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Towards integrating the ecosystem services cascade framework within the Life Cycle Assessment (LCA) cause-effect methodology

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Authors' contribution
B.R. designed the research work, conceived the methodology, and outlined the article contents. D.M.d.S. and B.W. contributed to the design of the research work and to writing the article; the remaining authors suggested discussion topics, revised the literature, and contributed to writing the article; F.V. and A.L. coordinated the overall initiative.

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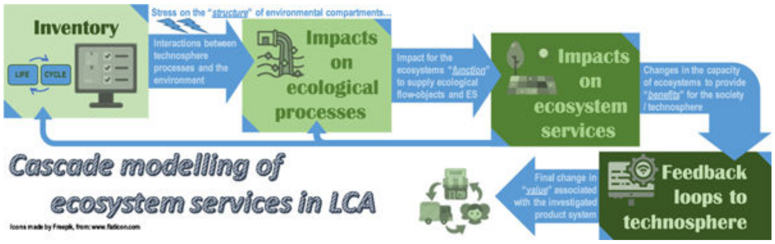
Abstract

The assessment of ecosystem services (ES) is covered in a fragmented manner by environmental decision support tools that provide information about the potential environmental impacts of supply chains and their products, such as the well-known Life Cycle Assessment (LCA) methodology. Within the flagship project of the Life Cycle Initiative (hosted by UN Environment), aiming at global guidance for life cycle impact assessment (LCIA) indicators, a dedicated subtask force was constituted to consolidate the evaluation of ES in LCA. As one of the outcomes of this subtask force, this paper describes the progress towards consensus building in the LCA domain concerning the assessment of anthropogenic impacts on ecosystems and their associated services for human well-being. To this end, the traditional LCIA structure, which represents the cause-effect chain from stressor to impacts and damages, is re-casted and expanded using the lens of the ES 'cascade model'. This links changes in ecosystem structure and function to changes in human well-being, while LCIA links the effect of changes on ecosystems due to human impacts (e.g. land use change, eutrophication, freshwater depletion) to the increase or decrease in the quality and/or quantity of supplied ES. The proposed cascade modelling framework complements traditional LCIA with information about the externalities associated with the supply and demand of ES, for which the overall cost-benefit result might be either negative (i.e. detrimental impact on the ES provision) or positive (i.e. increase of ES provision). In so doing, the framework introduces into traditional LCIA the notion of "benefit" (in the form of ES supply flows and ecosystems' capacity to generate services) which balances the quantified environmental intervention flows and related impacts (in the form of ES demands) that are typically considered in LCA. Recommendations are eventually provided to further address current gaps in the analysis of ES within the LCA methodology.

Graphical Abstract



Keywords

benefit; cascade model; cause-effect chain; ecosystem services; life cycle assessment (LCA); valuation

1. Introduction

It is now well-known that the pressures exerted by human activities on ecosystems can compromise the capacity of ecological cycles to regenerate and supply ecosystem services (ES) in ways that negatively affect human well-being (Costanza et al., 1997; MEA, 2005; Guerry et al., 2015; Krug et al., 2017). Ecosystem services have been described as "*the ecological characteristics, functions, or processes that directly or indirectly contribute to* *human well-being: that is, the benefits that people derive from functioning ecosystems*" (Costanza et al., 2017). To assess the magnitude and importance of different impacts on ecosystems and their services in different locations, it is crucial to use appropriate assessment tools.

To date, ES are insufficiently covered in traditional environmental decision-making tools, such as Life Cycle Assessment (LCA) (Hauschild et al., 2018; Alejandre et al., 2019). LCA is typically applied to comparatively assess the potential environmental impacts of product systems in a life cycle perspective, i.e., from extraction of raw materials to the final disposal of wastes. Recent proposals (Othoniel et al., 2016; Chaplin-Kramer et al., 2017; Liu and Bakshi, 2018) indicate that ecological models are available and operational for expanding life cycle impact assessment (LCIA) to include ES, such as for example the InVEST (Bare, 2011) or the GUMBO (Arbault et al., 2014) models. Nevertheless, a consistent conceptual framework is needed that can support the integration of these ecological models into the LCIA methodology. Moreover, insufficient concordance between the system boundaries in LCA and ES, and their inventory, (impact) indicators and taxonomy has so far hampered the development of a comprehensive cause-effect chain for rigorous modelling of ES impacts in the context of LCIA, e.g. Bare and Gloria (2008), Koellner et al. (2013), and Cao et al. (2015). The greatest efforts have mostly been concentrated into the definition of impact assessment scales for evaluating the loss of ES due to human pressure, e.g. Chaudhary et al. (2017) and Stoessel et al. (2018). Assessing the impact of product life cycles on ecosystems' health and their degradation is common in LCA (e.g. through land use impact assessment; Taelman et al., 2016) to analyse environmental costs, such as ES and biodiversity losses. However, only a few LCA attempts demonstrate the additional value of considering, next to the environmental costs, also the environmental benefits associated with ES, such as carbon sequestration (Rugani et al., 2015; Yan, 2018; Nayak et al., 2019).

Under the auspices of the Life Cycle Initiative flagship project on global guidance for LCIA indicators (Verones et al., 2017), a dedicated subtask was constituted to address ES in LCA. The present article is an outcome of this subtask that contributes towards consensus building in the assessment of human activities' impacts on the provision of ES and their beneficial uses for human well-being. More specifically, we propose to harmonize the cascade concept (Haines-Young and Potschin, 2010; Potschin-Young et al., 2018) from the ES literature and the cause-effect chain modelling used in LCIA.

Integrating the ES cascade concept into LCIA is important for two main reasons. First, it more comprehensively addresses environmental costs and benefits associated with human activities, thus reducing the risk of environmental burden-shifting and improving the identification of trade-offs and synergies. In this regard, the inclusion of externalities related to ES can foster the identification of new intermediate and final beneficiaries – next to the user(s) of the life cycle product – across the phases of inventory and impact assessment of human interventions. Secondly, the ES cascade concept encourages the consideration of feedback loops between processes across technosphere and biosphere which are generally neglected in LCA (Weidema et al., 2018). Cause-effect chains in LCA models generally consider impacts generated by "drivers" of change that affect specific areas of protection, such as ecosystems. However, current LCIA models built on those cause-effect chains do not further consider the capacity of ecosystems to react to those changes. This means that, without considering the effect of human/technological interventions from the ecosystems back to the human/technosphere, the actual load of the life cycle impacts can be underestimated.

The paper is organized as follows: first, the roots and criteria associated with the formulation of the cascade model in the domain of ES assessment is illustrated (Sections 2.1–2.3). Then, an analysis of the state-of-the-art on LCA-ES integration is conducted (Section 2.4) with the goal to identify major differences and complementary features between the assessment of ES outside and inside the LCA methodology. This pre-liminary analysis provides the knowledge base to propose, in a second stage, the development of a general cause-effect chain's diagram (Sections 3.1–3.5) that can be used as a reference to address impacts on, and benefits from, the provision of ES associated with the life cycle of a product. The limitations and challenges underlying this novel approach of combining ES-related impacts and benefits in one unique LCIA framework are eventually illustrated in Section 3.6, before drawing our conclusions concerning a future implementation of the model in LCA (Section 4).

2. TaxonoThy and state-of-the-art in LCA-ES integration

2.1. Intermediate and final ecosystem services

Many definitions of ES have been formulated over the past 20 years that emphasize the beneficiary perspective and the key role for sustaining and fulfilling human life underpinning the ES concept (e.g. Fisher et al., 2009, Seppelt et al., 2011, Danley and Widmark, 2016). Boyd and Banzhaf (2007) distinguish between *final* ES (the end products of ecosystems having a direct relevance for beneficiaries) and *intermediate* ES that are not directly enjoyed or used by beneficiaries, but which underpin the output(s) of final ES. For instance, while clean water can be a flow of a final ecosystem service to one beneficiary (e.g. a person who needs drinking water), for a recreational or commercial fisher, clean water is an intermediate ES providing habitat for the productive fishery that is the final ecosystem service for recreational fishing and commercial food production. The distinction between intermediate and final ES is important to avoid double-counting during the valuation of ES (Boyd and Banzhaf, 2007; Fisher et al., 2009; Potschin-Young et al., 2017), which should prioritize the quantification of *final* ecosystem service flows that directly contribute to human well-being.

2.2. Classification of ecosystem services

Different ES classification systems have emerged in the literature (Maes et al., 2013; La Notte et al., 2017), originating mostly from the ES categorisation exercise promoted by the Millennium Ecosystem Assessment (MEA, 2005) and refined within The Economics of Ecosystems and Biodiversity (TEEB) framework (Kumar, 2010). As a follow-up of the MEA and TEEB framework, the Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2018) – CICES v5.1 in its last released version – represents an attempt to construct global consensus on the assessment of ES. It offers a relatively high level of detail (the highest number of ES categories among the classifications already mentioned) in a nested hierarchical structure (Czúcz et al., 2018), disaggregating ES at three levels: “provisioning services,” “regulation and maintenance services” and “cultural services”. Because of its focus on final beneficiaries of the ES, and also because of the possibility to capture functional attributes or the ecosystem properties under consideration, CICES is the reference classification system implemented within the Mapping and Assessment of Ecosystems and their Services (MAES) framework (Heink et al., 2016; Maes et al., 2016) and the System of Environmental-Economic Accounting (SEEA) (UN, 2014), which are internationally established instruments for incorporating knowledge on ES in policy and decision-making processes. Other ES classification systems, e.g. FEGS-CS (Landers and Nahlik, 2013) and NESCS (USEPA, 2015), all have their strengths and special attributes (Yu et al., 2017; Bordt, 2018). For example, the NESCS approach is a classification system suitable for mapping ES flows from land cover classes to economic sectors, using the North American Industry Classification System (NAICS) (USCB, 2017). Accordingly, NESCS can be considered a good option to correlate existing life cycle inventory (LCI) flows (land use and cover types) and LCIA models that consider land use and/or land use change as the driver of impact on ES at national scales (Maia de Souza et al., 2018). Further information on the differences and complementary features of each ES classification system can be found in Costanza et al. (2017), Yu et al. (2017), and Bordt (2018).

Because these ES classification systems were developed for different purposes, such as the need to avoid double counting in ES accounting or to propose monetary valuation of ES, there is unlikely to be consensus on a single classification system. As outlined in the UN report on the SEEA (UN, 2014), CICES and other ES classifications must be used in conjunction with an understanding of the beneficiaries identified within the scope of the ES quantification. If beneficiaries are not clearly defined, a risk of overestimation and double counting may occur, i.e. by considering both the intra- and inter-ecosystem flows that reflect the operation of an ecosystem, and the “final” ES that consist of direct contributions to industrial or private beneficiaries. Adoption of one or another ES classification system in LCA is also made difficult by the range of stakeholder values and priorities for targeting ES. For example, if the ES of interest in LCA are typically local (and not regional or national), such as biological control or pollination, one could use CICES which provides well-established indicators (Czúcz et al., 2018; Maia de Souza et al., 2018). Therefore, in this paper we do not advocate in favour of an ES classification system. Additional work is needed to evaluate the pros and cons of a particular ES classification system in the context of LCA.

2.3. Modelling of impacts in the ES assessment domain: reviewing the suitability of the cascade model

In the ES literature, Haines-Young and Potschin (2010) proposed a “cascade model” to explain the linkages between ecological structures, functions/processes, as well as the derived benefits and values to humans. The model was also framed to conduct spatially explicit, quantitative assessments of ecosystems, ES and benefits (Maes et al., 2012).

The concept underpinning the cascade modelling approach is represented by an integrated system of indicators composed of four sections, each describing:

1. a biophysical *structure*, which creates the basis for the functioning of the ecosystem;
2. a *function* of ecosystems and biodiversity, which represents the ecosystem capacity to produce ES;
3. an identified *benefit*, i.e. the used share of the potential of ES;
4. a *value* (of the benefit), which from an ES concept perspective can have different utilitarian forms.

The cascade model has been further developed by other authors. Spangenberg et al. (2014) provided an update of the original model, to better apply it to socio-economic processes that lead to structural changes in ecosystems. Nassl and Löffler (2015) suggested positioning the ‘cascade’ in the broader cause–effect scheme of the Driver-Pressure-State-Impact-Response (DPSIR) framework. More recently, Gerner et al. (2018) demonstrated the suitability of investigating ES in a river restoration project, emphasizing the benefits underpinning the cascade model integrated in a DPSIR framework, which can allow multi-criteria assessment and cost-benefit analysis of ES. Mononen et al. (2016) approached ES models from a country-scale perspective, proposing an operational national framework with 112 indicators for 28 ES (four indicators for each stage of the cascade model), in compliance with CICES and the cascade model. Van Wensem et al. (2017) defined a set of three criteria to be fulfilled for an ES approach to be considered appropriate for use in decision-making. These criteria relate to the full connection between ES and human well-being, the completeness of ES considered, and the investigation of how the well-being of stakeholders is altered with changes in ES. Other approaches, e.g. by La Notte et al. (2017), provided a slightly modified version of the cascade model by linking the concept of the cascade with a system’s ecological approach, allowing a better distinction between services and benefits and attributing a stronger emphasis on the complex functions of ecosystems.

Recent research suggests to move beyond a linear cascade model (Costanza et al., 2017), which can oversimplify the complexity underpinning the functioning of ecosystems and their connections to human well-being. A more integrated, dynamic, non-linear model connecting natural systems and human systems is needed to assess these linkages (Othoniel et al., 2016; Costanza et al., 2017; Weidema et al., 2018).

The cascade model is in many ways parallel to the cause-effect models applied in LCIA (Verones et al., 2017), and it has been recently suggested as a way to superimpose life cycle impact pathways on ES (Maia de Souza et al., 2018; Pavan and Ometto, 2018). In this paper, we establish an operational cause-effect chain framework for LCIA and ES based on the cascade model (Section 4). We acknowledge the current limitations of cause-effect chain modelling dependent on a linear cascade model (Costanza et al., 2017), which is inherently unable to capture the complexity underpinning the functioning of ecosystems and their connections to human well-being. In this regard, an integrated, dynamic and non-linear modelling framework connecting natural systems and human systems is needed to assess these linkages. Changing the paradigm of assessing ES using a cascade model is not the goal of the present paper; however, we believe that it is beneficial to establish an effective cause-effect chain starting from the integrated system of indicators encompassed by the cascade model. Yet, we attempt to simultaneously address some of the gaps occurring in i) the cascade model concerning the lack of a quantitative impact assessment, and ii) the current practice of evaluating ES in LCIA.

2.4. State-of-the-art in LCIA-ES integration

Over the last few years, many authors have advanced knowledge on the integration of ES in LCIA. Tables 1a–1d summarize the most relevant efforts and elements emerging from a review of this literature, which can be regrouped into four main sets of reference studies, as follows:

1. *Critical review and position papers* (Table 1a) – Research reported under this group generally aimed to identify major gaps in the analysis of ES within the LCA framework, collecting information on state-of-the-art practices and providing recommendations on how to address methodological challenges, often taking an explicit position (based on critical reviews of the literature) on best practices, instruments and knowledge domains;
2. *UNEP/SETAC branch of frameworks and methods for land use impact assessment (LULCIA)* (Table 1b) – The publications under this category originate from a task force carried out within the project "Operational Characterization Factors for Land Use Impacts on Biodiversity and Ecosystem Services in the Life Cycle Impact Assessment" and are compatible with the Framework of the UNEP-SETAC Life Cycle Initiative (LULCIA). This task force had the goal of developing novel methodologies and guidelines for the calculation and use of characterization factors (CFs) in LCIA, for assessing impacts on key ES driven by land use and land use change;
3. *Analysis of ecosystem services in the framework of LCIA, alternative to UNEP/SETAC LULCIA branch studies* (Table 1c) – Studies included in this group, which originated from activities mainly performed outside the UNEP/SETAC LULCIA branch, provide examples of how to assess the impacts of life cycle activities on the provision of specific ES using different (usually not comparable) models and impact drivers; a common general objective was eventually to calculate CFs to be used in existing LCIA frameworks;
4. *Models developed outside the conventional LCIA framework* (Table 1d) – Finally, this group of studies intended to propose novel methodological integrations based on the use of ES modelling and assessment tools to account for damages on ES according to life cycle thinking (or adopting life cycle data or inventory models), without reaching a state of full operability in LCA (i.e. without developing CFs that could be directly implemented and used in LCIA).

Despite these remarkable advances, many methodological and conceptual issues remain to be addressed in order to support more robust ES impact assessment modelling in LCA. A deeper investigation of 33 studies from the ES-LCA literature included in Tables 1a–1d suggests that:

a. current impact characterization models in LCIA are not encompassing the whole range of ES potentially damaged by life cycle systems, but only a few specific ES are tackled and without considering their interconnections in the cause-effect chain;

b. the choice of assessing intermediate or final ES is still controversial, or dependent upon the goal of the study and the final beneficiaries;

c. the use of integrated assessment models, as suggested by Costanza et al. (2017), has been proposed or showcased, but not in a sufficient manner to establish a consistent and reliable LCIA framework that can capture complex and non-linear ecosystem functions.

An ideal cause-effect chain assessment framework for ES to be adopted in LCIA should account for different aspects of ecosystem *structure* and *function* that underpin the supply of ES, as well as their *benefit* and *value*, as conceptualized in the cascade model. This rationale was introduced by Othoniel et al. (2016) who, starting from a proof-of-concept elaborated in Arbault et al. (2014), recommended the use of dynamic integrated models to assess the (non-linear) impacts on the capacity of ecosystems to supply ES, as well as their beneficial value for the product system. The implementation of LCIA characterization models that can consider multiple space- and time-dependent dimensions associated with the complex interaction of processes occurring at the ecosystem level, which is often at a different time and place than the anthropogenic pressure, is still incompletely achieved. Similar conclusions have been reached by Chaplin-Kramer et al. (2017), who further advanced this knowledge by concretely combining the outputs from predictive ecological tools for ES mapping and assessment, e.g., InVEST (Sharp et al., 2018), with conventional LCIA indicators. Despite its efficiency for calculating CFs for ES impact models that consider fine spatial heterogeneities, the latter approach solves only partially the problem of how to consider non-linear effects and trade-offs in a cause-effect chain. Burkhard et al. (2014) and Bakshi et al. (2015) suggest a cause-effect chain based on the demand and supply for ES.

The links between ES flows and LCI flows, and how and where ES shall be positioned within the cause-effect chain still present open questions (Bruel et al., 2016; Blanco et al., 2018). For example, ES within the CICES categories could be considered at different levels in cause-effect chains, from environmental pressures, belonging to the LCI, to indicators at midpoint or endpoint levels along the impact pathways (Zhang et al., 2010b; Pavan and Ometto, 2018). The controversy on positioning ES in cause-effect chains can mainly be referred back to the arbitrary boundary between technosphere and ecosphere in LCA (Weidema et al., 2018) and to the metrics used for ES indicators, e.g. physical units for midpoint indicators (Koellner et al., 2013; Saad et al., 2013; van Zelm et al., 2018) and monetary units for endpoints (Cao et al., 2015). Linked with the need to define the position of ES in the cause-effect chain is the challenge of defining the final beneficiaries of these ES and the associated scale of assessment. Another issue is the need to clearly distinguish between ES assessments that sum up the total value of final flows of ES (Costanza et al., 1997) and ES assessments that are more consistent with the LCA approach in evaluating how human activities affect the flow of final ecosystem services (USEPA, 2015).

3. Framework for a cause-effect chain in LCIA based on the cascade model

The literature explored in Section 2 suggests that a cascade modelling approach can be generally applied in the framework of LCIA to assess impacts on the provision of ES and that there is an opportunity to harmonize concepts from the fields of ES and LCA. By comparing the cascade model for ES assessment and the cause-effect chain model for LCA (inventory > midpoint level > endpoint level > area of protection), it can be observed that the former ideally encompasses the entire range of impact category indicators used in LCA, their target beneficiaries, their interconnections at the level of areas of protection, and their space- and time-dependent variabilities (Antón et al., 2016; Othoniel et al., 2016; Maia de Souza et al., 2018). Given the current limitations associated with the reviewed LCIA characterization models for ES (Section 2.4), we propose here a general assessment framework for ES in LCIA in the form of four subsequent and interrelated assessment "steps," as shown in Fig. 1 (inventory, impacts on ecological processes, impacts on ES, valuation and feedback loops to technosphere). These steps are aligned with the four phases of the cascade model for ES: structure, function, benefit, and value. The meaning and attributes of each step in the proposed assessment framework are described in the following section.

3.1. Inventory step (I)

The inventory step represents a conventional LCI matrix with economic activities on one axis and flow-objects (products, emissions, lands and resources, including provisioning ecosystem services) on the other axis. Multiplying a demand vector f representing the functional output of the investigated system on the inverse of the square technology matrix part **A** produces a vector of scaling factors **s** which are then applied to the biosphere matrix **B** of elementary flows. This matrix can be understood as a rectangular array of numbers within the global LCI matrix that correspond to the flows of emission, land and resource (all of them usually arranged in rows), among which provisioning ecosystem services, possibly associated with each activity of the same matrix (those activities being usually arranged in columns). The output 1 from step I is the scaled matrix **Bs** of human pressures (emissions, lands and resources), associated with the functional output of the investigated system.

3.2. Impacts step (II)

The sphere of impacts on ecological processes, or step II, represents the place of interaction between the human pressures associated with the investigated product system and the geo-biosphere compartment. In LCA, this is typically represented by the cause-effect chain that links the spatially and temporally specified elementary flows to the characterization factors of impacts at midpoint level. In parallel to the ES cascade model, step II is where the human pressures operate on the "**structure**" of the ecosystems. Accordingly, this "impact" step applies the scaled matrix **Bs** of calculated elementary flows (*pressures*) to a matrix Y of *impact category indicators* (i.e. each matrix element $y_{ji} \neq 0$ corresponds to a spatially explicit midpoint impact characterization factor CF_{ji}). The output of step II is a new matrix containing the calculated scores of impact category indicators. Each midpoint impact shall be spatially and temporally resolved for ES assessments, which places a requirement on the LCI data to also be spatially specified. The characterization of impacts on ES shall include the time lag between the pressure and the occurrence of its effect on the state of the environmental compartment, as well as the spatial dimension, i.e. the place where the pressure influences the state (either local/regional or global, or both). This implies that the characterization is performed by multiplying specific **CFs** for each element in the **Bs** matrix rather than, as traditionally done in LCA, where the characterization is done on the traditional g vector that aggregates the elements of the original **B** matrix across all human activities without concern for spatial information (usually $g = \mathrm{B} \cdot \mathrm{A}^{-1} \cdot f$; see e.g. Heijungs and Suh, 2002).

Among the set of impact pathways depicted by the elements of Y, step II can include specific environmental mechanisms able to capture the effects of human activities on the provision of intermediate ES. A synthesis of how to align ES categories to LCI flows and LCIA indicators is offered in Table 2. By specifying the links between possible inventory flows and impact category indicators, a cause-effect chain for ES can therefore be depicted out of Table 2, as a follow-up of former cause-effect chain diagrams outlined by Koellner et al. (2013) and Antón et al. (2016). However, this still only partially explains what an impact assessment for ES would entail (see steps III and IV). Both qualitative (e.g. dimensionless indicators such as the increase or decrease of abundance of pollinator species) and quantitative measures can/shall be traced in step II to assess the potential impact of human pressures on the respective area of protection for the supply of ES, to further advance the knowledge on the intrinsic, instrumental, and/or cultural values underpinning each ES, see e.g. Table 1 in Verones et al. (2017).

3.3. Impacts on ecosystem services step (III)

The subject of the “impacts on ecosystem services” step, or step III, is the influence of the human pressure-related impacts from step II on the capacity of ecosystems to deliver final flows of ES. Here, the aim is to model how much and for how long the impacts from the system stressors alter the natural cycles and functionality of ecosystems, which as a first proxy can be related to “land cover” classes. The use of land cover and land cover change information is a common practice in the ES assessment domain (Seppelt et al., 2011; Maes et al., 2016). As suggested by Burkhard et al. (2014), land covers can be seen as Services Providing Units (SPUs, i.e. spatial units that are the source of an ES), which in turn can be considered the reference physical land types where a change in the ES provision can influence the areas of protection ‘Natural Resources’ and ‘Ecosystem Quality’.

In step III, the ecological processes (e.g. carbon and hydrologic cycles, terrestrial and aquatic food webs, and plant succession, etc.) of step II can be linked to changes in land cover. The output of step III is a matrix of ‘ES supply changes’. Because the ‘function’ of the SPUs is to provide services, the changes in the capacity of ecosystems to provide ecological flow-objects and ES are benchmarked through reference scores of “potential capacity to provide ES flows” specific to each land cover. These scores can then be optionally linked to the impact characterization profile obtained in step II (feedback from step III to step II in Fig. 1) and/or to the initial LCI in step I (feedback from step III to step I). There are two possible ways to provide those links:

1. One option is to assign qualitative scores of ES importance to each land cover type. Examples of semi-quantitative weighting matrices that link land cover types to ES potentials, flows, demands and budget estimates are provided by Burkhard et al. (2014). These can be used to approximate ES trade-offs and synergies in cases of data gaps or where other more robust ecological modelling or field analysis cannot be conducted. In this approach, the impact indicator scores (previously quantified in step II) are multiplied by the scores from, e.g., the Burkhard et al.'s (2014) ES tables. A consistent mathematical procedure shall nevertheless be formulated per each ecological process and affected land cover. A practical example of how to design a cascade model for LCA according to this option is illustrated in Section 3.5.1.

2. Another option can provide more robust results in terms of spatial and temporal representativeness than the first option. However, this is certainly more complicated to apply since it implies a soft or hard coupling between LCA and other approaches for ES quantification and assessment. A comprehensive description of the implications for combining (and possibly accommodating) LCA with other tools for ES assessment is offered in Section 3.5.2.

In both cases (options 1 and 2) when considering the importance of modelling the interactions occurring in step III, it is worth exploring different solutions to create a sound and scientifically robust model for the cause-effect chain for ES. This also depends upon the outputs from step II (see Table 2).

3.4. Valuation step (IV)

This final step accounts for the “benefits” and/or “costs” associated with changes in “final ES” that provide a benefit for society. Here, the outputs from matrix III (ΔES), i.e., the vectors of ES as a function of land cover type (SPUs identified in step III) are multiplied by their monetary value in P (representing the positive or negative externality costs associated with each ES flow). The value of ES can be retrieved from different sources, e.g. literature, site-specific surveys, or other monetary valuation techniques as outlined in the forthcoming ISO 14008 (ISO, 2019). The output from step IV represents the costs and benefits relating to the investigated product system, and may feedback to the technosphere.

3.5. Implications when applying a cascade model in traditional LCA

An ideal implementation of the cascade model would provide a complete integrated framework of *causes* (i.e. pressures due to the production of a FU) and *effects* (i.e. impacts on the ecosystems' capacity to generate ES and the value of these impacts) for the quantification and assessment of the ES in LCA. One advantage of using the cascade approach is that trade-offs and synergies among very different ES can be explicitly considered, notably within the output from steps III (in biophysical and/or qualitative terms) and IV (in universal units, such as monetary units). To this end, we outline below two possible modelling solutions that can guide practitioners into the design and implementation of a cascade model for ES assessment in LCA. The first solution (Section 3.5.1) is mathematically compatible with current LCI and LCIA calculation routines and may easily incorporate the criteria for qualitative and semi-quantitative assessment of ES anticipated as an “Option 1” in Section 3.3. While the second solution (Section 3.5.2) implies the design of an integrated cascade model that combines LCA with other modelling tools for ES assessment, in accordance with the criteria for “Option 2” anticipated in Section 3.3.

3.5.1. Cascade model compatible with LCA calculation routines—Weidema et al. (2018) have recently proposed the use of an expanded matrix calculation framework compatible with the traditional LCA approach of collapsing all activities and impacts for the life cycle model within a single time step. This approach is suggested in the present paper as an operational solution to develop a cascade model for ES assessment in LCA, because it would include the outputs 1, 2, 3 and 4 from Fig. 1 in the same calculation matrix routine. As depicted in Table 3, a matrix format containing input (“demand”) and output (“supply”) elements could be considered as a table of demands per activity (column) for supplies of flow-objects (rows). Supplies could be both physical items and services that remove physical items. According to this approach, it would then be possible to invert the entire matrix of Table 3, the result of which would be a matrix of scaling factors for life cycle impacts. When multiplied by the driving (column) vector f (the functional unit of demanding one or more specific products), this matrix could provide the life cycle impacts corresponding to f. Given sufficient data available to describe the environmental mechanisms underpinning the provision of ES (e.g. those data belonging to the LCA items in Table 2), this mathematical routine could ideally facilitate the assessment of impacts on ES in a fully integrated but simplified manner with LCA tools, considering feedback loops and information about the effect of human activities on ecosystems.

3.5.2. Cascade model not (yet) compatible with LCA calculation routines—While the approach described in Section 3.5.1 represents a “ready-to-apply” mathematical solution compatible with LCA, collecting data to fill some of the matrices described in Table 3 (in particular with regard to C_{II}, C_{III}, D_I and D_{III}) can be highly time-consuming. An alternative way to account for the impact of multiple human stressors on ecosystems and their ecological processes and feedback flows is represented by the use of integrated models. Those generally aim to quantitative understand the interdependency between science-based components, and the dynamic history and future of human–environment interactions at different spatial and temporal scales (Laniak et al., 2013; Turner et al., 2016). Integrated models can be very comprehensive and complex in that they can estimate data and quantitative relationships between elements of interconnected environmental and society/economy compartments. Multi-disciplined biophysical and economical models can also be integrated or interactively used to simplify and better determine quantitatively the interrelationships between provisioning ES flows and the components of water-food-land-energy nexus frameworks (Karabulut et al., 2018). Therefore, such models can ideally be used in combination with LCA as a modelling toolbox for generating the necessary information required from step II to steps III and IV in Fig. 1.

As anticipated by the studies included in Table 1d, several integrated assessment models and tools exist to evaluate the effect of human activities on the functionality of ecosystems, their integrity, structure and capacity to provide services (Bagstad et al., 2013; Oosterbroek et al., 2016; Posner et al., 2016; Rova et al., 2019), which can be applied to accommodate LCA needs for ES assessment. For example, starting from a proof-ofconcept (Arbault et al., 2014), the VALUES project (http://www.lifecycle-values.lu/) has been developing an integrated system dynamics-based model adapted from the MIMES tool (Boumans et al., 2015). This model integrates different modules interlinked with one another, which include the use of georeferenced/spatial datasets, economic input-output databases, ecological process-based models, socio-economic statistical parameters, etc. Moreover, it can consider the effect of future land use changes (and other impact drivers such as global climate change) on the capacity of ecosystems to supply ES. The outputs of this tool can be used to calculate specific spatially-explicit (country scale) and scenario-based characterization factors for some ES whose value is intrinsically dependent upon the interactions among the different attributes of the model over time (see the recent work of Othoniel et al. (2019) on this matter). Other deterministic tools, like the Environmental Policy Integrated Climate (EPIC) model, allow the evaluation of the effect of various land management and agricultural sustainability strategies on soil erosion and its productivity (Williams et al., 2015). van Zelm et al. (2018) show the strengths of applying the EPIC modelling approach to calculate CFs for the damage assessment of soil erosion impacts caused by crop production (see Table 1c), and Liu and Bakshi (2018) provide a test-bed method for combining the carbon supply and demand flows from the EPIC soil carbon cycle module into the LCI. Similarly to EPIC, models in InVEST (Sharp et al., 2018) include both service supply (e.g. living habitats as buffers for storm waves) and the location and activities of people who benefit from these services. The InVEST toolbox represents a suite of models based on production functions that define how changes in ecosystem structure and function are likely to affect the flows and values of ES across a land-or a seascape (see further in: http://www.naturalcapitalproject.org/invest/#what-is-invest). A practical use of InVEST in the framework of LCA can be found in Chaplin-Kramer et al. (2017) (Table 1d). A broader illustration of other examples of modelling tools which can be exogenously or endogenously combined to LCA is provided by Turner et al. (2016).

3.6. Limitations and challenges

The two solutions for building an ES cascade model in LCA described before are not free of potential shortcomings. The main limitation underpinning the operationalization of the first solution (Section 3.5.1) concerns the data collection phase. While the proposed mathematical approach can easily address spatial differentiation, which is an intrinsic characteristic of any ES analysis, the collection of background-regionalized data (i.e. secondary data, not under the control of the cascade modeller) on species, ecosystem functions, processes and impacts can be very complicated. So far, a harmonized, global database that can inform all those elements is not available, and knowledge in this field depends on the progress of science and on-field data collection and dissemination worldwide. However, this represents a common challenge in LCA every time a new life cycle impact characterization method or indicator is developed.

The lack of secondary data can somehow be addressed with the use of qualitative values. As suggested for the “Option 1” in Section 3.3, the practitioner interested in applying our cascade framework could invest some time in collecting first specific land cover data for his case study, and then in designing a “qualitative” matrix of scores of ES importance for each land cover type as a first proxy to assess changes in ecosystem functionalities.

Another limitation of the first solution concerns the lack of a temporal dimension associated with the matrix elements. In other words, the proposed mathematical model cannot, at the present stage of development, capture the time dependency of the impacts and feedback flows, which also hampers accounting for the non-linear effects possibly occurring between the ecosystem functions and the provision of ecosystem services. Conversely, all these characteristics are intrinsic of the integrated ecological modelling concept. Nevertheless, the implementation of such models is not easy to make operational in LCA, which represents a relevant potential shortcoming. As a consequence, the second solution proposed in Section 3.5.2 is considered to be further than the first one from a state of possible implementation in LCA, because it requires designing and applying modelling systems not typically compatible with LCA nomenclature, units of measurement, databases, etc.

As recently observed by Alejandre et al. (2019), several impact categories still need to be incorporated –and characterization factors developed– in current LCIA practice to achieve an optimal state for the coverage of ES in LCA. In accordance with our findings, these authors implicitly suggest that interdisciplinary cooperation shall be promoted to develop models that can help achieving such an optimal state without losing the representativeness (and spatial differentiation) in natural processes and effects that are desired to assess. We argue that the cascade model proposed in the present paper can meet this challenge. Cause-effect chain frameworks based on the cascade model could encompass indicators of ecosystem service that so far have not been fully encompassed by LCIA methods. One such indicator that has been discussed is emergy. Emergy uses the indicator of equivalent solar energy to account for the environmental work potentially required to support a product life cycle (Rugani et al., 2013; Coscieme et al., 2014). However, the relevance of using emergy as a proxy indicator for ES is still under debate within the scientific community (Raugei et al., 2014). Also, there is not full agreement within the same emergy community on how to apply/adapt the emergy analysis method to account for ES.

Additional opportunities could also be explored to strengthen the cascade impact pathway model from the drivers of change to the effects on the supply of services. For example, with regard to the interaction among ES and the identification of common drivers of provision of, and impact on, ES, Lee and Lautenbach (2016) have analysed pairwise relationships between ES according to a quantitative critical review of the literature and the CICES system. If an integrated assessment model cannot be designed and run to retrieve results from steps III and IV, such types of correlations among ES could also be used to qualitatively determine the hotspots in the profile of ES values.

4. Conclusions and recommendations

The cascade model (Potschin-Young et al., 2018) is a conceptual framework used to capture key aspects of the ecosystem services paradigm including the links between *structure*, *function*, *benefit* and *value* of ecosystems for human well-being. In this paper, we have proposed a first attempt to re-formulate traditional LCIA informed by the ES cascade conceptual model. This re-formulation builds upon and consolidates knowledge from recent advances in the LCA-ES literature and can be used to design an LCIA approach that quantifies the impacts from the life cycle of any product on the capacity of ecosystems to supply services. Moreover, an analysis of pros and cons associated with the potential application of the cascade model in LCA prompts us to emphasize the relevance of complementing the impact assessment with information about the externalities associated with the supply and demand of ES, and to eventually determine an endpoint cost-benefit balance result. While the cascade model has limitations (Costanza et al., 2017), it introduces into traditional LCIA the notion of “benefit” (in the form of ES supply flows and ecosystems capacity to generate services) which balances the quantified environmental intervention flows and related impacts (in the form of ES demands) that are typically considered in LCA.

On top of the proposed integration with the ES cascade framework, the present paper has highlighted the main research gaps for the evaluation of ES in LCA. Several concerns remain to be addressed in the future, the first of which is related to the choice of the ES classification system, and the mapping of the chosen ES to accepted LCI flows, clearly showing where elementary and product flows can be linked to ES. Secondly, the systems-level relationships between structural and functional aspects of biodiversity might lead to double-counting in the impact assessment, which is a concern that needs to be addressed in future ES-LCA development. Thirdly, the adequate temporal and spatial scales for quantification of ES needs to be determined, developing data and metrics based on supply and demand of ES, considering that ES are heterogeneously provided and valued across different spatial granularities, geographical scopes and time horizons.

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HIGHLIGHTS

- Ecosystem services (ES) are not fully encompassed in Life Cycle Assessments (LCAs).
- The ES cascade model is investigated and proposed as one solution to address this gap.
- This framework addresses externalities associated with the supply and demand of ES.
- Through a cascade model, LCA can account for both environmental costs and benefits.

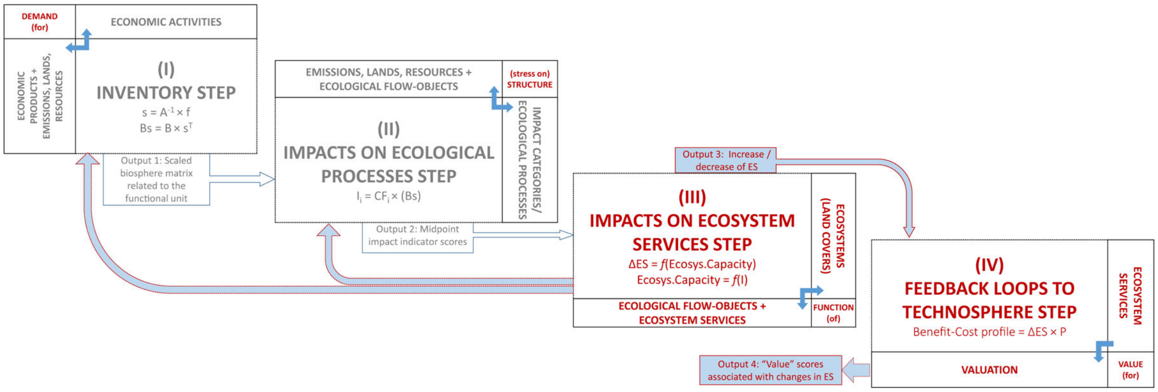


Fig. 1.

Conceptual cascade model (structure > function > benefit > value) of the LCIA for ecosystem services (ES). RED text represents what is new compared to current LCA practice, which is indicated in GREY. Arrows indicate the directionality of the computational framework. Interactions between technosphere processes and the environment are represented by the outputs of step I, which generate a stress on the environmental compartments' "structure"; while the outputs from step II are sources of impact for the ecosystems "function" to supply ecological flow-objects and ES; outputs from step III are "positive" or "negative" changes in the capacity of ecosystems (using land cover as a first proxy) to provide, respectively, a "benefit" or a "cost" for the society/technosphere, which are further reflected by the outputs from step IV that represent the final change in "value" associated with the investigated product system. The latter can be perceived in terms of ES balance as the benefits (positive externalities) and/or costs (negative externalities) caused by human stressors over a space- and time-dependent cause-effect chain. The dotted arrows indicate that the overall information related to changes in ES can potentially feed back into the initial life cycle inventory model and midpoint impact characterization step to complement the linear modelling associated with the original functional output of the investigated system.

Table 1a

State-of-the-art on modelling life cycle impact pathways for the assessment of ecosystem services: *critical review and position papers*.

Reference study	Goal & scope	Impact drivers	Reference ES classification and indicators	Limitations and/or recommendations
Zhang et al., 2010b	Proposal of a framework for including ES into LCA, proposing a hierarchy of metrics.	Services supporting the US economy in 1997.	Provisioning, regulating and supporting ES according to MEA classification.	The indicators are not easily compatible with LCIA endpoint indicators, they are at the midpoint; unsure how well Emergy and Exergy represent (some) services; based on 1997 economic input-output model.
Bare, 2011	Demonstration of the feasibility to use an existing model (e.g. the Natural Capital Project's InVEST) to conduct ES modelling in LCIA.	Primarily land use change, but can also include extraction of natural resources, etc.	All types of ecosystem services (i.e., provisioning, regulating, supporting, and cultural); classification system: (un)specified.	Models require site-specific input parameters to make them more defensible at individual locations; LCA community should consider existing models for incorporation into LCIA.
Antón et al., 2016	Proposal of an overview and explanations of most recent attempts of including different ES in LCA.	All possible impact drivers for the loss of biodiversity and ecosystem services are depicted.	Provisioning, regulating and supporting ES; classification system: MEA.	The chapter gives an overview of "state-of-the-art" in 2016, but does not provide new CFs; a general cause-effect chain diagram that encompasses impacts both on ES and biodiversity loss is provided.
Othoniel et al., 2016	Generation of consensus on the combination between LCA methodology and ES theory. Investigate approaches, strengths and knowledge gaps of LCIA cause-effect chains.	Land use change (but the use of other drivers is also discussed).	All types of ecosystem services; classification system: CICES.	Recommend to move towards the development and use of a multifunctional dynamic integrated ES model for the LCIA for ES. The combination of LCA with integrated ecological-economic models can increase modelling complexity, simulations time and uncertainty. Requirements for LCIA adaptations are provided in detail.
Callesen, 2016	Explicit subdivision of areas of protection in one on biodiversity and one on ES; discussion on related impact pathways and indicators, with proposal of use of modelling approaches from ES and biodiversity assessment.	Land use and land use change.	All types of ecosystem services; classification system: MEA.	Among others, the paper suggests that biodiversity and ES, i.e. in a broad sense ecosystem structure, functioning and composition are designated as two different areas of protection. However, since this critical review does not acknowledge other state-of-the-art approaches in the LCA-ES domain, the recommendations advanced by the author shall be considered with care (Rugani et al., 2017).
Crenna et al., 2017	Proposal of a framework for including the ES of pollination into LCA. Major focus on the impact drivers for pollination.	8 potential drivers: intensive land use, pesticide use, invasive plants, competition with invasive pollinators, climate change, pests and pathogens, electro-magnetic pollution, genetically modified crops.	Pollination services; classification system: MEA.	Suggestions are made for research to develop new CFs; no functional CFs exist as of yet for the proposed eight impact categories (except for greenhouse gases (GHGs) on a midpoint level for climate change impacts).
Vidal Legaz et al., 2017	Evaluation of existing models addressing impacts on soil quality, properties and functions, identified research needs, and proposal of recommendations for more robust modelling.	Land use and land use change (but the use of other drivers is also discussed).	All types of ecosystem services; classification system: unspecified.	The study identified research development needs for more robust modelling of life cycle impacts on soil quality. However, the study provided few recommendations on how to address these needs.
Maia de Souza et al., 2018	Contribution to address some of the challenges faced to integrate ES into decision making, reviews existing ES classification systems, and proposal of a conceptual	Land use and land use change.	All types of ecosystem services; classification system: CICES (and the cascade model).	Draws recommendations on the use of the cascade model to integrate ES into LCA, on the need to differentiate between the spatial and temporal scales in which ES are generated and delivered, and the choice of scales linked with different stakeholder groups. Some of these issues are

Reference study	Goal & scope	Impact drivers	Reference ES classification and indicators	Limitations and/or recommendations
	framework to link the cascade model and the LCA approach.			addressed on the integrated LCA and cascade model framework proposed. However, direct solutions to problems, such as how to account for spatial and temporal scales remains a challenge.
Pavan and Ometto, 2018	Comparison of the ES cascade model and LCA environmental mechanism for land use impacts, improving and synthesizing a new conceptual framework for soil-related ES assessment in LCA studies.	Land use and land use change.	Ecosystem services related to soil. Classification system: CICES	The proposed framework used the elements from cascade model of ES related to soil, which can help to understand the hierarchy among ES as well as support further refinements in LCIA by including new ES types and the benefits provided to society. However, the result is a conceptual model, requiring future studies for operationalization.
Karabulut et al., 2018	Proposal of a synthesis matrix system to integrate the life cycle thinking and assessment with the “nexus” framework Ecosystem-Water-Food-Land-Energy (EWFLE) to define better potential drivers of impacts and hotspots.	The EWFLE security nexus framework can encompass all the political, socio-economic and environmental drivers that are posing a risk to the provision of ecosystem services.	Only (abiotic and biotic) provisioning services are depicted. Classification system: CICES	The novelty of the proposed set of matrices stands in their capacity to anticipate tradeoffs and synergies at different scales (from global to local) between natural resource uses and ecosystems, and their effective relationships, through qualitative assessments. To capitalize the theoretical system underpinning the EWFLE security nexus and translating it into a quantitative assessment of the impacts, the LCA framework still requires adaptations to improve the comprehensiveness of the impact evaluation.

Table 1b

State-of-the-Art on modelling life cycle impact pathways for the assessment of ecosystem services: *UNEP/SETAC branch of frameworks and methods for land use impact assessment (LULCIA)* (Koellner et al., 2013).

Reference study	Goal & scope	Impact drivers	Reference ES classification and indicators	Limitations and/or recommendations
Koellner et al., 2013	Proposal of a framework to calculate land use and land use change impacts and provided guidelines and recommendations to address impacts on biodiversity and ecosystem services in LCIA	Land use and land use change.	Biotic production potential (BPP), climate regulation potential (CRP), freshwater regulation potential (FWRP), erosion regulation potential (ERP), water purification potential (WPP); classification system: MEA.	The framework includes several indicators on ES and biodiversity. It introduces an indicator on functional diversity (de Souza et al., 2013), which has the potential to link impacts on ecosystems, biodiversity and ecosystem services. This publication did not address the linkages between ES and final values to humans.
(Müller-Wenk and Brandäo, 2010)	Development of a climate regulation potential (CRP) impact category indicator.	Land use and land use change.	Climate regulation (regulating service); classification system: unspecified.	It is an operational model with a global scope that considers an important impact pathway. However, the quality of input data, such as carbon content in vegetation and soil and carbon transfers to air due to particular land use types for example, is still limited and needs improvement according the authors. Moreover, this study does not address the linkages between ES and the actual benefit or final values to humans.
(Brandão and i Canals, 2013)	Development of a biotic production potential (BPP) impact category indicator, based on soil organic carbon (SOC).	Land use and land use change.	Biotic production (provisioning service); classification system: MEA.	Model includes only one indicator, based on SOC, but with global coverage. Only a limited number of land use types considered, but land management practices are considered in the model.
(Saad et al., 2013)	Proposal of an operational LCIA characterization method that addresses land use impacts at a global scale by developing spatially differentiated CFs.	Land use and land use change.	Indicators: Erosion resistance, mechanical filtration, physicochemical filtration, groundwater replenishment; classification system: MEA.	Model includes several indicators. No distinction made on management practices (e.g. intensive vs extensive).
(Muñoz et al., 2014)	Application of seven novel impact categories on biodiversity and ecosystem services (BES) to an LCA study of ethanol production with different agricultural feedstock in different regions.	Land use and land use change.	Biodiversity damage potential (BDP), climate regulation potential (CRP), biotic production potential (BPP), freshwater regulation potential (FWRP), erosion regulation potential (ERP), water purification potential through physicochemical filtration (WPPPCF) and water purification potential through mechanical filtration (WPP-MF). Classification system: MEA	In this publication the recommended indicators in Koellner et al. (2013) are applied for the bio-based ethanol production. The study does not bring further methodological improvements and does not address the linkages between ES and final values to humans.
(Cao et al., 2015)	Operationalization of ES in LCIA via monetization using parameters for economic conversion, exposure factors, and adaptation capacity.	Land use change.	Biotic production, groundwater recharge,erosion regulation, water filtration, climate regulation. Classification system: MEA	No discrimination between crop types; assumes all biotic production due to soil carbon (ignoring capital, labour, climate, etc.). Improved modelling of ecosystem dynamics; more complete inclusion of ES; further research on ES-LCIA integration using the UNEP/SETAC framework; definition of appropriate spatial scales.

Table 1c

State-of-the-Art on modelling life cycle impact pathways for the assessment of ecosystem services: *Analysis of ecosystem services in the framework of LCA, alternative to UNEP/SETAC LULCIA branch studies.*

Reference study	Goal & scope	Impact drivers	Reference ES classification and indicators	Limitations and/or recommendations
(Núñez et al., 2013)	Development of a globally applicable and spatially resolved method for assessing land use impacts on the erosion regulation ES.	Land use.	Erosion regulation ecosystem service, with Loss of Net Primary Production (NPP) and Emergy indicators. Classification system: MEA.	The model does not include an uncertainty assessment and the characterization factors are not related to land use inventory flows. In addition, there is no clear link between the ecosystem service, its benefit and value to humans.
(Schaubroeck et al., 2013)	Proposal of an LCA framework to assess the impact of integrated Techno-Ecological Systems (TES), comprising relevant ecosystems and the technosphere.	Resource and emission flows, land use.	Classification system: unspecified.	The proposed mathematical framework does not distinguish between technosphere and ecosystem compartments. This may allow considering damages on ecosystems and provision of services (and associated benefits) in the same calculation routine.
(Xue et al., 2014)	Assessment of ecosystem service through carbon sequestration in different tillage systems calculated by the Sweden C tax and afforestation cost in China.	Agricultural activities and emissions.	Monetary valuation with the indicator in ¥ ha^{-1} $year^{-1}$. Classification system: unspecified.	This publication includes a monetary valuation but the relationships between carbon sequestration and other ecosystem services were not studied
(Bos et al., 2016)	Development of second generation CFs for LCIA on soil ES related aspects from the LANCA® tool.	Land use change.	Erosion Potential, Infiltration Reduction Potential, Physicochemical Filtration Reduction Potential, Groundwater Regeneration Reduction Potential, Biotic Production Loss Potential. Classification system: unspecified.	The model includes several indicators and covers a large set of land use types. No distinction is made onmanagement practices (e.g. intensive vs extensive). The model is limited in the geographic scope, only covering a limited number of regions.
(Bruel et al., 2016)	Development of a new approach based on bio economic models of ES to assess environmental externalities through LCA.	Extraction of natural resources; emissions and extractions.	Monetary indicator of the loss of drinking water benefit. Classification system: unspecified.	The calculated CFs are specific for a single case and only one ES is modelled. The proposed framework evaluates the loss of benefits through monetization techniques and includes the hierarchy of ES (differentiation between “intermediate” and “final” ES).
(van Zelm et al., 2018)	Use of a deterministic biophysically based agro-environmental simulation model (i.e. EPIC) to address soil erosion impacts on seven types of crops.	Agricultural production as a main driver: CFs express the damage caused per kg of crop, and not per m^2 of land use.	Amount of soil lost per kg of crop. Classification system: unspecified.	Model validation is still needed for some crops. Final correlation to endpoint impact category is not done. Moving towards an endpoint assessment, the calculated CFs could be coupled to damage scores in terms of monetary values.
(W. Liu et al., 2018)	Integration of carbon dynamic models and development of an approach to account for the impact of land use change on carbon sequestration as an ecosystem service.	Land use change.	Values of carbon sequestration rate (in CFs g C/m^2/year) associated land use changes in different scenarios. Classification system: unspecified.	The CENTURY4.0 model is used to estimate the carbon sequestration of different vegetation types during land use interventions. To determine the most suitable carbon dynamics model for a specific land use change, more validations need to be conducted, albeit the estimation of carbon dynamics is very complex.
(Jeswani et al., 2018)	Assessment of land use impacts on biodiversity and ecosystem services associated with the production of breakfast cereals through LCA.	Land occupation and land use change.	Biotic production, erosion resistance, groundwater regeneration, infiltration and physicochemical filtration. Classification system: MEA.	The authors applied LANCA v2.0 method (Bos et al., 2016) to evaluate ES impacts due to production of breakfast cereal as an illustrative example. Some limitations pointed about the method

Reference study	Goal & scope	Impact drivers	Reference ES classification and indicators	Limitations and/or recommendations
				includes the lack of differentiation between conventional and organic agricultural practices as well as uncertainties.
(Alejandre et al., 2019)	Definition of an optimal coverage of ES in LC, defined as the '*inclusion of a minimum number of ES categories that still sufficiently represents the wide variety of specific ES*'. Evaluation and recommendation on which ES categories form such optimal state.	Multiple drivers depending on which category indicator is selected to assess which impact on ES provision.	Fifteen aggregated impact categories proposed (starting from the LCIA method ReCiPe2016) for an optimal coverage of ES. From those fifteen categories, only four are found to be fully covered (1) "water provisioning", (2) "Atmospheric composition and conditions regulation", (3) "Mineral resources", and (4) "Non-mineral resources". Classification system: CICES v5.1.	Most of the impact categories required to cover the assessment of impacts on ES are still missing in LCIA, at least in the ReCiPe2016 method analysed by the authors. A step of prioritization for those missing ES categories, based on monetary valuation scores, can be used (and improved) as an indication of which ES require more attention and rapid integration in LCIA methods.

Table 1d

State-of-the-Art on modelling life cycle impact pathways for the assessment of ecosystem services: *models developed outside the conventional LCA framework.*

Reference study	Goal & scope	Impact drivers	Reference ES classification and indicators	Limitations and/or recommendations
(Zhang et al., 2010a)	Critical review of existing methods (e.g. ecology and ecological economics methods, impact-oriented methods and physically based resource accounting methods) and proposal of their integration, in order to more comprehensively account for ES in LCA.	Various drivers (land use, use of fossil fuels, etc.)	Provisioning, regulating and supporting ES according to MEA classification.	Methods do not account for a comprehensive range of ecosystem services and impacts are not modelled up to the damages to human well-being. The indicators are not easily compatible with LCIA endpoint indicators, they are at the midpoint.
(Arbault et al., 2014)	Demonstration of the feasibility and usefulness of applying a dynamic earth system model to calculate CFs for ecosystem services.	Extraction of natural resources; environmental and socio-economic impacts at global scale.	All types of ecosystem services. Classification system: Costanza et al. (1997).	The calculated CFs are not applicable as such in LCIA; the global resolution of the model items does not fit the LCA granularity. The nomenclature and spatial dimensions of the model stocks and flows shall be harmonized to the LCA framework.
(Bakshi et al., 2015)	Proposal of a framework to account for ecosystem services considering the relative difference between supply and demand of individual ecosystem services.	Pollution emissions, resource demand.	Air quality regulation, carbon sequestration and non-renewable energy resources. Classification system: various.	Method based on differences in supply and demand for particular ES. It remains difficult to aggregate differences in supply and demand across ecosystem services without applying weighting. Suggestion to apply weighting using monetization.
(Chaplin-Kramer et al., 2017)	Application of globally available, spatial data and newly accessible tools for ES to predictive modelling of large-scale changes in agricultural systems through LCA.	Land use change (from predictive “land-change” modelling (LCM)	Global warming potential, eutrophication potential, water consumption, erosion regulation potential, biodiversity damage potential. Classification system: unspecified.	Key elements of life cycle inventory in the agricultural stage of an attributional LCA with outputs from predictive land-change modelling (LCM) and spatially explicit ES modelling using the InVEST software. Detailed modelling needed that may only be done for foreground systems (i.e. systems that embed processes that are under the control of the decision maker for which the specific LCA is undertaken). Method needs spatially explicit information about the whole supply chain. Limitations of predictive land-change modelling. Landscape configuration is a major modelling gap in current LCA.
(Blanco et al., 2018)	Design of a framework for assessing ES as a midpoint in LCA which is demonstrated using a mining case study (water extraction) in Chile.	Land use change, resource extraction, and substance emissions	Food provision, carbon sequestration, tourism and recreation, and flood protection. Classification system: MEA.	Not able to account for feedbacks or inter-connections between impact pathways. The model only captures large changes (e.g. ecosystem transformation from brine disposal and water extraction). It considers socio-economic aspects of ES valuation as a normalization and weighting step. For pressures that do not lead to complete ecosystem transformations, scale the transformation area to reflect a smaller transformation.
(Liu and Bakshi, 2018)	Development of an approach for TES [Techno-Ecological Synergy]-LCA by expanding the steps in conventional LCA to incorporate the supply and demand of ES at multiple spatial scales. Calculation of absolute environmental sustainability metrics.	Resource and emission elementary flows as in traditional LCA. However, these are “translated” into demand of ES: “Water use” becomes “Demand for water provisioning service”	Carbon sequestration, air quality regulation (four pollutants: CO, NO_2, PM10 and SO_2), water provisioning. Classification system: various.	Data needs to put the proposed framework into practice (e.g. allocation issues). The approach helps identify opportunities for improving a life cycle not just by reducing impacts, but also by restoring and protecting ecosystems. The ES concept (specifying a supply of services) could be used to move towards absolute sustainability metrics in LCA by allowing for a comparison of supply and demand (traditional LCA elementary flows) of ES. Further, this would not only consider impact reduction (decreasing demand) but also increasing

Reference study	Goal & scope	Impact drivers	Reference ES classification and indicators	Limitations and/or recommendations
				ES supply to reach sustainable solutions. More information on computational structure of the proposed TES-LCA methodology is provided below.
(X. Liu et al., 2018a)	Development of a computational framework to assess techno-ecological synergies in LCA (TES-LCA) by expanding the computational structure of process LCA to explicitly include the role of ES.).	Resource use and emissions.	Classification system: unspecified.	An important limitation lies on the need to better model the delivery of each and every ES. Dynamic aspects associated with the delivery of different ES are not accounted for in this framework. The recommendation is to include the dynamics of ES to increase the time resolution in modelling. However, this framework facilitates better understanding of the interactions between the technological and ecological systems.
(X. Liu et al., 2018b)	Modification of the TES-LCA computational framework, to account for regional and serviceshed information. This adaptation addresses the issue of ecosystem services supply and demand at multiple scales, by including geographical information.	Regionalized resource use and emissions.	Classification system: unspecified.	Besides the limitations mentioned in the previous entry, this improved TES-LCA computational framework still needs better regionalized information in terms of both technological and ecological systems.

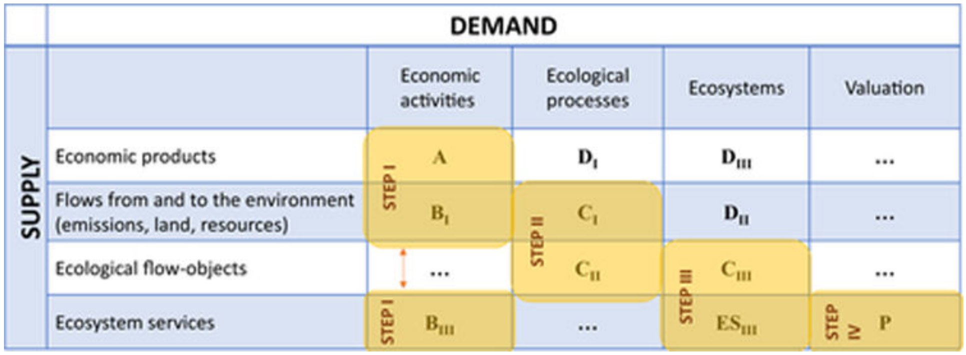
Table 2

Synthesis of the ideal relationship between life cycle inventory flows and potential environmental mechanisms, midpoint and endpoint indicators for use in the LCA cause-effect chain for ES (steps II and III in Fig. 1); the CICES v5.1 framework for ES classification is used for representation.

Ecosystem services (as classified in CICES v5.1)					**Life Cycle Assessment**				
Section	**Division**	**Group**	**Class**	**Class type**	**Possible inventory Issue**	**Possible affected environmental Mechanisms**	**Possible midpoint**	**Possible endpoint**	**Area of protection**
Provisioning services (biotic and abiotic)	Biomass, water, genetic material, other	e.g. Cultivated terrestrial plants for nutrition, materials or energy	e.g. Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes	e.g. Crops by amount, type (e.g. cereals, root crops, soft fruit, etc.)	e.g. Biological contamination; emissions of substances (GHGs, ozone and ozone precursor, respiratory inorganic, or toxic)	e.g. Eutrophication, reduced productivity of agricultural land, soil erosion	e.g. Productivity-adjusted hectare-years	e.g. Market value	Natural resources/ ecosystem quality
Regulation & maintenance services (biotic and abiotic)	Regulation of physical, chemical, biological conditions	e.g. Regulation of baseline flows and extreme events, regulation of soil quality	e.g. Control of erosion rates, weathering processes and their effect on soil quality, decomposition and fixing processes and their effect on soil quality	e.g. By reduction in risk, area protected, by amount/ concentration and source	e.g. Dissipative use of soil (including soil erosion), tillage (on-site movement of soil (top and, even, subsurface) → prone to water and wind erosion)	e.g. Changes in soil physical, chemical and biological properties, e.g. changes in soil permeability, runoff rates, water and nutrient retention capacity; altered organic matter content, reduction in soil productivity; changes in aeration for plant roots, change; impacts on soil biota, …	e.g. Landslide; impact on plant growth (mainly due to lower aeration and water availability); soil loss (loss of minerals, organic matter, ‘irreversible’ changes in soil structure), …	e.g. QALYs, DALYs, Ecosystem quality (PDF, loss of key ecosystem services), …	Human well-being/ ecosystem quality
Cultural services (biotic and abiotic)	e.g. Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	e.g. Physical and experiential interactions with natural environment	e.g. Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	e.g. By type of living system or environmental setting	Direct physical degradation; species dispersal, …	e.g. Change in species composition	Not identified	e.g. QALYs, Willingness-to-Pay for a beneficial change in experiential interactions	Human well-being/ ecosystem quality

Table 3

Simplified alignment of the cascade model steps depicted in Fig. 1 with the matrices describing the elements of a cause-effect chain for ES for traditional LCA analysis.



SUPPLY	DEMAND: Economic activities	Ecological processes	Ecosystems	Valuation
Economic products	$\mathbf{A}$	$\mathbf{D}_{\mathbf{I}}$	$\mathbf{D}_{\mathbf{III}}$	...
Flows from and to the environment (emissions, land, resources)	$\mathbf{B}_{\mathbf{I}}$	$\mathbf{C}_{\mathbf{I}}$	$\mathbf{D}_{\mathbf{II}}$	...
Ecological flow-objects	...	$\mathbf{C}_{\mathbf{II}}$	$\mathbf{C}_{\mathbf{III}}$	...
Ecosystem services	$\mathbf{B}_{\mathbf{III}}$	...	$\mathbf{ES}_{\mathbf{III}}$	$\mathbf{P}$

Matrix **A** is the traditional demand and supply table from LCI, where each required product specified in a driving vector **f** induces the product life cycle activities as given by the scaling vector $\mathbf{s} = \mathbf{A}^{-1} \cdot \mathbf{f}$.

Matrix $\mathbf{B}_{\mathbf{I}}$ is the traditional elementary flow matrix showing the demand on the environment per product life cycle activity also scaled by **s**.

Together, **A** and $\mathbf{B}_{\mathbf{I}}$ are the traditional LCI "database", which when A is inverted and both matrices scaled to **s**, provides the LCI result, as shown in step I of Fig. 1.

Matrices $\mathbf{C}_{\mathbf{I}}$ and $\mathbf{C}_{\mathbf{II}}$ together is the traditional matrix of characterization factors (**CFs** in step II of Fig. 1), which represents the supply fromthe activities of ecological processes in response to the demand from Matrix $\mathbf{B}_{\mathbf{I}}$. When multiplying $\mathbf{C}_{\mathbf{I}}$ and $\mathbf{C}_{\mathbf{II}}$ by the LCI result $\mathbf{B} \cdot \mathbf{s}$, the midpoint impact indicator matrix is obtained, as shown in step II of Fig. 1.

Matrix $\mathbf{C}_{\mathbf{III}}$ is a matrix of supply of ecological flows within ecosystems (as separate from the ecological processes that interact with the human activities via matrix $\mathbf{C}_{\mathbf{I}}$ and which do not provide ecosystem services) in response to the demand from impact matrix $\mathbf{C}_{\mathbf{II}}$.

Matrix $\mathbf{ES}_{\mathbf{III}}$ is a matrix of ecosystem services (as separate from ecological processes) supplied by ecosystems in response to the demand from impact matrix $\mathbf{C}_{\mathbf{II}}$.

Together, $\mathbf{C}_{\mathbf{III}}$ and $\mathbf{ES}_{\mathbf{III}}$ mirrors step III in Fig. 1.

Matrices $\mathbf{D}_{\mathbf{I}}$, $\mathbf{D}_{\mathbf{II}}$ and $\mathbf{D}_{\mathbf{III}}$ represent possible feedback loops in terms of generated demands for economic activities or elementary flows in response to changes in ecological processes or ecosystems. In Fig. 1 these are roughly represented by the arrows going back from step III.

Matrix $\mathbf{B}_{\mathbf{III}}$ represent those parts of the traditional elementary flowmatrix **B** that are provisioning ES and thus actually demanded by the economic activities resulting from the demand for the functional unit **f**.

Finally, matrix **P** represents the valuation of ES, represented by step IV in Fig. 1.