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Review

Accounting for Land-Use Changes in Environmental Impact Assessments of Wood Products: A Review

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Abstract: Environmental policy and the expansion of the bioeconomy sector has led to increased demand for wood and wood products, pressuring forests. In order to meet additional demand, foresters must either intensify forest management practices or alter forest area. One of the more observable shifts in forest management comes in the form of changes in land use or land cover. Yet despite the many short- and long-term consequences of land-use change, the environmental impacts of it are less explored in forestry than in agriculture. In this paper, we conduct a literature review over the period between 1993 and 2022 to better understand how the notions of land-use and land-cover change are included in environmental impact assessments related to the production of wood and wood products. Specifically, we identified five categories of impacts studied and found a surprising dichotomy in terminology between land-use/land-cover change and changes in forest management practices. We present general trends in the methods and indicators used and discuss potential methodological and conceptual challenges inherent to this literature. Our results are particularly important in light of the growing popularity of land-use and land-cover data in research, as we highlight how they have been integrated into existing environmental impact assessment methods and how we can improve them going into the future.

Keywords: carbon; environmental impact assessment; land-use and land-cover change; wood and wood products

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1. Introduction

Many countries are setting up action plans to address environmental challenges such as global climate change [1], biodiversity decline [2], and the unsustainable use of finite resources [3]. These plans, such as nationally determined contributions (NDCs) for carbon emissions or Finland's low-emission roadmaps [4], increasingly rely on the use of natural resources to produce renewable materials and energy that can also substitute for fossil fuels. (For reference, NDCs under the Paris Agreement provide an overview of the climate commitments made by 195 countries in accordance with the requirements given by the United Nations Framework Convention on Climate Change (UNFCCC) [5].) For example, the latest revised European Union Energy Directive raised the EU's renewable energy target to 42.5% of its total energy mix (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L2413 (accessed on 22 November 2024)). The emergence of these so-called bioeconomies raises questions related to management practices that enable countries to meet this new demand and their environmental impacts, as well as potential tradeoffs associated with other uses for the land [6,7]. This issue is particularly apparent in the forestry sector [8]. On the one hand, wood can be used to produce traditional goods such as furniture and paper, but it is also increasingly used for energy production, as a construction material, and as a source of chemical compounds [9]. Forest biomass can either originate directly from the forest (primary wood biomass) or be repurposed after its initial use (secondary wood biomass), with each having different environmental impacts and implications for sustainability [10]. On the other hand, forests have high environmental value, provide multiple ecosystem services (including carbon storage), and often contain valuable habitats for biodiversity [11]. Indeed, forests are often mentioned in climate mitigation policies due to their capacity to act as carbon sinks [12,13].

In order to meet additional demand for raw wood and final wood products, foresters may either intensify management practices (e.g., shorter rotations, introduction of fast-growing species) or extend forest area to exploit in the future (at the expense of agriculture and other land uses) [14], all while considering the environmental impacts of their decisions and the economic tradeoffs associated with other uses of the land (e.g., opportunity costs). In addition to expanding forest areas and intensifying management, reducing forest losses and waste are critical for minimizing environmental impacts and improving forest sustainability. Sustainable forestry practices, such as selective harvesting, pest control, and forest fire management, can increase resilience and reduce the impacts of disturbances like pests, wildfires, and storms [15]. Intensification methods like fertilization, improved water management, and irrigation can boost productivity, particularly in nutrient-poor soils, while maintaining forest health [16]. In the forestry industry, improving supply chain efficiency and reducing waste through better use of wood byproducts are efficient steps for limiting environmental impacts [17].

In this paper, we hope to identify the general trends in the forestry literature regarding the environmental impacts of forest management on meeting wood demand for all wood products, including raw biomass, to be transformed into final products. One of the more observable shifts in forest management comes in the form of changes in the allocation of land, or land-use changes (LUCs hereafter), which refers to a change in the purpose of land and potentially also implies a change in land cover (i.e., the bio-physical characteristics of the land) [18]. For example, deforestation (the conversion of forest land to other uses) is a commonly used category of LUCs. Changes in land use can have short-term and long-term impacts, e.g., deforestation satisfies wood demand in the short term but reduces carbon storage [19,20] while afforestation increases carbon uptake but only yields wood several years after planting [21]. Furthermore, as forest markets are global, additional demand in one region may also result in LUCs in other regions, e.g., through leakages and displacement effects [22], leading to environmental impacts abroad [23].

The environmental consequences of land-use and land-cover change can be evaluated using environmental impact assessments (EIAs), such as life cycle assessments (LCAs) and ecological footprints [24]. These methodologies share a common goal of assessing the environmental impacts of a product, production process, or sector along several axes, but they differ widely regarding supply chain part, type of impacts considered, or indicators used for measurement [25]. The environmental impacts of LUCs are well documented in the agricultural sector using EIA methods [25,26], most notably the expansion of agricultural areas to increase biofuel production [27]. Yet despite numerous EIA studies on wood production (particularly on energy wood biomass) [28], the specific question of LUCs is less explored in forestry.

The main objective of this paper is to better understand how the notion of land-use and land-cover change is included in environmental impact assessments related to the production of raw wood biomass and transformed wood products, including final products and after-life use. To do this, we conduct a literature review, covering the period from 1993 to 2022, to (i) identify the categories of LUCs that are studied in the forestry literature; (ii) highlight the EIA methods used and environmental impacts considered in the context of raw wood production and wood products; and (iii) discuss potential methodological or conceptual issues hindering a better consideration of LUC dynamics in EIA related to wood products. Certainly, land-use and land-cover changes in forests can be sometimes hard to measure. Forest management is characterized by a continuum of management options and forest compositions, including changes in both intensity and usage that might not be considered a change in land use if the trees are allowed to regrow. The effectiveness of land-use and land-cover analyses is dependent on the classification schemes [29], the source data quality [30], and the modeling methods applied [31]. Ensuring these components are carefully considered from the outset is crucial for producing meaningful and reliable outcomes. However, with the growing usage of land-use and land-cover data in the scientific literature—such as the US Landsat (https://www.usgs.gov/centers/eros/science/annual-national-land-cover-database (accessed on 22 November 2024)) and the European CORINE Land Cover (https://land.copernicus.eu/en/products/corine-land-cover (accessed on 22 November 2024)) databases—it is important to understand how they have been integrated into existing methods and how we can improve going into the future.

The rest of this article is organized as follows. In the next section, we define the main concepts addressed in this article and describe the methodology of the review. In the third section, we present our main findings, beginning with a bibliometric analysis of the sample, followed by an overview of research practices, methods, and primary research findings. Finally, we discuss our findings and raise some important discussion points on LUC research methodology, including directions for future research.

2. Materials and Methods

2.1. Concepts and Definitions

2.1.1. Environmental Impact Assessments

EIA approaches aim to identify, evaluate, and predict the impacts of a project or product on the environment, along multiple sectors of the production supply chain [32]. During the course of our literature review, we will cover the types of methods used, impacts considered, and the indicators used to measure them. While several EIA methods exist, they all follow the same core process: define the objectives of the assessment, screen and gather information necessary for the study, define alternative scenarios, quantify impacts, and communicate the final results. Yet while they may follow a common procedure, they often differ in how they delimit system boundaries, evaluate environmental impacts and indicators, mobilize databases, and their choice of modeling tools [33]. EIA methods are regularly used to support environmental policy, to improve the quality of decisions, and propose solutions to reduce potential impacts of wood production.

Impacts and indicators are two key concepts related to environmental impact assessments. According to the European Environment Agency (EEA), an environmental impact can be defined as "an alteration of environmental conditions or creation of a new set of adverse or beneficial environmental consequences caused by the action under consideration" (https://www.eea.europa.eu/help/glossary/gemet-environmental-thesaurus/environmental-impact (accessed on 22 November 2024)). As defined by the OECD Development Assistance Committee (DAC), an indicator corresponds to "a quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect the changes connected to an intervention" [34]. In other words, impacts represent the consequences of changes brought to the environment, while indicators correspond to numerical variables chosen to quantify those impacts [35]. Impacts commonly studied in EIA include climate change mitigation, biodiversity losses, and water pollution, and indicators include the quantity of carbon emitted in the atmosphere, species numbers, and nitrate levels, respectively [36,37].

2.1.2. Land Cover, Land Use, and Land-Use Changes

The literature usually distinguishes between the concepts of land cover and land use. The former refers to the physical characteristics of the land, whereas the latter is an interpretation of how people are using it [38]. The two concepts frequently overlap, as there is confusion between the biological aspects of land-cover representation and the socioeconomic dimensions of land use [29].

Research on land use changes has a long history (see [18] for a review of this literature). With the advent of satellite imagery in the 1970s, the terms land use and land cover sometimes came to be used interchangeably. Since satellite images provide observations of land cover but not direct insights into land usage, it became common to associate a specific land use with each observed land cover, leading to a blending of the two concepts. However, with advancements in technologies and the integration of production data processes, the need to distinguish between these two concepts and establish separate classifications has become apparent [39].

Land use and land cover are defined according to categories that distinguish different types of purposes or bio-physical properties of land [40]. A change in land use or cover is therefore the transition from one category to another and is defined relative to a given nomenclature. For example, a land-use typology that distinguishes several crop varieties (e.g., cereals/oilseeds) will register a land-use change if the farmer decides to convert one variety to another. This effect will not be classified as land-use change with a coarser categorization (e.g., crop/grazing/forest). Some classifications mix categories of land cover and land use. For example, the CORINE land cover database includes 44 classifications of land across the European continent, from urban fabric to arable land and pastures, forests, and wetlands (https://land.copernicus.eu/en/products/corine-land-cover (accessed on 22 November 2024)). Here, classifications such as rice fields, vineyards, olive groves, and pasturelands are land-use categories, whereas dunes, glaciers, and waterways are land-cover categories. Such confusion constitutes a potential issue for data processing and can be explained, in addition to historical reasons, by the multifunctionality of some land covers (i.e., the capacity for a parcel of land to serve several uses at the same time). This is all the truer when these different uses are not directly observable [41], such as in is the case of the recreational use of forests.

There is extensive literature related to LUCs associated with agricultural activities, particularly concerning biofuel production and greenhouse gas emissions [39–43]. Moreover, this literature distinguishes direct and indirect causes of land-use change. A direct land-use change (dLUC) takes place when the cultivation of raw material on a parcel of land directly changes the use of that land (e.g., food crops replaced by biofuel crops), while an indirect land-use change (iLUC) is a form of spillover effect where a land-use change in one location is caused by a land-use change in another through market mechanisms [44]. To the best of our knowledge, there is no comparable literature for the forestry sector, which encompasses all activities related to the production and consumption of transformed and raw wood, upstream and downstream of the supply chain. This is likely due to the multifunctional nature of forests (e.g., serving several purposes at the same time) [11] and the often comparatively slower land transitions in forests.

For example, forestry is often characterized by long production periods (i.e., rotations) of 20 up to 200 years. Yet, increasingly, land-use and land-cover data in the form of satellite imagery are being used in the forestry sector to understand changes in forest size and composition [45,46]. More and more land-use and land-cover data sets—such as CORINE land-use databases—are available to and are used by researchers. Moving forward, it is important to broadly understand how past forestry research has treated land-use and land-cover change and where it may be limited going forward in future studies.

2.1.3. Responses to Increased Demand: At the Intensive and Extensive Margins

Additional demand for wood can be met either at the intensive margin (i.e., by increasing non-land inputs) or at the extensive margin (i.e., by increasing area) (as defined by [14]. Note that the definitions here are different from the "intensively and extensively managed forest" in Ecoinvent sustainability assessment database (https://ecoinvent.org/database/ (accessed on 22 November 2024)). Specifically, changes at the extensive margin refer to increases or decreases in forest area through afforestation or deforestation. That there is a subtle difference between managing at the intensive or extensive margins and extensively managing a forest. Depending on whether we examine deforestation or afforestation from methodological, ecological, or legal perspectives, different definitions for these practices may apply [47]. For instance, the Global Forest Resource Assessment defines deforestation as "the conversion of forest to other land uses, whether human-induced or not" [48]. However, as we focus on human-induced land changes, we use the UN Framework Convention on Climate Change (UNFCC) definition of deforestation which is "the direct human-induced conversion of forested land to non-forested land" (https://www.un-redd.org/glossary/deforestation (accessed on 22 November 2024)). In contrast, the UNFCC defines afforestation as "the establishment of forest on land that has not been forested for at least 50 years" (https://www.un-redd.org/glossary/afforestation (accessed on 22 November 2024)). Since this definition includes a temporal criterion, which may not be reported in many studies evaluating land-use changes [49], we adopt the Global Forest Resource Assessment definition, which is given as "the establishment of forest through planting and/or deliberate seeding on land not classified as forest" [48].

Changes at the extensive margin generally fall into the definition of land-cover change described in Section 2.1.2. They have important environmental implications, as deforestation can greatly reduce carbon sequestration and modify soil properties [50] while afforestation in one place can involve deforestation abroad to meet wood demand [51]. Changes at the intensive margin, or changes in forest management practices (FMPs), include but are not limited to reductions in rotation periods or increases in harvest levels and changes in silvicultural operations (e.g., thinning) or site preparation methods (e.g., fertilization). They are often used to minimize the quantity of land necessary and to respond faster to an additional demand for wood [52]. In the long term, they may also include changes in species composition (e.g., replacement of slow growing species with faster growing ones) and alterations to forest structure [53] or conversions from one type of forest to another (e.g., from a natural, non-managed forest into one meant for timber and firewood production) [54]. How changes at the intensive margin fit into the definition of land-use change is not as clear, as many of the changes associated with it are gradual with long-term implications for the provision of ecosystem services and the portfolio of products supplied. Often there is no formal conversion of land use or cover from one type to another, even though the characteristics of the land have changed. For instance, transitioning a forest to a high-intensity management regime can lower biodiversity rates, carbon storage, and recreation supply services but provides higher timber production [11,55]

2.2. Review Methodology

Our systematic review was performed in several steps. First, we constructed a search query to retrieve publications falling within the scope of our study. The query was implemented on the Scopus database in April 2022, and the results were limited to the "journals" category. It consisted of three blocks of keywords (Figure 1), set to be found in Title-abstract-keywords:

1. A first block related to EIAs (e.g., "life cycle assessment", "environmental evaluation"), based on methods commonly used in the literature [24].
2. A second block related to wood products and forests (e.g., "forest products"). We consider wood products as products coming from forest areas.
3. A third block of generic terms for land-use and land-cover changes (e.g., "land use", "land cover change", "land conversion") and terms specific to the forest sector (e.g., "afforestation", "displacement").

Boolean operators were applied within and between blocks. Specifically, the operator "OR" was used within each block, and the operator "AND" between them. We discuss the limitations of this approach in the Discussion section.

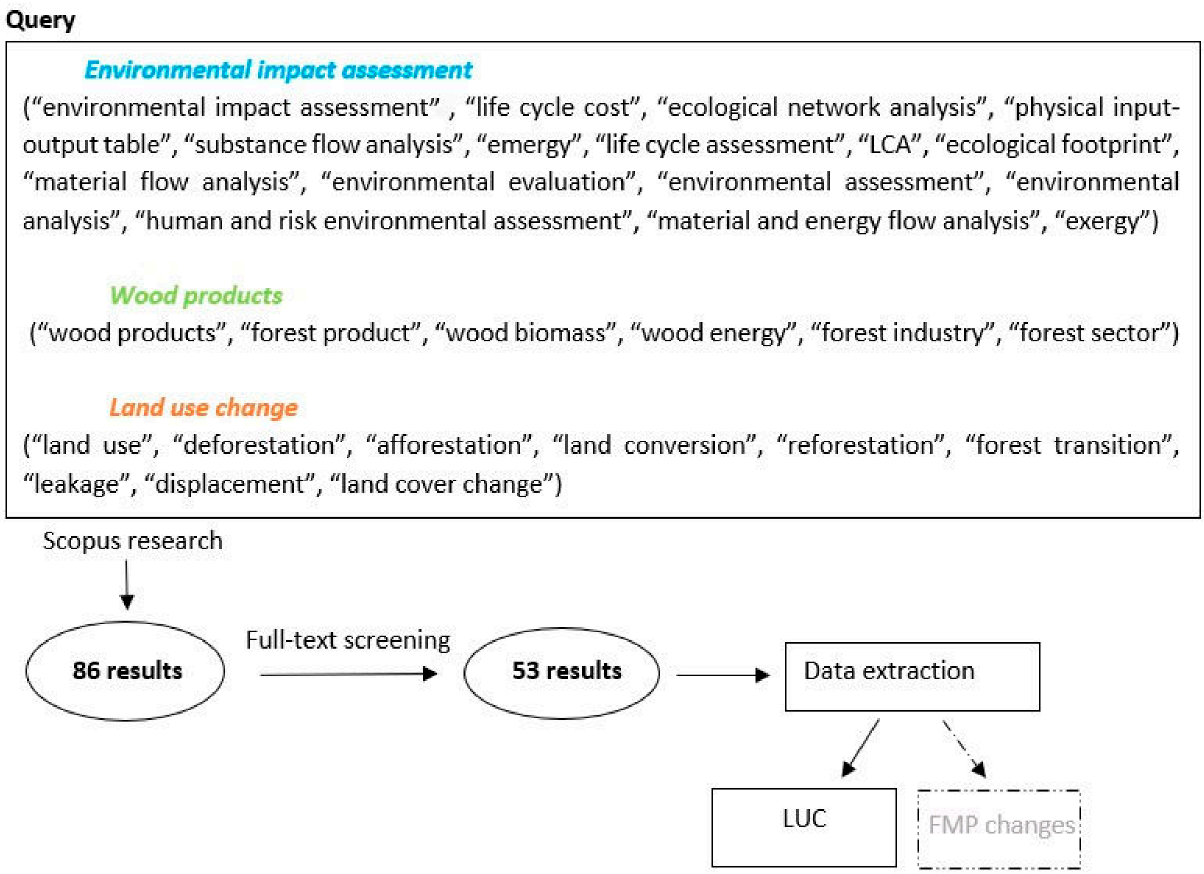


Figure 1. Illustration of the steps in the literature review process. Note that the Boolean operator "OR" was used within blocks; the operator "AND" was applied between them.

To be included, publications needed to satisfy five conditions: (1) publications must be research articles or book chapters published in either English or French; (2) they must perform an EIA, regardless of the method used; (3) they must concern wood products, transformed or not (e.g., including raw forest wood biomass such as wood pellets, transformed intermediate or final products such as furniture, or waste); (4) they must include any type of direct or indirect LUC or land-cover changes; and (5) the research must be motivated or justified by the need to meet an increased demand for use of wood biomass. The systematic search yielded 86 publications, 33 of which did not fit our criteria, yielding a corpus of 53 articles (cf. Supplementary Materials).

2.3. Analysis Methodology

Upon reviewing the documents, we identified broad categories of land-use change, methods used, and impacts studied, which we recorded and analyzed in detail (Sections 3.3–3.5). A screening of abstracts was performed and, when necessary, full-text searches to identify publications that fit the intent of our study. A full read through of the retrieved articles was conducted, and articles were classified based on several criteria: type of land-use or land-cover change considered (Section 3.2), EIA methods used (Section 3.3), environmental impacts quantified (Section 3.4), wood product considered and how they were measured (indicators), geographical scope, and the position of the study in the production supply chain.

To aid in visualizing patterns in the studies, we conducted a scientometric analysis (Section 3.1) based on co-occurrence of keywords and authors, using VosViewer software 1.6.20, an open-access software tool created to visualize bibliometric networks [56]. For the keyword co-occurrence network, keywords are represented as nodes or hubs, where the size of each node is given as the number of times that keyword was mentioned in our review. Links between keywords (item relatedness) appear when keywords are used together in the same publication. Links strength is defined as the number of co-occurrences between any two keywords. The resulting network of keywords (nodes) and links (edges) can then be visually divided into clusters according to the overall number and strength of linkages between keywords, where each cluster is made up of groups of closely connected keywords. (The clustering method is not a formal clustering algorithm like a hierarchical or K-means clustering analysis or a finite mixture model.) Labels for each cluster are added afterwards following a closer study of their corresponding papers (e.g., the types of methodologies or topics commonly associated with the keywords). In a similar fashion, we built an author co-occurrence network, with authors as the nodes or hubs.

3. Results

3.1. Publishing Dynamics and Bibliometric Analysis

Based on the Scopus categories, the majority of papers belong to the fields of environmental sciences (38.2%), agricultural and biological sciences (21.8%), and energy (10.9%). The journals most represented are *Biomass* and *Bioenergy* (four articles), *Forests* (four), *GCB Bioenergy* (three), and *Water*, *Air*, *& Soil Pollution* (three). Papers were mainly written by researchers affiliated to institutions in the USA (27), Germany (11), Finland (8), and Brazil (6) and most commonly considered cases in the USA (10 articles), Scandinavia (7 articles), Brazil, Congo, and Italy (3 each).

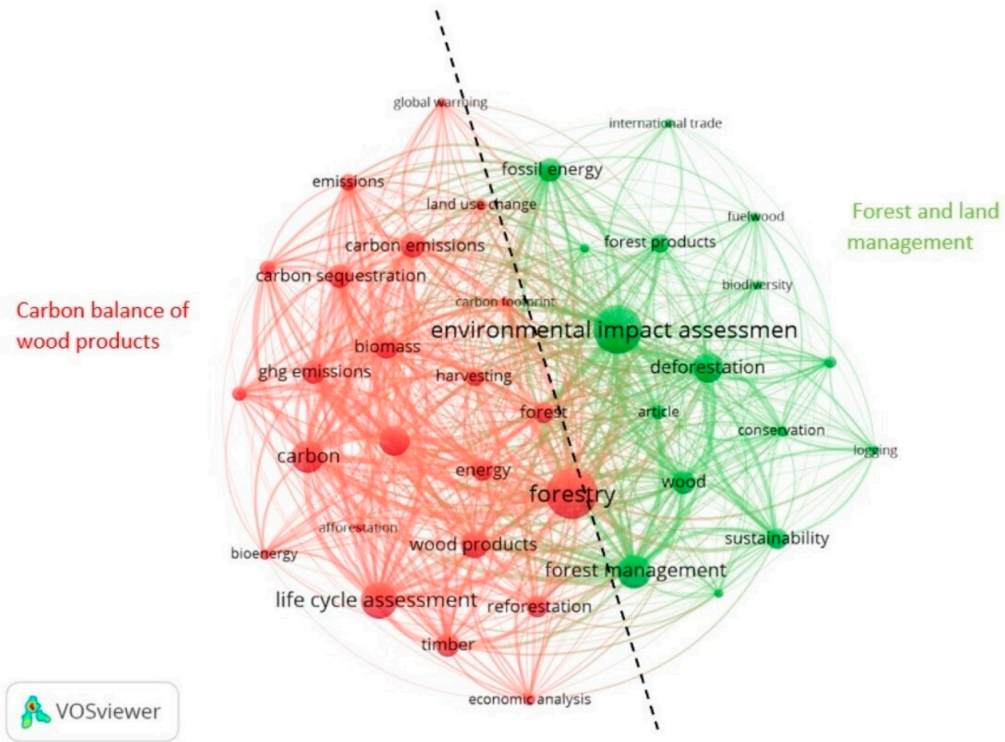
Of the studies considered in the corpus, twenty-three articles are national-level study cases, and twenty-one are local-level study cases. The global scale is addressed in six articles, which mostly analyses shifts in wood production, trade, and forest area across countries [57,58]. One article is at the regional scale (Europe), specifically focusing on a life cycle inventory of forestry operations in Europe [59]. Two articles do not mention any geographical scale and focus solely on methodological aspects [60,61].

Figure 2 gives an overview of the research field based on a co-occurrence network of keywords and authors, respectively. In each network, node size is proportional to the number of occurrences, and link thickness is proportional to the number of times two keywords are associated together. For visualization, distances between nodes are proportional to item relatedness. The most frequently used keywords are “forestry” (thirty-one times), “environmental impact assessment” (thirty times), “carbon” (twenty times), and “life cycle assessment” (twenty-two times). Two clusters were identified in the keyword co-occurrence network (Figure 2a). The first thematic cluster relates to the carbon balance of wood products, in particular bioenergy and through the life cycle assessment method, while the second thematic cluster relates to more general aspects of forest management, in particular deforestation, logging, conservation, etc. The latter has a stronger focus on the upstream forest sector than the former. Based on author disciplines, the author co-occurrence network showed that the query articles came from two main fields of literature: the land-use/land-cover literature on the one hand (authors like Lambin, Erb, and Asner) and forestry activities and silviculture on the other (Kellomaki, Sathre, and Peltola) (Figure 2b).

3.2. Land-Use and Land-Cover Changes

Thirty-nine articles (45%) were published after 2010 (Figure 3), coinciding with the development of public policies supporting the bioenergy sector and following the seminal article by Searchinger et al. 2008 [28], one of the first articles to quantify LUC emissions from biofuel use. Prior to 1993, no publications met our search criteria. One reason for this is that, prior to the 1990s, geographic information systems (GISs) and satellite imagery data—critical tools for studying land-use changes—were largely restricted to governmental use and had limited accessibility, particularly due to a lack of domestic computing power. As these technologies became more advanced and data widely available in the 1990s, the number of publications increased accordingly [62].

(**a**) **Keyword co-occurrence network**



(**b**) **Author co-occurrence network**

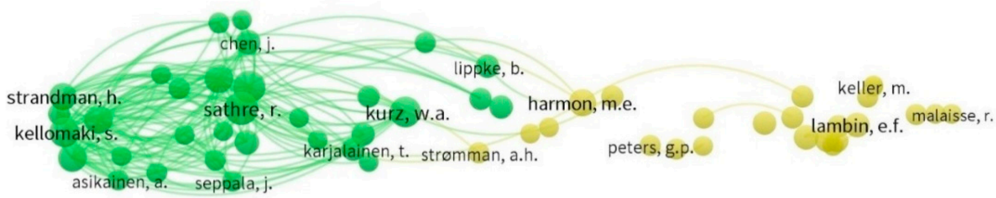


Figure 2. Keywords (**a**) and author (**b**) co-occurrence networks. The size of the nodes (keywords, authors) represents the number of occurrences in the literature review. Link thickness (connections) between nodes corresponds to the number of times two keywords are associated together. For visualization, distances between nodes are proportional to item relatedness. We identified two clusters in the keyword co-occurrence network. The first thematic cluster (red) relates to the carbon balance of wood products, in particular bioenergy through the life cycle assessment method, while the second thematic cluster (green) relates to more general aspects of forest management. Two clusters were identified in the author co-occurrence network based on author disciplines: land use/land cover on the one hand (yellow) and forestry and silviculture activities on the other (green).

Two main categories of articles were identified, based on the types of LUC studied:

(1) The first category of thirty articles addressed the extensive margin, i.e., changing forest area via afforestation or deforestation [63,64]. In general, these papers investigated the environmental implications of changes in different land-cover types to supply additional wood biomass. Fifteen of these considered deforestation, ten considered afforestation, and five articles addressed both. Most articles dealing with afforestation and deforestation focused on long time horizons (eight out of ten and eleven out of fifteen, respectively). Articles studying both afforestation and deforestation relied on forest transition theory [58,65] and the concept of leakages [57,66,67].

(2) The second category of twenty-three articles addresses changes in FMPs, i.e., the intensive margin [61,68,69]. The extensive margin production is the main topic for case studies concerning deforestation-prone areas, with focuses either on urban de-

velopment and agricultural expansion (e.g., Brazil) or illegal logging and regulations (e.g., the Congo). American and European study cases focus on changes in FMPs, with a particular emphasis on bioenergy production. Only four articles out of fifty-three in the corpus mention the concept of indirect LUCs, land-use displacements, and leakages [51,57,66,70].

The following sections (Sections 3.3 and 3.4) focus on the thirty articles that address the extensive margin. The specific case of changes in FMPs (the intensive margin), and of their status as LUC, is discussed separately (in Section 3.5).

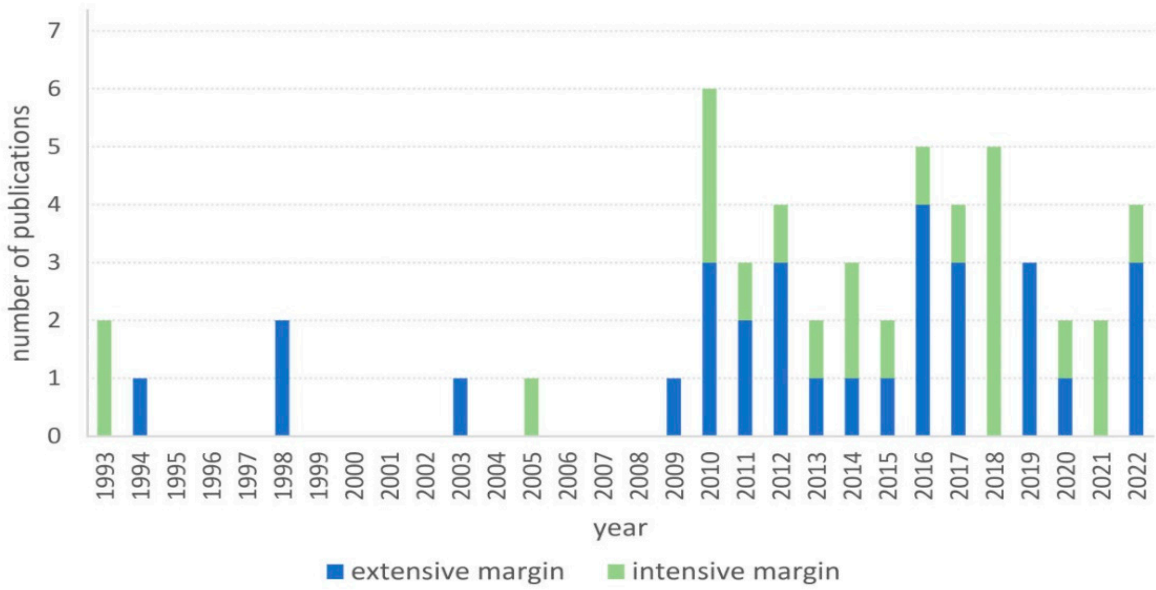


Figure 3. Number of publications over time in our literature review. For reference, we have divided publications by the extensive margin (blue) and intensive margin (green).

3.3. *EIA Methods*

Twenty-six out of the thirty articles evaluating the extensive margin performed dynamic analyses [58,70], measuring changes in impacts over time. Four articles performed static analyses [71,72], evaluating forest area or carbon stock measured for given years [73]. Two articles included the effects of climate change in their analysis: [74] studied the consequences of climate change on the expansion of forest area and [75] used the integrated terrestrial ecosystem model to assess the effects of climate change and disturbances on land-use and land-cover changes. Twenty-one articles focused on the upstream forest sector [76,77] while nine articles focused on downstream wood products, especially energy products (six articles, e.g., [78,79]). Four main EIA methodologies were identified within the sub-group of thirty articles.

3.3.1. Life Cycle Assessment, Nine Articles (17%)

Life cycle assessments (LCAs) seek to evaluate the impacts of a product or a service on the environment during its entire life cycle (or part thereof). They consist of four phases: defining the goal and the scope of the study, collecting data from life cycle inventory databases, assessing impacts, and interpreting results [80]. LCAs were used in nine articles, with four studying afforestation [79,81], three studying deforestation [63,78,82], and two studying both [66,83]. These studies assessed environmental impacts in the form of carbon emissions of the use of specific wood products, e.g., construction wood [84] or pulpwood [63]. The most commonly used approach, employed in five articles [81,84], was the cradle-to-grave method, which considers the entire life cycle of wood, from raw material extraction to product consumption. The cradle-to-gate approach, which follows raw materials to product manufacturing, was used in three articles [82,83,85].

3.3.2. Ecological Footprint, Six Articles (11%)

The ecological footprint (EF) framework provides a measure of whether a society's natural capital is sufficient to meet its needs, focusing on inputs consumed and waste products generated and how these relate to sustainability [86]. It was used in six articles. Two sought to quantify the short-term carbon implications of converting cropland and open land to forest [76,87], two investigated carbon emissions due to deforestation [75,88], and the final two compared land-use change and forest area variations across countries [57,65].

3.3.3. Other EIA Methods, Two Articles (4%)

Sustainable impact assessment, an EIA method based on the analysis and weighing of three-dimensional environmental, economic, and social indicators [69], was used by [89]. They assessed options to reduce forest depletion in Nigeria through forest protection, plantations, and different options of energy diversification. Material flow analysis (MFA), which represents interactions between the economy and the environment by quantifying material flows across several compartments (e.g., [90]), was used by [58]. Specifically, they investigated forest transition dynamics in the USA between 1870 and 2012 and quantified evolutions of the carbon sink.

3.3.4. Empirical Analyses, Thirteen Articles (24%)

Thirteen articles followed the general approaches of an EIA, albeit without following any of the well-defined protocols such as those mentioned above. These articles all have strong empirical components based on the analysis of survey or observation data [71,91,92]. Ten addressed the topic of deforestation; three addressed afforestation.

Of the former, three studies were mostly descriptive and used empirical data to quantify forest degradation, e.g., [73], who quantified deforestation in Northeast Brazil by comparing landscapes in 1968 and 2009. Seven studies went further and sought to explain the causes of deforestation using measures of correlations. For instance, Fuller et al. (2019) [70] found a strong correlation between China's timber imports from Congo and forest cover loss in Congo. In both cases, deforestation is the final impact considered. Of the latter, three articles used correlative methods to evaluate the environmental impacts of afforestation on, e.g., annual streamflow [93].

3.4. Environmental Impacts

Five categories of environmental impacts were identified among the articles reviewed:

(1) The effects on global warming were the most frequently studied throughout the corpus, with seventeen articles (56%). Seven assessed carbon dynamics related to afforestation [76,81], six focused on deforestation [63,88], and four on both [65,83]. Indicators largely consisted of estimations of greenhouse gas emissions for CO2 [75,83]. Seven articles quantified carbon storage in wood products or in forest biomass [61,69], four quantified GHG emissions [59,94], two assessed GHG mitigation options [95,96] by either maintaining higher forest stocks or substituting less emission-intensive wood products, and four assessed displacement factors or substitution effects [97,98].

(2) Three other environmental impacts were assessed within the corpus, with one article each. Hydrological changes were studied in Silveira and Alonso (2009) [93], who measured the effects of afforestation on runoff and water loss, and the indicator used was annual streamflow as the primary indicator. Palmer et al. (2013) [87] studied land degradation using nitrate emissions as an indicator of disturbances of afforestation to soil nitrogen cycling and, eventually, soil productivity. Finally, one article assessed biodiversity loss as forest understory biodiversity species richness [85], concluding that afforestation with Pinus radiata trees had a relatively low biodiversity impact due to the minimal use of pesticides and fertilizers.

A total of twenty papers addressed at least one of the impacts above. The remaining papers in the corpus were general studies of the impacts of land-use and land-cover changes such as deforestation [91,92].

3.5. Articles Focusing on Forest Management Practice Changes

In the corpus regarding studies at the intensive margin, twenty-three articles assessed the environmental impacts of increased production on land already used for commercial forestry (i.e., the intensive margin), with most comparing silviculture and forestry practices at varying levels of intensity. Although not directly related to LUCs in the strictest sense (i.e., afforestation, reforestation, or deforestation), these articles consider the environmental impacts resulting from management. Overall, the management practices in these articles can be ranked on a continuum, from less intensive practices that may alter forest composition but do little to change land usage or cover to more intensive practices that profoundly affect forest structure and/or composition, thus closing the gap to being land conversion. The former includes changes in extraction methods or machinery [69] or thinning/felling rates and rotation lengths [97,99]; the latter includes very intensive management practices such as clear cuts [100], particularly if the land is thereafter converted to another use.

On one end of the spectrum, three articles focused on the use of technologies to increase productivity [69,99,101]. For instance, Lindner et al. (2010) [69] compared natural regeneration to replanting. Such technologies did not significantly affect forest structure or composition and thereby constitute minor changes to the land. On the other end of the spectrum, six articles assessed the implications of major changes in a forest's structure or composition [102], including transitions from primary to secondary or plantation forests [68,100], which could be considered a change in land use (depending on the classification of land-use types). In between these extremes, a wealth of articles considered intensification through changes in rotation lengths (nine articles, e.g., [59,68,103]) and changes to the frequency and rate of silvicultural operations such as thinning and harvests (twelve articles, e.g., [69,94]). The impacts of production were measured through multiple indicators of management intensity, often approximated through different forms of product output.

Like the section on the extensive margin, LCAs were again the most widely used EIA method (fifteen articles, e.g., [59,99]). Similarly, global warming impacts were the most commonly assessed impacts (seventeen articles, e.g., [69,100]) with other non-carbon impacts including land degradation (two articles) and water pollution (three articles).

4. Discussion

In this article, an overview of how land-use and land-cover changes are considered in environmental impact assessments of the production of wood and wood products is provided. We performed a literature review, focusing on conceptual aspects, how land-use change was defined in the articles, the impacts assessed, and the methods used to assess them.

4.1. Land-Use Changes in Forestry

A majority of the reviewed articles focused on wood production at the extensive margin (afforestation, deforestation), using a rather classical definition of the LUC concept. However, a sizable share of articles studied changes in forest management practices, emphasizing the environmental consequences of production at the intensive margin. This duality raises questions regarding how to define LUCs in the forestry sector, as gradual changes in practices and forest multifunctionality make distinguishing land-use and land-cover changes particularly challenging. Some studies account for changes at the intensive margin, such as alterations in rotation periods or clear-cutting practices, but do not categorize these as land-use or land-cover changes, often because such activities are frequently followed by forest regrowth [49]. Furthermore, forestry is often characterized by long production periods (i.e., rotations) of 20 up to 200 years, leading to much more gradual and less frequent land-use and land-cover changes compared to other sectors (e.g., agriculture). Finally, forests are often said to be multifunctional. In terms of ecosystem services, forests provide provisioning services (e.g., food, fuels, and fiber), regulating and supporting services (climate change mitigation, soil regulation, water quality, habitat for pollinators), and cultural services (e.g., aesthetic, spiritual, and existence value, recreation, education) [11]. In terms of industry, a single forest generally provides biomass to several industrial firms simultaneously. This issue is further compounded by the fact that some forests are granted protected status, such as national parks or conservation areas, which aim to preserve biodiversity and limit commercial exploitation (though there may exist illegal infractions to official protections). Overall, this makes it challenging to assign a single use or cover type to a given forest, regardless of the classification system.

4.2. Lack of Clarity Between Existing Classifications

Indeed, half of the papers considered forest management practices rather than land-use changes in the strict sense, suggesting a difference in terminology between author groups, with the same concepts but different words. This is particularly apparent in articles that consider a conversion from primary forest to tree plantations or conversions from one forest type to another over the course of several years. The explicit use of the land-use change concept in forestry is further hindered by the fact that many popular classifications approximate land uses for forests through forest types, which are closer to land-cover categories. For instance, the CORINE land-cover classification categorizes forests into broad-leaved, coniferous, and mixed forest types [104]; the System of Integrated Environmental and Economic Accounting (SEEA) land-use classification system distinguishes between natural and planted forests [105]; the Forest Resource Assessment database distinguishes management objectives as "productive forests" and "multiple-use forests", the latter referring to sustainably managed areas (https://fra-data.fao.org/definitions/fra/2020/en/tad#3a (accessed on 22 November 2024)); and the FAO land-cover classification system uses combinations of independent features such as spatial characteristics and tree size (e.g., "high closed forest") [105]. In terms of national policy, some countries (like France (https://fradata.fao.org/assessments/fra/2020/EU/sections/designatedManagementObjective (accessed on 22 November 2024)) categorize all of their forests as "multiple-use", while others do not, leading to inconsistencies. Future research could better develop the concept of land-use and land-cover change specifically for forests, taking into account the characteristics of forests when designing the classification system. Additionally, this could involve considering leakages and displacement effects due to the global nature of wood products [22,23], e.g., additional demand in one region may result in land-use change in other regions, or explicitly distinguishing direct and indirect effects of land-use changes [106].

4.3. Limitations of EIA Methods

Our analysis identified starkly different methods of evaluating the impacts of land-use change at the intensive and extensive margins. In general, quantifying the environmental impacts of wood production at the extensive margin is simpler, since it consists of evaluating changes in surface area [107]. Yet a deeper discussion of EIA methods reveals limitations in their use for wood production analysis, either for their direct application to intensive margin production or their ability to act as standalone methodologies. For instance, the ecological footprint method measures the land area needed to meet society's demand for resources using land-cover data [108], whereas management at the intensive margin focuses on increasing production using the same amount of land. Therefore, it may not be readily applicable for questions of production at the intensive margin. Although life cycle assessment (LCA) methods can evaluate the impacts of forest management practices, often the wide variety and lack of harmonization of existing indicators for intensive production in forests results in insufficient data for the EIA. To the best of our knowledge, to date only one global-scale study has empirically quantified production intensity [109]. Material flow analysis (MFA) primarily quantifies how much material flows in and out of a given system, without necessarily assessing the environmental impacts [110]. Its strength lies in its ability to account for the entire production system, including energy exchanges across each stage of the production process [111]. However, in order to evaluate the environmental impacts associated with outputs, MFA cannot act as a standalone analysis and must be complemented with an LCA [112].

Assessments of the impacts of wood production at the intensive margin through LCAs are more comprehensive and applicable to the extensive margin because many life cycle inventory databases specify intensity changes. For instance, the Ecoinvent database distinguishes between primary and secondary forests and between extensively or intensively managed forests based on differences in extraction rate, stand age, and deadwood diameter [113]. Specifically, extensively managed forests are defined as forests of tree cover >15%, with extractive use and associated disturbances like hunting and selective logging, where timber extraction is followed by regrowth, and including at least three naturally occurring tree species with an average stand age >30 years and deadwood with >10 cm diameter exceeding five times the annual harvest volume. Intensively managed forests are defined as forests of tree cover >15% with extractive use, with either even-aged stands or clear-cut patches exceeding 250 m in length, less than three naturally occurring species at planting/seeding, or (current) average stand age. (Note the subtle distinction between extensively and intensively managed and managing at the intensive and extensive margins, the definitions of which are quite different from those of [14] used in this paper.) Some LCA methods go further, such as ReCipe, which distinguishes between changes in land cover ("land transformation", which implies a conversion from one land use to another) and changes in intensification ("land occupation") and their corresponding environmental impacts [114]. This approach quantifies area and production duration. While this kind of approach could be developed for other EIA methodologies, solutions relying on the existence of databases often suffer from a lack of data [59].

4.4. Indicators of the Management Intensity

Twenty-three studies investigated the environmental impacts of increased production on land already used for commercial forestry, focusing on management at the intensive margin. These studies compared various silvicultural practices, ranging from low-intensity methods like natural regeneration to high-intensity practices such as clear cutting and forest conversion. Some examined technologies to boost productivity with minimal impact on forest structure, while others explored significant changes in forest composition.

Impacts of production at the intensive margin are measured through multiple indicators of management intensity, often approximated in forestry through a measure of product output [109]. There is no consensus in the literature regarding which indicator should be used to approximate forest management intensity, leading to the existence of several indicators. A common approach used in forest inventories is the ratio of harvested timber volume to net annual increment of stand growth (IGN mémento 2023 (https://www.ign.fr/files/default/2023-10/cp_ign_memento_2023.pdf (accessed on 22 November 2024)), which is an indicator of both forest productivity and management sustainability [109]. By comparing stand density and diameter at breast height between managed and unmanaged forests, Luyssaert et al. (2011) [115] created a land-use and disturbance intensity indicator as the difference between potentially available biomass and observed available biomass across different management schemes to assess the degree of human disturbance in forest stands. As a final example, Schall and Ammer (2013) [116] developed the silvicultural management intensity indicator, which assumes that tree species selection reflects management intensity. In other words, more productive species are related to shorter rotations or more intense management. We would recommend that future research focus on the harmonization of EIA indicators between the extensive and intensive margins, with a particular incorporation of forest management intensity indicators into EIAs.

4.5. Environmental Impacts and Carbon Neutrality

Within our corpus, eighteen out of fifty-three articles considered short- and long-term environmental impacts of global warming from land-use or forest management policy changes, primarily through greenhouse gas emissions [93]. We recovered general trends in the overall forestry literature. Afforestation effects (as carbon sinks) are more beneficial for longer assessment periods [81], while in the short term, afforestation can lead to soil carbon losses or NO2 emissions [87,117], especially when carbon-rich lands (e.g., grasslands) are converted to forests [63]. Our review also confirms the negative impacts of deforestation on the carbon sink [82,84], such as that the degradation of residues following wood extraction leads to nitrogen (NO2) emissions in the short term [75,88]. Forest carbon storage rates differ across management intensities: sustainably managed forests or low-intensity harvests increase forest carbon storage compared to high-intensity harvest regimes [68,97]. Moreover, the full impacts depend on the final product in the production chain—short-lived products (bioenergy) are more polluting than long-lived products (construction material).

The remaining thirty-five articles did not consider the short- or long-term environmental impacts of land-use changes, instead operating under an assumption of carbon neutrality. In other words, they considered that harvested areas were immediately offset by tree regrowth, without considering biodiversity loss, time lags, or changes in carbon sequestration rates, potentially leading to an underestimation of environmental impacts. Such assumptions of carbon neutrality are convenient for simplifying analyses but are only satisfied under well-defined conditions [118]. A recent study by Peng et al. (2023) [49] highlighted that many studies report the net effect between harvested wood and regrowth from old harvests, leading them to conclude that wood products are carbon neutral. This approach masks the actual impact of harvesting on the carbon cycle by aggregating it with regrowth that would occur anyway. Additionally, the temporal dimension is often ignored [119]. While wood harvests may tend towards neutrality over long periods due to forest regeneration, this is not always the case in the short term. It depends on future regrowth dynamics (e.g., species chosen.) and the consideration of direct emissions, such as biogenic emissions from decaying residues or emissions from machinery during harvests that may even postpone carbon parity time [120]. Unfortunately, there is no consensus in the general literature on the use of carbon neutrality assumptions.

Relatively few studies considered environmental impacts outside of global warming (hydrological changes, land degradation, and biodiversity loss), nor did we observe studies measuring the short-term impacts of land-use change on soil nitrogen loss or changes in carbon sinks. Interestingly, we found only two articles that explicitly included the impacts of climate change in their analysis. This seems a relevant area of research for future studies, specifically the effects of climate change in forests—such as increased tree mortality, drought conditions and occurrences of storms, or decreasing soil quality—on land-use change decisions. We recommend future research to move beyond persistent simplifications and prioritize exploring the multi-interactions and feedback among the impacts of land-use changes [121,122].

4.6. Limitations of the Literature Search

Like any literature review, our study is limited by the scope of the search keywords. Our terms chosen in the query in the EIA methods block are based on Loiseau et al. (2012) [24], which is quite old. However, to the best of our knowledge, it is the most recent review on this topic. Additionally, it is possible that the combination of Boolean operators could inadvertently exclude potentially relevant papers.

There is a broad range of articles that investigate the environmental consequences of timber production at the intensive margin that did not emerge through our query [123,124]. Such articles often focus on the more technical dimensions of silviculture and forest management and, compared to articles within the economics literature, rarely use keywords related to land-use and land-cover changes. Indeed, if the land-use and land-cover keywords are removed from our query, we obtain over five hundred results. This suggests that the effects of land-use change may be only marginally addressed in the EIAs of the production of wood and wood products and, more importantly, that there is a great need to harmonize and standardize what the concept of land change means in the context of forestry and forest management.

Similarly, many of the prominent names in the field (such as Eric Lambin or A.J. Comber) did not appear among the results and the selected publications. Nor did the corpus include many of the seminal papers in the literature (such as [45], Searchinger et al.'s biofuel emissions paper). The reason for this is that many of these authors (and papers) do not address wood products or conduct environmental impact assessments but rather provide conceptual and more general contributions to different aspects of the field of land-use changes. Therefore, they fall outside the search query for this literature review.

5. Conclusions

In this article, an overview of the consideration of LUCs in EIAs of wood products is provided by performing a systematic literature review and a bibliometric analysis, focusing on conceptual aspects, e.g., the definition of LUCs used in articles, and methodological aspects, e.g., the methods used and impacts assessed.

More than half (n = 30) of the fifty-three reviewed articles focused on wood production at the extensive margin (afforestation, deforestation), using a rather classical definition of the LUC concept. However, a sizable share of articles studied changes in FMPs, emphasizing the environmental consequences of production at the intensive margin. This duality raises questions regarding how to define LUCs in the forest sector, as gradual changes in practices and forest multifunctionality make distinctions between LUCs and intensity changes challenging.

Due to methodological specifications, life cycle assessments were the main method used for environmental impact assessments, especially in articles studying management practices, followed by the ecological footprint approach. The most assessed impacts were those related to global warming potential (greenhouse gases emissions, in particular), with fewer articles focused on hydrological cycles, land degradation, and biodiversity.

While LUCs are increasingly taken into account in the forestry literature, they remain a relatively minor aspect in the environmental analysis of wood products. Obstacles to a better integration of LUCs into EIAs of wood products include multiple definitions of the LUC concept in forestry and distinguishing between land use and land cover in existing classifications. Moreover, many studies are based on the strong assumption of carbon neutrality, which has significant implications for interpreting their results.

Research should focus on harmonizing the different methodologies, clarifying concepts surrounding LUCs specifically for the forestry sector, and developing management intensity indicators. Furthermore, we suggest that future studies should consider evaluating direct emissions arising from LUCs instead of relying on carbon neutrality assumptions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15122242/s1, Table S1: included papers and land use changes, methods and impacts studied; Table S2: excluded papers and exclusion criteria. Refs. [125–167] are cited in Supplementary Materials Tables S1 and S2.

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