discussing underlying drivers such as international trade flows and conflict tended to propose fewer specific steps or actions to implement their recommendations.

To ensure robustness, intercoder reliability was assessed for the Likert scale variables using SPSS software. Parallel coding of 49 randomly selected articles was undertaken by two additional coders (originally 50, one Spanish language article removed for one of the three coders). For the replication and implementation indicators on a 1–5 Likert scale, Fleiss' kappa was used to determine intercoder reliability, which was selected over Cohen's kappa due to the presence of three coders rather than two (Hallgren 2012). Intercoder reliability results are included in the Supplementary Materials (Appendix I Table I). With values interpreted as "substantial agreement," the indicators were found to be suitably reliable for the purposes of this study and were significantly more reliable than by chance ($p < 0.001$) (Appendix I Table I). For both Likert-scale variables, there was almost perfect agreement for the "very difficult" individual categories. There was the least agreement between easy, neutral, and difficult categories, but all ranged between moderate and substantial agreement.

The complete database constructed was used for analysis of driver types identified, with attention to scale integration and methodological approach. Simple cross-tabulations and correlative analysis, including chi-squared tests, Pearson's correlation coefficient, and t-tests were used to determine if there were significant differences between drivers identified at different scales and using different categories of methods. Additionally, implementation of recommendations by scale and methods was also assessed, addressing the need for studies that focus on implementation of recommendations as suggested by Oliveira and Meyfroidt (2021) and Bele (2015).

Limitations

Notably, this study has several important methodological limitations concerning both the broader research design and specific procedures. First, this article contributes to conversations regarding the replicability, scale, implementation of recommendations, and action orientation of articles identifying drivers of deforestation and forest degradation. Driver identification itself, while an important component, is not the sole contribution of the article, and we refer readers to Pendrill (2022) and Hänggli et al. (2023) for thorough

identification of drivers. Considering the different objectives and research questions in this article, this keyword search may not have captured all possible terms referring to drivers of deforestation. However, we believe that this review captures a segment of the drivers of deforestation literature that is nonetheless sufficient to draw useful insights regarding replicability, scale, implementation of recommendations, and action orientation within the literature. Second, considering the primacy of intercoder reliability analysis to the robustness of measures included in this study, we focused on English language studies or Spanish and French articles that had been translated to English to reflect the common language of team members contributing to intercoder reliability. However, Rudel et al. (2000) and Amano et al. (2023) have found persistent bias toward English language literature in biodiversity literatures, and non-English literature is particularly relevant and critical at national and local levels (Amano et al. 2023, p. 846). Future global, pantropical, or regional reviews regarding drivers of deforestation and degradation should include non-English databases with studies written in Spanish and/or French. This may also enable the final sample of articles to include more local authors within the regions of interest. Next, we note that several studies have critiqued the use of Google Scholar to identify articles for systematic reviews (Haddaway et al. 2017, 2018). We followed Haddaway et al. (2015) in using Google Scholar alongside other databases, not as the only search tool or database for our systematic review.

Finally, as previously described, this study was undertaken within a broader research project focused on Central Africa, which informed the research design and sampling of articles to ensure more regional balance in the sample and a more proportionate degree of representation of Sub-Saharan African articles relative to Latin America (Pendrill et al. 2022). That said, to address potential regional imbalances in future reviews, future research could focus on issues of replicability, scale, implementation of recommendations, and action orientation of drivers of deforestation articles specifically within Sub-Saharan Africa or sub-regions such as Central Africa.

Findings

This section presents quantitative and qualitative findings associated with our analysis of the database prepared as described above. We employed descriptive statistics and other quantitative analyses to determine how methodological approach and scale of analysis influence the quantity and type of drivers of deforestation and forest degradation identified. We also sought evidence of influence on conservation policy and program action – including implementation of recommendations, data availability, and reproducibility.

Sample overview and descriptive statistics

Of the 231 articles reviewed and coded in the final database after cleaning, 33% were primarily global, 26% were regionally focused in Africa, 23% were regionally based in Latin America (including South America and the Caribbean), and 11% in Southeast Asia (Table 3; Fig. 2).

Subregional articles were commonly focused on the Amazon, Congo Basin, and Mekong subregions given the importance of forests in those regions to biodiversity conservation. However, due to the inclusion of articles from two Africa-focused FAO databases, there is greater representation in the sample of articles in Sub-Saharan Africa, primarily

Table 3 Frequency of articles with global and regional coverage, and driver types identified.

Global and regional coverage		
	Frequency	Percent
Global	77	33.3
Africa	61	26.4
Latin America	54	23.4
Southeast Asia	26	11.3
North America	8	3.5
Asia	4	1.7
Oceania	1	0.4
Total	231	100.0
Driver types identified		
	Frequency	Percent
Underlying	44	19.0
Proximate	86	37.2
Both	100	43.3
Total	231	100.0

"Both" indicates articles that explicitly featured both proximate and underlying drivers, and articles that included reference to drivers that were at times proximate and at other times underlying within the context of the article

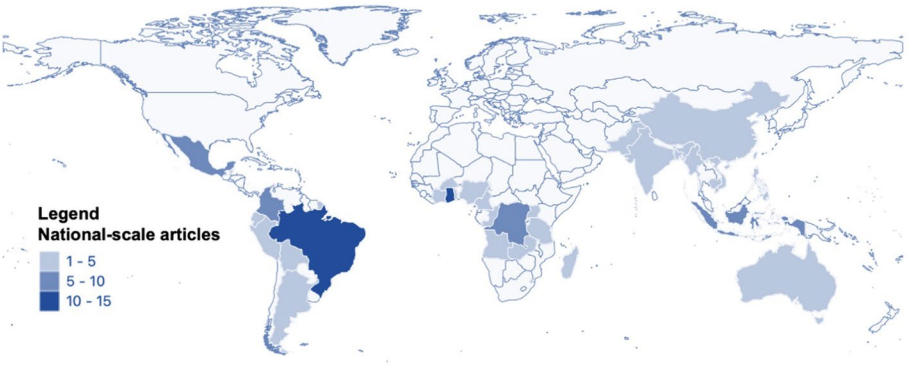

Fig. 2 Global coverage of countries represented in national or locally scaled articles that were coded as national level for primary scale

focused on Central and West Africa (Table 3; Fig. 2). Studies in the Amazon context tend to focus on Brazil and Colombia, with fewer studies identifying drivers in, for example, the Peruvian and Ecuadorian Amazon (Table 3). Studies primarily scaled at the national level were most commonly Brazil (15 articles), Ghana (14), Colombia (9), and Democratic Republic of Congo (7) (Fig. 2).

Of the articles analyzed, 37% identified or explicitly discussed proximate drivers (Table 3). Only approximately 19% explicitly discussed underlying drivers, though 43%

of articles described both. Importantly, many of the articles which described both were implicit. Although in a few cases articles explicitly identified certain underlying and proximate drivers of deforestation or forest degradation, there was often terminological ambiguity as documented by Meyfroidt (2016). Authors would explicitly discuss proximate drivers and refer to underlying conditions without naming them as such.

As is well-documented in the literature and across scales, the most common drivers identified were agricultural land conversion (for both small scale and commercial, and for cash crops driven by international commodity markets), logging (legal and illegal), fires, and, particularly for the African region, fuelwood, charcoal, and other basic needs.

While there was alignment in many cases in the underlying and proximate drivers that were identified via the different methodologies and analytical scales represented in the articles, there were inconsistencies and variations specific to certain regions. For example, there were common themes in agricultural land conversion as a proximate driver, based on relevant crops and underlying-cause commodity markets (e.g., soybean and cattle ranching in Amazon, rubber in Congo Basin, and rice and palm oil in Greater Mekong) that pressure various regions for increasing agricultural production and land conversion (Fehlenberg et al. 2017; Gasparri et al. 2013; Grau et al. 2005; Grogan et al. 2019; Lohani et al. 2020). For inter-scalar studies, consumption demand from Europe and the US was a commonly cited underlying cause or underlying driver of deforestation and forest degradation (Paim, 2021; Mammadova et al. 2020). That said, there were some underlying and proximate drivers identified for specific regions or subregions that were not discussed in coarser-scaled analysis yet were revealed with finer-scale study (Mayer 2019). For example, elections and government turnover was highlighted as an important underlying driver of deforestation and forest degradation by studies that focused sub-regionally on Congo Basin (Morpurgo et al. 2021). Additionally, from an agricultural production perspective, it was noted across several studies at various scales that while increasing pressure to convert land to monoculture and commercial agriculture is a threat to forests in the Amazon and Greater Mekong subregions, in Sub-Saharan African and Congo Basin, the agricultural threat to forests continues to be smallholder-based and livelihoods-oriented (Pendrill et al. 2019; Grogan et al. 2019; Sandker et al. 2017; Twongyirwe, 2018; Waha et al. 2016).

Methodological approach and scale integration

Methodologies varied and were partially correlated with year of publication and scale. Studies that were coded as "quantitative" and implying statistical modeling leaned primarily on econometric and spatial econometric natural experimental and quasi-experimental designs, such as regression or border discontinuity, including those explicitly undertaking causal inference. These quantitative-statistical studies were increasingly common over time, particularly in the 2015–2021 period. However, when combined with the quantitative studies using algorithmic modeling approaches for image classification such as random forest, 76% of the sample featured studies could be considered quantitative from this broader perspective (Breiman 2001). While there was a predominance of statistical modeling in the quantitative category, remote sensing was a similarly common category and used algorithmic or classification methods such as random forest, or focused on change detection (e.g., via image subtraction). 71% of the articles reviewed in the sample used algorithmic modeling for remote sensing classification, and combined this algorithmic classification approach with some statistical analysis later in an article.

Quantitative studies were largely coarser-scaled, with fewer purely (as in, both data collection and analysis technique) quantitative studies taking place at the finer-grain local scale. These articles were more likely to identify nonspecific agriculture ($\chi^2 = 31.88$; $p < 0.05$), nonspecific land conversion ($\chi^2 = 28.23$; $p < 0.1$), and specific common commodities such as maize, oil palm, and cocoa ($\chi^2 = 27.45$; $p < 0.15$) as proximate drivers than qualitative studies. However, they also tended to describe fewer drivers ($t = 32.55$; $p < 0.001$). In alignment with Ferrar Velasco et al. (2020) and Mayer (2019), this indicates that qualitative studies, which were associated with finer scales of analysis (e.g., local), may be more adept at capturing heterogeneity of drivers of deforestation and degradation at particular locations.

Table 4 presents the total figures for primary scale of analysis and reflection scale of recommendations and conclusions within articles. Figure 3 presents the primary scale of quantitative articles, and the flow into their reflection scales visualized by a Sankey diagram. As described in Table 2, "Primary scale" refers to the explicit scale of the study (e.g., authors indicate that the study is conducted at national scale). However, reflection scale is a more interpretable concept in that this refers to the scale at which the article suggests recommendations, even if its explicit primary scale was different. While Table 4 shows the overall distributions of primary scale and reflection scale of the total, Fig. 3a breaks this down further to illustrate the scale of reflections within each primary scale category by percentage (e.g., of the 30.7% of all articles that were primarily globally-scaled as indicated in Table 4, Fig. 3a shows that 26.8% of those featured regionally-scaled reflections).

There was evidence of incongruencies in scale integration within studies. "Downward linkages" indicates that the primary scale was more coarse, yet these studies inferred results or made recommendations for a finer scale. "Upward linkages" indicates that studies were conducted at an explicitly finer scale, yet drew recommendations relevant to more coarse scales (Fig. 3b). These interlinkages and incongruencies within studies were further broken down by methodology type. Downward linkages within studies were more common

Table 4 Primary scale and reflection scale for articles analyzed

Primary scale		
	Frequency	Percent
Local	18	7.8
National	96	41.6
Subregional	26	11.3
Regional	20	8.7
Global	71	30.7
Total	231	100.0
Reflection scale		
	Frequency	Percent
Local	47	20.3
National	38	16.5
Subregional	31	13.4
Regional	58	25.1
Global	57	24.7
Total	231	100.0

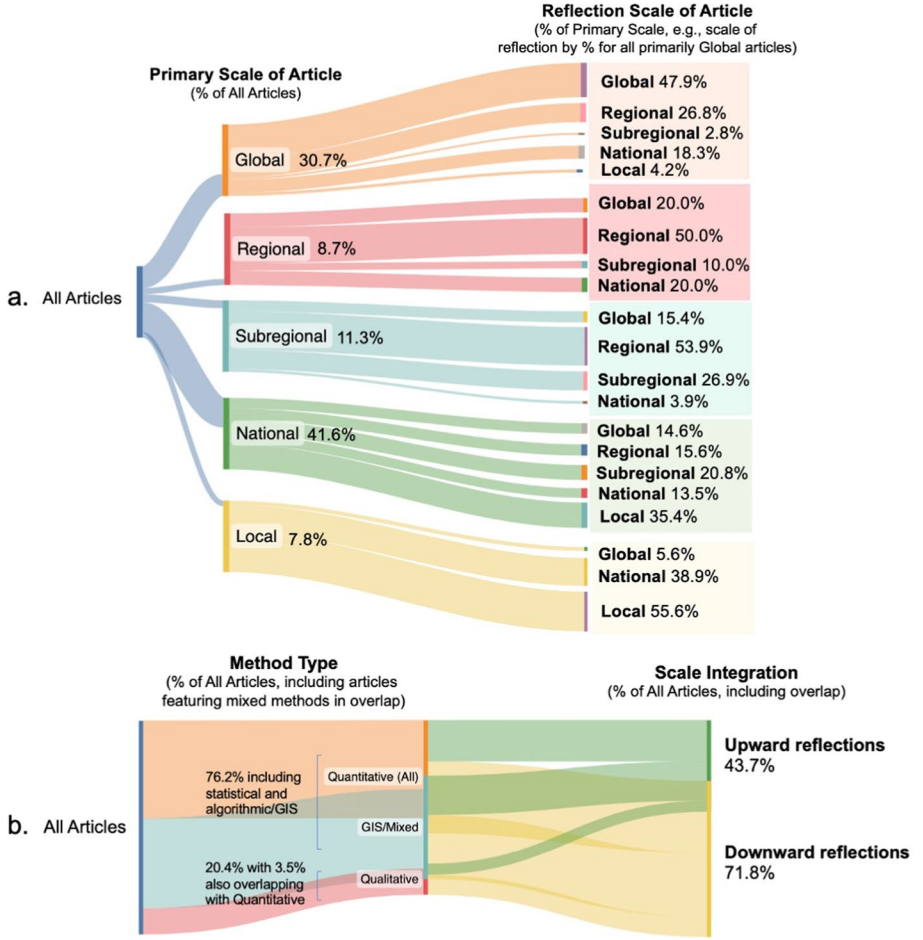

Fig. 3 **a** Sankey diagram illustrating primary scale to reflection scale integration for studies reviewed. For example, many quantitative studies undertaken at a national primary scale featured recommendations or reflections at local levels. Note: Some Reflection Scale percentages may add to 100.1 or 99.9 due to rounding error. **b** Sankey diagram illustrating upward (e.g., national level article reflecting globally) and downward (e.g., national level article reflecting locally) scale reflections for studies reviewed, by method type

across all methodologies used (e.g., national-scale studies reflecting on local-scale drivers of deforestation within a country) (Fig. 3b). Many broad-scale studies remain broad in their discussion and implications, such as global-scale studies which maintain globally oriented economic and policy recommendations. Very few studies across all methodologies reflected upwards more than two scale levels (e.g., local-scale studies reflecting on global drivers of deforestation). When conducted at the national and local levels, there was less inter-scale reflection (upward or downward) with algorithmic studies than, for example, statistically based studies, for which national scale studies tended to reflect on subregional issues.

Only 20% of the articles reviewed were coded as qualitative in their analysis techniques, and several of these also featured spatial or quantitative components. While most articles relying on interview data and qualitative analysis techniques were local and nationally

scaled, this category also included secondary literature reviews and meta-analysis applying qualitative techniques such as text, content, and thematic analysis. Qualitative articles that were considered primarily global or regional used such methods for literature review or meta-analysis. Very few of these qualitative analyses conducted at the local scale, for example, reflect upwards to subregional or regional levels. This is illustrated further in the Supplementary Materials, in Appendix I Figure II. In contrast, the qualitative-based review studies conducted at the global level tended to provide more insights at national and regional scales. Overall, 44% of all studies featured upward scale reflections (e.g., local to national, national to regional, etc.) and 72% of studies analyzed featured downward reflections (e.g., regional to subregional) (total > 100% because some articles featured both, as illustrated in Fig. 3).

Implementation

In terms of good practices for applied research, 57% of studies reviewed were considered to have recommendations that would be difficult or very difficult to implement based on 1–5 Likert scale with substantial intercoder reliability (Supplementary Materials Appendix I Table I). Challenges identified included vague recommendations or recommendations that were addressing deeper global systems such as commodity markets and global or regional demand for certain products. Only 8% of studies had recommendations that were considered relatively "easy" to implement; examples of such studies included those that had specific policy or program recommendations, or those that were associated with practical guides for implementation.

Online availability of data for these studies trended positively with more recent publication years, yet even still, fewer than half (41%) of the studies reviewed used data publicly available online, or published the dataset associated with the article. This was associated with studies that applied quantitative and remote sensing methods. Additionally, only 44% of studies reviewed were considered easily or very easily replicable, with clearly outlined methodologies or code available online with the published article. Again, these were associated with studies that applied quantitative statistical or algorithmic methods. Qualitative studies that used interview, observation, or focus group methods of data collection were unlikely to publish data, and these were often coded as difficult to replicate, but this was not necessarily the case for all qualitative studies, such as those using qualitative data analysis methods like thematic coding in literature reviews. Lastly, only 1% of studies reviewed were part of an updating series or discussed future replication of the same study.

Finer scale was also associated with the clarity of or ability to implement the recommendations ($\chi^2 = 32.78$; $p < 0.05$). Global and regional studies – which were also often based on quantitative and remote-sensing based methods – often featured loose recommendations that would be difficult to implement or were targeted to large-scale problems and lacking specificity. The most implementable recommendations were focused on ways to improve a specific program or policy (e.g., conservation intervention or REDD+), specific improvements that could be made to increase the accuracy of models or studies identifying drivers, or featured contextual specifics of a particular location which could be used in implementation.

Over time, studies across methodologies and scales increasingly utilized methods which could account for scale and context dependency, in addition to regional variations in identified drivers. While several 2015–2017 articles identified scale dependency as a problem, as illustrated in the following examples, more recent 2020–2022 articles built on this segment

of the literature to fill these gaps. Some even highlighted additional dimensions of the scale problem, incorporating unit of analysis. For example, Moonen et al. (2016), a primarily national-scale article with local-level reflections, identified problems associated with individual versus household-level units of analysis resulting from scale dependency. In particular, the authors found that policy design, when based on studies undertaken primarily at a household or even more coarse scale, did not account for high levels of variation in individual household contributions to deforestation (Moonen et al. 2016, p. 132).

Similarly, Armenteras et al. (2017) identified problems associated with scale dependency and spatial variation in drivers identified at the broader national, subregional, and regional scales. A key issue was that deforestation measurements taken at some scales were mismatched with the scale or forest types at the scale of policy or program intervention. The authors suggest that perhaps the actual measurements of deforestation intended for application at these different scales and for specific contexts could address these challenges (Armenteras et al. 2017, p. 139). An additional example specific to methodology was highlighted by Dalla-Nora et al. (2014). The study highlighted the lack of modeling approaches in the deforestation and forest degradation literature which account for scale and local variation. The authors subsequently suggest, however, that global or regional economic models may offer one solution from the quantitative and coarse-scale perspective, but struggle with the detail provided by alternative methodological approaches such as place-based qualitative study. In summary, themes revealed by analysis of this body of reviewed literature overall highlight the importance of alignment of method and scale with respect to recommendations and subsequent policy or program implementation.

Discussion and recommendations

First, the findings of this study indicate that there is often divergence between scale of analysis within studies – between the "primary scale" explicitly emphasized – and the "reflection scale" at which results were often attributed. Additionally, in alignment with existing literature such as Busch and Ferretti-Gallon (2017), Ferrer Velasco et al. (2020), and Scrieciu (2007), finer-scale analysis was associated with more drivers identified for specific locations (e.g., agricultural land conversion, infrastructure, fires, mining, in addition to regionally specific elections and government turnover); qualitative studies also tend to identify greater heterogeneity of drivers than quantitative or remote sensing-based studies. An important point to note, however, is that some of these results relate to underlying features or characteristics of quantitative-statistical methods themselves. For example, basic statistical "rules of thumb" such as parsimony and the "one-in-ten" rule constrain coarser-scale regression analyses that may have fewer observations or events, depending on the scale of data collection and analysis (Harrell et al. 1984; Coelho et al. 2019). Following the "one-in-ten" rule, for instance, finer-scaled quantitative studies may feature more drivers because the increased number of observations or events enables more prediction parameters (Peduzzi et al. 1996;). The relationship we find between heterogeneity of drivers and scale, then, may not be a function of the characteristics of the drivers themselves, but rather a function of the constraints of the methods used to identify them (Ferrer Velasco et al. (2020). This only further supports our suggestion that recommendations and interventions based on studies identifying drivers of deforestation should be cautious not only of the scale at which studies are undertaken, but the methods used to derive those findings (Turner Gardner 2015; Cattarino et al. 2014).

Next, this systematic review indicates that integration of results from studies of drivers of deforestation at different scales and with different methodologies could be supported by a logical and cohesive standard protocol for method selection and reconciliation for development of coherent policy and program recommendations. Such a protocol would facilitate useful policy recommendations for land use planning and other on-the-ground forest management activities (Bele et al. 2015; Börner et al. 2020; Knight et al. 2019; Reyers et al. 2010). With the goal of developing such guidance in mind, we present in Table 5 the advantages, limitations, and standardized avenues for reconciliation of findings in deforestation research across scales and methodologies.

While upward and downward reflection within studies is often desirable, such as when a carefully designed study is generalizable to a larger population or when global dynamics are relevant for local scales, it is also important that studies continue to explicitly acknowledge scale integration and dynamics that match the scale relevant for implementation of recommendations (Millington 2022; Newman et al. 2019; Landholm et al. 2019; Ferrer Velasco, 2020). Further, recommendations and reflections should be appropriate scaled considering the methodological approach used. Careful interpretation is required, for example, when a qualitative, locally scaled study reflects on global dynamics in its recommendations; similarly, a global quantitative-statistical article may not be able to appropriately reflect on local-level dynamics in a specific context. While a local scale study that features qualitative data collection and analysis, or qualitative data collection coupled with quantitative or spatial analysis, can be of great use in policymaking and program development, the unique contextual characteristics or features that may be influencing deforestation and forest degradation in that location warrants attention (Reyers et al. 2010).

Returning to the concept of archetypal clusters or groupings of drivers which are commonly found together, locations may have a mix of overlapping and scale-dependent drivers that uniquely interact with underlying conditions. This links with Oshan et al. (2022)'s differentiation of *type I and II scale multiplicity*, suggesting that notion of scale (e.g., scale of data collection and scale or range of spatial process) needs to be defined, and in cases where multiple complex scales are simultaneously used, the dynamics could be teased apart or explicitly addressed as multiscale factors with methods designed to illuminate multiscale factors. This carries over to implementation as well. Even when identified by regional or national scale remote sensing analysis, "rural complex" drivers (which includes small-scale artisanal agriculture alongside accompanying roads and settlements that often precede or follow agricultural conversion and expansion) may be influenced by local land tenure regimes, recent elections or conflict, proximity to national borders, or other context-specific factors (Morpurgo et al. 2021; Cuaresma Heger, 2019; Landholm et al. 2019; Mayer 2019; Molinario et al. 2020). For example, in reconciling divergent findings by scale and method, for Central African national or local-level practitioners may consider weighting more heavily governance, elections cycles, and conflict (e.g., proxied by conflict fatalities), and emphasizing smallholder farming activities, in conservation and land use planning due to the regional and subregional importance of these underlying and proximate drivers as identified by this systematic literature review (Butsic et al. 2015; Andrieu et al. 2018; Shapiro et al. 2023). In this sense, linking driver archetypes and multilevel complexity, it is apparent that scale-explicit methods and explicit attention to matching scale of results with scale of proposed intervention are critical. This aligns with Oshan et al. (2022)'s identified need for more intentional choice of methodology when varying notions of scale are relevant.

Previous literature reviews have synthesized global drivers of deforestation and forest degradation, and have described underlying and proximate drivers and causal mechanisms

Table 5 Advantages, limitations, and ways to reconcile findings with other types and scales of study, for quantitative-statistical approaches

Methods	Scale	Advantages	Limitations	Reconciliation
Quantitative: Statistical	Global Regional	Broad scale findings capture global economic conditions, consumption patterns, and the international demands that place pressure on tropical forests. Quantitative methods such as spatial econometric techniques also allow study of spillover effects and leakage, which is increasingly important in the literature	Scale dependency and regional variations are increasingly important in the literature, and global studies that use countries or regions as units of analysis are not able to adequately capture these dynamics (especially considering statistical rules of thumb such as parsimony and "one-in-ten"). Further, very broad scale studies may not yield actionable recommendations for practitioners working in specific contexts and locations	Considering regional variation and scale and context dependencies, global and regional quantitative studies can illuminate broad-scale issues and highlight potential spillovers and leakage effects, for further examination at subregional, national, and local levels
	Subregional National Local	More context-oriented quantitative studies may yield results that isolate underlying and proximate drivers while capturing variation in space and time. Certain designs enable causal inference	While capturing more locally relevant drivers, it is important to also take the global level influences into account	To ensure that the local variation in potential drivers is captured, it will also be critical to incorporate the results of global and regional findings to situate studies in global deforestation context. This can be done also using remote sensing and mixed methods approaches highlighted in the Mixed Methods rows

Table 5 (continued)

Methods	Scale	Advantages	Limitations	Reconciliation
Quantitative: Algorithmic, and mixed methods*	Global Regional	Increasingly, remote sensing studies at higher scales are incorporating quantitative and/or causal inference-oriented techniques such as spatial econometrics (e.g., using zonal statistics from remote sensing) beyond standard change detection and classification to identify possible drivers. Machine learning and AI techniques can also enable processing and analysis of large-scale trends	These limitations are shared with global and regional quantitative studies: global studies that use countries or regions as units of analysis struggle to adequately capture local variation, context, and regional variation and dynamics. Further, these coarse scale studies sometimes struggle to yield actionable recommendations	Mixed methods studies combine many of the benefits of purely remote sensing, purely quantitative, or purely qualitative studies. But by using case studies, adding national or local dynamics, or otherwise incorporating finer-grained scales, some regional variation and context issues can be addressed. Reference to specific global or regional economic policy, trade, or other systems will also be important in developing recommendations which can be actionized
	Subregional National Local	Mixed methods studies at scales lower than global and regional yielded dynamic and relevant drivers of deforestation and forest degradation which incorporated context	Each specific methodology is subject to its own limitations, but generally finer-scale mixed methods studies tended to capture fewer temporal trends in drivers of deforestation and degradation	Mixed methods studies can address the qualitative challenge of high internal validity, but lower external validity (see Qualitative rows) by including multiple types of knowledge and triangulating with quantitative and spatial studies. These need to be linked to actionable recommendations for practitioners

Table 5 (continued)

Methods	Scale	Advantages	Limitations	Reconciliation
Qualitative	Global Regional	Global and regional qualitative-based studies are often literature reviews or meta-analyses. These offer important insights for shaping the direction of research and practice	Literature reviews and meta-analyses need to emphasize drawing actionable and implementable recommendations and for reducing deforestation and forest degradation in specific locations	These studies can shape the direction of future research by identifying gaps and areas for potential intervention. However, these drivers distilled in by review of these studies should be confirmed with narrower-scale approaches as well
	Subregional National Local	Qualitative studies at finer scales are often interview and focus group discussion based in the dataset reviewed. These provide critical context and ensure that local voices are heard and that their understanding of local drivers in a particular context are incorporated into recommendations	While context-oriented, qualitative studies at finer scales are sometimes limited in capturing temporal trends or in neighboring locations. These may have high internal validity, but lower external validity	Quantitative and qualitative studies can complement each other by filling gaps. Quantitative studies that may be able to compare between regions, countries, and locations in identifying drivers should be complemented by qualitative studies to bolster internal validity. With these parallel data types, accurate and actionable recommendations can be made for contextually relevant land use planning options

*In this table, quantitative-algorithmic and mixed methods are combined because many of mixed-methods studies included in the sample also utilized GIS-based algorithmic methods (such as land-use classification algorithms) alongside the qualitative approach (e.g., Makunga Misani, 2017)

(Hänggli et al. 2023; Balboni et al., 2023; Garrett et al. 2021; Pendrill et al. 2022; Busch Ferretti-Gallon 2017; Meyfroidt 2016; Atmadja Verchot 2012). However, this study has provided an additional contribution to this body of literature by disaggregating by method and scale, to illustrate what types of data collection and analysis reveal certain drivers across the globe and in particular regions of the tropics (Scrieciu 2007). Acknowledging the linkages between scale, method, and the drivers identified – including the archetypal groupings of drivers commonly found together – is important for achieving both effective national biodiversity and forest monitoring, as described by Armenteras et al. (2017), and global biodiversity conservation and deforestation and emissions-reduction aims. Further, the study provides a step towards synthesizing divergent findings resulting from studies undertaken at various scales and with different methods, and in highlighting the need for clarity in recommendations. Clear, implementable recommendations can be derived from results identified at coarse or fine scales, or using a variety of methodological tools, yet the recommendations should be clear and appropriate to the type of analysis (Garrett et al., 2019; Börner et al. 2020; Knight et al. 2019). Future research could explore the role of transdisciplinary research practices in developing clear and implementable recommendations for reducing deforestation and forest degradation (Brandt et al. 2013; Margules et al. 2020). Transdisciplinary research, which involves non-academic stakeholders such as policymakers and conservation or land use organizations throughout the research process, could encourage more clear and actionable recommendations from research on drivers of deforestation and forest degradation from the outset (Mauser et al. 2013). Furthermore, additional research can continue to develop guidance for development of actionable and implementable recommendations geared toward specific policy- and decision-makers.

Conclusion

In summary, this study systematically reviewed 231 articles in the drivers of tropical deforestation and forest degradation literature to assess how methodological approach and scale of analysis influence the quantity and type of drivers of tropical deforestation and forest degradation identified, and to understand possible implications for conservation policy and program action. The focus on subregional, national, and local dynamics is critical in determining clear and effective paths forward for land use planners and other practitioners working to reduce deforestation and forest degradation on the ground. Recommendations tended to be coded as more action-oriented and implementable when locally relevant or specific (Börner et al. 2020; Knight et al. 2019). In addition to divergence of scale used between studies, the findings indicated divergence between scale of analysis within studies – between the "primary scale" explicitly emphasized and the "reflection scale" at which results were attributed. In alignment with existing literature such as Busch and Ferretti-Gallon (2017), Ferrer Velasco et al. (2020), and Scrieciu (2007), finer-scale analysis was associated with more drivers identified for specific locations (e.g., agricultural land conversion, infrastructure, fires, mining, in addition to regionally specific elections and government turnover); qualitative studies also tend to identify greater heterogeneity of drivers than quantitative or remote sensing-based studies. The coarser scale of analysis was negatively associated with the ability to implement recommendations suggested in articles. Global and regional studies tended to feature recommendations that would be difficult to implement, or which are targeted to large-scale problems lacking specificity. The most implementable recommendations focus on improvements that can be made to a specific

program or policy (e.g., conservation intervention or REDD+), specific adjustments to increase the accuracy of models used in studies, or recommendations that feature specific location context. The scale of analysis should be appropriately aligned to the scale of interventions and decision-making; for example, at the national level, most countries can only enact regulations or interventions at national or sub-national scales. International agreements and collective climate actions, which might result in pressures to reduce demand enacted at global scales, can be more complicated to agree upon and implement.

This study illustrates the importance of method and scale selection that is attuned to the type and scale of deforestation and forest degradation challenges, and to the types of interventions that may be recommended. Future research can use this work to identify scale-appropriate recommendations for effective implementation, and to ensure alignment of methods, data, and scale when addressing deforestation and forest degradation in the tropics.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10531-023-02747-z.

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Author contributions KPB and ACS: contributed to the study conception and design. CAH: reviewed the study conception materials. Material preparation, data collection and analysis were performed by KPB. The first draft of the manuscript was written by KPB and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability A complete list of articles reviewed is included in Supplementary Materials. The cleaned database of articles included in the analysis with codes assigned to each article is available upon request in Microsoft Excel format. The pre-cleaning Zotero folder can also be shared upon request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose, nor competing interests to declare. The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter of this manuscript.

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