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Review

Ecosystem services and life cycle assessment: A bibliometric review

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ABSTRACT

This paper uses bibliometric mapping and network analysis to review decades of research on ecosystem services and life cycle assessment (LCA). The study reveals how these two academic fields evolved to become distinct fields with little interaction despite shared environmental sustainability objectives. In assessing more than 56,000 publications, we identified just 91 LCA studies that integrate biotic ecosystem services in a meaningful way. We further classified these papers based on an ecosystem service standardization system – the Common International Classification for Ecosystem Services (CICES) – and the use of LCA midpoints and endpoints. LCA research has focused on a relatively small number of regulation and maintenance ecosystem services (especially carbon balance), with far less emphasis on provisioning services. Research on cultural services is especially scarce. Land use is a particularly promising area for integrative ecosystem services–LCA research but will require more sophisticated accounting of geographic and temporal variation, as well as the dynamic exchanges of flows between regions. We conclude by illustrating how Geographic Information Science (GIScience) can help address these challenges, enabling much deeper and wider integration of ecosystem service accounting in the LCA field.

1. Introduction

Ecosystem services (ES) have emerged as a primary means to account for the functions provided by nature. Humans directly and indirectly depend on ES for a range of benefits, from basic materials to climate regulation to the psychological benefits of spending time in nature. The Millennium Ecosystem Assessment (2005) famously divided these services into four overarching buckets: Provisioning, Regulating, Cultural, and Supporting. The *Assessmen*t introduced a novel framework for understanding the effect of environmental change on ES and human well-being. It has since been widely used by scientists and policy makers as they structure approaches to research, conservation, and development (Carpenter et al., 2009; Daily and Matson, 2008). Although identifying, classifying, accounting for, and valuing ES is not without controversy, it has emerged as an influential approach to internalize external environmental costs and estimate the value of nature's services for society (Costanza et al., 1997; Daily, 1997; Daily et al., 2000; Daly and Farley, 2010; McCauley, 2006). Codified ES classification systems, such as the Common International Classification for Ecosystem Services (CICES) (Haines-Young and Potschin, 2010) enable users to systematically catalog and account for ES. However, despite increased recognition of ES as key components of socioecological systems and the advances of classification techniques like CICES, ES protection is yet plagued by inconsistent approaches to modeling, assessment, and valuation (Costanza et al., 2017). Liu et al. (2018) suggest the CICES ES classification scheme could fulfill a critical role in the development of consistent LCA approaches to quantifying ES supply and demand.

Life cycle assessment (LCA) has become a central instrument in environmental management. It proffers an internationally standardized approach to modeling, assessing, and valuing the impacts of a product or process throughout its life cycle. LCA aims to assess impacts on ecosystems, natural resources, and human health, as three primary areas of protection. It accounts for the impacts of production systems on nature's ecosystems through the life cycle stages, beginning with resource extraction in forests, wetlands, oceans, and other biomes, and extending through end-of-life disposal (Antón et al., 2016; Hauschild et al., 2018). However, LCA does not fully acknowledge impacts on the supply of ES. Assessing the impacts of production systems on ES supply is a new – and contested – paradigm of the latest years (Alejandre et al., 2019; Bakshi et al., 2018; de Souza et al., 2018; Othoniel et al., 2016; Rugani et al., 2019; Zhang et al., 2010a, Zhang et al., 2010b). It must confront clear challenges including information availability and the definition of appropriate aggregate indicators (Zhang et al., 2010b). A cursory review indicates wide variation in the overall aims, underlying assumptions, level of detail, and accounting methods scholars are using as they attempt to account for ES in LCA. We also find that a comprehensive

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characterization and quantification of which ES are being considered by LCA scholars is missing from the literature.

The purpose of this paper is twofold: to characterize the nature and extent of interaction between the ES and LCA scholarly communities and to quantify the breadth and depth of biotic ES topics scholars in the nexus have covered. We use bibliometric techniques to reveal the most cited papers and the co-citation patterns between them in order to draw a general picture of ES and LCA fields and to determine the articles that bridge them. Along these lines, we assess and document the evolution (and importance) of particular disciplines, thought traditions, and ideas over time. We then identify key publications situated at the ES-LCA research intersection and systematically explore and inventory their content. With this research we address four questions:

1) To what extent are researchers in ES and LCA fields interacting and on what intellectual basis?
2) What types of ES are being incorporated into LCA research and what is missing?
3) What factors are limiting the integration of ES accounting and LCA, and what can be done to address this?
4) What areas of future work on ES in LCA look especially promising or urgent?

Answering these questions stands to provide further guidance to the scientific community working to integrate ES in LCA by quantitatively elucidating both salient gaps and promising opportunities.

Based on bibliometric analysis conducted in August 2019 of over 56,000 Web of Science™ (WoS) citation records, we effectively mapped the co-citation interactions between biotic ES and LCA. This network mapping reveals a persistent divide between the two research communities. We identified just 91 publications in which LCA has integrated such ES in a meaningful way. To classify ES in these 91 papers, we used the CICES framework definitions for individual biotic ES. We also classified these papers in terms of LCA midpoints using the International Reference Life Cycle Data System (ILCD). By and large, LCA research has focused on one or a few ES, especially carbon balance, sequestration, and emissions. The work has prioritized regulation and maintenance and provisioning services, with work especially scarce on cultural services.

Based on this inventory of the state of ES-LCA interaction, we then consider how to advance the use of ES accounting into LCA protocols, models, and practices. We identify land use as a focal point of LCA-ES integration, especially the impacts of land use on biodiversity, provisioning, and regulation and maintenance ES. This is confirmed by analyzing the connections between ES classifications and LCA midpoint categories. We conclude the paper by reflecting on the potential of Geographic Information Science (GIScience) to wed ES and LCA through a spatially and temporally explicit approach to impact characterization and inventory modeling.

2. Methods

To conduct the literature review, we used bibliometric and citation analysis, followed by deeper reading of a subset of papers (91 in total) against an evaluation matrix. This was a necessary step to capture novel and important research excluded from the bibliometric mapping exercise.

According to Strozzi et al. (2017), bibliometric citation methods document the trends and focal issues influencing the development of research fields in a more scientific and objective manner than conventional, descriptive literature reviews. This assessment builds off White (1990, p. 84) who maintains there is nothing better for systematically delineating "the intellectual structure of scholarly fields."

Although the use of bibliometric analysis to assess scientific performance is not without controversy (see Aksnes et al. (2019) for a historical overview of the basic concepts and theories), current discussions focus more on methodological differences rather than how citations relate to scientific quality. As Aksnes et al., (2019, p. 2) note, "it is often taken for granted that citations in some way measure scientific impact, one of the constituents of the concept of scientific quality." Another challenge for bibliometric analysis is simply the fact that new research is constantly being produced. It takes time for these publications to accrue citations and, therefore, to be recognized in analyses.

Co-citations are the preferred and most frequently adopted bibliometric analysis method (Pournader et al., 2020) as they are seen as "accurate markers for the emergence of new topics" (Garfield, 2001, p. 3). Yet, it is important to be cognizant of limitations created by the assumptions underlying the interpretation of co-citation patterns (Trujillo and Long, 2018). Co-citation analysis assumes that observed citation patterns reveal how multiple authors commonly recognize documents for advancing important concepts. However, authors may choose to cite a paper for a number of reasons; a citation may not necessarily be made in recognition of a paper's scientific merit of ideas, findings, or experiments.

Fig. 1 summarizes the five-step process used to conduct this research. We began with a broad search in Web of Science™ for all ES and LCA literature published from 1900 to 2019 and then visualized the clusters formed by the 56,000 citations found to span these two bodies of literature. We then conducted a second search for articles *combining* ES and LCA, visualized the clusters formed by citation networks in this smaller selection of literature (91 papers), and concluded by systematically inventorying how the 91 papers incorporated ES into an LCA framework. These methods are described in detail below.

Step 1. To identify relevant publications on ES and LCA in the Institute of Scientific Information's Web of Science™ (WoS) database, we conducted our searches using the Topic field, which includes the Title, Abstract, Author Keywords, and Keywords Plus®. Search timespans were from 1900 to 2019 and searches were conducted in August 2019.

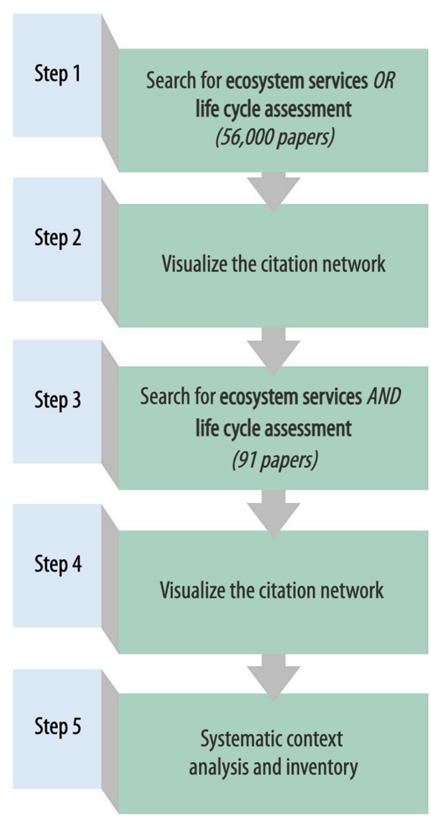

Fig. 1. The step-wise approach to conducting the bibliometric review.

WoS has well-known limitations: trade journals, books, and book chapters are excluded, as are other non-English language databases. To partially overcome these limitations, we exported the “Full record with cited references” for each WoS entry. To capture the maximum number of relevant papers, we iteratively constructed the search strings to develop a broad range of keywords. We also used ‘OR’ joins to link synonymous keywords and used ‘*’ wildcards to capture alternative endings (e.g., pluralization). Separate ES and LCA searches were performed. For ES, we used the following search terms: *“ecosystem service*”* OR *“ecosystem good*”* OR *“agrosystem service*”* OR *“agrosystem good*”* OR *“environmental service*”* OR *“environmental good*”* OR *“ecological service*”* OR *“ecological good*”* OR *“agroecological service*”* OR *“agroecological good*”*. For LCA, we used the terms: *“lifecycle assessment”* OR *“life cycle assessment”* OR *“life cycle thinking”* OR *“life cycle costing”* OR *“lifecycle costing”* OR *“life cycle impact assessment”* OR *“lifecycle impact assessment”* OR *“life cycle inventory”* OR *“lifecycle inventory”* OR *“lifecycle analysis”* OR *“life cycle analysis”* OR *“life cycle impact analysis”* OR *“lifecycle impact analysis”*. We limited our search results to articles. These searches produced 56,000 combined results.

Step 2. To visualize interactions between the large ES and LCA datasets, we combined the results of the respective ES and LCA searches in VOSViewer and generated a co-citation map. See van Eck and Waltman (2009) for details of the VOSViewer bibliometric network analysis algorithm. Co-citation mapping enables identification of key publications and relationships within and between given bodies of literature (i.e., intellectual communities) (Zhao and Strotmann, 2015). It reveals publications that belong to the same area of a field’s intellectual base (Noyons, 2004; Persson, 1994).

Once imported into VOSViewer, the publications that make up the combined ES and LCA WoS results referenced some 1400,000 sources. To reduce this a manageable number, we mapped the 1000 most cited publications. Mapping the most strongly and frequently coupled publications in a broader dataset is common practice (Zhao and Strotmann, 2015). Bibliometric mapping and analysis requires balancing a large number of objects with the analytical capacity of the tools being used and visual clarity of the resulting citation networks (Zhao and Strotman, 2015). We cleaned the reference entries by eliminating typographical errors and standardizing data formats.

To visualize and analyze the results, we used the open-source network analysis software *Gephi* and the ForceAtlas2 algorithm, which clusters nodes based on the density of links (Jacomy et al., 2014). Each node in the resulting map denotes a document that has been cited along with another document from the ES or LCA dataset. Links indicate nodes that have been cited together. The spatial arrangement of each node reflects its relatedness to other nodes. Articles cited together more frequently are more closely arranged. More heavily cited articles appear as larger nodes. The process delineated five distinct communities (or clusters), which we then evaluated by identifying key thinkers, prominent publications, theoretical bases, and language. Unable to clearly discern a community bridging ES and LCA communities, we conducted a deeper search.

Step 3. The process of identifying LCA publications that meaningfully incorporate ES accounting was as follows. We combined the originally separate ES and LCA WoS search queries into one long search string with an “AND” join. The initial combined search yielded 292 publications which we refined by type to include only peer-reviewed journal articles, bringing our count to 238. Of these 238, publications we eliminated those that did not directly relate to our central theme of inquiry: included publications had to be grounded in conventional LCA methods and explicitly detail steps taken to account for ES. We excluded papers that were reviews so as to focus on empirical studies we could inventory; and we excluded papers that addressed ES topics through means beyond the scope of this study. For example, we excluded the related “emergy,” and “exergy”, as well as “hemeroby,” topics, following Alejandre et al. (2019), who rationalized their exclusion based on topic incompatibility with current LCA practices and limited focus on ES impacts. However, a future study focused on emergy as a bridging concept for ES and LCA could be illuminating. H.T. Odum, the “father” of emergy, is a foundational scholar in the ES literature (Månsson and McGlade, 1993; Odum, 1971) and emergy has migrated to some LCA communities (Hau and Bakshi, 2004; Rugani and Benetto, 2012; Sciubba, 2010; Sciubba and Ulgiati, 2005; Wang et al., 2020). As emergy, exergy, and hemeroby concepts continue to develop in ways that complement LCA, they offer potential directions for future research.

Step 4. The refinement process reduced the count to 91 articles; 72 case studies and 19 conceptual frameworks (See SI for an itemized listing of all 91 papers). We generated a co-citation map to explore key publications and relationships within and between scholars in this smaller body of interstitial literature. The 91 papers referenced a total of 4798 sources. We required the mapped sources have a minimum of five citations, which rapidly narrowed the dataset to 47 sources that we cleaned and mapped. Because our primary aim with the bibliometric mapping exercise was to identify the papers and co-citation patterns most influential to ES and LCA integration, we assumed that papers with fewer citations would not act as significant bridge or boundary objects between communities. Setting a threshold value for ‘citedness’ is standard for such studies (Zhao and Strotmann, 2008a; Zhao and Strotmann, 2008b; Zhao and Strotmann, 2008c; Zhao and Strotmann, 2011b, Zhao and Strotmann, 2014a, Zhao and Strotmann, 2015,.

Step 5. We next systematically explored the content of each of the 91 LCA papers by inventorying them based on their thematic, methodological, and conceptual treatment of biotic ES. We classified these papers using the CICES system developed by Haines-Young & Potschin (2018). CICES is a hierarchical classification scheme that adheres to the following structure: 1. ecosystem sections, 1.1 divisions, 1.1.1 groups, and 1.1.1.1 classes (Fig. 2). We selected the CICES system given its relatively high level of detail and hierarchically nested structure; features that facilitated our accounting for ES in LCA at multiple taxonomical levels. Moreover, Liu et al. (2018) propose using CICES to develop consistent LCA approaches to quantify ES supply and demand: CICES is internationally recognized and has been widely used and accepted by academics and policy makers (European Environment Agency, 2020).

It was not feasible to cover the entire diversity of both biotic and abiotic ES within one study as this would require the inclusion of 90 ES class types. Therefore the scope for this paper was limited to biotic ES. A similarly structured investigation of abiotic ES could be a potential avenue for future study. In cases where the use of ES was vague in the papers, we designated a “generalized” approach. Since biodiversity is a concept parallel to, and sometimes within ES (Mace et al., 2012; Teixeira et al., 2019), we coded these slightly differently by using an asterisk to denote relational connection while maintaining conceptual separation.

LCA results can be calculated using distinct midpoint or endpoint impact assessment methods (Guinée and Lindeijer, 2002; ISO 1997, ISO, 2006). Impacts are studied as the result of a cause–effect chain; for example, from the emission of a toxic chemical to instances of premature death. A midpoint method identifies impacts that occur between the emission and the end of the cause–effect chain; for example, potential harm to human well-being arising from increased concentrations of toxic emissions. An endpoint method identifies the impact at the end of the cause–effect chain; for example, as the impact on human health in terms of lost life years. To identify the LCA midpoint and endpoint indicators in the 91 publications, we used the International Reference Life Cycle Data System (ILCD) and designated novel midpoint categories not included in the classification system as “Other.” See the SI for category details. When specified in the body of the text, we also catalogued each study’s modeling approach. Finally, again using best judgment, we corresponded class-level CICES codes to ILCD defined midpoint and endpoint categories to identify opportunities for connections.

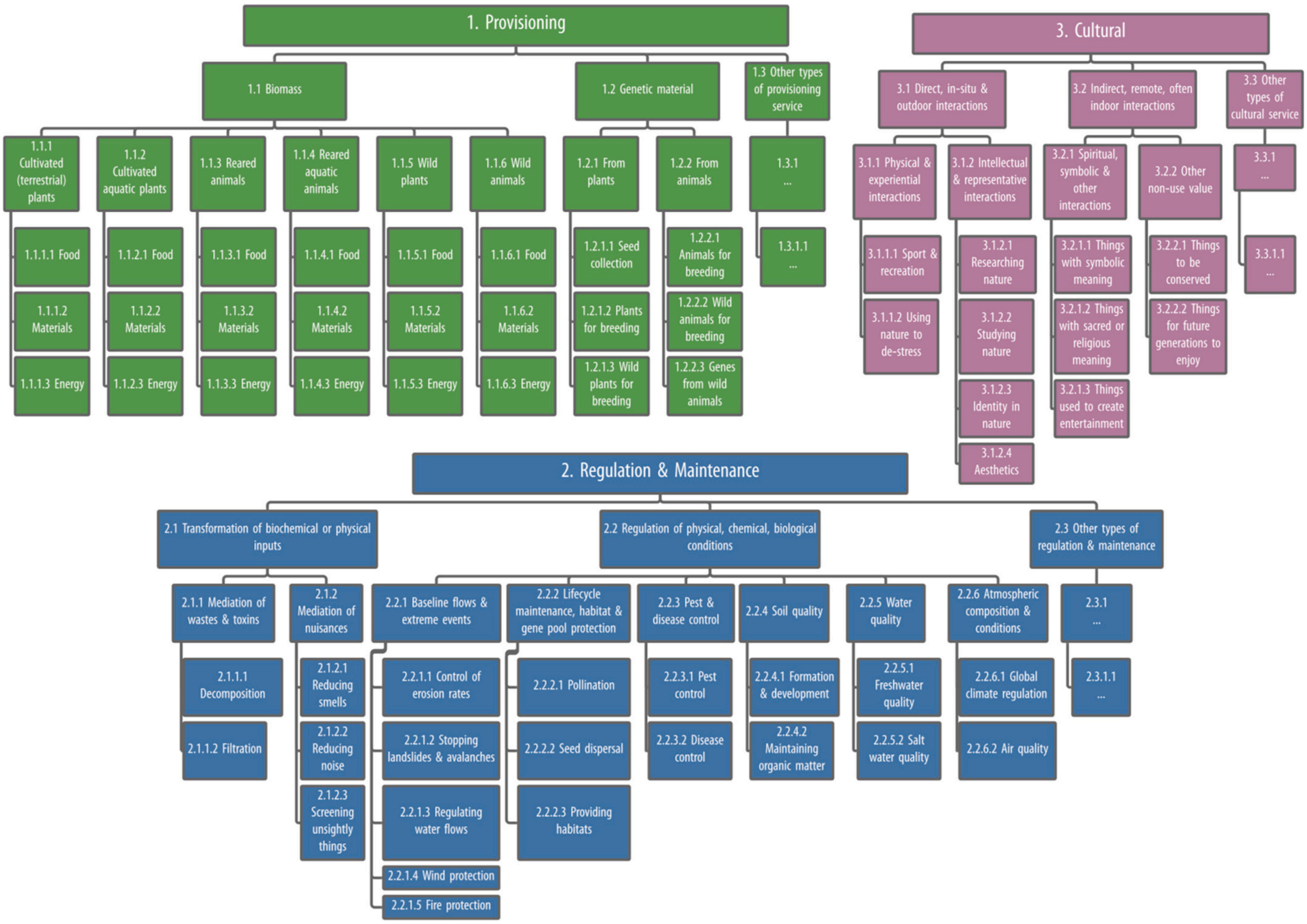

Fig. 2. Common International Classification of Ecosystem Services (CICES). This hierarchy, adapted from Haines-Young and Potschin (2018), enables coding of ecosystem services in life cycle assessment.

3. Results

3.1. ES and LCA literatures: separate scholarly communities

ES research and LCA research have evolved to become well-established fields, but as Fig. 3 illustrates, they are largely separate from each other, barring a few significant interactions. The strong preference, roughly 3:1, for ES papers compared to LCA papers in the top 1000 most cited papers, reflects disciplinary bias in publication and citation patterns. Disciplinary bias is a critically debated issue in citation impact metric evaluation (Kaur et al., 2013). The ES literature spans multiple disciplinary domains and includes environmental economists (e.g., Constanza, Daily, de Groot) and biodiversity-focused ecologists (e. g., Foley, Tscharntke, Cardinale), as well as those broadly quantifying anthropogenic impacts on Earth's ecosystems (e.g., Rockstrom, Vitousek). In the ES field, we identify four distinct scholarly clusters, labelled as follows: 1. Ecosystem Services (265 nodes, Teal); 2. Biodiversity (257, Orange); 3. Ecology and Society (119 nodes, Green); and 4. Conservation and Payments for Ecosystem Services (84, Blue). The clusters are generally agglomerated, which reflects community interconnectedness. Both disciplinary proclivity and topical foci have helped form the four ES clusters. Nodes of importance are ordered by co-citation occurrences.

1 *The Ecosystem Services cluster (Teal)* focuses on classifying and valuing ES, including how to incorporate them into decision-making. Prominent nodes (publications) in this cluster include Costanza et al., 1997; Daily, 1997; de Groot et al., 2002, de Groot et al. (2010) and Fisher et al., 2009. A highly influential non-journal publication is the Millennium Ecosystem Assessment (2005).
2 *The Biodiversity cluster (Orange)* focuses on how loss of biodiversity impacts ecosystem functioning, especially the provisioning of goods and services. Important nodes include Foley et al., 2005; Tscharntke et al., 2005; Cardinale et al., 2012; Klein et al., 2007; and Hooper et al., 2005.
3 *The Ecology and Society cluster (Green)* addresses anthropogenic impacts, interactions, and feedbacks with Earth's ecosystems. Prominent nodes include Rockström et al., 2009; Bolund and Hunhammar, 1999; Vitousek et al., 1997; Ostrom, 2009; and Holling, 1973.
4 *The Conservation and Payments for Ecosystem Service cluster (Blue)* explores how payments for ecosystem services can promote human welfare while achieving environmental objectives, often in the context of conservation. Prominent nodes include Engel et al., 2008; Myers et al., 2000; Muradian et al., 2010; Wunder et al., 2008; and Kosoy and Corbera, 2010.

In contrast, the LCA literature forms just one large cluster, which we have labelled as Life Cycle Assessment (Pink). Prominent nodes in the Life Cycle Assessment cluster include work by Finnveden et al., 2009; Guinée and Lindeijer, 2002; and Jolliet et al., 2003, as well as the International Standards Organization's (ISO) guidance documents for LCA procedures (ISO 14040–14044 standards).

Ten of the 91 LCA-ES papers appear in Fig. 3 (Bare, 2011; Brandão and Milá i Canals, 2013a; Dewulf et al., 2015; Koellner et al., 2013b; Maes et al., 2009; Milà i Canals et al., 2013; Pelletier and Tyedmers,

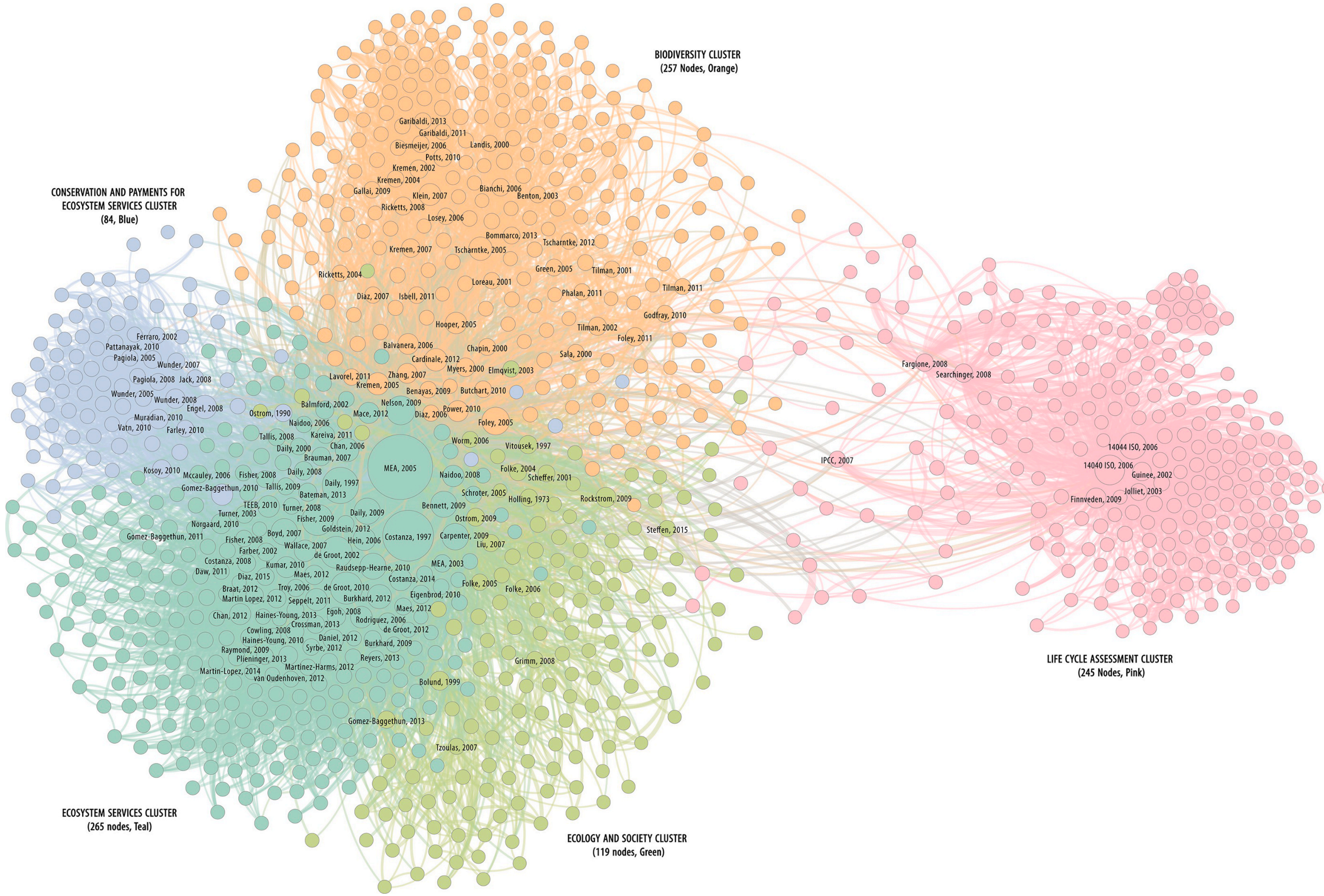

Fig. 3. Citation map of research on ecosystem services and life cycle assessment. Note: Four scholarly communities (clusters) pertain to ecosystem services and one to life cycle assessment. Only the 100 most cited papers are labeled.

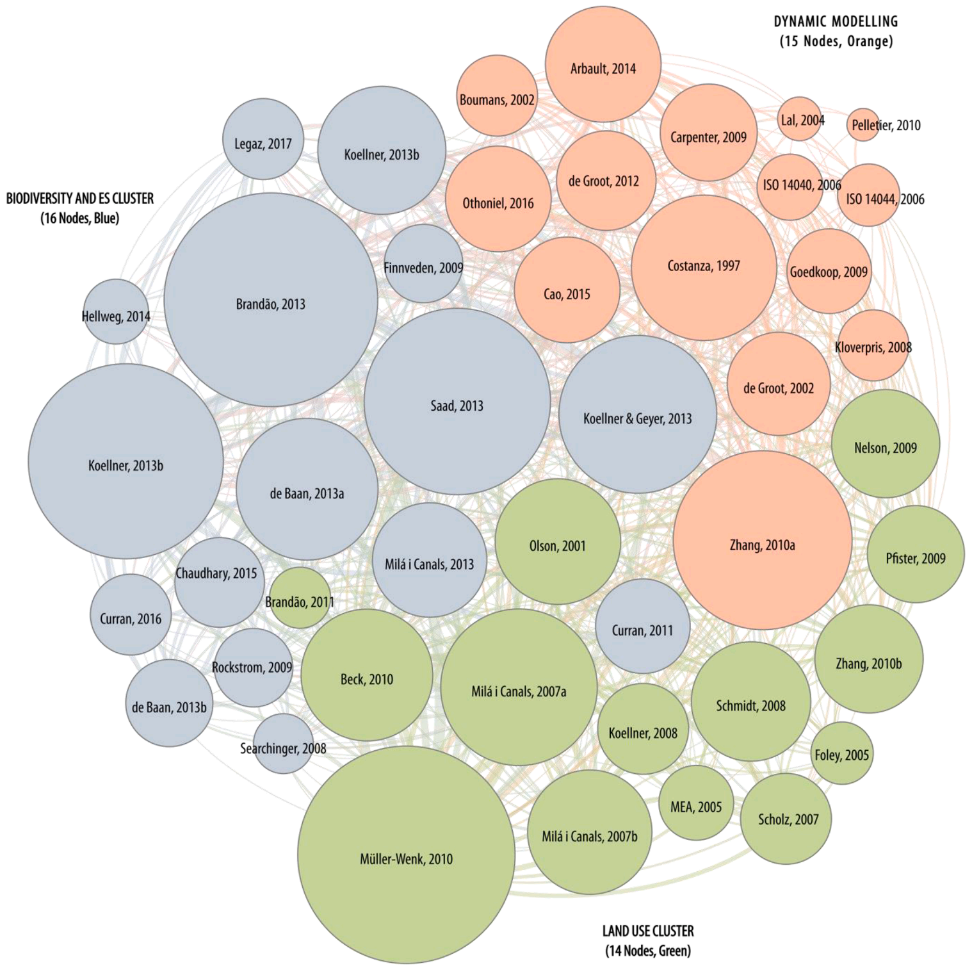

Fig. 4. The three scholarly communities formed around the study of ecosystem services in life cycle assessment.

2010; Saad et al., 2013, 2011; Strohbach et al., 2012). However, none are prominent nodes (note, only the 100 most cited papers are labeled in Fig. 3).

3.2. ES in LCA literature: in-depth analysis

ES accounting in LCA is an emerging area of research. The first publication did not appear until 2004, a case study in Maryland that developed and applied indicators to evaluate resource use versus economic benefit (Wainger et al., 2004). But more than 80% of the 91 papers have been published after 2014. Prominent journals publishing this work include *Journal of Cleaner Production* (18 total papers), *International Journal of Life Cycle Assessment* (12), *Science of the Total Environment* (9), *the Journal of Industrial Ecology* (4), and *Agricultural Systems* (4). Roughly one-quarter (23) of the empirical papers focused on the U.S., with other notable regions being Brazil (8) and Italy (7). The thematic foci were as follows: bioenergy/biofuels (18); livestock (14); general methodologies (13); agriculture (12); forestry (6); and soils (6). General methodological papers tended to concentrate on quantifying land use impacts as a basis for assessing ES in LCA. Impacts were calculated as a factor of the total area of land use (change) and the biophysical or monetary value of that land use type, e.g., cropland versus forestland. Examples include: Glendining et al. (2009), Nguyen et al. (2012), and Ripoll-Bosch et al. (2011). Only two (of 13) explicitly applied their proposed methodology in a case study. See the SI for details.

Co-citation network analysis of the 91 papers revealed the formative presence of three ES-LCA sub-clusters (Fig. 4), which we have labeled as *Biodiversity and ES (Blue, 16 nodes), Dynamic Modelling (Orange, 15 nodes),* and *Land Use (Green, 14 nodes)*. The prominent nodes indicate the publications that can be considered foundational to each cluster's intellectual base.

1 *The Biodiversity and ES Cluster (Blue)* focuses on developing UNEP-SETAC guidelines to build methods for land use assessment based on biodiversity and ES impacts. Prominent nodes include Brandão and Milá i Canals, 2013; de Baan et al., 2013a, 2013b; Koellner et al., 2013a, 2013b; and, Koellner and Geyer, 2013.
2 The *Dynamic Modelling cluster (Orange)* melds LCA with other fields (e.g., ecological economics and valuation) and tools (e.g., earth systems models) in order to account for ES impacts. Prominent nodes include Zhang et al., 2010b; Costanza et al., 1997; Arbault et al., 2014; and Cao et al., 2015.
3 The *Land Use cluster (Green)* focuses on using and advancing UNEP-SETAC Life Cycle guidance on quantifying the impacts of land use on biodiversity, biotic production, climate regulation, and other ES. Prominent nodes include Beck et al., 2016; Milà i Canals et al., 2007a, 2007b; and, Müller-Wenk and Brandão, 2010.

3.3. ES in LCA literature: ecosystem classification codes and midpoint indicators

LCA scholars focused on regulation and maintenance services (55 papers), followed by provisioning services (40 papers). Just six publications included cultural services (Arbault et al., 2014; Blanco et al., 2018; Callesen, 2016; Pavan and Ometto, 2018; Styles et al., 2015) revealing a gap in the literature.

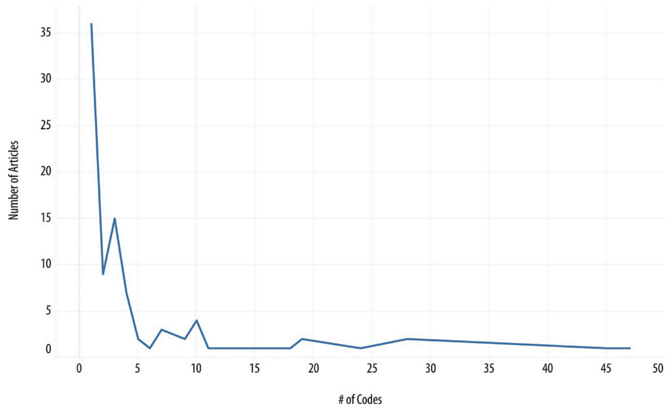

Fig. 5. Number of ecosystem service codes (based on CICES class-level) mentioned in life cycle assessment studies. Note: the vast majority of articles consider only one ecosystem service.

Each of the 91 LCA papers focused on just one or a few ES. One-third focused on just one code or referred to ES as a generalized concept, and over three-quarters addressed five or fewer ES codes (Fig. 5). Some of the conceptual or framework papers included more comprehensive accounting: Callesen (2016) proposed a system for addressing 47 (of 56) ES codes, and in a similar manner, Alejandre et al. (2019) proposed 45 ES codes as especially suitable for LCA.

In terms of divisions, 40 studies focused on regulation and maintenance: regulation of physical, chemical, biological conditions (2.2) and 40 on provisioning: biomass (1.1). Refined to the class-level, 35 publications mentioned regulation and maintenance: regulation of physical, chemical, biological conditions – atmospheric composition and conditions (2.2.6); 32 mentioned regulation and maintenance: regulation of physical, chemical, biological conditions – water conditions (2.2.5); 32 mentioned provisioning: biomass – cultivated terrestrial plants for nutrition, materials, or energy (1.1.1); and 31 mentioned regulation and maintenance: regulation of physical, chemical, biological conditions – regulation of soil quality (2.2.4).

At the code-level of analysis, studies predominately focused on carbon-sequestration related ES. These included: regulation of physical, chemical, biological conditions – atmospheric composition and conditions – global climate regulation (2.2.6.1); and regulation of physical, chemical, biological conditions – regulation of soil quality – maintenance of soil organic matter (2.2.4.2) (Fig. 6).

Fifty-two papers suggest ES be measured within LCA using a purely biophysical approach; 13, a purely monetary approach; and six, a mixed biophysical and monetary approach. The remaining 23 papers do not provide such details.

As roughly seventy percent of the papers did not include endpoint indicators, we focused on identifying the midpoints covered. The most common ES-related midpoint indicators were climate change (53 studies), eutrophication (31), resource depletion (23), acidification (21), and land use (21) (Fig. 7). The most widely covered LCA midpoint categories connect most neatly to ES relevant to carbon flows: waste decomposition (2.1.1.1), soil development (2.2.4.1), maintenance of soil organic matter (2.2.4.2), and global climate regulation (2.2.6.1).

3.3.1. *Cultural ES in LCA literature*

As mentioned above, cultural ES have been minimally considered in the ES-LCA literature. We summarize the relevant work here. Arabualt et al. (2014) coupled GUMBO with LCA to inventory ES values and dynamics. The metamodel includes indicators for "recreational & cultural" ES with an impact indicator based on the "combined marginal change of biomass production minus marginal change of Social Capital Index." Blanco et al. (2018) specifically considered recreation and ecotourism cultural services by utilizing wetland area as a proxy indicator. They drew on tourism data and made assumptions that the amount of tourists visiting the area of interest is proportional to the wetland area. Callesen (2016) proposed LCA be restructured to include a new area of protection for biodiversity and ES. Impact pathways for various ES and for cultural ES are proposed using indicators such as: valuation of landscapes; valuation of recreation and tourism; number of references to the biosphere in arts, crafts and design; quantitative or qualitative valuation of expressed statements from human beings; and the number of educational activities with a focus on biosphere. Styles et al. (2015) and Liu and Bakshi (2019) included ES assessment alongside, but separate from, their LCA. Both assigned values to ES effects, including cultural, in relative terms. Styles et al., 2015 designated the relative value of ecosystem (dis)services accompanying modelled biogas, biofuel and biomass scenarios for large arable farms in the UK. Cultural ES were included in terms of the expected direction (positive or negative) and value (on a one to three point scale) of impacts on socially valued landscapes. Liu and Bakshi (2019) depicted differences on ES effects among two wastewater treatment options. They included the cultural ES "educational and recreational usage." Pavan and Ometto (2018) recommended characterizing ES impacts with endpoints expressed in monetary terms. The tendency to overlook cultural ES persists for the broader ES scholarship, in part because quantifying a person's values, perspectives, experiences, and histories faces steep challenges long familiar to those in the social and behavioral sciences (Chan et al., 2012; Satz et al., 2013).

Alejandre et al. (2019) argue that cultural ES fall outside of the realm of environmental LCA and recommend they be left for Social LCA scholars. However, Chan et al. (2012) make the case that the decision-making effectiveness of ES frameworks categorically suffer when they fail to recognize cultural ES. These services strongly influence the manner in which ecosystems are viewed and managed, often presenting some of the most compelling reasons for ecosystem conservation. The Millennium Ecosystem Assessment (2005) asserts that cultural ES cannot be treated in isolation of other services due to the inextricable interconnectedness of all categories. Collective recognition of provisioning, regulation and maintenance, and cultural ES is thus necessary to avoid bias towards other environmental impacts, other ES, and unwanted trade-offs due to shortsighted decision making.

3.4. *Linking ES classification codes with LCA midpoints*

We identify potential linkages between 40 (out of 56) CICES codes and ten (out of eleven) ILCD midpoint categories (Fig. 8). From a midpoint category perspective, key areas for integration are in the areas of (1) Land Use, (2) Resource Depletion, and (3) Climate Change.

Land Use connects to CICES-defined provisioning ES and a number of regulation and maintenance services. Provisioning ES principally depend on land use; the impacts of land use and land use change dictate long-term biomass production capacities (Brandão and Milá i Canals, 2013a). Crenna et al. (2018) likewise call attention to the central role of land use change in the availability of the biotic resources from provisioning ES. Cultural ES, which influence the occupation or transformation of land, are also land use relevant. Land used for recreational purposes may lead to better management of ES (Conrad and Hilchey, 2011). Impact pathways have already been defined for some CICES codes using land use as a midpoint. For example, with the development of the Land Use Indicator Calculation Tool (LANCA®), Beck et al. (2016) defined indicators for: biotic production potential (BPP) which partially covers plant biomass production (1.1.1); erosion resistance which connects with controlling or preventing soil loss (2.2.1.1); physiochemical filtration and mechanical filtration which coincide with filtering wastes (2.1.1.2); and groundwater replenishment which is related to the regulation of flows of water in our environment (2.2.1.3). Jeswani et al. (2018) applied the LANCA method to measure land use impacts on ES in an illustrative study of the production of breakfast cereals. They concluded that a meaningful and practical indicator for land use impacts

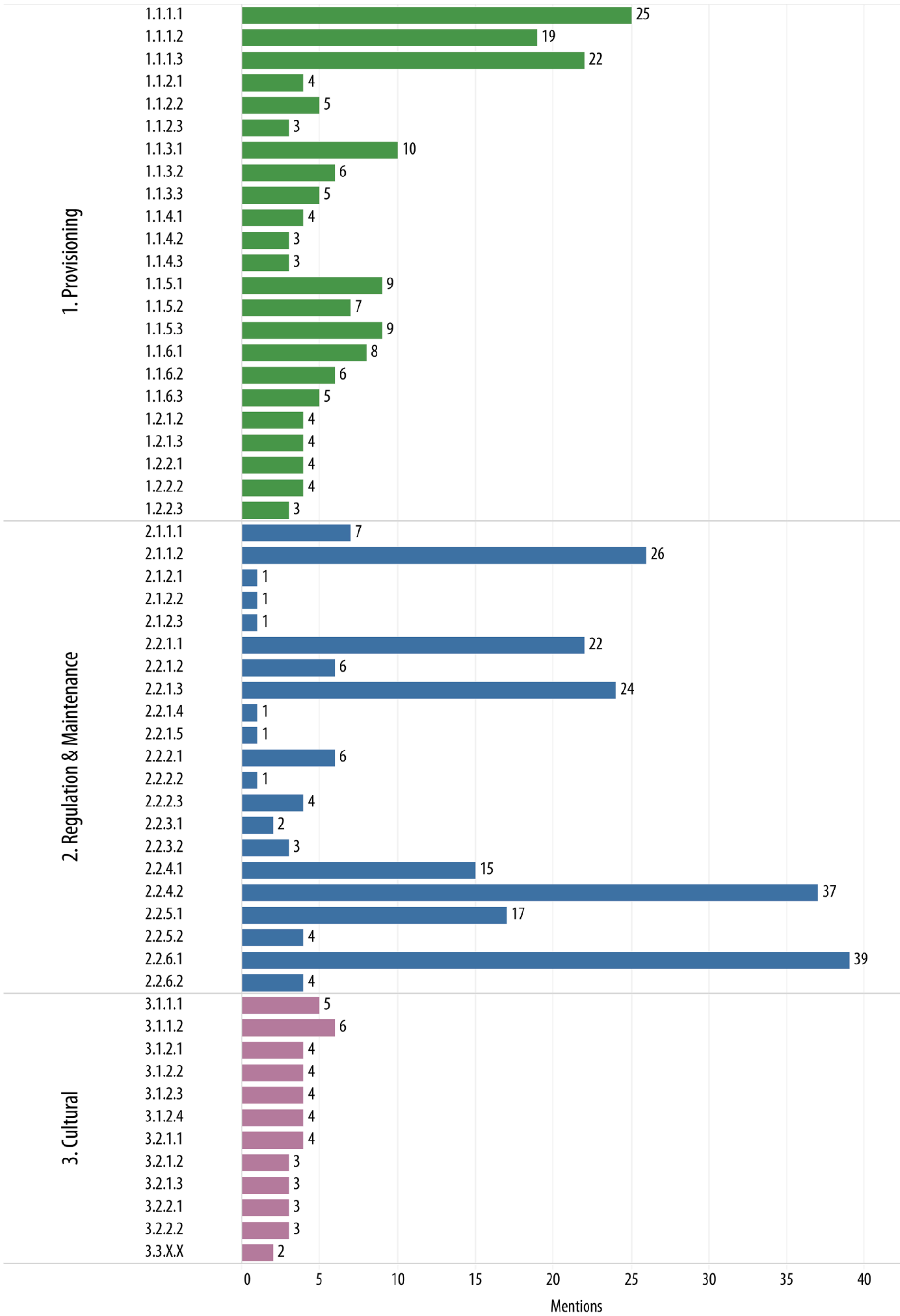

Fig. 6. Frequency of ecosystem services (class-level) mentioned in life cycle assessment publications.

is needed.

Resource depletion similarly provides opportunities to account for a number of provisioning ES. There are many overlaps between impacts on ecosystems from land use and resource depletion (Crenna et al., 2018). Provisioning ES principally dictate that the availability of biotic resources and stocks of biotic natural resources and water can directly be depleted by their removal. Although ILCD does not yet consider the depletion of biotic resources, there have been several attempts over the years to recognize biotic resources within an LCA framework (Alvarenga et al., 2013; Bach et al., 2017; Crenna et al., 2018; Dewulf et al., 2007; Emanuelsson et al., 2014; Langlois et al., 2014; Rugani et al., 2011; Steen, 1999; Taelman et al., 2014). Beylot et al. (2020) propose a comprehensive approach to characterizing impacts from overexploitation of naturally occurring biotic resources. As biotic resources include “all resources extracted by humankind from nature” (Beylot et al., 2020, p. 6), we classified all CICES-defined provisioning ES as potentially relevant to resource depletion. The work of Langlois et al. (2014) supports the inclusion of biomass from aquatic animals in the resource depletion category; they modelled biotic resource depletion for fish. We also drew linkages with a number of regulation and maintenance ES including those related to water availability (2.2.1.3; 2.2.5.1; and 2.2.5.2).

Climate change directly links to regulation and maintenance ES. Within this category, we classified five carbon-sequestration related ES: waste decomposition (2.1.1.1), waste filtration (2.1.1.2), soil development (2.2.4.1), maintenance of soil organic matter (2.2.4.2), and global

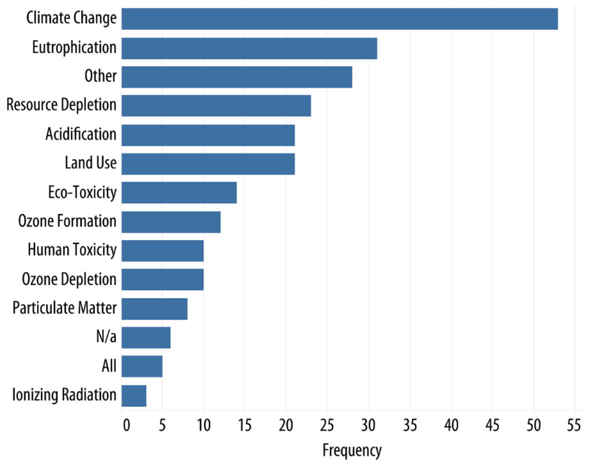

Fig. 7. Frequency of life cycle assessment midpoint indicators used to account for ecosystem services.

climate regulation (2.2.6.1). The most often mentioned ES in LCA publications relate to carbon balance, partially due to the *relative* ease of integrating greenhouse gas emissions as a climate change midpoint indicator. Scholars can follow conventional LCA methods for calculating climate change impacts and then consider carbon-sequestering ES as a manner of emission mitigation. While the calculations themselves are underpinned by complex modeling exercises, carbon balance integration, broadly speaking, comes down to subtracting carbon sequestered as soil organic matter from the whole-system efflux of GHG emissions. For example, Müller-Wenk and Brandão, (2010) present a study on the integration of climate impacts from carbon transfers between vegetation, soil, and the atmosphere in LCA. They express carbon transfer quantities in a manner that facilitates a relatively straightforward summing of carbon amounts into the usual LCA indicator for climate change potential.

4. Discussion

What are limiting factors to the integration of ES accounting into LCA modeling and practice? Other bibliometric studies have identified a suite of reasons for persistent scholarly divides between academic fields (Newell and Cousins, 2014; Meerow and Newell, 2015; Meerow et al., 2016). These range from fundamental differences in epistemology (e.g., positivist versus critical realist and constructivist approaches), to the object and method of study, to the disciplinary-bound reward structure of the academy (Newell and Cousins, 2014). But in considering the limited interaction between ES and LCA, we can identify more specific challenges, namely that ES interact dynamically, vary geographically, and exhibit temporal heterogeneity. These challenges will need to be addressed sufficiently for more robust ES-LCA integration. They are briefly described here.

- *Ecosystem services interact dynamically*

ES arise from interlinked feedback loops amongst ecological processes. As an example, waste decomposition (2.1.1.1) influences the amount of carbon dioxide in soils and the atmosphere, which in turn has implications for soil composition (2.2.4.1), soil maintenance (2.2.4.2), and global climate regulation (2.2.6.1). Conversely, LCA assumes linear burden-impact pathways and typically relies on static models (Finnveden et al., 2009). A review by Othoniel et al. (2016) highlights how LCA's static calculation framework presents a challenge for incorporating the multifunctional services provided by a particular ecosystem. de Souza et al. (2018) and Rugani et al. (2019) detail a number of unsolved issues related to the quantification of impacts of ES in LCA. Both highlight particular challenges that stem from the spatial-temporal variation of ES as they "are heterogeneously provided and valued across different spatial granularities, geographical scopes and time horizons" (Rugani et al., 2019, p. 1297).

- *Ecosystem services vary geographically*

ES vary across space, and these variations necessarily define the type of benefits they provide (Hein et al., 2006). Complex interactions exist between environmental variables spanning micro to macro geographic scales. For example, as soil microbes decompose waste (2.1.1.1), they influence the amount of carbon in local soils (2.2.4.1; 2.2.4.2) and the amount of carbon dioxide in the global atmosphere (2.2.6.1). For this reason, spatially explicit mapping and analysis of ES have emerged as a key component of ES research (Rau et al., 2018). Conversely, many LCAs assume geographic uniformity and spatial consistency in impact calculations – such aggregation masks critical spatial and scalar variations in the ecological landscape (Othoniel et al., 2016).

- *Ecosystem services exhibit temporal heterogeneity*

Ecosystem services emerge from temporally dynamic processes. As an example, carbon flux dynamics vary depending on the season such as in the spring when nature decomposes wastes (2.1.1.1), releasing carbon dioxide. Amongst ecologists, temporal modeling of ES is an emerging, but still understudied, area of inquiry (Bennett et al., 2015; Rau et al., 2018). LCA modeling generally relies on temporal homogeneity, and characterization factors assume similar impacts regardless of the time period (Reap et al., 2008). Temporal issues have plagued LCA since its theoretical and practical introduction (Finnveden, 2000; Finnveden et al., 2009; Guinée et al., 2011; Hellweg and Milà i Canals, 2014; Owens, 1997). Lueddeckens et al. (2020) conducted a systematic review of temporal issues in LCA. While they found consensus in the literature that temporally dynamic inventories and characterization methods improve the accuracy of LCA, such inventories and characterization factors are not readily or widely available. Experimental approaches to dynamic LCA modeling have been proposed and represent significant progress in the field (Beloin-Saint-Pierre et al., 2014; Beloin-Saint-Pierre et al., 2017; Collinge et al., 2013; Levasseur et al., 2013; Pigné et al., 2020; Tiruta-Barna et al., 2016). However, approaches still lack the sophistication needed for modeling the temporal heterogeneity of ES as they exhibit variation over a combination of daily, seasonal, and long-term time horizons.

4.1. Land use in LCA

In terms of advancing integration of ES into LCA models, methods, and practice, we identify further development of land use and its impacts as especially promising. A focus on land use is not a novel proposal in itself; we have illustrated and described clusters of research concerning land use above. However, we advance the conversation by exploring how land use can be more meaningfully considered using *Geographic Information Science* (GIScience). Integrating land use in a meaningful way entails addressing the dynamic interactions, geographic variation, and temporal heterogeneity previously mentioned. Such a combination of spatial and temporal characterization in LCA has yet to be addressed (Pigné et al., 2020). We briefly discuss current approaches to land use before expounding upon the potential of GIScience.

LCA scholars such as Milà i Canals et al. (2007b) have long called for LCI inventories to account for spatial and temporal variation, including differentiating between the many land use types, ecosystems, and geographic regions. Under the auspices of a working group to develop

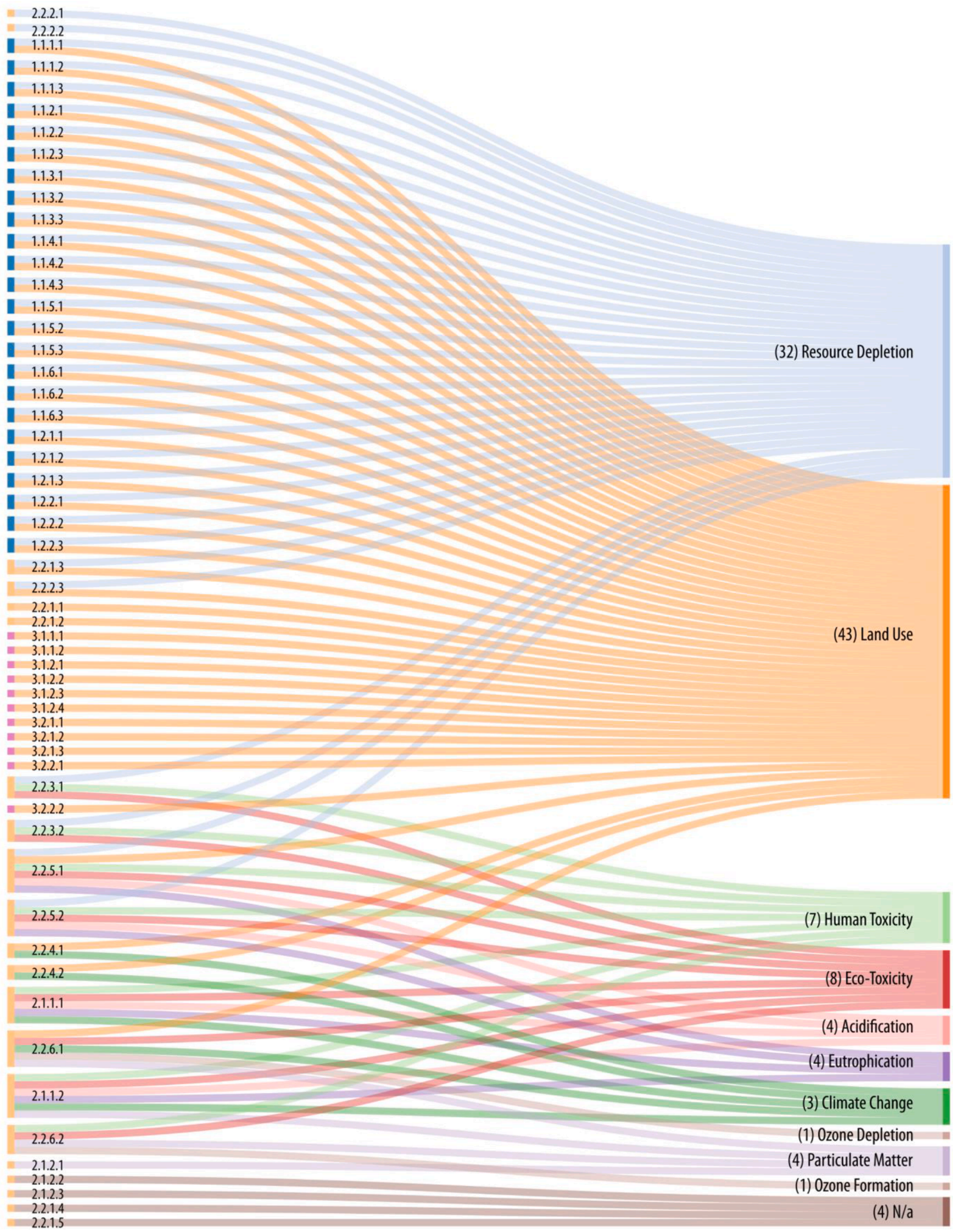

Fig. 8. Proposed linkages between ecosystem services (CICES class-level) codes and life cycle assessment midpoint categories.

UNEP-SEATAC land use guidelines, Koellner et al. (2013a; 2013b) have responded to this call by presenting standardized land-cover and land use classification schema and an approach to regionalize land use flows.[1] This classification scheme consists of four levels, from general land use and land-cover classes all the way down to the relative intensity of land uses (e.g., extensive versus intensive). The regionalization of land use flows consists of five tiered levels, which differentiates between the various biomes (e.g., terrestrial, freshwater) all the way down to the 867 ecoregions identified by Olson et al. (2001). At the most geographically specific level, Koellner et al. (2013a) call for identifying the geo-referenced information of land use in grid cells of one square kilometer or less.

Efforts to address the geographic variations associated with land cover and land use are a welcome advancement. The four-tier system offered by Koellner et al. (2013a) provides a flexible approach for LCA to refine land use impacts by defining general to very specific types of land transformation and occupation. Their land use classification scheme is included in Ecoinvent version 3 (Weidema et al., 2011). But Ecoinvent does not include specific guidance with respect to variability associated with the productivity (e.g., quality) of a particular area of land under occupation or transformation. One option to capture this variation is to use net primary productivity (NPP), a measurement of ecosystems long used in the ecological community (Lieth, 1975; Esser et al., 1994). A related persistent challenge that life cycle impact assessment (LCIA) has not successfully addressed is how to accurately characterize impacts where the category of land (e.g., forest) remains the same, but the carbon pools, for example, in that land have been fundamentally disturbed (Newell and Vos, 2012). Terrestrial carbon modeling reveals a complex

[1] In addition to these limitations, UNEP-SEATAC land-use guidelines Koellner et al. (2013b) outline generic characterization factors for just a few ecosystem services: biotic production potential (partial connections to 1.1), climate regulation potential (2.2.6.1), freshwater regulation potential and water purification potential (2.2.1.3), and erosion regulation potential (2.2.1.1). And, indeed, these are the most frequently covered in the ES-LCA literature.

dynamic of the carbon pools in forests, but rarely a 'carbon neutral' flux profile as has been modeled traditionally in LCA (Johnson, 2009). Searchinger et al. (2008) remind us of the potential for 'accounting' error if biogenic carbon emissions related to land use are not heeded.

An example of how land use tends to be accounted for in LCA in practice can be illustrated by considering the specifics of the ReCiPe (Huijbregts et al., 2016) LCIA methodology utilized in SimaPro and other LCA accounting software. While ReCiPe is one of many available life cycle inventory assessment methods,[2] it offers the most recently updated methods and boasts the broadest set of indicators (Alejandre et al., 2019). Moreover, Hauschild et al., (2013) identify ReCiPe as the best method for incorporating ES impacts, while acknowledging and voicing caution of its shortcomings: it remains incomplete in scope and applicability.

ReCiPe faces essential limitations with regards to impacts of land use on biodiversity. The characterization factors utilized in ReCiPe result from a literature review conducted by Elshout et al. (2014) to generate the values, and work by de Baan et al. (2013a; 2013b), who relied on (1) global literature in the GLOBIO3 database and (2) national biodiversity monitoring data from Switzerland (BDM, 2004). In essence, ReCiPe *land use* characterization factors use globally averaged values that do not reflect the spatio-temporal variation of land quality and biodiversity.

The combinations of land-cover and land use type and the regional variation of ES associated with ecosystem variation requires a wide range of characterization factors and inventory to properly represent this diversity. They require characterization factors that are "more realistic, evidence-based and related to actually modelled effects on ecosystems" (Teixeira et al., 2018, p. 15). Towards this end, we suggest the integration of GIScience in LCA procedures and practices.

4.2. GIScience and LCA

In the pursuit of integrating ES accounting, GIScience is positioned to be perfectly complementary to LCA modeling (Geyer et al., 2010a). Far more than an analytical tool (i.e., geographic information systems – GIS), *GIScience* is a basic research field that emphasizes the redefinition of geographic concepts and their use in GIS (Goodchild, 1992). This includes spatial data collection and modeling, spatial statistics, algorithms, and display. Data sources are wide-ranging, including remote sensing, AI and machine learning, and volunteered geographic information. A cadre of LCA scholars continue to advocate for more spatially explicit LCA using GIS (Azapagic et al., 2007; Bengtsson et al., 1998; Escamilla and Habert, 2017; Gasol et al., 2011; Geyer et al., 2010a, 2010b; Hillier et al., 2009; Liu et al., 2014; Mutel et al., 2012; Núñez et al., 2009; Mutel et al., 2012; Rodríguez et al., 2014; Rodríguez and Greve, 2016). However, research has focused on inventory spatialization and impact regionalization within the existing LCA framework.

There are a growing number of GIS-based models to assess ES across time and geographical scale. One well-developed application is the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model (Nemec and Raudsepp-Hearne, 2013; Ochoa and Urbina-Cardona, 2017). The open-source InVEST model utilizes GIS to quantify how changes to terrestrial and aquatic ecosystems affect their ability to provide services. It is able to model spatially explicit relationships among multiple ES at the local, regional, and global scale. Modules cover dozens of ES including carbon storage and sequestration, nutrient retention, pollination, and habitat quality. InVEST is also able to account for different land use intensities and land management practices – characteristics that scholars such as Jeswani et al. (2018) and Teixeira et al. (2019) have declared require further development in LCA. Liu et al. (2018) recommend ecological models be used to gain information about ES supply for LCA. Bare (2011) concluded that InVEST was the tool most appropriately sophisticated and practicable for coupling with LCA. Yet, in the LCA community there has been limited use of InVEST for modeling (Bare, 2011; Chaplin-Kramer et al., 2017; Othoniel et al., 2019). Using the InVEST model, in combination with the typologies proposed by Koellner et al. (2013a), LCA modelers could build out spatially and temporally relevant land use inventories and characterization factors. As a further step, GIScience techniques for gathering volunteered geographic information could be used to inventory and characterize land use connections to cultural ES.

InVEST should be viewed as just one example of how GIScience–LCA integration could more deeply enable LCA modeling to meaningfully incorporate land use variation and ES. InVEST suggests the capabilities of GIScience; it is a tool that resides in one part of the geographic information whole that concerns the fundamental issues of GIScience. GIS models such as InVEST provide a foundation upon which to build out a GIScience-LCA relationship; a relationship through which LCA is reimagined through spatial data collection and modeling, spatial statistics, algorithms, and displays.

4.3. Future research

Melding GIScience and LCA is just one avenue for future research. The bibliometric methods deployed in this paper could be used to explore exciting avenues that were beyond the scope of this study. These include the degree to which LCA addresses abiotic ecosystem services, the prospects for emergy as a bridging concept for ES and LCA, and the use of nontraditional LCA methods when considering ES. As noted earlier, bibliometric analyses have their limitations (e.g., emergent papers may be excluded). Thus, literature reviews that rely on expert author judgement will always have a place when assessing fruitful pathways for transformative, boundary crossing scholarship.

Conclusion

This article utilized bibliometric techniques, including clearly defined search terms and citation minimums, to conduct a structured and critical literature review of the fields of ES and LCA. Bibliometric analysis allowed us to assess and document the connections (or more often separations) between these disciplines, traditions, and ideas. While ES and LCA research fields are historically distinct, LCA scholars are increasingly recognizing their attractive co-benefits and synergies. To date, provisioning and regulation and maintenance ES have received the most attention. LCA studies have tended to account for one or few ES rather than a broad suite of them. We identify land use as one particularly fruitful area of continued research, making the case that it is central for ES-LCA interaction and development. Land use cuts across a broad swath of ES categories and presents an opportunity to leverage collaboration between applied ecologists, geographers, ecosystem service scientists, and LCA modelers. The LCA community is just scratching the surface with respect to considering how to incorporate ecosystem services associated with land use change. We advocate for the integration of GIScience to incorporate spatial and temporal variation associated with land use on ecosystems and associated services. This includes GIS of course, but also a plethora of other concepts, models, and tools – from remote sensing, to spatial statistics, to understanding and visualizing spatial resource flows. Pursuing this research agenda will enable us to better assess environmental sustainability in terms of *who* is causing impact, in *what* environmental and ES impact areas, *when* in time, and *where* in space.

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[2] For example, the CML impact assessment method (Guinée et al., 2002), Eco-indicator 99 (Goedkoop and Spriensma, 2000), and Impact World+ (Bulle et al., 2019).

Collaborative Research: The FEW-Meter - An Integrative Model to Measure and Improve Urban Agriculture (#1829627).

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. The authors declare no conflict of interest.

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Supplementary materials

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