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Review

A review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective

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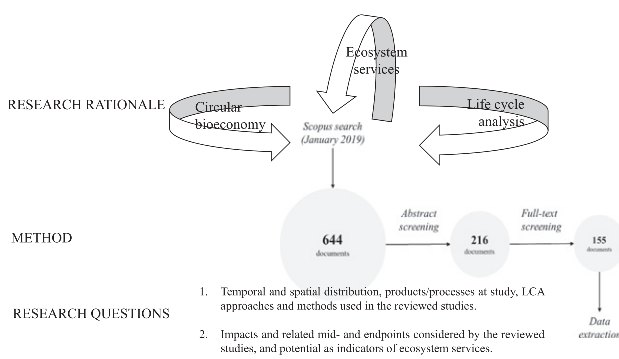
HIGHLIGHTS

- Comprehensive review of 155 empirical studies
- Studies are life cycle analysis (LCA) on bioeconomy products/processes.
- Environmental LCA most used, often assessing low-value biomass uses.
- Climate change assessed in >90% of studies, some ecosystem services unaccounted for.
- Land use considerations in LCA needed for assessing sustainability of bioeconomy.

GRAPHICAL ABSTRACT



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ABSTRACT

The emergence of politically driven bioeconomy strategies worldwide calls for considering the ecological issues associated with bio-based products. Traditionally, life cycle analysis (LCA) approaches are key tools used to assess impacts through product life cycles, but they present limitations regarding the accounting of multiple ecosystem service-related issues, at both the land-use and supply chain levels. Based on a systematic review of empirical articles, this study provides insights on using LCA assessments to account for ecosystem service-related impacts in the context of bioeconomy activities. We address the following research questions: what is the state of the art of the literature performing LCA assessments of forest-based bioeconomy activities, including the temporal distribution, the geographic areas and products/processes at study, and the approaches and methods used? 2. Which impacts and related midpoints are considered by the reviewed studies and what types of ecosystem service- related information do they bear? Out of over 600 articles found through the Scopus search, 155 were deemed relevant for the review. The literature focuses on North-America and Europe. Most of the articles assessed the environmental impact of lower-value biomass uses. Climate change was assessed in over 90% of the studies, while issues related to ozone, eutrophication, human toxicity, resource depletion, acidification, and environmental toxicity were assessed in 40% to 60% of the studies. While the impact categories accounted for in the reviewed LCA studies bear information relevant to certain provisioning and regulating services, several ecosystem services (especially cultural ones) remain unaccounted for. The implications of our study are relevant for professionals working in the ecosystem services, circular bioeconomy, and/or LCA communities.

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Contents

1. Introduction

The bioeconomy is globally promoted to foster economic development while accommodating social and ecological goals. It proposes to replace fossil-based resources with bio-based ones in production-consumption systems (Bennich and Belyazid, 2017; D'Amato et al., 2017). This entails the development and marketization of low- and high-value products and services with diverse requirements for biomass availability, such as energy and fuels, commodity products, construction, textiles, plastics and packaging, chemicals, cosmetics, food additives, and pharmaceuticals (hereinafter referred to as bio-based or bioeconomy products).

Currently, more than forty nations have explicit political bioeconomy strategies set in place, despite national strategies differing depending on the natural resources available, on the economic development level, and on the political and institutional system (Bracco et al., 2018; Dietz et al., 2018; Meyer, 2017). The European bioeconomy strategy has recently been amended to explicitly address the circularity of resource use and ecological sustainability (EC, 2018a, 2018b). In fact, concerns have been raised by the international scientific community about the effective contribution of bioeconomy strategies to sustainability transformations, especially regarding the finite nature of living biomass resources and the need for their sustainable sourcing and use (Eyvindson et al., 2018; Marchetti et al., 2015; Pfau et al., 2014). The nodal problem is that biomass use as a resource for the bioeconomy competes with other potential uses and societal goals (e.g. food production); in addition, land uses aimed at maximizing biomass production may negatively affect the viability of regulating and cultural ecosystem services, such as the maintainance of water and soil proceses, of biodiversity or of recreational opportunities (Lee and Lautenbach, 2016; Stafford-Smith et al., 2017). It is thus of primary importance to identify and account for relevant socio-ecological impacts along the supply chain (Costanza et al., 2017; MA, 2005).

Life cycle assessment (LCA) approaches are internationally standardized tools used to assess impacts in production processes and are thus also suitable for the sustainability assessment of bio-based products (Bjørn et al., 2017; Karvonen et al., 2017). However, land-use considerations – as previously mentioned, particularly important for the bioeconomy – are currently poorly integrated in these approaches, and impacts accounted for along the rest of the chain are represented by a limited number of environmental or social indicators (Alejandre et al., 2019; Rugani et al., 2019).

A review by Weiss et al. (2012) performed a meta-analysis concerning the environmental impacts of bio-based materials to draw comparisons with traditional alternatives, focusing on greenhouse gases (GHG), eutrophication, stratospheric ozone depletion, acidification, and photochemical ozone formation. They suggested that future LCA research should integrate direct and indirect land-use issues, especially biodiversity, deforestation, soil degradation, and related carbon emissions. A recent review on LCA approaches addressing bio-based products processing in Sweden has also highlighted methodological limitations related to sustainability indicators (Martin et al., 2018). The study reported that societally relevant indicators, such as biodiversity loss, water depletion, ecosystem quality, and indirect land-use change, are in fact excluded or poorly integrated in LCA.

Recently, some scholars have suggested that the ecosystem services concept and cascade model can support the inclusion of multidimensional socio-ecological impacts in LCA methods (Alejandre et al., 2019; Bruel et al., 2016; Maia de Souza et al., 2018; Othoniel et al., 2016; Rugani et al., 2019). Maia de Souza et al. (2018) have linked their analysis to the case of biofuels, highlighting challenges and opportunities for ecosystem services assessment. Nonetheless, 'methodological and conceptual issues remain to be addressed' regarding LCA assessments of ecosystem services (Rugani et al., 2019, p. 1289). Moreover, only a handful of studies establish an additional link with the bioeconomy (see Maia de Souza et al., 2018; Martin et al., 2018).

Our study thus addresses two emerging phenomena and related research gaps. First, the need to assess the socio-ecological impacts of bioeconomy activities along the entire supply chain. Second, the current development of LCA approaches striving to overcome limitations concerning to ecosystem service-related information. The overall framing of this study is based on a recent review on sustainability indicators and tools for assessing sustainability impacts of the bioeconomy in the context of the forest sector (Karvonen et al., 2017). The authors listed LCA approaches, inter alia, as an important tool set relevant for the assessment of sustainability issues in the forest bioeconomy. LCA approaches include environmental, economic, and social assessments (respectively, ELCA, LCC, and SLCA) as a 'widely-adopted and standardized method, which uses a functional unit as a reference to measure environmental, economic and social impacts of a product over its full life cycle' (Karvonen et al., 2017, p. 13). Moreover, their statement that 'the concept of the ecosystem services […] can be considered the core of [ecological] sustainability' (Karvonen et al., 2017, p. 3) provides further impetus to our analysis.

Based on a comprehensive review of empirical studies, we use an ecosystem services perspective to analyse the existing evidence from LCA empirical analyses regarding the impacts of various bio-based activities. The focus of the review is on bio-based products and processes from wood, as this represents a major source of biomass in the current bioeconomy (Roos and Stendahl, 2015). In addition to being key primary production systems for raw materials used in the bioeconomy, natural and semi-natural forests are critical for delivering multiple ecosystem services of vital importance to human well-being globally such as water purification and carbon storage.

The research questions are articulated as follows: 1. What is the state of the art of the literature, including the temporal distribution of the literature, the geographic areas and products/processes analysed by the literature, and the approach and methods used? 2. Which impacts and related midpoints are considered by the reviewed studies, and what types of ecosystem service-related information do they bear? Notably, the aim of the review is not to investigate the sustainability performance of bio-based products against traditional alternatives, but rather to provide grounds for discussing the challenges and opportunities for LCA assessment of ecosystem service impacts in the context of bioeconomy activities. Implications are thus relevant for professionals working in the ecosystem services, bioeconomy, and/or LCA communities.

2. Conceptual background

2.1. The bioeconomy

Several definitions of bioeconomy exist, proposed in policy documents or in the scientific literature (Bugge et al., 2016; Hausknost et al., 2017; Meyer, 2017). These definitions are conflicting at times. For the purpose of this review, it is sufficient to adopt the view that the bioeconomy – as a political, industrial, and scientific phenomenon – 'places a renewed emphasis on the value of our biological resources harnessing the technological efficiencies and capabilities of the modern industrial era' (Devaney et al., 2017, p. 41).

Primary production sectors, such as forestry, agriculture, and fisheries, are the backbone of the bioeconomy as biomass providers. In particular, the forest sector is leading the development of this emerging concept in the context of business sustainability (D'Amato et al., 2019a). However, industry boundaries are thinning, with energy and manufacturing industries also involved in the further refinement of various bio-based products (Bugge et al., 2016; Mengal et al., 2018; Meyer, 2017). In fact, bioeconomy strategies pose expectations on knowledge- and technology-based innovation to develop and introduce market products based on non-fossil biomass, ranging from energy, fuels, and commodity products to construction, textiles, plastics and packaging, chemicals, cosmetics, food additives, and pharmaceuticals (Hurmekoski et al., 2018) (Fig. 1).

Lignocellulosic feedstock is generally used for large-scale bioproducts production, including food and non-food crops, residues, and waste. Forests are one of the most important sources of biomass in the bioeconomy sector (Roos and Stendahl, 2015). In the recent discussion concerning bioeconomy, emphasis has been posed on circularity, and the use of forestry residues and waste from industrial processes have also been emphasized (Antikainen et al., 2017; D'Amato et al., 2020; Thorenz et al., 2018).

As a sustainability concept, the bioeconomy is mainly occupied with prescribing which resources should be used in production-consumption

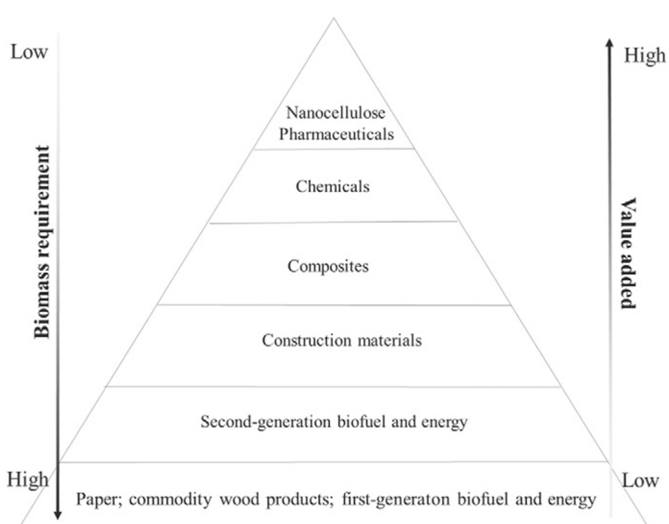

Fig. 1. The bioeconomy pyramid classifying products based on biomass requirements and added value. Modified from Toppinen et al. (2018).

systems. Limitations of this concept are therefore reported in scholarly literature, especially against strong sustainability frameworks (D'Amato et al., 2019b; Liobikiene et al., 2019; Pfau et al., 2014). Consequently, scholars have proposed that the bioeconomy should also draw from elements of the circular economy and address absolute volumes and efficiency of resource use (Bennich and Belyazid, 2017; Loiseau et al., 2016; Velenturf et al., 2019). The term 'circular bioeconomy' has thus emerged (Toppinen et al., 2020). Moreover, recent literature has proposed that the bioeconomy (along with the circular economy) may benefit from a more ample conceptualization of nature, away from a resource-centred vision, by acknowledging impacts and dependencies on multiple ecosystem services (Breure et al., 2018; Marchetti et al., 2015; Székács, 2017). Aspects related to circularity and to ecosystem services awareness are also emphasized in the updated bioeconomy strategy by the European Union (EC, 2018b).

2.2. LCA and ecosystem services

LCA methods have traditionally been employed as environmental management tools to assess environmental impacts of production processes from "cradle to grave". The method was developed in the 1960s in reaction to the 'Limits to Growth' discourse raising concerns about natural resource finiteness. The assessments were initially limited to energy efficiency and emissions as information for internal use by companies. After the 1980s, LCA began to also be used also in academia and at the governmental level; methodological development progressed, also supported by formal attempts towards international standardization (Bjørn et al., 2017). LCA has since become a reference tool for the assessment of sustainability issues in the context of production-consumption systems, obviously bearing both strengths and weaknesses (Curran, 2013).

Within the LCA realm, various approaches are used to gather information useful for the sustainability assessment of products and processes, and thus to inform decision-making (Gundes, 2016). These include life cycle costing (LCC), social LCA (SLCA), and life cycle sustainability assessment (LCSA). The first focuses on economic assessments, the second evaluates social and socioeconomic aspects, and the third aims at a more comprehensive overview of sustainability issues.

Relevant variables to consider when performing or reviewing LCA approaches are the methods used by the assessor (i.e. standardized frameworks such as ReCiPe, CML, TRACI); the system boundary defining the spatial, temporal, and production chain limit of the analysis (e.g. cradle to grave, cradle to gate, gate to gate, cradle to cradle); the functional unit for the data (e.g. kWh of heat, m^3 of roundwood); and the type of mid- and/or endpoints considered, i.e. indicators (e.g. greenhouse gasses emission, eutrophication, human health).

In terms of limitations, LCA approaches do not comprehensively account for several concurrent environmental and ecological aspects (Alejandre et al., 2019; Rugani et al., 2019), which have gained increasing relevance and visibility over past decades such as the worldwide anthropogenic disruption of ecosystems and related services (MA, 2005; Rockstrom et al., 2009).

The ecosystem services idea lays at the foundation of the current conceptualization of socioecological sustainability challenges and has gained great scientific and political momentum (Costanza et al., 2017; Droste et al., 2018). This concept emphasizes the interconnectedness of human society and economy with natural and semi-natural systems and their healthy functioning. Ecosystem services are generally defined as ecological processes, delivered by natural and semi-natural ecosystems, which contribute to human well-being through economic or social benefits (Haines-Young and Potschin, 2010; La Notte et al., 2017; TEEB, 2010). Three macro-categories are generally recognized: provisioning, regulating, and cultural services.[1] Examples of ecosystem

[1] These are underpinned by basic ecological processes called supporting services (e.g. biomass growth, habitat availability) and by biological diversity.

services include the supply of wild and crop foods and clean water (provisioning); the regulation of local and global climate, the regulation of water and biogeochemical cycles, pollination and control of pests (regulating); the enablement of recreational opportunities, and aesthetic or spiritual experiences (cultural).

Various classification systems have been proposed for ecosystem services (e.g. Landers and Nahlik, 2013; MA, 2005; TEEB, 2010) to serve different research purposes (Potschin-Young et al., 2016; Wallace, 2007). This article refers to the Common International Classification of Ecosystem Services (CICES), which is a continuously updated European-driven initiative. The classification is hierarchically organized like a taxonomy, including five levels, each representing more specific and detailed information then the previous level: section, division, group, class, and type.

Despite attempts to systematize the understanding of ecosystem services, it is important to note that they are not universally determined, but depend on the geographical, historical, ecological, and socioeconomic context, and are ultimately defined by stakeholders such as the observer or beneficiary(ies). Ecosystem services are also characterized by non-linear spatial and temporal ecological dynamics; they are interlinked to the extent that pairs or bundles of ecosystem services can be mutually exclusive or reinforcing (trade-offs or synergies) (Davies et al., 2015; Kremen, 2005; Smith et al., 2017). For example, the maximization of provisioning services through intensive land uses (e.g. wood fibre from plantation forestry) under a resource-oriented bioeconomy strategy would impose trade-offs on regulating services related to water and soil cycles (Lee and Lautenbach, 2016; Malkamäki et al., 2018; Smith et al., 2017). While attempting to mitigate trade-offs, ecosystem management and governance must agree upon the delivery of certain ecosystem services in favour of others, and such decisions also affect various beneficiary groups.

On the one hand, the prosperity and viability of economic sectors, industries, and processes require and rely on ecosystem services: for example, several land-use -intensive sectors demand water and materials for the production of goods and rely on the maintenance of atmospheric, water, and soil quality to avoid disruptions in their operations. On the other hand, economic activities cause impacts on ecosystems and on their ability to deliver the services they rely on, along with services beneficial to other societal actors (e.g. D'Amato et al., 2018; TEEB, 2012; Winn and Pogutz, 2013). Relevant impacts to ecosystem services do not exclusively occur at the land-use level. Industrial processes also affect on ecosystem services, for example through water abstraction, and air and water emissions.

The complex interplay between ecosystems and human well-being reinforces the need to understand conceptual and technical limitations for assessing ecosystem services (e.g. Guerry et al., 2015; Müller and Burkhard, 2012) and for integrating them in LCA (e.g. Bruel et al., 2016; Maia de Souza et al., 2018; Weiss et al., 2012).

3. Methods

This work comprises a systematic literature review of empirical studies performing LCA approaches on forest- and/or wood-based products and processes. The review was based on the process described by Khan et al. (2003) to conduct a systematic review, which includes defining review questions, identifying relevant work, selecting criteria, synthetizing the evidence, and interpreting the findings.

A literature search of English language publications was conducted in January 2019 using Scopus. The search string was iteratively tested and refined so that it would be both synthetic and comprehensive (Livoreil et al., 2017).

The final search string was as follows: TITLE-ABS-KEY("life cycle" OR "LCA" OR "SLCA" OR "S-LCA" OR "LCC" OR "ELCA" OR "E-LCA" OR "LCSA" AND "bio*" AND "forest" OR "wood*" AND "*fuel*" OR "*diesel*" OR "*gas" OR "*ethanol" OR "*plastic*" OR "wood-plastic*" OR "*composite*" OR "*packaging" OR "*film*" OR "*chemical*" OR "lactic acid" OR "furfural" OR "*ethylene" OR "building*" OR "construction" OR "fertilizer*" OR "heating" OR "pellet*" OR "chip*" OR "textile*" OR "cup*" OR "coating*").

The search string included the three LCA approaches identified by Karvonen et al. (2017) as tools for sustainability assessments in the context of the bioeconomy, relevant keywords already used in a review on LCA and sustainability indicators in the Swedish forestry bioeconomy (Martin et al., 2018), along with a series of wood-based bioeconomy products considered potential for commercialization by Hurmekoski et al. (2018) in four major forest industry countries, i.e. Finland, Sweden, USA, and Canada.

As the bioeconomy is a recent phenomenon that is increasingly addressed in scientific literature after 2015 (D'Amato et al., 2017), we decided to limit the search to 2016–2019. This resulted in 644 documents (Fig. 3), which were further screened based on the documents' title, authors, and abstract. The screening process was aided by the web-based software Abstrackr (Wallace et al., 2012). To be suitable for inclusion in the review, the documents had to: 1. be a scientific article written in English (books, book chapters, and conference proceedings were excluded), 2. use LCA approaches directly and in an empirical way (e.g. literature reviews on LCA were rejected), and 3. analyse bio-based products or processes with biomass from forest- and/or wood-based products. The 216 articles meeting the inclusion criteria were further admitted to full-text screening. During this process, additional documents were rejected because they ultimately did not comply with the inclusion criteria, or because the authors' institution had no access to the full text. The final sample of articles included 155 documents.

The articles suitable for the review ($N = 155$) were read thoroughly, and the following data were extracted: type of product or process at study; geographical location of the study; type of approach (e.g. LCA, LCC, SLCA) and method used for the analysis (e.g. ReCiPe); system boundaries and functional unit; type of midpoints or/and endpoints considered.

The data were analysed using descriptive statistics. The analysis was performed in an abductive and iterative manner, meaning that both the theory and the data informed the final results, specifically regarding the aggregation of data and formulation of groupings/categories. In other words, we used categorizations provided by previous literature to inform our analysis, and we modified them to better fit the data. When grouping bioeconomy products for the analysis, we referred to the bioeconomy pyramid (Toppinen et al., 2018, Fig. 1). For categorizing LCA approaches, methods, and midpoints, we referred to Karvonen et al. (2017) and Klöpffer and Grahl (2014). Finally, to identify the relation between midpoint/endpoint categories and ecosystem services, we referred to the ecosystem services classification by CICES (Haines-Young and Potschin, 2018, Fig. 2). The data file is available as additional material with this article.

This review has the following limitations. The search was performed by using only one search engine (Scopus): i.e. the review is thus extensive, but not systematically performed. The records found are dependent on the search string used: we attempted to be as comprehensive as possible, but we do not know whether relevant articles may have been excluded from the search. Data extraction and analysis were challenging due to the high level of diversity in the scope, methods, and indicators adopted by the reviewed studies. The synthesis of over a hundred studies necessarily implies some loss of information. Finally, because this is a review of empirical studies, the analysis of links between LCA impact categories and ecosystem services is limited to what has been done in the field so far. The analysis of such links could be more comprehensive if performed as a conceptual work (e.g. Alejandre et al., 2019; Rugani et al., 2019), but it would then fail to address our objective of assessing the state of the art.

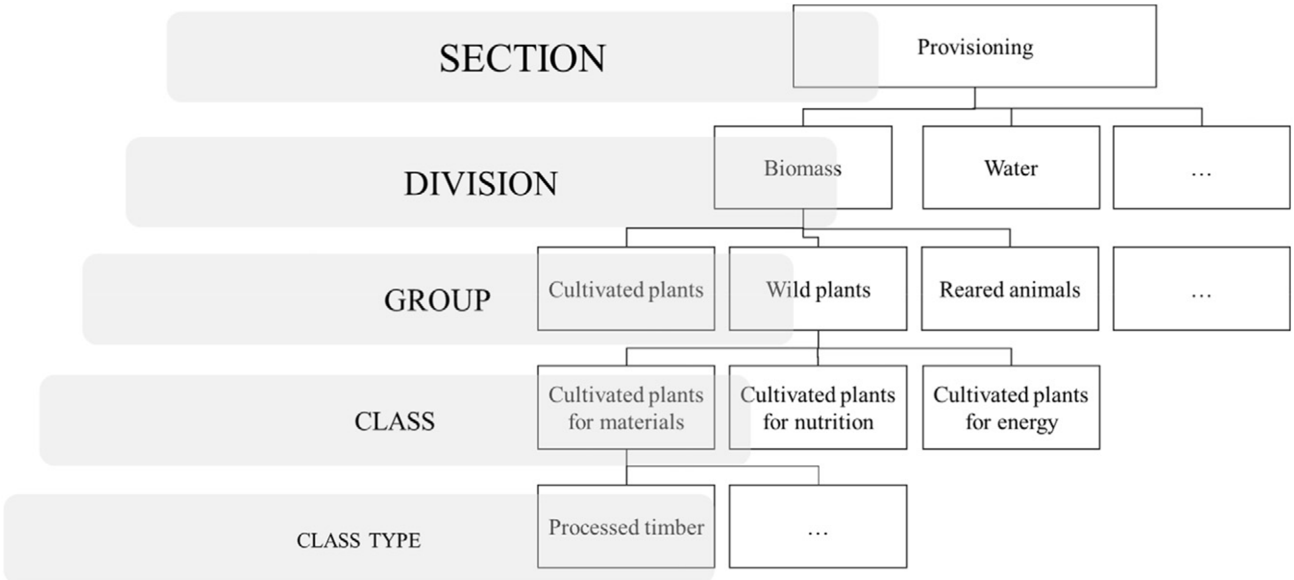

Fig. 2. The hierarchical structure of the Common International Classification of Ecosystem Services (CICES).

4. Results

The 155 scientific articles included in the review were evenly distributed between 2016 and 2018 (ca. 50 per year), with <10 articles found in 2019 (note that the search was performed in January 2019). Studies were found from all continents (Fig. 4), but one-third regarded North America (USA = 33; Canada 18). European countries, such as Italy, Sweden, Germany, and Finland, were investigated with more than five studies each.

Bioenergy was investigated in 35.5% of the studies and included both power and/or heat generation (29 articles) and second-generation biofuels (26 articles). *Feedstock* accounted for 20.6% of the articles, and regarded the production, harvesting, transportation, and processing of wood materials. This includes e.g. pellet or chip production for energy use, wood plantation for producing both energy and construction materials, harvesting operations and effects on biodiversity. *Industrial processes* were discussed in 16% of the articles focusing on, among others, the pre-treatment of biomass, along with its refinement, torrefaction, pyrolysis, gasification, and hydrothermal liquefaction; and enzyme and catalyst production, wood treatment, and optimization in a coupled heat and power plant. Another 16% of the articles dealt with *biomaterials*, such as construction materials; composites (woody-plastic composites, wood-based furniture, and polylactic composite with bio-based fillers); bioplastics (bio-based polyethylene terephthalate (PET) bottles, formaldehyde-free pine tannin foams from bark, bio-based polyethylene and polypropylene, phenolic resin); treatment application; and management. *Biochemicals* were investigated by 5% of the articles and included biobutanol, isobutanol, hydrogen, oxymethylene ether, acetonitrile, adipic acid, lignin, and aromatic-rich hydrocarbons. *Management, planning, and policy* evaluations were mentioned in 5% of

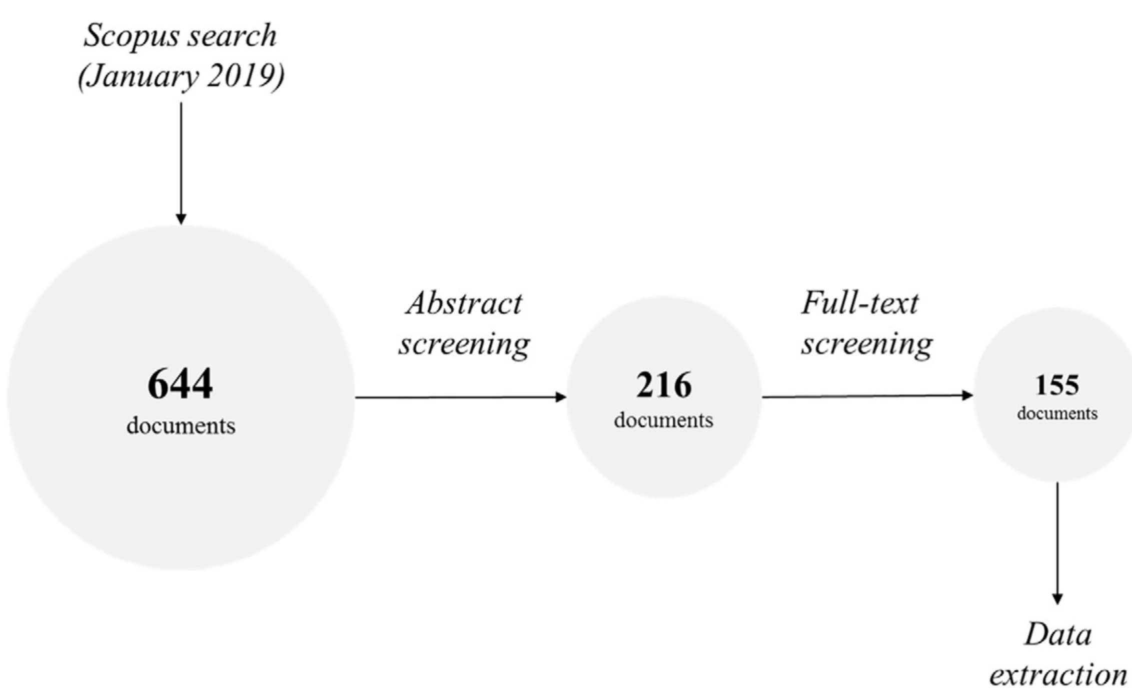

Fig. 3. Process of sample selection for the literature review.

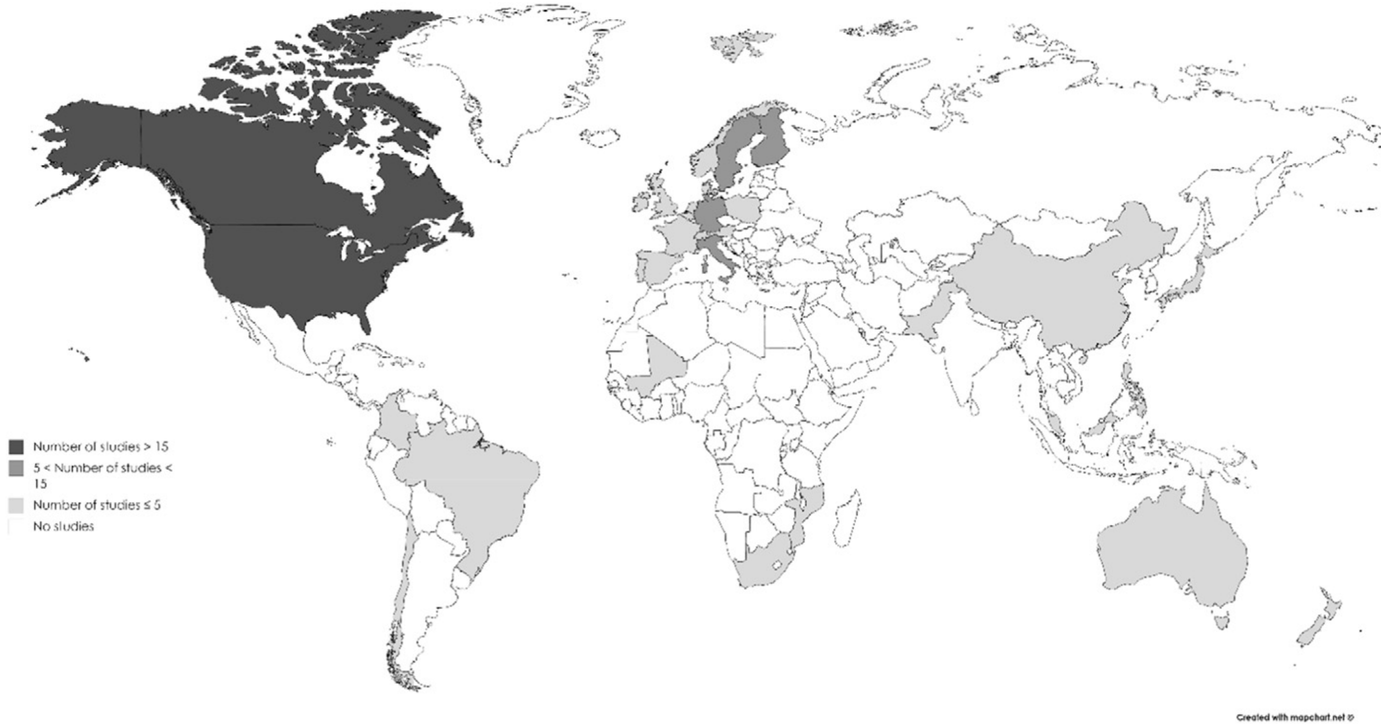

Fig. 4. Geographical distribution of the reviewed studies. Note that the location represents the area where the study was conducted (not the authors' affiliation).

the studies. Finally, 0.6% of the articles dealt respectively with *nanofibre cellulose* production and with *papermaking* from forest residues (Fig. 5).

The vast majority of the studies used environmental life cycle assessment analyses (86%), while 10% used mixed methods: three studies used LCC, one applied LCSA, and three employed other methods. Various system boundaries were used, most commonly the cradle to gate (almost 47.7%), cradle to grave (34%), and gate to gate (8%) approaches. Certain studies (4.5%) defined no system boundary (mainly those focusing on *Management, planning, and policy* evaluations). Various impact assessment methods were used in the reviewed studies, and each method assessed mid- and/or endpoints. Approximately 17% of the reviewed studies used ReCiPe, which allows calculating both mid- and endpoints. Approximately 15% of the studies did not specify the method. CML was used in 13% of the studies. The TRACI method was used in ca. 10% of the studies, while the authors specifically developed the methods used in 7% of the studies. The remaining studies (ca. 40%) used other LCA mid- or endpoint methods, or a mix of them.

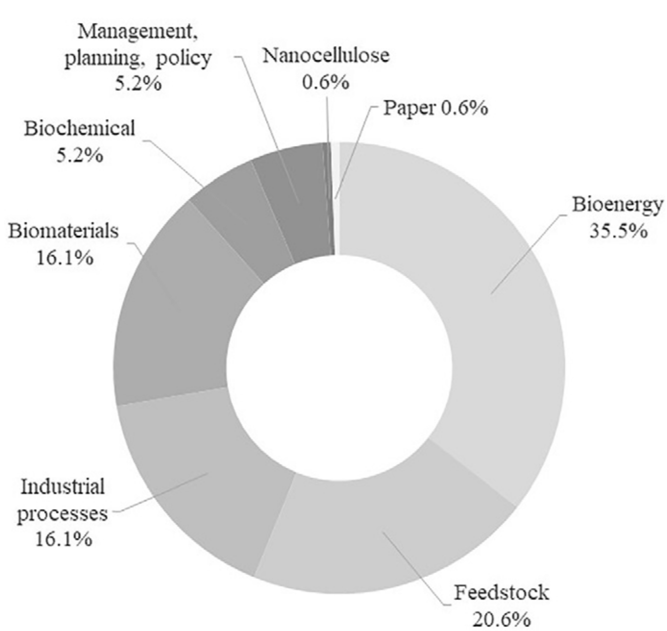

Fig. 5. Wood-based products or processes considered in the reviewed studies.

Each of the reviewed articles was based on the analysis of various mid- and/or endpoints. We grouped them based on their similarity into the following macro-categories: climate change, ozone, eutrophication, human toxicity, resource depletion, acidification, environmental toxicity, particulate matter, land, energy, smog, radiation, materials consumption, human health, ecosystem, and waste. Note that, as only a few studies used methods other than ELCA, we only consider ELCA indicators in the analysis of midpoint macro-categories and their relation to ecosystem services.

'Climate change' occurred in 93.5% of the studies, and global warming potential (Kg CO_2 eq.) and greenhouse gas emission (Kg CO_2 eq.) were the main considered midpoints. 'Ozone' was found in 60.6% of the studies, mainly expressed as ozone depletion (Kg CFC_{11}eq.) and photochemical oxidant formation (Kg VOC). 'Eutrophication' was used in 53.55% of the studies, with midpoints such as freshwater and marine eutrophication (Kg P eq.; Kg N-eq.).

'Human toxicity' was found in 54.2% of the studies and the main midpoints considered were human toxicity (Kg 1,4-dichlorobenzene eq.) and respiratory effect (Kg PM2.5 eq). 'Resource depletion' was calculated in 49% of the studies, mainly as fossil depletion (Kg Oil-eq.), depletion of fossil resources (MJ), and water depletion (m^3). 'Acidification' was present in 46.5% of the studies, mainly as acidification (general meaning) in Kg SO_2 eq., followed by terrestrial acidification (Kg SO_2 eq.).

'Environmental toxicity' was included in 43.23% of the studies, with the main focus on freshwater aquatic ecotoxicity (kg 1,4-dichlorobenzene eq.) followed by marine aquatic ecotoxicity (kg 1,4-dichlorobenzene eq.) and terrestrial ecotoxicity potential (Kg DCB eq). All other categories were present in <20% of the studies, specifically: 'particulate matter' (14.84%) focusing more on particulate matter formation (Kg PM10 eq.) and 'land' (14.84%) focusing on both agricultural and urban land as m^2*years (Fig. 6).

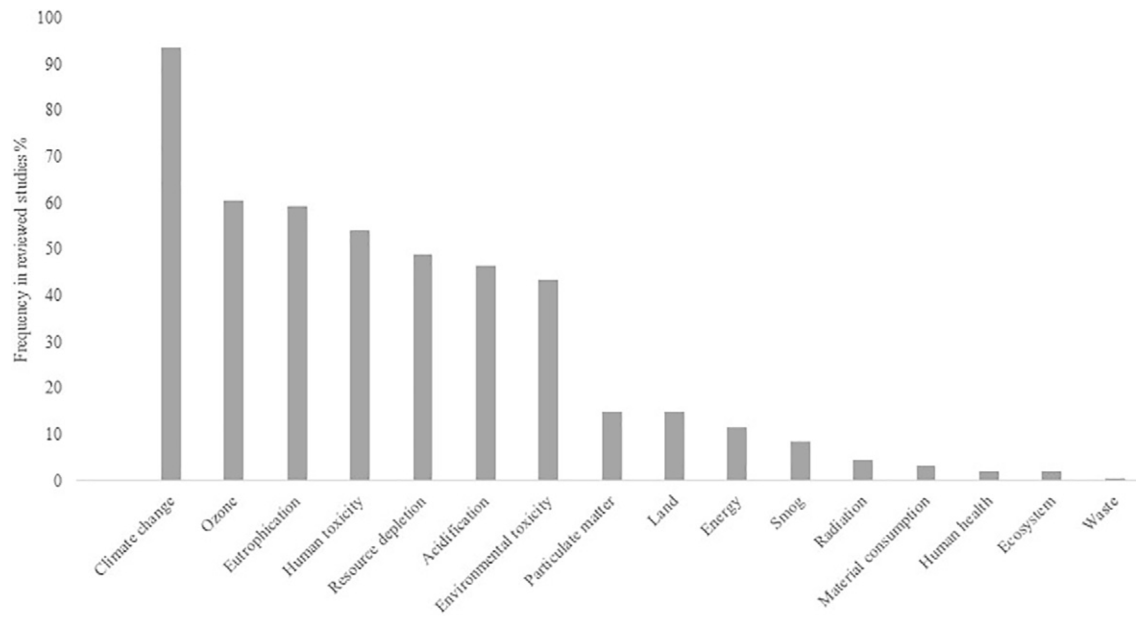

Fig. 6. Frequency of the individual impact categories analysed in the reviewed studies.

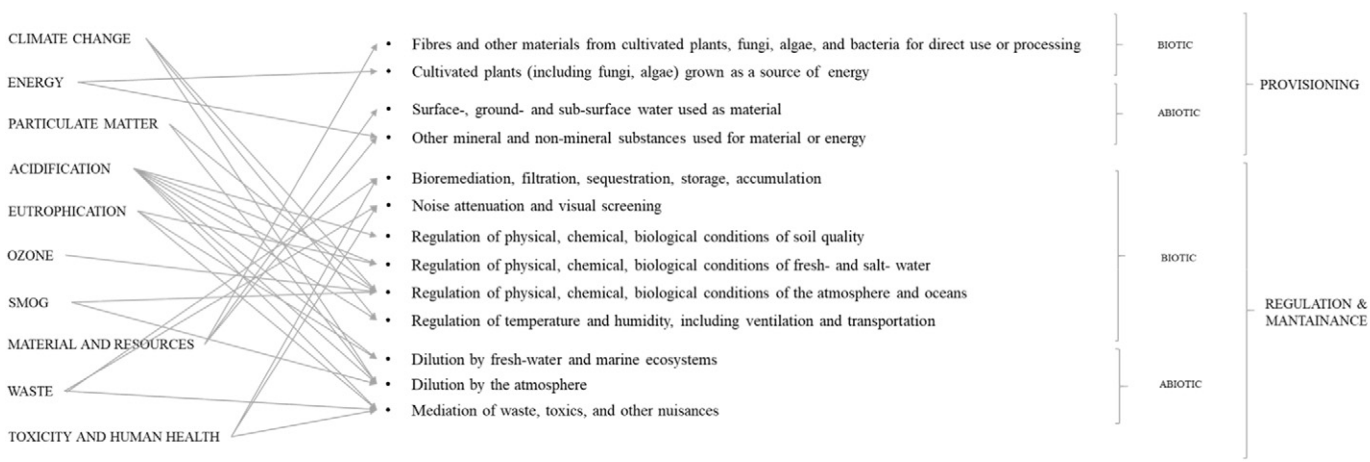

Fig. 7. Representation of LCA impact categories and their relations to ecosystem services.

The identified macro-categories were then linked to ecosystem services, with reference to the CICES classification. Note that, to aid the analysis, the macro-categories 'resource depletion' and 'material consumption' were coupled together as 'materials and resources'; similarly, the macro categories of 'human toxicity', 'environmental toxicity', and 'human health' were grouped into 'toxicity and human health'. The macro-categories were found to be relevant for a few classes of provisioning and/or regulating services, while no direct connection could be established with cultural services (see footnote[2] and Appendix). Each macro-category relates to multiple ecosystem services, stemming from biotic and abiotic elements (Fig. 7) (Table 1).

In this analysis, macro-categories and related midpoints are to be interpreted as potential, yet not exhaustive, indicators for a selected number of ecosystem services. In particular, an individual or a group of midpoints (aggregated as macro-categories) convey information about dependencies and/or impacts of economic activities on a specific ecosystem service. As mentioned in Section 2.2, economic activities, including those related to the bioeconomy, simultaneously depend on and impact ecosystem services. For example, the current bioeconomy strongly depends on biomass production from forestry and agriculture; however, overharvesting or overly intensive land management impacts the ability of these systems to continue delivering that ecosystem service along with others. Similarly, above a certain concentration threshold of anthropogenic-originated nutrients, there is a shift in the ability of ecosystems to continue delivering certain ecosystem services relevant to economic activities and beneficial to other societal groups, e.g. the provision of clean water or recreational opportunities.

Therefore, the macro-categories 'energy' and 'material and resources' can be interpreted as indicators of the dependencies of economic activities on provisioning services and as indicators of stressors produced by such activities. In the reviewed articles, energy sources needed for harvesting and industrial processes were derived from both renewable and non-renewable feedstock, including abiotic sources (biomass, fossil fuels, or other energy forms). For this reason, we linked the 'energy' macro-category to the ecosystem services 'cultivated plant (including fungi, algae) grown as a source of energy' and 'other mineral or non-mineral substances or ecosystem properties used for nutrition, material, or energy'.

[2] The CICES classes identified were: 1.1.1.2; 1.1.1.3; 2.1.1.1; 2.1.1.2; 2.1.2.2; 2.1.2.3; 2.2.4.1; 2.2.4.2; 2.2.5.1; 2.2.5.2; 2.2.6.1; 2.2.6.2; 4.2.1.2; 4.2.2.2; 4.3.1.2; 4.3.2.6; 5.1.1.1; 5.1.1.2; 5.1.1.3; 5.1.2.1.

Table 1
Representation of LCA impact categories and their relationships with ecosystem services, including CICES codes.

Midpoint macro-category	Relevant ecosystem service	CICES code (v.5)
Climate change	Regulation of chemical composition of atmosphere and oceans by organisms; Regulation of temperature and humidity, including ventilation and transpiration, by organisms; Dilution by atmosphere.	2.2.6.1; 2.2.6.2; 5.1.1.2
Radiation	na	na
Energy	Cultivated plants (including fungi, algae) grown as a source of energy; Other mineral or non-mineral substances or ecosystem properties used for nutrition, materials or energy.	1.1.1.3; 2.2.6.2; 4.3.2.6
Particulate matter	Regulation of chemical composition of atmosphere and oceans by organisms; Dilution by the atmosphere.	2.2.6.1; 5.1.1.2
Acidification (aquatic, terrestrial, atmospheric)	Regulation of physical, chemical, and biological conditions in the soil, water, and atmosphere by organisms; Dilution and mediation of waste, toxics, and other nuisances by non-living processes in the soil, water, and atmosphere.	2.; 2.2.4.2; 2.2.5.1; 2.2.5.2; 2.2.6.1; 5.1.1.1; 5.1.1.2; 5.1.1.3
Eutrophication	Regulation of the chemical condition of fresh- and saltwaters by organisms; Dilution and mediation of waste, toxics, and other nuisances by non-living processes in the water.	2.2.5.1; 2.2.5.2; 5.1.1.1; 5.1.1.3
Ozone	Regulation of chemical composition of atmosphere and oceans by organisms.	2.2.6.1
Smog	Regulation of chemical composition of atmosphere and oceans by organisms; Dilution by the atmosphere.	2.2.6.1; 5.1.1.2
Material and resources	Fibres and other materials from cultivated plants, fungi, algae, and bacteria for direct use or processing and as a source of energy; Surface- and groundwater used as a material (non-drinking purposes); Mineral substances used for material purposes; Other mineral or non-mineral substances or ecosystem properties used for nutrition, materials, or energy.	1.1.1.2; 1.1.1.3; 4.2.1.2; 4.2.2.2; 4.3.1.2; 4.3.2.6
Waste	Mediation of wastes or toxic substances of anthropogenic origin by organisms and by non-living processes.	2.1.1.1; 2.1.1.2; 2.1.2.2; 2.1.2.3; 5.1.1.1; 5.1.1.2; 5.1.1.3; 5.1.2.1
Toxicity and human health	Mediation of wastes or toxic substances of anthropogenic origin by organisms and by non-living processes.	2.1.1.1; 2.1.1.2; 2.1.2.2; 2.1.2.3; 5.1.1.1; 5.1.1.2; 5.1.1.3; 5.1.2.1
Land	na	na
Ecosystem	na	na

On the other hand, other macro-categories convey information about the dependencies and impacts of biotic and abiotic origin on regulating services. This means that such indicators capture two aspects: the dependency of economic activities on the buffer capacity of ecosystems and the stressors exercised by such activities that affect buffer capacity. For example, the 'climate change' macro-category relates to ecosystem services such as 'regulation of chemical composition of atmosphere and ocean'; 'dilution by atmosphere'; and 'regulation of temperature and humidity, including ventilation and transportation'. 'Acidification' links to the following ecosystem services: 'regulation of physical, chemical, biological conditions in the soil, water, and atmosphere by biotic organisms'; 'dilution and mediation of waste, toxics, and other nuisances by non-living processes in the soil, water, and atmosphere'.

In our analysis, no ecosystem service was identified as relevant for the 'radiation' macro-category, and certain macro-categories, such as 'ecosystem' and 'land', were too generic to be connected to specific ecosystem services. It is noteworthy that impacts and dependencies are two faces of the same coin, because impacts exercised on ecosystems through anthropic activities also affect the possibility of relying on ecosystem services to guarantee the viability and continuity of such activities.

5. Discussion

The reviewed literature focuses on North America and Europe. This finding can be interpreted in light of the historical use and development of LCA approaches (Bjørn et al., 2017), along with the recent relevance of bioeconomy policies in those regions (Dietz et al., 2018). In general, bioeconomy research is strongly present in North America and Europe (D'Amato et al., 2017).

After initially screening over 600 articles, we found a consistent number of relevant studies for our review ($N = 155$), especially considering the rigid limits imposed during the database search: the scope of the review was, in fact, restricted to empirical studies published from 2016 to 2019; in addition, only studies dealing with forest and/or wood-based activities were considered (note that other origins of feedstock are common in the bioeconomy).

Nearly all of the studies used environmental LCA. This result was expected, as other approaches, such as LCC and SLCA, are less commonly used due to less capacity availability (methods, data) (Jacquemin et al., 2012; Weiss et al., 2012). About half of the reviewed articles focused on a cradle to gate approach as their chosen system boundary, thus highlighting a main interest in assessing the environmental impacts related to the upstream and core production of forest-based bioeconomy products, rather than those related to their use and disposal. Although this obviously depends on the study scope (e.g. to guide a company in improving its production process rather than to demonstrate the sustainability along the entire life cycle for obtaining an ecolabel), it is often due to lack of reliable data for modelling downstream processes (Sierra-Pérez et al., 2016).

A large part of the studies (35%) dealt with bioenergy (power, heat, second-generation biofuel), which represents a low-value biomass use (see Fig. 1 and Toppinen et al., 2018). Twenty per cent of the studies focused on general feedstock production, harvesting, transportation, and processing. Feedstock impacts are obviously a key issue for guaranteeing the sustainability of the entire supply chain. Higher biomass uses studied were for example biomaterials (e.g. construction, furniture, hybrid composites, fillers, bioplastics, foams) (16%) and biochemical (5%). The lesser extent to which these activities are assessed by LCA was expected considering their only emergent market presence (Toppinen et al., 2020).

The macro-categories most often assessed by the reviewed studies were climate change, ozone, eutrophication, human toxicity, resource depletion, acidification, and environmental toxicity. In comparison, a review of Swedish LCA studies of forest bio-based value chains found climate, energy, and acidification to be the most common impact categories when assessing energy, construction, and commodity goods (e.g. bio-based plastics, cups, and fertilizers) (Martin et al., 2018[3]).

We linked the macro-categories identified in the reviewed studies to ecosystem services, with reference to the CICES classification. Links could be established to a small number of provisioning and/or regulating services (approximately 20% of the total CICES classes); however,

[3] Note, their search strategy for gathering the scientific literature was quite different, which is likely to account for a large part of the differences in the results.

none of the impact categories related to cultural services. It is important to keep in mind that our study offers an overview of which ecosystem services are currently accounted for by LCA studies related to bioeconomy activities; however, impacts related to other affected ecosystem services may occur without being represented. In other words, there is a discrepancy between the current state of ecosystem services accounting in LCA approaches and their relevance at the global or local scales (similarly, Martin et al., 2018 observed a dissonance between sustainability issues considered urgent and relative LCA coverage).

Recent works have been advancing potential avenues towards a more inclusive LCA assessment of multiple ecosystem services. For example, Othoniel et al. (2019) proposes a new method for assessing the impacts of land use on ecosystem services in LCA. Rugani et al. (2019) established a connection between the life cycle inventory flow and the CICES classification. They suggested examples of potential mid- and endpoints for better representing ecosystem services (e.g. for provisioning services: productivity adjusted hectare-years; for regulating services: landslide, impact on plant growth, soil loss). Alejandre et al. (2019) performed a gap analysis, highlighting the ecosystem services (CICES categories) currently covered or missing in ReCiPe2016. They show that five midpoint impact categories are linked to issues such as climate change, ozone depletion, water use, mineral resource scarcity, and fossil resource scarcity; and they indicate improvement areas for an optimal coverage of ecosystem service issues in LCA, based on indicators proposed in scientific literature.

6. Conclusions

The emerging bioeconomy idea proposes to shift the global production and consumption from fossil to biomass-based resources; this is operationalized through regional/national strategies that need to secure biomass availability, among other conditions. Bioeconomy activities simultaneously depend on and impact ecosystems and related services. For example, trade-offs with multiple regulating and cultural ecosystem services are an inevitable consequence of land uses that maximize biomass production. Industrial processes also affect ecosystems, for example through emissions. In this context, LCA approaches hold potential for assessing impacts and dependencies of bioeconomy activities on ecosystem services. However, these three areas of research remain largely siloed in scientific literature.

This review included 155 empirical studies that used LCA approaches to evaluate the impacts of forest-based bioeconomy products or processes. The findings outline the state of the art, in terms of the temporal distribution, the geographic areas and products/processes being studied, and the approaches, methods, and midpoints used in the studies.

The reviewed literature largely focused on assessing the impact of lower-value biomass uses. The vast majority of the documents assessed environmental impacts, and thus ELCA approaches were most commonly used. The most frequent issues assessed were related to climate change, reported in over 90% of the studies, while ozone, eutrophication, human toxicity, resource depletion, acidification, and environmental toxicity were assessed in 40% to 60% of the studies. Other categories (particulate matter, land, energy, smog, radiation, material consumption, human health, ecosystem, and waste) were reported in <20% of the studies.

We then articulated the link between the macro-categories found in LCA and ecosystem services; we suggest that LCA midpoints (individually or as macro-categories) could be interpreted as indicators of the impacts and dependencies of bioeconomy activities on natural systems. In particular, we found that only ca. 20% of ecosystem services (calculated as CICES classes) are accounted for in the reviewed LCA studies: specifically, these only include certain provisioning and regulating services, while cultural services are excluded.

In conclusion, this study is embedded in a three-fold perspective and thus offers insights to three communities of professionals working in the sustainability context: LCA, (circular) bioeconomy, and ecosystem services. The overall contribution of the study includes a conceptual basis that connects the three scholarly areas (Section 1 and 2). Furthermore, the findings from the review (Section 4) shed some light on the empirical use of LCA approaches in the context of bioeconomy products and processes, with a specific focus on ecosystem services considerations.

The current political effort to transition towards a bioeconomy at the global level requires determining the sustainability performance of bioeconomy activities (also in comparison to fossil alternatives). However, accounting for the conceptual and technical limitations of such assessments is key to contextualizing the results. Future theoretical and empirical research tackling remaining gaps is important for informing decision-making towards sustainability in the context of production-consumption systems. Despite the emerging interest in the topic, additional work is needed for tackling the integration of ecosystem service issues in LCA approaches.

The strengthening and deepening of other cross-disciplinary areas is strongly encouraged. Considering that the European bioeconomy places an important focus on high-value products, the lack of relevant LCA studies, while expected, represents an area of potential development. Moreover, the intersection of LCA and bioeconomy could further shed light on circularity issues, also a priority in national policies at European level (i.e. circular bioeconomy). Finally, the link between bioeconomy and ecosystem services remains an under-represented area of research, including understanding the impacts and dependencies of diverse bioeconomy activities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.135859.

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