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Review

A framework for integrating ecosystem services as endpoint impacts in life cycle assessment

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ABSTRACT

Life cycle assessment is an analysis technique used to assess the environmental burdens of products or production processes. Ecosystem services is a concept used to understand the ways functioning ecosystems support human wellbeing. Both are used to understand how anthropogenic pressures impact the environment. The integration of ecosystem services as indicators in life cycle assessment is increasingly being explored, however there are several limitations with current frameworks. A brief review of existing approaches found they incorporate ecosystem services as midpoint indicators within traditional life cycle assessment structures and aggregate these impacts under the conventional 'areas of protection' (i.e., groupings of impacts). These approaches typically only focus on how product systems negatively affect ecosystem service supply (predominantly through land use) and overlook how product systems use up ecosystem services to mitigate their emissions or how interventions in product systems could improve ecosystem service supply. It is argued by several authors that ecosystem services are better placed as endpoint indicators representing damage to the instrumental value of ecosystems in a manner distinct to existing life cycle assessment impact categories, so that any changes in their delivery should be assessed within a new area of protection. In this paper, the potential for an ecosystem services area of protection within life cycle assessment is explored and a novel framework for modelling endpoint characterisation factors related to ecosystem service impacts that addresses the limitations of existing approaches is presented. The proposed novel framework respects existing life cycle assessment protocols by quantifying the endpoint damage to ecosystem services from product systems alongside existing methodologies for modelling endpoint impacts to ecosystem quality (biodiversity), human health and natural resources. This approach, based on small number of pertinent end-point indicators, has potential to broaden out LCA assessments of product systems and quantify the multiple ways they impact ecosystem services.

1. Introduction - Integration of ecosystem services into life cycle assessment

Life Cycle Assessment (LCA) is used for comparing the potential environmental burdens or 'impacts' associated with products, processes, systems, or supply chains[1] throughout their life cycle (i.e., from cradle (extraction of resources) to grave (disposal of wastes)). Identifying ways to improve the sustainability of product systems using sustainability assessment tools such as LCA requires a broad suite of metrics that demonstrate impacts in relation to planetary boundaries (Zeug et al., 2021). Several authors argue that inclusion of ecosystem services (ESs) in LCA to broaden the range of metrics used is a key part of assessing and decreasing the impacts of product systems on the environment (Alejandre et al., 2019; Callesen, 2016; Koellner and Geyer, 2013; Othoniel et al., 2016; Pascual et al., 2017; Rugani et al., 2019; VanderWilde and Newell, 2021). The ES concept frames the human-nature relationship and societal dependence on the functional aspects of ecosystems (Braat and de Groot, 2012; Costanza et al., 2017; de Groot et al., 2010a) and ESs are broadly understood to be the multiple benefits that humans derive from the ecological functions and processes of ecosystems (Fisher et al., 2009; Seppelt et al., 2011). Assessing ES provision is a widely applied way to evaluate how the benefits generated by ecosystems are affected by human-induced change and other stressors, often through monetary valuation of the benefits delivered in current and hypothetical

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[1] Herein, these are all referred to as 'product systems'.

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ecosystem states (Seppelt et al., 2011, 2012; Vihervaara et al., 2010). Inclusion of ES within LCA methodologies allows for not only the environmental burdens of products systems to be assessed but also the contribution of these burdens to societies encroachment on planetary boundaries.

Unlike ES assessments which are heavily place-based, LCA methods typically have broad system boundaries and consider a diverse set of impacts from product systems which may cause damage to the three AOPs across multiple scales, including distant indirect impacts from upstream resource extraction, land use change, or land occupation (Weidema et al., 2018). It has been discussed that the impact assessment stage of LCA to should be broadened to include impacts on ES supply as a more comprehensive means of evaluating the impacts of product systems on ecosystems (Liu et al., 2018a, 2018b; Othoniel et al., 2019). Widespread integration of ES in LCA is scarce (De Luca Peña et al., 2022; Othoniel et al., 2016), particularly in relation to methods for integration of ES in the impact assessment stage of LCA (D'Amato et al., 2020; VanderWilde and Newell, 2021). A number of authors have explored some of the conceptual challenges of integrating ES and LCA that stem from the characteristics of ES as a concept (Alejandre et al., 2019; Callesen, 2016; Othoniel et al., 2016; Rugani et al., 2019; VanderWilde and Newell, 2021; Zhang et al., 2010b) and the main points surrounding these broad concept related considerations are outlined in Table 1.

1.1. Ecosystem services should be integrated into life cycle assessment as endpoint impacts

There is an ongoing debate that underpins the integration of ESs into LCA surrounding how and where ESs should be positioned within LCA cause-effect chains (Blanco et al., 2018; Callesen, 2016; Othoniel et al., 2016; Rugani et al., 2019). Standardised ISO LCA methods involve comprehensive assessment of the factors that impact on humans or place pressure on ecosystems, characterising these in the impact assessment stage using 'midpoint' indicators such as global warming potential. These midpoint indicators describe environmental 'problems'. These are, in some cases, linked to 'endpoint' indicators which describe environmental 'damage', aggregating and summarising the individual midpoint impacts under three areas of protection (AOP): ecosystem quality, natural resource availability and human health (Baumann and Tillman, 2004). These endpoint indicators describe and aggregate the 'damage' to aspects of social concern caused by a wide range of environmental problems from product systems. There are divergent views on whether ESs should be represented as a midpoint impact category (Koellner and Geyer, 2013; Pavan and Ometto, 2018; Schaubroeck et al., 2013; Zhang et al., 2010b) or an endpoint impact category (Callesen, 2016; Dewulf et al., 2015). The added value of modelling based on endpoint impacts is that they quantify the relative significance of the LCA midpoint impact categories by enumerating the actual damage they cause to ecosystems, human health, and natural resources, rather than just their potential to cause damage.

The majority of current approaches for integrating of ESs into LCA are based on linking inventory flows (such as land occupation and transformation) to ES damage as novel midpoint impact categories. Existing studies have developed methodologies and regionalised characterisation factors[2] (CFs) for land use and land use change impacts on ES (including biotic production, climate regulation, freshwater regulation, erosion regulation and water purification) for inclusion in existing LCA protocols (Arbault et al., 2014; Brandão and i Canals, 2013; Cao et al., 2015; Koellner et al., 2013; Koellner and Geyer, 2013; Saad et al., 2013; Zhang et al., 2010a). A key limitation of these studies is the small number of ESs for which characterisation models have been developed. Further limitations relate to the focus solely on degradation of ES supply

[2] Characterisation factors convert the life cycle inventory results to the common unit of the impact category indicators.

Table 1
Broad issues for integrating ecosystem services and life cycle assessment examined in existing literature.

Issues	Key points	Limitations of existing LCA methodology
Ecosystem services interact dynamically	– ESs are the emergent benefits of multiple interactions and feedback loops from ecological characteristics, processes, and functions. – Often what is referred to as ESs in LCA studies are in fact ecological functions (Othoniel et al., 2016), which are one step back up the ES cascade as outlined by Potschin and Haines-Young (2011). – Some ESs provide benefits directly or indirectly by influencing the supply of other ESs (Carpenter et al., 2009). – Some ESs occur in bundles with others, hence one stressor may impact simultaneously on multiple ESs (Cord et al., 2017).	– LCA cause-effect chains typically assume a linear relationship between a burden and its effects, which presents a challenge for accounting for the multiple potential impacts of a stressor on ES supply and potential feedbacks on other ESs (VanderWilde and Newell, 2021; Zhang et al., 2010b). – This multi-functionality is often omitted in LCA studies aiming to assess impacts on ESs (Othoniel et al., 2016).
The supply of ecosystem services is spatially heterogenous	– A significant challenge stems from the spatial variation in the supply of ESs and 'use' of ESs. – Rugani et al. (2019) note that ESs are heterogeneously supplied across a range of different scales and simultaneously benefitted from across a range of completely different scales. – This provides an issue for quantification of impacts on ESs and setting the assessment scale (or 'system boundary') so that multi-scalar interactions are captured (Rugani et al., 2019). – Spatially explicit assessment tools using complex process-based models are widespread in ESs research (Costanza et al., 2017; Schägner et al., 2013; Seppelt et al., 2011).	– LCA approaches often assume spatial homogeneity when calculating ES impacts, masking spatial variation in ecosystems capacity to deliver ESs (Othoniel et al., 2016). – Some authors have explored how spatially explicit ES modelling might be applied in LCA (Blanco et al., 2018; Liu et al., 2018a, 2018b; Zhang et al., 2010a), but this is limited to land use impacts on ESs and limited set of ESs. There is a need to further explore how this can be applied to a broader set of ES impacts.
Ecosystem services supply varies temporally	– The supply of ESs also varies temporally with seasonal or yearly variation in supply levels (Qiu et al., 2020). – Similarly, the impacts of land use change on ESs will not emerge at the same rate in all locations, nor will the change in ES supply occur in the same location to the anthropogenic pressure (Folke et al., 2004). – The historically understudied temporal aspects of ES supply are beginning to be explored by ES researchers (Qiu	– Conventional LCA modelling typically assumes temporal heterogeneity and uses characterisation factors that assume no temporal differentiation in impacts (VanderWilde and Newell, 2021). – Dynamic LCA modelling has also explored some of the temporal issues within conventional LCA (Lueddeckens et al., 2020; Pigné et al., 2020). – However, the temporal aspects of ES have not been explored within existing case studies

(continued on next page)

Table 1 (*continued*)

Issues	Key points	Limitations of existing LCA methodology
	et al., 2020; Rau et al., 2018, 2020).	looking at ES-LCA integration, this poses a large challenge to be addressed.

by product systems and land use as the main driver of ES impacts. This work has been consolidated with generic frameworks for ES and LCA integration and metrics that can be used to model context specific CFs for broad ES categories (Crenna et al., 2017; Maia de Souza et al., 2018; Pavan and Ometto, 2018; Rugani et al., 2019; Zhang et al., 2010b).

The CFs and frameworks developed by this existing work describe the relative contribution of the impacts of land use occupation and land use change (as an inventory flow object) to damage on ESs measured in biophysical units. The generalised CFs and frameworks are based on linking these novel midpoint impact categories to the three conventional AOPs relating to human health, natural environment (often referred to as 'ecosystem quality') and natural resources (Arbault et al., 2014; Koellner et al., 2013; Saad et al., 2013). This midpoint approach adds more 'noise' to existing LCA protocols, potentially reducing the ease of interpretation by decision makers. An endpoint approach, while involving a trade-off around increased data requirements for practitioners, would provide easier understanding for decision-makers.

It is understood that LCA midpoints describe environmental 'problems' and LCA endpoints describe the damage caused by these problems (Bare et al., 2000; Verones et al., 2017). ESs are the benefits humans derive from functioning ecosystems (Braat and de Groot, 2012; Costanza et al., 2017; de Groot et al., 2010b) and assessing ES supply is used to understand the impacts of anthropogenic damage on ecosystems and their functions by measuring changes in the benefits generated by these ecosystem functions. Following the line of argument that LCA endpoints describe damage, it is more appropriate that impacts to ESs are modelled as an endpoint impact category. This is because ESs are not an environmental 'problem' in themselves and do not fit with the definition of LCA midpoints impacts, rather, they are damaged by environmental problems quantified using LCA midpoint modelling. While there may be merit to including ES as midpoint impacts and linking these to existing AOPs (for example changes in ES provision may well damage human health), arguably ES are more appropriate as endpoint impact categories.

Several authors have started to support inclusion of ESs as part of LCA endpoint modelling as a better means of quantifying the relative significance of the impacts of human activities on ecosystems by modelling damage to ES provision from existing LCA impact pathways (Callesen, 2016; Othoniel et al., 2019; VanderWilde and Newell, 2021). The Environmental Priority Strategies (EPS) method (Steen, 2015) includes a number of endpoints indicators for damage to ecosystem services (e.g., provisioning ES including 'food production' and cultural ES including 'quality time'), however these are generic non-regionalised characterisation factors for a limited range of ES that take no account of the spatial heterogeneity of ES supply. Monetary values of ES supply have also been proposed as endpoint indicators for modelling ES impacts by some authors (Cao et al., 2015; Othoniel et al., 2019). However, monetary values are just a means of normalising performance across a range of ES categories with differing biophysical units, they do not represent a point further on the cause-effect chain. Accounting for damage to ES 'flows' may be an appropriate way to represent a point further on the cause-effect chain. Flows of ESs describes the point where the benefits generated by ecosystem functions actually impact upon human well-being through use or extraction (Schröter et al., 2014). Modelling ES flows requires an understanding of this human use or 'demand', and without it, the damages to human well-being cannot be assessed (Fisher et al., 2009; Jax et al., 2013). But this approach also does not fit with the differentiation between LCA midpoints and endpoints. Consequently, there is a need to develop an adaptable endpoint modelling approach for ES damage in LCA that builds on existing midpoint stressors to formalise endpoint impacts on ES and utilises spatially referenced CFs.

1.2. *Ecosystem services need their own area of protection in life cycle assessment*

The impact of product systems on ecosystems is most commonly modelled at endpoint level under the 'ecosystem quality' AOP using the metrics 'potentially affected fraction' (PAF) or 'potentially disappeared fraction' (PDF) of species. These indicators describe the response of species to toxic concentrations of environmental stressors or the potential extinction of species within a given spatial and temporal scale caused by an environmental stressor respectively (Callesen, 2016; Curran et al., 2011). Callesen (2016) contends that the ecosystem quality AOP only captures the intrinsic value of the biodiversity aspects of ecosystems which are depletable and in some case damage to them is irreversible. The existing ecosystem quality AOP neglects the utilitarian values of ecosystem functions and the benefits they provide to society (or ESs). While biodiversity and ESs are inextricably linked, the intrinsic and instrumental value of ecosystems are two distinct matters of social concern. ES damage does not necessarily fit with existing endpoint indicators such as PAF or PDF, therefore it is important that these biodiversity metrics are not the only measure used to evaluate the impacts of product systems on ecosystems, nor is ES damage modelled using them in LCA.

The potential extinction of species is one form of damage potentially caused by some product systems, but the ecosystem functions that underpin human well-being through the provision of ESs are affected/damaged by stressors from product systems far before species go extinct (Callesen, 2016; MEA, 2005). Consequently, Callesen (2016) argues that biodiversity and ES should be two separate AOPs. Verones et al. (2017) echo this but follow different line of argument stating that the 'ecosystem quality' AOP should not encompass ESs. This is because ecosystem quality covers intrinsic values (related to biodiversity), whereas ESs cover instrumental values (Verones et al., 2017). Differentiation of these biodiversity and ES aspects when assessing the contribution of a product life cycle to environmental damage is important for identifying trade-offs between impacts. Hence, ES aspects should be assessed under its own AOP with its own independent endpoint indicators, not made to fit the existing ecosystem quality AOP and endpoint indicators.

1.3. *Paper aims and structure*

A brief review of the state of the art in relation to integrating ES in LCA highlights that ES are more appropriately placed in the LCA cause-effect chain at endpoint level, not at midpoint level as some authors have suggested. Placing ES as indicators at endpoint level further requires their own AOP because they are describing a conceptually different form of damage to other existing AOPs. Given this, there exists a gap related to a potential modelling framework for assessing ES impacts within LCA at endpoint level. The primary aims of this paper are to explore the potential for assessing ES impacts in LCA via endpoint modelling and to propose a novel endpoint modelling methodology, including the conceptual development of an ES AOP. To further this integration of ESs into LCA methodologies as endpoint impacts, this paper is organised in the following manner:

1) Section 2 explores two key challenges for integrating ESs in LCA, relating to modelling the path between LCA midpoint impacts and effects on ES supply, and modelling the different ways product systems impact ES supply.

2) Section 3 proposes a modelling framework and novel damage assessment approach to address these challenges with a view to moving towards an ESs AOP in LCA.

2. Key issues for endpoint modelling of ecosystem services

In addition to the existing broad issues for integration of ESs into LCA outlined in Table 1 that derive from ESs as a concept, there are two other important challenges for endpoint modelling of ES impacts in LCA:

1) Modelling the path from midpoint impacts to effects on ES supply.
2) Representing multiple relationships between product systems (on which LCA focus) and ES.

2.1. Diversity of links between midpoint impact categories and ecosystem services

Including ESs as an endpoint indicator requires additional characterisation models to aggregate the environmental damage of individual midpoint indicators on a higher level further along the cause effect chain. This requires a modelling approach that is not hugely different to those proposed by a number of authors (Arbault et al., 2014; Cao et al., 2015; Othoniel et al., 2019; Pavan and Ometto, 2018; Rugani et al., 2019), except that land use, which has been the focus of much of the early integration of ESs and LCA, is only one of the potential 'stressors' that can affect the provision of ES.

Some authors have explored the links between a broader set of ES categories and LCA midpoint impact categories (Pavan and Ometto, 2018; VanderWilde and Newell, 2021) and conclude that land use impacts provide the most promising area to explore endpoint ES characterisation factors. However, arguably, other midpoint impact categories beyond land use can adversely affect the provision of ES. Mapping out the links between the full Common International Classification of Ecosystem Services (CICES) and commonly used midpoint impact categories, in a similar manner to VanderWilde and Newell (2021), confirms that focussing solely on developing endpoint characterisation factors for land use impacts on ESs within LCA risks missing damage to ESs from several other midpoint impact categories (as shown in Fig. 1). VanderWilde and Newell (2021) are right to point out that land use is a good starting point for modelling impacts on ESs in LCA as it links to all 31 CICES ES groups. However, there is a far greater diversity of links between midpoint impact categories and ES (Fig. 1).

Some of the other midpoint impact categories such as ozone layer depletion, ecotoxicity, photochemical oxidation and ionising radiation link to 14, 12, 11 and 10 out of the 31 CICES ES groups respectively (Fig. 1). While they may not lead to direct ecosystem transformation (like land use change does), other midpoint impact categories including ionising radiation (Hinton et al., 2004), particulate matter formation (Grantz et al., 2003), ozone layer depletion and photochemical oxidation (Barnes et al., 2019; Solomon, 2008) can lead to significant stress on ecosystems. This stress can ultimately lead to changes in ES supply that should be captured by LCA studies. Modelling the impacts of these and other stressors (including acidification and eutrophication, for example) on ES will not be straightforward but should not be omitted. Many midpoint characterisation models of land use impacts on ESs exist that can be adapted for use at endpoint level, however, for other impact categories characterisation models will need to be developed.

2.2. Product systems do not just damage ecosystem service supply

LCA is broadly applied as a tool to quantify the impacts of a) technological product systems (which include only human and industrial elements), and b) techno-ecological product systems (which include human/industrial and ecosystem elements such as a stand of trees in a forest) on the environment (Schaubroeck et al., 2013). Current integration of ESs into LCA methodologies has primarily focussed on assessing the 'damage' caused to ES supply by the land use impacts of

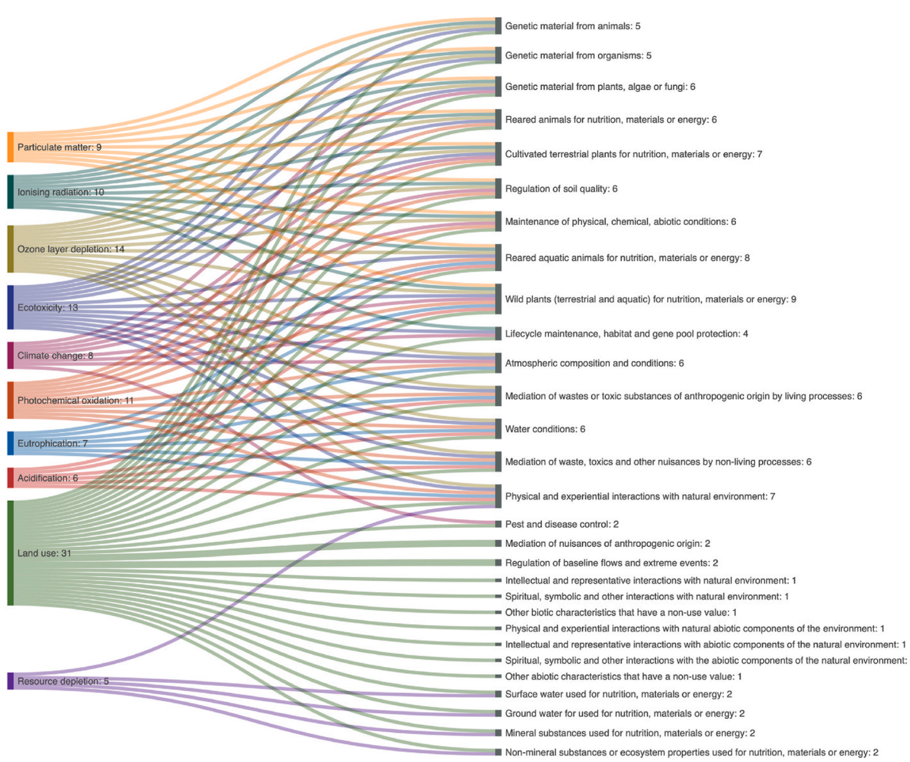

Fig. 1. Linkages between ecosystem services as defined by the CICES classification (at CICES group level) and life cycle impact assessment midpoint impact categories. Numbers after each impact category indicate the number of potentially affected ecosystem services and numbers after each CICES category indicate the number of midpoints impacts that affect each ecosystem service.

product systems (Arbault et al., 2014; Brandão and i Canals, 2013; Koellner et al., 2013; Saad et al., 2013; Zhang et al., 2010a). But damage is not the only relationship between product systems and ES supply. There are two ways product systems interact with ESs:

1) Product systems can stress ecosystems (e.g., via emissions) which use up (demand) ES supply to mitigate theses stressors.
2) Product systems can also affect ES supply by transforming (through land use occupation and change) or stressing (through emissions) local, regional, or global ecosystems; this can degrade or in some instances improve ES supply.

Fig. 2 sets out these relationships between the two types of product systems and ES supply. Accounting for these multiple relationships is key in understanding the net impact of product system on ES and capturing where product systems may in fact lead to benefits in terms of improved ES supply.

2.2.1. *Relationship one – using up ES supply*

The first relationship between product systems and ESs describes a reliance on ES supply where ESs are used up by the product system, this is known as ES demand (yellow arrows in Fig. 1). For example, product systems can often rely on certain regulating ESs (such as carbon sequestration or biological filtration) to mitigate emissions from production (Liu and Bakshi, 2019a; Zhang et al., 2010b). Some impacts from product systems may damage ESs with no potential for mitigation, whereas for others there is capacity for ESs to mitigate them before they cause further damage to ecosystems and ES supply. In some circumstances, the demand for ESs by a particular product system may also overshoot the total available or allocated ecosystem capacity within the 'serviceshed' to provide the required ES. A serviceshed describes a geographical area that provides a specific ES (Boyd and Banzhaf, 2007; Tallis and Polasky, 2009) and these can span local, regional, national and global scales. A sustainable product system will demand ESs at a level lower than the available supply from the relevant scale of serviceshed able to deliver that ES. There are two dimensions to why overshooting the total available ecosystem service supply within a serviceshed is unsustainable and ES demand from a product system needs to be considered:

1) Demand for ESs to mitigate certain emissions above a level that can be met by the carrying capacity of the ecosystem serviceshed can cause significant ecosystem damage and damage to provision of other ES (Burns et al., 2008; Clark et al., 2017; Forsius et al., 2021; Lovett, 2013).
2) Demand for ESs from a particular product system, while potentially below the remaining carrying capacity of the serviceshed, diverts ES supply away from other beneficiaries and users, possibly causing overshoot from a combination of product systems.

Accounting for the relationship between the carrying capacity of ecosystems to provide ESs across a range of serviceshed scales and the level of ESs demanded by a product system is argued to be key in understanding the absolute environmental sustainability of a product systems within LCA (Liu et al., 2018a; Liu and Bakshi, 2019b). Current LCA methodologies for including ESs focus only on the ways product systems may damage ES supply and do not consider how product systems use up (demand) a portion of ES supply to mitigate some of their impacts (e.g., emissions that may cause acidification or eutrophication). A notable example of this is greenhouse gas (GHG) emissions in the context of climate neutrality targets. Climate stabilisation will require net zero CO_2 emissions in the second half of this century, along with a substantial reduction in methane emissions (Rogelj et al., 2018). The sustainable level of residual emissions requiring mitigation from specific product systems (or nations) within difficult-to-abate sectors, such as aviation and agriculture, will depend on the scale of available global CO_2 removals and global methane emissions determined by the suite of global activities and climate action (Prudhomme et al., 2021).

2.2.2. *Relationship two – affecting ES supply*

The second relationship between product systems and ESs describes the way impacts from these processes can affect ES supply (red and green arrows in Fig. 2). Ecosystems have varying capacities to supply ESs which are a function of their conditions (including land cover, ecological integrity, climate, soils and disturbance regimes) and management (Burkhard et al., 2010, 2012, 2014). Product systems can impact on an ecosystems' capacity to generate ESs through stress or transformation (Maia de Souza et al., 2018).

Ecosystem stress, leading to changes in ES supply, can be caused by eutrophication and acidification from production exceeding the carrying capacity of ecosystems to assimilate the emissions that cause these problems; these excess emissions cause damage to the ecological functions that supply ES (Persson et al., 2010). For example, atmospheric nitrogen deposition above a particular level can lead to decreased soil pH, decreased productivity in natural systems, slower carbon cycling and ultimately lower carbon sequestration by ecosystems (Carpenter et al., 2009; Jones et al., 2014). Ecosystem transformation, leading to alterations in ES supply, is most widely driven through land use change and land occupation particularly relating to agricultural activities. Land use change and occupation alters the land cover conditions of the ecosystem, altering ecosystem functions and in some case improving ES supply (particularly provisioning benefits) but most often degrading the supply of regulating ESs (Hasan et al., 2020). Current methodologies typically focus on ecosystem transformation through land use change when modelling impacts to ESs in LCA, but future modelling needs to also reflect the effects of ecosystem stress on ES supply.

Ecosystem transformation need not only reduce ES delivery. Transformations from one ecosystem state to another can improve the supply of some ESs, for example improvement of semi-natural grassland to carry more livestock within a farming system can increase provisioning ESs. Similarly, some emissions up to a particular level can be beneficial for some ecosystem services, for example deposition of atmospheric nitrogen (modelled by acidification potential at midpoint level) can in some cases increase plant growth and carbon sequestration (Jones et al., 2014; Persson et al., 2010). Ultimately, increases in some ESs may incur trade-offs with others, and beyond a critical load stressors become detrimental to ecosystem functioning (Irvine et al., 2017; Jones et al., 2014). Future modelling needs to account for the potential positive impacts on ESs (where they arise, potentially below specified thresholds), as well as negative impacts.

2.3. *Implications for moving towards and ecosystem service area of protection*

The challenges highlighted in this section have several implications for future endpoint characterisation modelling of ESs impacts in LCA. With regards to the issues summarised in Table 1, an ideal modelling framework should be sensitive to the varying ecosystem structures and the dynamic interactions between ecosystem functions that underpin ES supply. Similarly, it should be spatially and regionally differentiated to account for the spatial heterogeneity in the supply of ESs. Spatial dimensions relating to 'telecoupling', which describes the impact from human-induced processes in one location that arise in distant areas (Sonderegger et al., 2020), should also be included in characterisation models. Similarly modelling approaches should account for the time-lags between ecosystem transformation or stress and changes to ES supply. Characterisation models based on dynamic integrated earth systems and process-based ES models to simulate the non-linear responses of ESs to stressors from product systems have been developed by several authors, and account for the spatially differentiated and interacting aspects of ES supply (Arbault et al., 2014; Chaplin-Kramer et al., 2017; Othoniel et al., 2019; van Zelm et al., 2018). While these

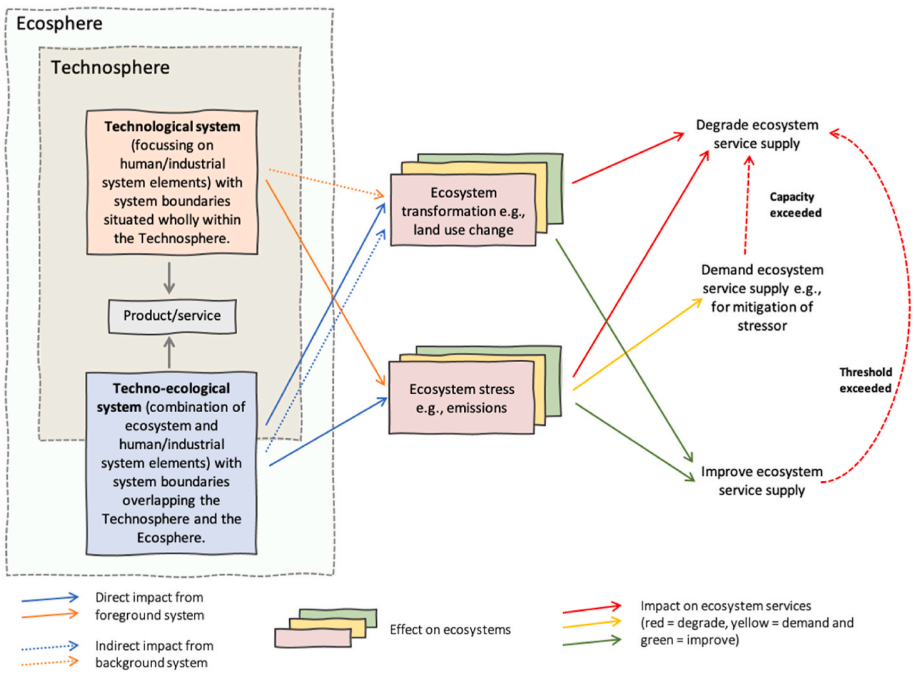

Fig. 2. Conceptual diagram setting out the relationship between product systems and ecosystem services. The three main relationships between product systems and ecosystem services include a) improved supply through emissions (up to certain level), land use and land use change (green arrows), b) demand to mitigate emissions (yellow arrows) and c) degraded supply through emissions, land use and land use change (red arrows). The pink, yellow and green boxes indicate that the effects on ecosystems from product system impacts may occur in multiple different locations and at different scales. Orange arrows represent impacts from technological systems and blue arrows represent impacts from techno-ecological systems. Dotted blue and orange arrows indicate indirect impacts from upstream processes in the background system. Solid blue and orange arrows indicate direct impacts from processes in the foreground system.

characterisation approaches based on global and finer scale modelling are efficient for modelling CFs relating to ES impacts that stem from land use and land use change based on land cover data and other biophysical parameters, further refinement of their use is required to pick up on telecoupling and other time-dependent aspects.

Land use and land use change causes *in situ* changes to ES supply as it directly modifies the biophysical structure of the ecosystem on a 'local' scale. Many of the other midpoint impacts (beside land use) that link to ES (outlined in Fig. 2) cause *ex situ* changes to ES supply, some at a regional scale (e.g., particulate matter, acidification, and eutrophication) and others on a global scale (e.g., photochemical oxidation and ozone layer depletion). Modelling the impact of regional level stressors will require spatially explicit methods that incorporate aspects of fate, exposure and effect models (see van Zelm et al. (2009)) to determine the ecosystems and ESs damaged by these stressors. Global level stressors (including ionising radiation, ozone layer depletion and photochemical oxidation) will not cause a discrete change in ES supply but rather add a marginal contribution to global ES damage. Characterisation models for these stressors will require deriving CFs from sensitivity analysis of global ES models.

Many existing approaches to develop midpoint CFs for ES impacts focus on the ways outputs from product systems affect (either negatively or positively) ES supply by quantifying changes to ES supply against a reference situation (Brandão and i Canals, 2013; Koellner et al., 2013; Koellner and Geyer, 2013; Saad et al., 2013). Endpoint characterisation models will be able to follow very similar approaches when considering how ES supply is affected by midpoint environmental impacts. However, capturing how product systems use up ES at endpoint level will require additional modelling drawing on aspects of TES-LCA,[3] quantifying the level of 'demand' for ESs required to mitigate a midpoint stressor such as acidifying emissions (Liu et al., 2018a, 2018b; Liu and Bakshi, 2019a; Schaubroeck et al., 2013).

3. Towards an ecosystem services area of protection

Building on the arguments in favour of an ESs AOP (as outlined in § 1.2) and the issues relating to modelling impacts on ESs in LCA outlined in § 2, this paper presents a potential stand-alone 'ecosystem services' AOP to sit alongside existing LCA AOPs for human health, ecosystem quality and natural resources (as shown in Fig. 3). Given the current limitations associated with existing approaches to assessing the impacts of product systems on ESs in LCA outlined in prior sections, here a general assessment framework for modelling endpoint CFs for ES impacts under this additional AOP is proposed (Fig. 3). This includes the indicator 'ecosystem service impacts' (ESI) for modelling endpoint damage to ESs in LCA. The indicator ESI focusses on the two ways ES supply and product systems interact by assessing how much the midpoint impacts from a product system a) 'use up' ES supply and b) affect ES supply (as shown in Fig. 4).

3.1. *'Damage' assessment framework*

Within this ES AOP, a damage assessment framework is proposed based around two streams of analysis that culminate in the calculation of endpoint CFs for impacts on ES. The framework follows four steps:

1) Determine if any of the midpoint impacts can be mitigated by ES from an associated serviceshed.
2) If they can, then the fraction of ES supply used up to mitigate these impacts is calculated (see § 3.1.1).
3) If they cannot, i.e., the midpoint impact cannot be mitigated by ESs from an associated serviceshed or if the midpoint impacts exceed the mitigation capacity of the associated serviceshed, then the fraction of ES supply affected by these midpoint impacts is calculated (see § 3.1.2).
4) These then are aggregated to determine the overall total 'damage' (percentage change) to global ES supply from the product system (see § 3.1.3).

[3] Techno-Ecological Synergy – LCA (TES-LCA) is a method for expanding the LCI stage of LCA to calculate the 'absolute' sustainability of products (Liu et al., 2018a, 2018b; Liu and Bakshi, 2019a; Schaubroeck et al., 2013). TES-LCA models how product systems enhance or degrade ES supply and how demand for ES (as inputs for production or to mitigate emissions) from product systems is met by ES supplied by an associated serviceshed. The TES-LCA approach includes ES supply and demand in the inventory stage rather than in the impact assessment stage.

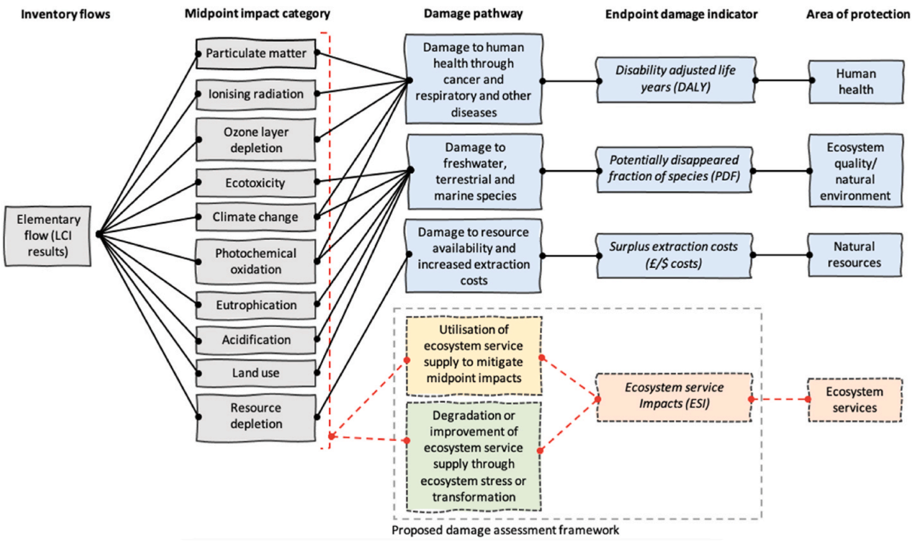

Fig. 3. Proposed ecosystem services area of protection in life cycle impact assessment. The proposed life cycle impact assessment endpoint indicator for damage to ES supply is 'ecosystem service impacts' composed of two elements quantifying how much the midpoint impacts from a product system a) use up ecosystem service supply and b) affect ecosystem service supply. Blue solid boxes represent existing areas of protection and their associated damage pathways and endpoint damage indicators. Boxes with a dashed outline describe the proposed damage assessment framework which is explored in Fig. 4 and §3.1.

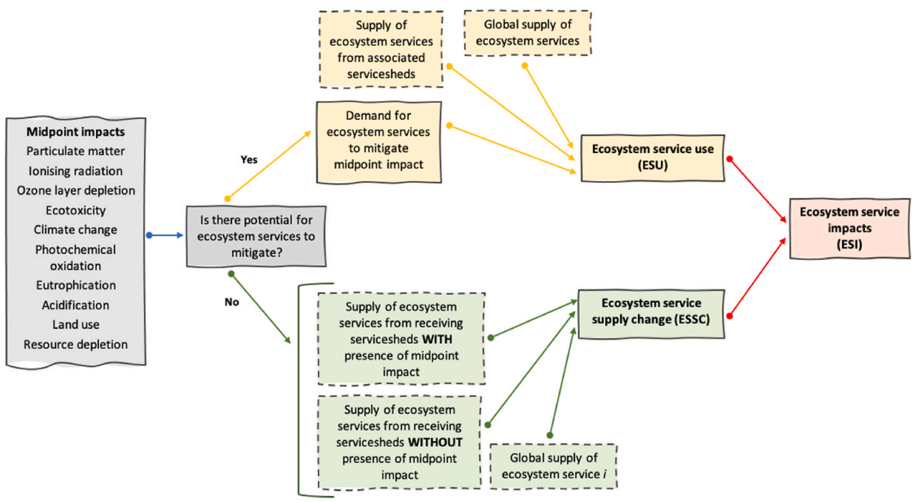

Fig. 4. Proposed damage assessment framework. Yellow boxes describe the stages of quantifying 'ecosystem service use' (ESU), see § 3.1.1. Green boxes describe the stages of quantifying 'ecosystem service supply change' (ESSC), see § 3.1.2. The red box describes the final endpoint indicator for ecosystem service damage, see § 3.1.3. Boxes with a dashed outlines describe stages that will require the use of geographical information systems and spatially explicit ecosystem service models.

3.1.1. *Ecosystem service use*

The portion of global ES supply used to mitigate midpoint impacts is quantified using the indicator 'ecosystem service use' (ESU) (Fig. 4) and is scaled as a decimal ranging from 0 to 1. The ESU score for each midpoint impact *j*, ESU_j can be modelled using the following Equation (1):

$$ESU_j = \sum_{I=1}^{n} \left(\frac{(ES_{i,k} - ES_{demand,i,j}) - ES_{i,global}}{ES_{i,k,global}} \right) \times w_i \tag{1}$$

where *I* is the index of all ESs being assessed, $ES_{demand,\ i,\ j}$ is the required supply of ES *i* to mitigate midpoint impact *j* and $ES_{i,k}$ is the local supply of ES *i* from serviceshed *k*, $ES_{i,global}$ is the global supply of ES *i*, w_i is the weighting given to ES *i* and $\sum w_i = 1$. Modelling the parameters $ES_{demand,\ i,\ j}$, $ES_{i,k}$ and $ES_{i,global}$ can be done following the computational framework of Liu, Ziv and Bakshi (2018a, 2018b) and utilising spatially explicit ES modelling frameworks such as INVEST (Kareiva et al., 2011), ARIES (Villa et al., 2014) or TESSA (Peh et al., 2013).

3.1.2. *Ecosystem service supply change*

The portion of global ES supply affected by midpoint impacts (either through degradation or improvement) is quantified using the indicator 'ecosystem service supply change' (ESSC) and is scaled as decimal from −1 to 1 (-ve values indicate degradation and +ve value indicate improvement). The ESSC score for each midpoint impact *j*, $ESSC_j$ can be modelled using the following Equation (2):

$$ESSC_j = \sum_{I=1}^{n} \left(\left(\frac{ES_{i,k} - ES_{i,k,ref}}{ES_{i,k,ref}} \right) \times \left(\frac{ES_{i,k}}{ES_{i,global}} \right) \right) \times w_i \tag{2}$$

where *I* is the index of all ESs being assessed, $\Delta ES_{i,j,k}$ is the change in supply of ES *i* from receiving serviceshed *k* attributable to midpoint impact *j*, $ES_{i,k}$ is the supply of ES *i* from receiving serviceshed *k* under the current ecosystem state (with the presence of a certain level midpoint impact *j*), $ES_{i,k,ref}$ is the supply ES *i* from receiving serviceshed *k* modelled assuming midpoint impact *j* does not exist, $ES_{i,global}$ is the global supply of ES *i* (with the presence of a certain level midpoint impact *j*), w_i is the weighting given to ES *i* and $\sum w_i = 1$. The parameters $ES_{i,k}$ and $ES_{i,global}$ may also be modelled using spatially explicit ES modelling frameworks with regional and global coverage such as INVEST (Kareiva et al., 2011), ARIES (Villa et al., 2014) or TESSA (Peh et al., 2013).

The parameter $ES_{i,k,ref}$ may be retrieved again by using existing spatially explicit ES models, for an in depth review of available models see Turner et al. (2016) and Willcock et al. (2019), or by developing bespoke models that can assess the impacts of stressors (such as acidification) on ES supply. When the midpoint impact j being assessed leads to ecosystem stress, the parameter $ES_{i,k,counterfactual}$ may be retrieved by carrying out a sensitivity analysis using these models assuming the stressor from the product system does not exist. When the midpoint impact j being assessed leads to ecosystem transformation, the parameter $ES_{i,k,ref}$ may be retrieved by carrying out a sensitivity analysis using these models assuming the ecosystem has reverted to a reference state.

There are a wide range of potential ecosystem reference states that may be used, however there are two main options for determining the reference state in LCA (Koellner et al., 2013) which are appropriate for modelling the parameter $ES_{i,k,ref}$ when the midpoint impact j being assessed leads to ecosystem transformation:

1) Potential natural vegetation, which describes the state of ecosystem vegetation without the presence of human intervention.
2) Quasi-natural land cover, which describes the natural mix of land covers (e.g., forests, wetlands, and grasslands) for the biome or ecoregion.

The reference state used to model $ES_{i,k,ref}$ is a value choice, however for this proposed modelling approach to applicable across contexts and scales further exploration and determination of a universally agreed reference situation is required.

3.1.3. Ecosystem service impacts

The overall 'damage' to ES supply through use and affected provision is quantified using the indicator 'ecosystem service impacts' (ESI) which scores the aggregated impacts of a given product system on ES supply through ES use or by degradation or improvement of supply. The ESI score is on a scale of −1 to 1. A negative ESI score indicates that the product system causes net damage to ES supply, an ESI score of zero indicate no damage to ES supply and a positive ESI score indicates the product system improves ES supply. The ESI score for the product system being evaluated can be calculated using the following Equation (3):

$$ESI = \sum_{J=1}^{n} \left(\left(ESU_j + ESSC_j + \left(ESU_j \times ESSC_j \right) \right) \times w_j \right) \tag{3}$$

where J is an index of all midpoint impacts from product system x, ESU_j is the damage to ES supply through use from midpoint impact j (see § 4.1.1), $ESSC_j$ is the damage to ES supply through changes in provision from midpoint impact j (see § 4.1.2), w_j is the weighting given to midpoint impact j and $\sum w_j = 1$.

3.2. Key considerations and challenges

The damage assessment approach described in § 3.1 represents a ready to apply framework for modelling endpoint damage to ES in LCA that addresses some of the issues explored in earlier sections of this paper. The proposed framework is suitable for application in both attributional and consequential LCA where midpoint impacts have been quantified using existing characterisation models. However, there are several key considerations for implementation of this framework.

3.2.1. Ecosystem service categories

The modelling framework outlined above involves calculating the portion of global ES supply that is impacted either negatively or positively by a product system. The index I of ESs being assessed needs to be a unified 'basket' of ESs, i.e., it remains constant across all applications of the framework, to allow for the ES impacts of different product systems to be benchmarked against each other. This is because Equation (1) calculates how much of this basket is used to mitigate midpoint impacts from the product system and Equation (2) calculates how much this basket is either degraded or improved by the product system. Alejandre, van Bodegom and Guinée (2019) propose a set of 15 ES categories to provide optimal coverage of the different ES groups within the CICES classification. This may provide a robust starting point for defining the basket of ESs used in this modelling framework. Nonetheless, having a broad basket of ESs does add an additional challenge. Different ES categories have different biophysical units and the modelling framework presented here requires that the supply of ESs is expressed in the same units. While not without some limitations, monetary valuation of ES supply (Laurans and Mermet, 2014; Tinch et al., 2019) is a suitable approach for normalising different biophysical values into a common and easily understood unit. Many of the existing ES modelling tools allow for ES supply to be valued in monetary terms and comprehensive databases of monetary values for ES exist for valuation of ES supply in LCA such as the Ecosystem Services Valuation Database (de Groot et al., 2012). A critique of a monetary approach would be that it neglects the intrinsic 'value' of ES, however, arguably these are captured in the conventional PDF endpoint and ecosystem quality AOP.

3.2.2. Weighting factors

There are two options for applying weighting factors within the proposed damage assessment framework. The parameter w_i in Equations (1) and (2) and the parameter w_j in Equation (3) can be used to weight the different ES and midpoint impacts equally (e.g., each has a weight of 0.2 if five ES or damage from five midpoint impacts is being assessed) or differentially to reflect differential importance of each ES or midpoint impact being assessed. Differential weightings for the w_i and w_j parameters could be derived from multi-criteria approaches which can draw on stakeholder preferences (De Luca et al., 2017; Zanghelini et al., 2018). Equal weightings may be appropriate for aggregating ES impacts across the different midpoint impacts being assessed in Equation (3). However, applying equal weightings to different ES in Equations (1) and (2) assumes they are equally important, substitutable, and that impacts on different ESs are commensurate with each other (i.e., degradation of the supply of one ES category can be offset by improvement to the supply of another). People do ascribe different levels of importance to different ESs (Arias-Arévalo et al., 2018; Hein et al., 2006; Kenter et al., 2015), hence differential weightings may be more appropriate here to reflect different stakeholders values.

3.2.3. Application to foreground and background processes

This proposed modelling approach can readily address spatial differentiation of ES impacts through the use of spatially explicit ES models to generate context specific endpoint CFs, which is a limitation of some existing approaches (Steen, 2015). The high level of geographical specificity using site-specific data that this approach allows is suitable for modelling endpoint impacts on ES from foreground processes. That being said, many of the integrated ES models that may be used when implementing this framework are quite complex, data intense and computationally demanding. Applying this framework to the background processes in LCA where the locations of certain background processes are unknown or globally distributed may be problematic and unfeasible for practitioners because the required data may not be available or lead to hyper-regionalisation (Heijungs, 2012). To circumvent these issues, a compromise approach would be to use the proposed framework to build up a database of regionalised CFs (across a range of scales) that could be applied to background processes. These endpoint CFs could be at similar scales to the global midpoint CFs for land use impacts on ESs presented by a number of authors (Brandão and i Canals, 2013; Koellner et al., 2013; Koellner and Geyer, 2013; Saad et al., 2013), however, the approach presented here would allow the number of ESs being assessed to be broadened.

4. Conclusions and recommendations

The ES concept is a robust (often spatially explicit) analytical approach for evaluating how ecosystem transformations affect the benefits that humans derive from functioning ecosystems. Meanwhile, LCA captures environmental pressures and impacts incurred by entire value chains, across multiple areas. LCA is, however, limited in terms of representation of the damage caused to ecosystem functions by product systems. Bridging the two concepts by including ES as indicators in LCA allows for the impact of human activities that both directly and indirectly affect ecosystem to be assessed. A brief review of existing literature indicates that ES are most appropriately integrated into LCA as endpoint impacts within a stand-alone AOP. Accounting for ESs as endpoints within a standalone AOP is conceptually purer than a midpoint approach and involves a smaller number of indicators for easier interpretation and action. In this paper an approach for including net changes in ES delivery as endpoint impacts within a new AOP in LCA is proposed. This proposal builds upon existing literature examining the potential for ESs to be incorporated into LCA and attempts to address some of the limitations of existing approaches. Modelling of impacts of product systems on ES supply in LCA should account for both use of ES supply to assimilate emissions, and alteration of ES supply through ecosystem stress and/or transformation. The approach presented here provides a platform for doing so. While the proposed conceptual framework is ready to apply, there are some challenges. These relate to which ES to include, how to weight different ES and impacts, and the establishment of a database of ES impacts for background processes. The proposed framework requires more data and research to develop region specific ES CFs but could draw on existing natural capital and ES assessment modelling tools and data to do so. The next step should be to apply this framework to a range of case studies in order to validate this conceptual proposition for a dedicated ESs AOP. Integration of LCA and ESs to generate a small number of pertinent end-point indicators using the approach presented here has the potential to enhance the analytical capacity of LCA. Particularly with respect to ecosystem functioning, contributions to societies encroachment on planetary boundaries and to drive necessary sustainability actions.

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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.

Data availability

No data was used for the research described in the article.

References

Alejandre, E.M., van Bodegom, P.M., Guinée, J.B., 2019. Towards an optimal coverage of ecosystem services in LCA. J. Clean. Prod. 231, 714–722. https://doi.org/10.1016/j.jclepro.2019.05.284.

Arbault, D., Rivière, M., Rugani, B., Benetto, E., Tiruta-Barna, L., 2014. Integrated earth system dynamic modeling for life cycle impact assessment of ecosystem services. Sci. Total Environ. 472, 262–272. https://doi.org/10.1016/j.scitotenv.2013.10.099.

Arias-Arévalo, P., Gómez-Baggethun, E., Martín-López, B., Pérez-Rincón, M., 2018. Widening the evaluative space for ecosystem services: a taxonomy of plural values and valuation methods. Environ. Val. 27, 29–53. https://doi.org/10.3197/096327118X15144698637513.

Bare, J.C., Hofstetter, P., Pennington, D.W., de Haes, H.A.U., 2000. Midpoints versus endpoints: the sacrifices and benefits. Int. J. Life Cycle Assess. 5, 319. https://doi.org/10.1007/BF02978665.

Barnes, P.W., Williamson, C.E., Lucas, R.M., Robinson, S.A., Madronich, S., Paul, N.D., Bornman, J.F., Bais, A.F., Sulzberger, B., Wilson, S.R., Andrady, A.L., McKenzie, R.L., Neale, P.J., Austin, A.T., Bernhard, G.H., Solomon, K.R., Neale, R.E., Young, P.J., Norval, M., Rhodes, L.E., Hylander, S., Rose, K.C., Longstreth, J., Aucamp, P.J., Ballaré, C.L., Cory, R.M., Flint, S.D., de Gruijl, F.R., Häder, D.P., Heikkilä, A.M., Jansen, M.A.K., Pandey, K.K., Robson, T.M., Sinclair, C.A., Wängberg, S.Å., Worrest, R.C., Yazar, S., Young, A.R., Zepp, R.G., 2019. Ozone depletion, ultraviolet radiation, climate change and prospects for a sustainable future. Nat. Sustain. 2, 569–579. https://doi.org/10.1038/s41893-019-0314-2.

Baumann, H., Tillman, A.-M., 2004. The Hitch Hiker's Guide to LCA: an Orientation in Life Cycle Assessment Methodology and Application. Studentlitteratur, Lund.

Blanco, C.F., Marques, A., van Bodegom, P.M., 2018. An integrated framework to assess impacts on ecosystem services in LCA demonstrated by a case study of mining in Chile. Ecosyst. Serv. 30, 211–219. https://doi.org/10.1016/j.ecoser.2017.11.011.

Boyd, J., Banzhaf, S., 2007. What are ecosystem services? The need for standardized environmental accounting units. Ecol. Econ. 63, 616–626. https://doi.org/10.1016/j.ecolecon.2007.01.002.

Braat, L.C., de Groot, R., 2012. The ecosystem services agenda: bridging the worlds of natural science and economics, conservation and development, and public and private policy. Ecosyst. Serv. 1, 4–15. https://doi.org/10.1016/j.ecoser.2012.07.011.

Brandão, M., i Canals, L.M., 2013. Global characterisation factors to assess land use impacts on biotic production. Int. J. Life Cycle Assess. 18, 1243–1252. https://doi.org/10.1007/s11367-012-0381-3.

Burkhard, B., Kandziora, M., Hou, Y., Müller, F., 2014. Ecosystem service potentials, flows and demands-concepts for spatial localisation, indication and quantification. Landsc. Online 34, 1–32. https://doi.org/10.3097/LO.201434.

Burkhard, B., Kroll, F., Müller, F., 2010. Landscapes‘ capacities to provide ecosystem services – a concept for land-cover based assessments. Landsc. Online 15, 1–22. https://doi.org/10.3097/LO.200915.

Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012. Mapping ecosystem service supply, demand and budgets. Ecol. Indicat. 21, 17–29. https://doi.org/10.1016/j.ecolind.2011.06.019.

Burns, D.A., Blett, T., Haeuber, R., Pardo, L.H., 2008. Critical loads as a policy tool for protecting ecosystems from the effects of air pollutants. Front. Ecol. Environ. 6, 156–159.

Callesen, I., 2016. Biodiversity and ecosystem services in life cycle impact assessment – inventory objects or impact categories? Ecosyst. Serv. 22, 94–103. https://doi.org/10.1016/j.ecoser.2016.09.021.

Cao, V., Margni, M., Favis, B.D., Deschênes, L., 2015. Aggregated indicator to assess land use impacts in life cycle assessment (LCA) based on the economic value of ecosystem services. J. Clean. Prod. 94, 56–66. https://doi.org/10.1016/j.jclepro.2015.01.041.

Carpenter, S.R., Mooney, H.A., Agard, J., Capistrano, D., DeFries, R.S., Diaz, S., Dietz, T., Duraiappah, A.K., Oteng-Yeboah, A., Pereira, H.M., Perrings, C., Reid, W.V., Sarukhan, J., Scholes, R.J., Whyte, A., 2009. Science for managing ecosystem services: beyond the Millennium Ecosystem Assessment. Proc. Natl. Acad. Sci. USA 106, 1305–1312. https://doi.org/10.1073/pnas.0808772106.

Chaplin-Kramer, R., Sim, S., Hamel, P., Bryant, B., Noe, R., Mueller, C., Rigarlsford, G., Kulak, M., Kowal, V., Sharp, R., Clavreul, J., Price, E., Polasky, S., Ruckelshaus, M., Daily, G., 2017. Life cycle assessment needs predictive spatial modelling for biodiversity and ecosystem services. Nat. Commun. 8, 15065 https://doi.org/10.1038/ncomms15065.

Clark, C.M., Bell, M.D., Boyd, J.W., Compton, J.E., Davidson, E.A., Davis, C., Fenn, M.E., Geiser, L., Jones, L., Blett, T.F., 2017. Nitrogen-induced terrestrial eutrophication: cascading effects and impacts on ecosystem services. Ecosphere 8. https://doi.org/10.1002/ecs2.1877.

Cord, A.F., Bartkowski, B., Beckmann, M., Dittrich, A., Hermans-Neumann, K., Kaim, A., Lienhoop, N., Locher-Krause, K., Priess, J., Schröter-Schlaack, C., Schwarz, N., Seppelt, R., Strauch, M., Václavík, T., Volk, M., 2017. Towards systematic analyses of ecosystem service trade-offs and synergies: main concepts, methods and the road ahead. Ecosyst. Serv. 28, 264–272. https://doi.org/10.1016/j.ecoser.2017.07.012.

Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008.

Crenna, E., Sala, S., Polce, C., Collina, E., 2017. Pollinators in life cycle assessment: towards a framework for impact assessment. J. Clean. Prod. 140, 525–536. https://doi.org/10.1016/j.jclepro.2016.02.058.

Curran, M., de Baan, L., De Schryver, A.M., van Zelm, R., Hellweg, S., Koellner, T., Sonnemann, G., Huijbregts, M.A.J., 2011. Toward meaningful end points of biodiversity in life cycle assessment. Environ. Sci. Technol. 45, 70–79. https://doi.org/10.1021/es101444k.

D'Amato, D., Gaio, M., Semenzin, E., 2020. A review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective. Sci. Total Environ. 706, 135859 https://doi.org/10.1016/j.scitotenv.2019.135859.

de Groot, R., Alkemade, R., Braat, L., Hein, L., Willemen, L., 2010a. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol. Complex. 7, 260–272. https://doi.org/10.1016/j.ecocom.2009.10.006.

de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L.C., ten Brink, P., van Beukering, P., 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosyst. Serv. 1, 50–61. https://doi.org/10.1016/j.ecoser.2012.07.005.

de Groot, R., Fisher, B., Christie, M., Aronson, J., Braat, L., Haines-Young, R., Gowdy, J., Maltby, E., Neuville, A., Polasky, S., Portela, R., Ring, I., 2010b. Integrating the ecological and economic dimension in biodiversity and ecosystem service valuation. In: Kumar, P. (Ed.), The Economics of Ecosystems and Biodiversity. Ecological and Economic Foundations. Earthscan, London, pp. 9–40.

De Luca, A.I., Iofrida, N., Leskinen, P., Stillitano, T., Falcone, G., Strano, A., Gulisano, G., 2017. Life cycle tools combined with multi-criteria and participatory methods for agricultural sustainability: insights from a systematic and critical review. Sci. Total Environ. 595, 352–370. https://doi.org/10.1016/j.scitotenv.2017.03.284.

De Luca Peña, L.V., Taelman, S.E., Préat, N., Boone, L., Van der Biest, K., Custódio, M., Hernandez Lucas, S., Everaert, G., Dewulf, J., 2022. Towards a comprehensive sustainability methodology to assess anthropogenic impacts on ecosystems: review of the integration of life cycle assessment, environmental risk assessment and ecosystem services assessment. Sci. Total Environ. 808, 152125 https://doi.org/10.1016/j.scitotenv.2021.152125.

Dewulf, J., Benini, L., Mancini, L., Sala, S., Blengini, G.A., Ardente, F., Recchioni, M., Maes, J., Pant, R., Pennington, D., 2015. Rethinking the area of protection "natural resources" in life cycle assessment. Environ. Sci. Technol. 49, 5310–5317. https://doi.org/10.1021/acs.est.5b00734.

Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. Ecol. Econ. 68, 643–653. https://doi.org/10.1016/j.ecolecon.2008.09.014.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., Holling, C. S., 2004. Regime shifts, resilience, and biodiversity in ecosystem management. Annu. Rev. Ecol. Evol. Syst. 35, 557–581. https://doi.org/10.1146/annurev.ecolsys.35.021103.105711.

Forsius, M., Posch, M., Holmberg, M., Vuorenmaa, J., Kleemola, S., Augustaitis, A., Beudert, B., Bochenek, W., Clarke, N., de Wit, H.A., Dirnböck, T., Frey, J., Grandin, U., Hakola, H., Kobler, J., Krám, P., Lindroos, A.-J., Löfgren, S., Pecka, T., Rönnback, P., Skotak, K., Szpikowski, J., Ukonmaanaho, L., Valinia, S., Váňa, M., 2021. Assessing critical load exceedances and ecosystem impacts of anthropogenic nitrogen and sulphur deposition at unmanaged forested catchments in Europe. Sci. Total Environ. 753, 141791 https://doi.org/10.1016/j.scitotenv.2020.141791.

Grantz, D.A., Garner, J.H.B., Johnson, D.W., 2003. Ecological effects of particulate matter. Environ. Int. 29, 213–239. https://doi.org/10.1016/S0160-4120(02)00181-2.

Hasan, S.S., Zhen, L., Miah, M.G., Ahamed, T., Samie, A., 2020. Impact of land use change on ecosystem services: a review. Environ. Dev. 34, 100527 https://doi.org/10.1016/j.envdev.2020.100527.

Heijungs, R., 2012. Spatial differentiation, GIS-based regionalization, and the boundaries of LCA. In: Ioppolo, G. (Ed.), Environment and Energy. Franco Angeli, pp. 162–176.

Hein, L., van Koppen, K., de Groot, R.S., van Ierland, E.C., 2006. Spatial scales, stakeholders and the valuation of ecosystem services. Ecol. Econ. 57, 209–228. https://doi.org/10.1016/j.ecolecon.2005.04.005.

Hinton, T.G., Bedford, J.S., Congdon, J.C., Whicker, F.W., 2004. Effects of radiation on the environment: a need to question old paradigms and enhance collaboration among radiation biologists and radiation ecologists. Radiat. Res. 162, 332–338. https://doi.org/10.1667/RR3222.

Irvine, I.C., Greaver, T., Phelan, J., Sabo, R.D., Houtven, G. Van, 2017. Terrestrial acidification and ecosystem services: effects of acid rain on bunnies, baseball, and Christmas trees. Ecosphere 8. https://doi.org/10.1002/ecs2.1857.

Jax, K., Barton, D.N., Chan, K.M.A., de Groot, R., Doyle, U., Eser, U., Görg, C., Gómez-Baggethun, E., Griewald, Y., Haber, W., Haines-Young, R., Heink, U., Jahn, T., Joosten, H., Kerschbaumer, L., Korn, H., Luck, G.W., Matzdorf, B., Muraca, B., Neßhöver, C., Norton, B., Ott, K., Potschin, M., Rauschmayer, F., von Haaren, C., Wichmann, S., 2013. Ecosystem services and ethics. Ecol. Econ. 93, 260–268. https://doi.org/10.1016/j.ecolecon.2013.06.008.

Jones, L., Provins, A., Holland, M., Mills, G., Hayes, F., Emmett, B., Hall, J., Sheppard, L., Smith, R., Sutton, M., Hicks, K., Ashmore, M., Haines-Young, R., Harper-Simmonds, L., 2014. A review and application of the evidence for nitrogen impacts on ecosystem services. Ecosyst. Serv. 7, 76–88. https://doi.org/10.1016/j.ecoser.2013.09.001.

Kareiva, P., Tallis, H., Ricketts, T., Daily, G.C., Polasky, S., 2011. Natural Capital: Theory and Practice of Ecosystem Service Valuation. Oxford University Press.

Kenter, J.O., O'Brien, L., Hockley, N., Ravenscroft, N., Fazey, I., Irvine, K.N., Reed, M.S., Christie, M., Brady, E., Bryce, R., Church, A., Cooper, N., Davies, A., Evely, A., Everard, M., Fish, R., Fisher, J.A., Jobstvogt, N., Molloy, C., Orchard-Webb, J., Ranger, S., Ryan, M., Watson, V., Williams, S., 2015. What are shared and social values of ecosystems? Ecol. Econ. 111, 86–99. https://doi.org/10.1016/j.ecolecon.2015.01.006.

Koellner, T., Baan, L., Beck, T., Brandão, M., Civit, B., Margni, M., Canals, L.M., Saad, R., Souza, D.M., Müller-Wenk, R., 2013. UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. Int. J. Life Cycle Assess. 18, 1188–1202. https://doi.org/10.1007/s11367-013-0579-z.

Koellner, T., Geyer, R., 2013. Global land use impact assessment on biodiversity and ecosystem services in LCA. Int. J. Life Cycle Assess. 18, 1185–1187. https://doi.org/10.1007/s11367-013-0580-6.

Laurans, Y., Mermet, L., 2014. Ecosystem services economic valuation, decision-support system or advocacy? Ecosyst. Serv. 7, 98–105. https://doi.org/10.1016/j.ecoser.2013.10.002.

Liu, X., Bakshi, B.R., 2019a. Ecosystem services in life cycle assessment while encouraging techno-ecological synergies. J. Ind. Ecol. 23, 347–360. https://doi.org/10.1111/jiec.12755.

Liu, X., Bakshi, B.R., 2019b. Ecosystem services in life cycle assessment while encouraging techno-ecological synergies. J. Ind. Ecol. 23, 347–360. https://doi.org/10.1111/jiec.12755.

Liu, X., Ziv, G., Bakshi, B.R., 2018a. Ecosystem services in life cycle assessment - Part 1: a computational framework. J. Clean. Prod. 197, 314–322. https://doi.org/10.1016/j.jclepro.2018.06.164.

Liu, X., Ziv, G., Bakshi, B.R., 2018b. Ecosystem services in life cycle assessment - Part 2: adaptations to regional and serviceshed information. J. Clean. Prod. 197, 772–780. https://doi.org/10.1016/j.jclepro.2018.05.283.

Lovett, G.M., 2013. Critical issues for critical loads. Proc. Natl. Acad. Sci. USA 110, 808–809. https://doi.org/10.1073/pnas.1219007110.

Lueddeckens, S., Saling, P., Guenther, E., 2020. Temporal issues in life cycle assessment—a systematic review. Int. J. Life Cycle Assess. 25, 1385–1401. https://doi.org/10.1007/s11367-020-01757-1.

Maia de Souza, D., Lopes, G.R., Hansson, J., Hansen, K., 2018. Ecosystem services in life cycle assessment: a synthesis of knowledge and recommendations for biofuels. Ecosyst. Serv. 30, 200–210. https://doi.org/10.1016/j.ecoser.2018.02.014.

MEA, 2005. Millennium Ecosystem Assessment, Ecosystems and Human Well-Being: Synthesis.

Othoniel, B., Rugani, B., Heijungs, R., Benetto, E., Withagen, C., 2016. Assessment of life cycle impacts on ecosystem services: promise, problems, and prospects. Environ. Sci. Technol. 50, 1077–1092. https://doi.org/10.1021/acs.est.5b03706.

Othoniel, B., Rugani, B., Heijungs, R., Beyer, M., Machwitz, M., Post, P., 2019. An improved life cycle impact assessment principle for assessing the impact of land use on ecosystem services. Sci. Total Environ. 693 https://doi.org/10.1016/j.scitotenv.2019.07.180.

Pascual, U., Palomo, I., Adams, W.M., Chan, K.M.A., Daw, T.M., Garmendia, E., Gómez-Baggethun, E., De Groot, R.S., Mace, G.M., Martín-López, B., Phelps, J., 2017. Off-stage ecosystem service burdens: a blind spot for global sustainability. Environ. Res. Lett. 12 https://doi.org/10.1088/1748-9326/aa7392.

Pavan, A.L.R., Ometto, A.R., 2018. Ecosystem services in life cycle assessment: a novel conceptual framework for soil. Sci. Total Environ. 643, 1337–1347. https://doi.org/10.1016/j.scitotenv.2018.06.191.

Peh, K.S.-H., Balmford, A., Bradbury, R.B., Brown, C., Butchart, S.H.M., Hughes, F.M.R., Stattersfield, A., Thomas, D.H.L., Walpole, M., Bayliss, J., Gowing, D., Jones, J.P.G., Lewis, S.L., Mulligan, M., Pandeya, B., Stratford, C., Thompson, J.R., Turner, K., Vira, B., Willcock, S., Birch, J.C., 2013. TESSA: a toolkit for rapid assessment of ecosystem services at sites of biodiversity conservation importance. Ecosyst. Serv. 5, 51–57. https://doi.org/10.1016/j.ecoser.2013.06.003.

Persson, L., Arvidson, A., Lannerstad, M., Lindskog, H., Morrissey, T., Nilsson, L., Noel, S., Senyagwa, J., 2010. Impacts of Pollution on Ecosystem Services for the Millennium Development Goals. Stockholm Environment Institute.

Pigné, Y., Gutiérrez, T.N., Gibon, T., Schaubroeck, T., Popovici, E., Shimako, A.H., Benetto, E., Tiruta-Barna, L., 2020. A tool to operationalize dynamic LCA, including time differentiation on the complete background database. Int. J. Life Cycle Assess. 25, 267–279. https://doi.org/10.1007/s11367-019-01696-6.

Potschin, M.B., Haines-Young, R.H., 2011. Ecosystem services: exploring a geographical perspective. Prog. Phys. Geogr. 35, 575–594. https://doi.org/10.1177/0309133311423172.

Prudhomme, R., O'Donoghue, C., Ryan, M., Styles, D., 2021. Defining national biogenic methane targets: implications for national food production & climate neutrality objectives. J. Environ. Manag. 295, 113058 https://doi.org/10.1016/j.jenvman.2021.113058.

Qiu, J., Carpenter, S.R., Booth, E.G., Motew, M., Kucharik, C.J., 2020. Spatial and temporal variability of future ecosystem services in an agricultural landscape. Landsc. Ecol. 35, 2569–2586. https://doi.org/10.1007/s10980-020-01045-1.

Rau, A.-L., Burkhardt, V., Dorninger, C., Hjort, C., Ibe, K., Keßler, L., Kristensen, J.A., McRobert, A., Sidemo-Holm, W., Zimmermann, H., Abson, D.J., von Wehrden, H., Ekroos, J., 2020. Temporal patterns in ecosystem services research: a review and three recommendations. Ambio 49, 1377–1393. https://doi.org/10.1007/s13280-019-01292-w.

Rau, A.-L., von Wehrden, H., Abson, D.J., 2018. Temporal dynamics of ecosystem services. Ecol. Econ. 151, 122–130. https://doi.org/10.1016/j.ecolecon.2018.05.009.

Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D.P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., Havlík, P., Humpenöder, F., Stehfest, E., Tavoni, M., 2018. Scenarios towards limiting global mean temperature increase below 1.5 °C. Nat. Clim. Change 8, 325–332. https://doi.org/10.1038/s41558-018-0091-3.

Rugani, B., Maia de Souza, D., Weidema, B.P., Bare, J., Bakshi, B., Grann, B., Johnston, J. M., Pavan, A.L.R., Liu, X., Laurent, A., Verones, F., 2019. Towards integrating the ecosystem services cascade framework within the Life Cycle Assessment (LCA) cause-effect methodology. Sci. Total Environ. 690, 1284–1298. https://doi.org/10.1016/j.scitotenv.2019.07.023.

Saad, R., Koellner, T., Margni, M., 2013. Land use impacts on freshwater regulation, erosion regulation, and water purification: a spatial approach for a global scale level. Int. J. Life Cycle Assess. 18, 1253–1264. https://doi.org/10.1007/s11367-013-0577-1.

Schägner, J.P., Brander, L., Maes, J., Hartje, V., 2013. Mapping ecosystem services' values: current practice and future prospects. Ecosyst. Serv. 4, 33–46. https://doi.org/10.1016/j.ecoser.2013.02.003.

Schaubroeck, T., Alvarenga, R.A.F., Verheyen, K., Muys, B., Dewulf, J., 2013. Quantifying the environmental impact of an integrated human/industrial- natural system using life cycle assessment; A case study on a forest and wood processing chain. Environ. Sci. Technol. 47, 13578–13586. https://doi.org/10.1021/es4046633.

Schröter, M., Barton, D.N., Remme, R.P., Hein, L., 2014. Accounting for capacity and flow of ecosystem services: a conceptual model and a case study for Telemark,

Norway. Ecol. Indicat. 36, 539–551. https://doi.org/10.1016/j.ecolind.2013.09.018.
Seppelt, R., Dormann, C.F., Eppink, F.V., Lautenbach, S., Schmidt, S., 2011. A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. J. Appl. Ecol. 48, 630–636. https://doi.org/10.1111/j.1365-2664.2010.01952.x.
Seppelt, R., Fath, B., Burkhard, B., Fisher, J.L., Grêt-Regamey, A., Lautenbach, S., Pert, P., Hotes, S., Spangenberg, J., Verburg, P.H., van Oudenhoven, A.P.E., 2012. Form follows function? Proposing a blueprint for ecosystem service assessments based on reviews and case studies. Ecol. Indicat. 21, 145–154. https://doi.org/10.1016/j.ecolind.2011.09.003.
Solomon, K.R., 2008. Effects of ozone depletion and UV-B radiation on humans and the environment. Atmos.-Ocean 46, 185–202. https://doi.org/10.3137/ao.460109.
Sonderegger, G., Oberlack, C., Llopis, J.C., Verburg, P.H., Heinimann, A., 2020. Telecoupling visualizations through a network lens: a systematic review. Ecol. Soc. 25, art47. https://doi.org/10.5751/ES-11830-250447.
Steen, B., 2015. The EPS 2015d Impact Assessment Method – an Overview.
Tallis, H., Polasky, S., 2009. Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. Ann. N. Y. Acad. Sci. 1162, 265–283. https://doi.org/10.1111/j.1749-6632.2009.04152.x.
Tinch, R., Beaumont, N., Sunderland, T., Ozdemiroglu, E., Barton, D., Bowe, C., Börger, T., Burgess, P., Cooper, C.N., Faccioli, M., Failler, P., Gkolemi, I., Kumar, R., Longo, A., McVittie, A., Morris, J., Park, J., Ravenscroft, N., Schaafsma, M., Vause, J., Ziv, G., 2019. Economic valuation of ecosystem goods and services: a review for decision makers. J. Environ. Econ. Policy 8, 359–378. https://doi.org/10.1080/21606544.2019.1623083.
Turner, K.G., Anderson, S., Gonzales-Chang, M., Costanza, R., Courville, S., Dalgaard, T., Dominati, E., Kubiszewski, I., Ogilvy, S., Porfirio, L., Ratna, N., Sandhu, H., Sutton, P.C., Svenning, J.-C., Turner, G.M., Varennes, Y.-D., Voinov, A., Wratten, S., 2016. A review of methods, data, and models to assess changes in the value of ecosystem services from land degradation and restoration. Ecol. Model. 319, 190–207. https://doi.org/10.1016/j.ecolmodel.2015.07.017.
van Zelm, R., Huijbregts, M.A.J., van de Meent, D., 2009. USES-LCA 2.0—a global nested multi-media fate, exposure, and effects model. Int. J. Life Cycle Assess. 14, 282–284. https://doi.org/10.1007/s11367-009-0066-8.
van Zelm, R., van der Velde, M., Balkovic, J., Čengić, M., Elshout, P.M.F., Koellner, T., Núñez, M., Obersteiner, M., Schmid, E., Huijbregts, M.A.J., 2018. Spatially explicit life cycle impact assessment for soil erosion from global crop production. Ecosyst. Serv. 30, 220–227. https://doi.org/10.1016/j.ecoser.2017.08.015.
VanderWilde, C.P., Newell, J.P., 2021. Ecosystem services and life cycle assessment: a bibliometric review. Resour. Conserv. Recycl. 169, 105461 https://doi.org/10.1016/j.resconrec.2021.105461.
Verones, F., Bare, J., Bulle, C., Frischknecht, R., Hauschild, M., Hellweg, S., Henderson, A., Jolliet, O., Laurent, A., Liao, X., Lindner, J.P., Maia de Souza, D., Michelsen, O., Patouillard, L., Pfister, S., Posthuma, L., Prado, V., Ridoutt, B., Rosenbaum, R.K., Sala, S., Ugaya, C., Vieira, M., Fantke, P., 2017. LCIA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative. J. Clean. Prod. 161, 957–967. https://doi.org/10.1016/j.jclepro.2017.05.206.
Vihervaara, P., Ronka, M., Walls, M., 2010. Trends in ecosystem service research: early steps and current drivers. Ambio 39, 314–324.
Villa, F., Bagstad, K.J., Voigt, B., Johnson, G.W., Portela, R., Honzák, M., Batker, D., 2014. A methodology for adaptable and robust ecosystem services assessment. PLoS One 9. https://doi.org/10.1371/journal.pone.0091001.
Weidema, B.P., Schmidt, J., Fantke, P., Pauliuk, S., 2018. On the boundary between economy and environment in life cycle assessment. Int. J. Life Cycle Assess. 23, 1839–1846. https://doi.org/10.1007/s11367-017-1398-4.
Willcock, S., Hooftman, D.A.P., Balbi, S., Blanchard, R., Dawson, T.P., O'Farrell, P.J., Hickler, T., Hudson, M.D., Lindeskog, M., Martinez-Lopez, J., Mulligan, M., Reyers, B., Shackleton, C., Sitas, N., Villa, F., Watts, S.M., Eigenbrod, F., Bullock, J. M., 2019. A continental-scale validation of ecosystem service models. Ecosystems 22, 1902–1917. https://doi.org/10.1007/s10021-019-00380-y.
Zanghelini, G.M., Cherubini, E., Soares, S.R., 2018. How multi-criteria decision analysis (MCDA) is aiding life cycle assessment (LCA) in results interpretation. J. Clean. Prod. 172, 609–622. https://doi.org/10.1016/j.jclepro.2017.10.230.
Zeug, W., Bezama, A., Thrän, D., 2021. A framework for implementing holistic and integrated life cycle sustainability assessment of regional bioeconomy. Int. J. Life Cycle Assess. 26, 1998–2023. https://doi.org/10.1007/s11367-021-01983-1.
Zhang, Y.I., Anil, B., Bakshi, B.R., 2010a. Accounting for ecosystem services in life cycle assessment part II: toward an ecologically based LCA. Environ. Sci. Technol. 44, 2624–2631. https://doi.org/10.1021/es900548a.
Zhang, Y.I., Singh, S., Bakshi, B.R., 2010b. Accounting for ecosystem services in life cycle assessment part I: a critical review. Environ. Sci. Technol. 44, 2232–2242. https://doi.org/10.1021/es9021156.