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Towards an optimal coverage of ecosystem services in LCA

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Our society relies on the sustained provisioning of ecosystem services (ES), while such provisioning has been negatively affected by human activities. Recently, several authors proposed indicators for the assessment of ES in Life Cycle Assessment (LCA) studies and developed corresponding characterization factors for integration in the impact assessment phase of LCA (LCIA). However, the vast majority of these indicators are still not operational and not a single study has presented a comprehensive list of ES for inclusion in LCIA. As a result, the individual efforts to incorporate ES in LCIA lack guidance from a framework to comprehensively assess and prioritize ES for inclusion in LCIA. This study addresses the aforementioned knowledge gap, and presents an original framework for the optimal coverage of ES in LCIA. We first identify, describe and visualize ecosystem services assessed currently (directly and indirectly) included in the widely applied LCIA method ReCiPe2016. Next, we propose an optimal coverage of ES in LCIA consisting of 15 categories of ES, including provisioning, regulation and maintenance, and cultural services, derived from the ES classification method CICES V5.1. Next, we identify the gap between the current and optimal coverage, consisting of 11 ES categories currently not covered by ReCiPe2016. As a proposal to help accelerate the incorporation of missing ES, we finally prioritize missing categories using available monetary valuation data, resulting in a ranking of ES categories to be included in LCIA. The four categories that rank highest are “Regulation of flows and protection from extreme events”, “Mediations of wastes, toxics and nuisances”, “Water conditions” and “Aesthetic value”. Our analysis and prioritization helps setting a research agenda for the scientific community to collaboratively and comprehensively incorporate missing ES categories in LCIA.

1. Introduction

A key sustainability challenge of the 21st century is to assess and decrease the variety of anthropogenic impacts to the environment (Díaz et al., 2018). Human societies depend on the natural environment to obtain multiple goods and services, generally referred to as ecosystem services (ES). Ecosystem services have become a trending field of research over the past decade, with an approximate of 3000 scholarly articles published on the topic just in 2016 (McDonough et al., 2017). According to Costanza et al. (2014), the term ‘ecosystem services’ appeared in 1981 by Ehrlich and Ehrlich (1981), as a synonym of an older term: ‘nature's services'. Both terms refer to the idea that natural systems provide benefits that support human well-being (Costanza et al., 2014). As presented by the Millennium Ecosystem Assessment (MA, 2005), the majority of the services studied show severe degradation due to human activities. In turn, this degradation of ecosystem services poses a risk for human well-being and in order to help prevent further damages and exploitation of ES, it is necessary to assess potential impacts on them applying environmental assessment methods.

One of the most widely applied environmental assessment methods is life cycle assessment (LCA). LCA is method of which the general principals and requirements have been laid down in International Organization for Standardization (ISO) series of Standards on LCA. Applying LCA, the potential environmental impacts associated with a product over its entire life cycle can be quantified (Guinée et al., 2002). According to the ISO 14040–14044 standards (ISO, 2006), the framework of an LCA follows four phases; goal and scope definition, inventory analysis, impact assessment and interpretation. LCA requires continuous improvement to deliver up-to-date results that are relevant for addressing current societal and environmental problems. An improvement proposed over the last years includes the idea of incorporating the impact assessment of ES in life cycle impact assessment (LCIA) methods. While ES are increasingly considered a key component in the relation between

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human society and the environment, LCA studies hardly include explicit impacts on ecosystem services. The impact categories assessed in LCA mainly consider impacts on resource availability and ecosystem quality, without explicitly considering ecosystem services. However, a wide variety of processes and conditions that are essential for the technosphere rely on ecosystem services (See Fig. 1). Thus, it is necessary to more comprehensively and explicitly include ES in LCA to achieve a better coverage of potential impacts on ES associated with a product system.

In the past years, several studies have focused on the topic of ecosystem services in LCA. Some authors have worked on modelling characterization factors for LCIA to assess impacts of land use on ES, such as impacts on biotic production (Brandão and I Canals, 2013; Saad et al., 2013), freshwater regulation, water purification and erosion regulation (Beck et al., 2010; Cao et al., 2015; Saad et al., 2013). Global characterization factors and guidelines have been published for assessing ES in LCA (Koellner et al., 2013; Koellner and Geyer, 2013) and the limitations and challenges for such integration have been extensively described in the literature (Othoniel et al., 2015; Tang et al., 2018; Zhang et al., 2010). Furthermore, several approaches have been proposed for the explicit assessment of ES within LCIA, each with very different methods and considerations, such as the use of provisioning rates as characterization factors for ES (Blanco et al., 2017), the incorporation of socioeconomic aspects of ES to calculate an aggregated endpoint (Cao et al., 2015) or the evaluation of environmental externalities (Bruel et al., 2016), as well as frameworks assessing techno-ecological synergies that could be considered in parallel to or complementing LCA (Xinyu et al., 2018).

However, there is no framework in the literature pointing at which selection of ecosystem services would comprise an optimal coverage in LCA. Drafting such a framework demands an appropriate integration of knowledge from both the ecosystem services and the LCA community to determine relevant ES categories for inclusion in LCA. This paper aims to bring together knowledge from both communities in order to define an optimal coverage of ES in LCA, and therefore, evaluate and recommend which ecosystem services categories form such optimal state. Optimal coverage of ES in LCA is defined here as the 'inclusion of a minimum number of ES categories that still sufficiently represents the wide variety of specific ES'. To achieve this, we first determine which ES are already covered by a state-of-the-art LCIA method, which ES have been proposed to add to LCA by other authors, and which ES are distinguished by the ES scientific community. Subsequently, we derive the ideal level of ES inclusion in LCA by presenting an optimal coverage composed of multiple ES categories derived from internationally accepted classification systems. Finally, we conduct a prioritization analysis among ES according to their monetary values as an approach to guide efforts and accelerate their inclusion in LCA.

2. Methods

Fig. 2 summarizes the research steps adopted for defining an optimal coverage of ES in LCA. The first step consists of determining the 'current' state of ES in LCA. The current state was composed by preparing an overview of which ES are already covered by LCIA methods and which ES have been proposed for addition in LCA. We selected an LCIA and an ES classification method on which we based our analysis. To complete our analysis, we conducted a bibliometric analysis was carried out of the ISI Web of Science (WoS) published by Thomson Reuters on efforts made so far by other authors proposing concrete indicators for ES in LCA. The keywords used were 'Life Cycle Assessment' AND 'Ecosystem Services' (accessed on 16/02/2018). Only those articles that proposed specific indicators for the assessment of ES in LCIA were taken into account.

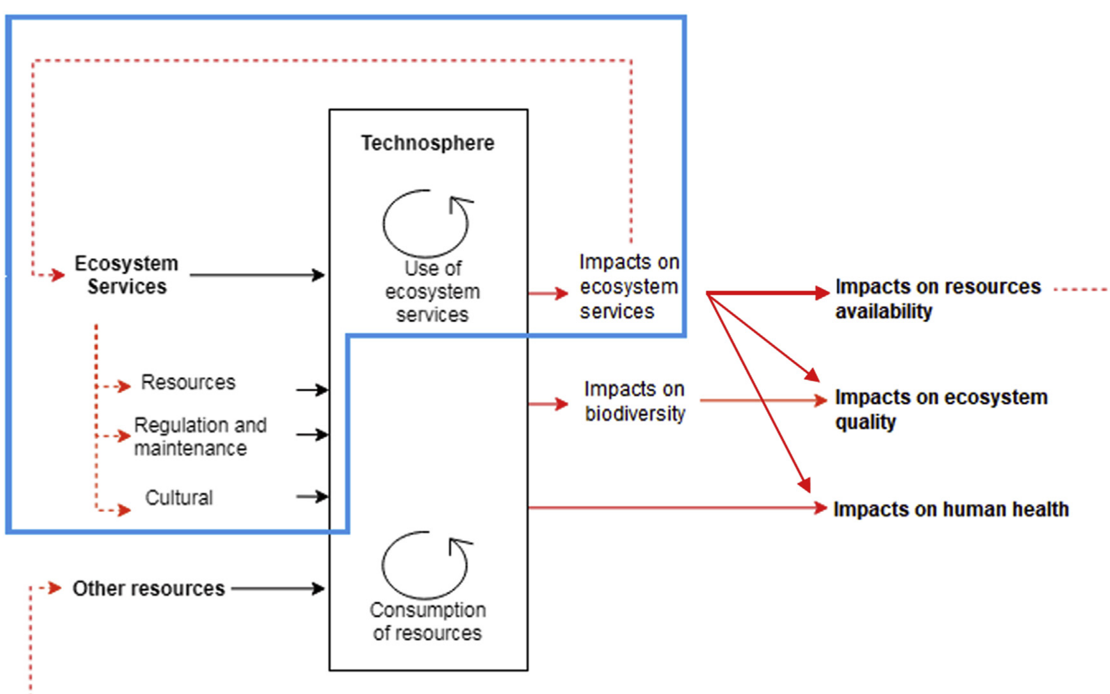

Fig. 1. Relations between technosphere and environment. Ecosystem services are inputs (black arrows) to the technosphere, along with other resources that do not classify strictly as ecosystem services (e.g. soil, chemicals, etc.). The impacts from the technosphere (red arrows) have effects on ecosystem services, of which some are directly linked with the three main areas of protection used in LCA, resource availability, ecosystem quality and human health. The impacts on ecosystem services have a negative feedback on the technosphere that consumes and benefits from these services. This study focuses on the assessment of ecosystem services, which is shown by the blue box that excludes biodiversity and impacts to other aspect such as human health.

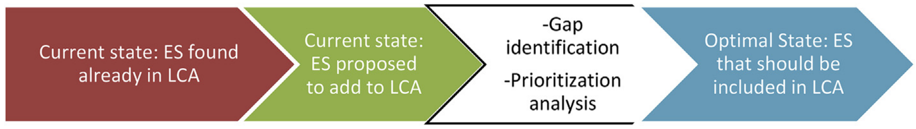

Fig. 2. Steps of the research. The current state of ES in LCA will be determined based on existing ES in a widely applied LCIA method and those additionally proposed in the LCA literature. The optimal state will be developed to indicate ES distinguished by the ES scientific community that should be included in LCA as a minimum. We will identify the gap between current and optimal coverage, and conduct a prioritization analysis based on existing monetary values for ES. .

From the literature search we obtained a list of 274 articles, from which 34 contained information about LCA and ecosystem services. We further selected only those studies that contained information specifically about the implementation of ecosystem services in LCA and that propose concrete indicators for their evaluation in LCA. Articles proposing indicators to assess ES in LCA based on emergy (e.g. Rugani et al., 2013)and hemeroby (e.g. Fehrenbach et al., 2015) were also excluded also because of their incompatibility with current practices and limited focus on the impacts on ES.

The next step was deriving an optimal coverage based on a representative ES classification method. Based on a comparison of results from the 'optimal' and 'current' coverage, we assessed which indicators are already proposed in the LCA-ES literature for complementing the current coverage of ES in impact assessment methods. The last step consisted of a prioritization exercise in which ES from the optimal state currently missing in LCIA methods were ranked based on available information, in this case, monetary values.

2.1. Selection of ES terminology and classification system

Since the introduction of the term 'ecosystem services', a multitude of definitions and classification systems for ecosystem services has arisen. This has caused a wide variety of interpretations on what exactly are ecosystem services, with different classification systems existing such as the 'Common International Classification of Ecosystem Services' (CICES), the 'Final ecosystem goods and services classification system'(FEGS-CS), the 'National ecosystem services classification system' (NES-CS), and the ones used by The Economics of Ecosystems and Biodiversity (TEEB), and the Millennium Ecosystem Assessment (MA). For this study, the classification system for ES selected was CICES V5.1 (Haines-Young and Potschin, 2018), since it is widely used and vastly accepted by policy makers. In contrast to other ES classifications, such as the one used by the Millennium Ecosystem Assessment and the TEEB, CICES also accounts for abiotic resources as provisioning services, which are an important element of LCA inventories and crucial for the assessment of the impact category "abiotic resource depletion". CICES is also an international classification, unlike the FEGS-CS and NES-CS which are focused and developed by the United States government.

CICES distributes ecosystem services into three categories: provisioning, regulating and maintenance, and cultural services. However, this classification scheme does not provide a clear distinction between services and benefits. To avoid misunderstandings, we will refer to ecosystem services as the service provided by ecological functions and processes that contribute to human well-being (La Notte et al., 2017), and benefits as the perceived value for humans of such services. In order to use the CICES classification within the framework of LCA we will adapt the terminology used by CICES to better reflect the difference between service and benefits in the classification and categorization of our results.

This study focuses exclusively on ecosystem services. Since biodiversity is not an ecosystem service itself, it is left out of the scope of this study. The link between species and ecosystem services depends on the functional relevance of the species. This means, the importance of species depends on their service to the technosphere (for example, do they serve as materials or do they serve other purposes that contribute to human well-being). Therefore, we can only take particular species into account as ecosystem services if we know that those species are being used for a certain purpose. If the functional relevance cannot be determined, as is the case with the "Disappeared fraction of species" indicator used in LCA, for which we do not know the exact species considered, we cannot link it to an ecosystem service. It should still be included in LCA as a biodiversity impact, but it is out of the scope of this study.

2.2. Selection of the LCIA method

There is a wide variety of LCIA methods, some containing only midpoint indicators such as the CML impact assessment method (Guinée et al., 2002), some others focusing on end-points only as the Eco-indicator 99 (Goedkoop and Spriensma, 2000), and some with both midpoint and endpoints as for example the methods LC-Impact (Verones et al., 2016), Impact World (Bulle et al., 2019) and ReCiPe (Huijbregts et al., 2016). We selected the most recently updated method with the broadest set of indicators, in this case ReCiPe2016. ReCiPe is an acronym that represents the initials of the institutes that were the main contributors and collaborators in its design: RIVM and Radboud University, CML, and PRé Consultants. ReCiPe2016 contains 17 midpoint categories and 3 endpoint categories (Huijbregts et al., 2016). For this study we use ReCiPe2016 to analyze in depth its impact categories and determine if (and which) ES are accounted for within these categories.

For the impact categories climate change and toxicity, external models had to be consulted for further clarification on the aspects involved in their characterization factors. Climate change relies on the characterization factor "Global Warming Potential" (GWP), which is provided by the IPCC (2006). The characterization factors for toxicity in ReCiPe2016 are based on the USES-LCA model (Van Zelm et al., 2009).

2.3. Prioritization of ES

Based on the inventory of ES categories constituting the optimal state in LCAs, a prioritization was made to steer and accelerate research for assessing and incorporating ES in LCA. Ideally, such prioritization would use indications of their value, degree of impact or degradation, and regeneration time. However, the only databases available evaluating and comparing ES of diverse categories across the globe are based on monetary valuation (de Groot et al., 2012; Van der Ploeg et al., 2010). Despite its limitations (Schild et al., 2017; Silvertown, 2015), monetary valuation can help prioritize *among* the ES categories proposed for the optimal coverage, and the ES *within* the proposed categories. Based on the estimated monetary valuation of ES as presented by de Groot et al. (2012) we ranked categories of ES that have not been incorporated in ReCiPe2016, and (if possible) the ecosystem services within those categories. In order to rank the ES categories by monetary value, we matched the ES categories used and evaluated by de Groot et al. (2013) with our proposed ES categories (See SI3 for detailed procedure).

3. Results

3.1. Current coverage of ES in LCA

3.1.1. Ecosystem services already covered in ReCiPe2016

We found that five mid-point impact categories of ReCiPe2016 are linked with specific ecosystem services (see Fig. 3):

- The category of *climate change* is related to regulation and maintenance services. Within this category, carbon sequestration -which is a service that contributes to climate regulation-is taken into account in the characterization model of the IPCC and thus also in the characterization factor GWP. Carbon sequestration and its effects on climate regulation are affected by increased anthropogenic emissions. Its dynamics is modelled as part of the GWP.
- The *stratospheric ozone depletion* category is also directly linked with regulation and maintenance services. The stratospheric ozone layer serves as protection against UV radiation and can be considered an ecosystem service itself.
- The category of *water use* refers to both fresh and groundwater availability. This category can be seen as the ecosystem service of water provisioning.
- *Mineral resource scarcity* and *Fossil resource scarcity* correspond directly to the ecosystem services of mineral and non-mineral resources provisioning, where increased extraction decreases the availability of the corresponding resources.

For the remaining impact categories, the relation with specific ecosystem services was either not found, or considered to be too uncertain and indirect. Next to "disappeared fraction of species", major uncertainties apply to *ionizing radiation*, where it could be argued that DNA damage through radionuclides exposure can

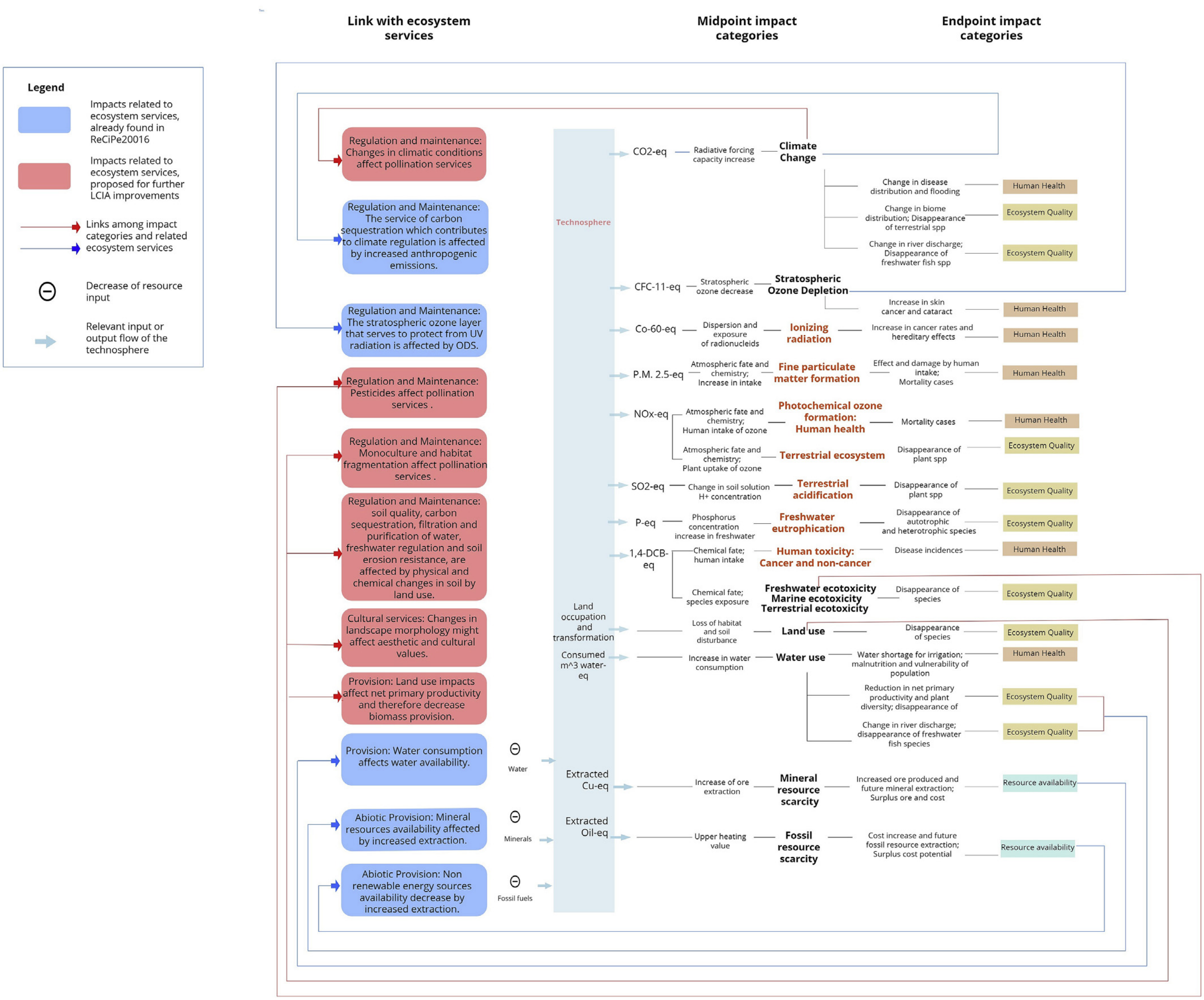

Fig. 3. Relations between impact categories and ecosystem services. Impact categories of ReCiPe2016, showing the current and proposed relations between impact categories and ecosystem services in LCIA. Impact categories for which the connection to ecosystem services was not found (or considered to be too uncertain and indirect) are coloured orange. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

cause cancer and hereditary effects, affecting the provisioning of biomass and genetic resources. *Photochemical ozone formation* also has negative effects on biomass, reducing net primary productivity. Until the relationships with ES are further clarified, these categories cannot be considered as impacting on ES.

3.1.2. Ecosystem services proposed for inclusion in LCA currently found in the literature

The publications eventually selected for describing the current coverage of ES in LCA are listed in SI1. Most indicators proposed focus on land use impacts (Beck et al., 2010; Cao et al., 2015; Milà i Canals et al., 2007a; Núñez et al., 2013) and their effects on regulation and maintenance services (see Fig. 3). Only one article was found proposing to include a cultural service indicator into LCA (Burkhard et al., 2012; Vidal Legaz et al., 2017).

3.2. An optimal coverage of ES

Based on the complete list and description of CICES V5.1 classification, we summarized the data and obtained a total of 31 ecosystem services groups (see Table 1). Four groups were considered as non-pertinent for LCA, these are cultural services that are assessed through societal aspects and would be more suitable for social LCAs instead of environmental LCAs (the topic of this study). Only ecosystem services that are targeted or assessed through an ecological function or process are considered as pertinent for environmental LCAs.

Once the non-pertinent groups had been removed, we summarized and derived categories from the remaining groups (see detailed explanation in SI2). For example, the category “Biomass provision” is derived from the CICES groups regarding biomass, including cultivated and wild plants and animals, both aquatic and terrestrial. At the end, we obtained 15 categories that form the optimal coverage of ecosystem services.

From those 15 categories, only four are covered (some partially) in ReCiPe2016. This is the case for 1) “water provisioning”, covered by the water use impact category. 2) “Atmospheric composition and conditions regulation” can be linked to both climate change impact category and stratospheric ozone depletion. 3) “Mineral resources” are directly assessed in the mineral resource scarcity impact category, and 4) “Non-mineral resources” in the fossil resource scarcity impact category.

The remaining 11 categories of our optimal state proposed are still entirely lacking in LCAs. However, several of these can be covered by LCIA methods if the indicators proposed and presented in the previous section become operational (although we are not endorsing any of the methods or indicators proposed, but merely describing the advantages from the point of view of ES coverage). In the end, 4 out of the 15 categories proposed have neither been included nor proposed as indicators for their inclusion in the impact assessment method of LCA. These 4 categories correspond to “Genetic material resources”, “Mediation of smell, noise and visual impacts”, “Pest and disease control”, and “Maintenance of abiotic conditions”.

3.3. Prioritizing ES for incorporation in LCAs

Based on the estimated monetary valuation of ES as presented by de Groot et al. (2012) we first ranked the eleven remaining categories of ES that have not been incorporated in ReCiPe2016, and secondly, the ecosystem services within the eleven categories of ES. For this purpose, we first allocated each of the 22 types of ES used in the study by de Groot et al. (2012) to the ES categories proposed for an optimal coverage by this study (presented in Table 1). For example, the categories *food*, *medicinal resources*, *raw material* and *ornamental resources* used in de Groot et al. (2012) were grouped under the category “Biomass provision”. The total estimated monetary value of ecosystem services across biomes was calculated per category by summing the monetary value of each of the ES considered within a category (Table 2).

The ES category with highest priority for inclusion in LCA was “Regulation of flows and protection from extreme events” (Table 2). Within this category, the most valuable ES corresponds to erosion prevention, followed by disturbance moderation. The category “Mediation of wastes, toxics and nuisances” and “Water conditions” were placed together as the second highest valuable (waste treatment and water purification are grouped together in the TEEB classification used by de Groot et al. (2012)). The “Aesthetic value” category, ranking as the third most valuable, represents cultural services such as aesthetic information, recreation and cognitive development, with recreation being the most valuable ES type within this category.

4. Discussion

This study presents a list of 15 ES categories that should be considered in LCA and that together could constitute an optimal state for ES coverage (Table 1). This optimal state can be used as guidance for future research to provide characterization factors for those ES that still need to be included in LCA. By providing an optimal state, and therefore an indication or reference point of ES that we should focus on, we can help accelerate the incorporation of a more complete coverage of relevant impacts while minimizing overlap and avoiding double-counting. At the same time, the list of categories provided in this study helps shedding a light on the increasing number of indicators needed for incorporation in LCA. If we consider all categories that could be included in LCA regarding ES, the impact assessment of LCA would easily consist of at least 27 midpoint impact categories in total. While some efforts have focused on trying to find common ground among existent categories to minimize the amount of impact categories needed in the impact assessment of LCA (Steinmann et al., 2017), it is also arguable that the impact assessment of LCA is still considerably limited, and the addition of impact categories assessing a wide range of impacts is essential to improve its robustness. A major complication is that this increased number of impact categories complicates the interpretation and decision making based on LCA results. This issue will have to be addressed in future research studying how to help practitioners deal with an increased number of indicators while facilitating their selection and interpretation for decision making processes.

4.1. Robustness of the optimal state

The optimal state proposed in this study comprises 15 ES categories that were derived from the internationally accepted ES classification method CICES. These categories and their subsequent prioritization may have been influenced by the choice of impact assessment and classification methods that were used to assess the current state of ES in LCA and to derive the optimal state proposed. If instead of using ReCiPe2016 to assess the current state we had chosen another impact assessment method (e.g. LC-Impact, Impact World+, etc.), we would have found a different number of ecosystem services considered (e.g. non-mineral resources would not consistently have been considered, for instance the LC-Impact method does not assess fossil resource scarcity), resulting in a larger or smaller gap between the current and optimal state. On the same note, if another ecosystem services classification system had been used, the proposed categories might have differed slightly (e.g. the Millennium Ecosystem Assessment has limited the concept

Table 1
Deriving the optimal state for coverage of ES in LCAs First column corresponds to the CICES classification by sections of ecosystem services. Second column presents the summarized groups of ES according to CICES V5.1. Third column presents the 15 aggregated categories we propose for the optimal coverage of ES. Categories that are already accounted for in ReCiPe2016 are highlighted in green. The groups considered as non-pertinent for LCA are highlighted in Red. Categories for which indicators have already been proposed in the literature are followed by an asterisk (*).

Classification by CICES V5.1	ES groups by CICES V5.1	Proposed ES categories for optimal state
Provision (biotic and abiotic)	Cultivated terrestrial plants for nutrition, materials or energy	1. Biomass provision *
	Cultivated aquatic plants for nutrition, materials or energy	
	Reared animals for nutrition, materials or energy	
	Reared aquatic animals for nutrition, materials or energy	
	Wild animals (terrestrial and aquatic) for nutrition, materials or energy	
	Wild plants (terrestrial and aquatic) for nutrition, materials or energy	
	Genetic material from plants, algae or fungi	2. Genetic material resources
	Genetic material from animals	
	Genetic material from organisms	
	Mineral substances used for nutrition, materials or energy	3. Mineral resources
	Non-mineral substances or ecosystem properties used for nutrition, materials or energy	4. Non-mineral resources
	Surface water used for nutrition, materials or energy	5. Water provision
	Ground water for used for nutrition, materials or energy	
Regulation & Maintenance (Biotic and abiotic)	Mediation of wastes or toxic substances of anthropogenic origin by living processes	6. Mediation of wastes, toxics and nuisances (Filtration, sequestration, storage, etc.) *
	Mediation of waste, toxics and other nuisances by non-living processes	
	Mediation of nuisances of anthropogenic origin	7. Mediation of smell/noise/ visual impacts
	Mediation of nuisances of anthropogenic origin	
	Regulation of baseline flows and extreme events	8. Regulation of flows and protection of extreme events *
	Regulation of baseline flows and extreme events	
	Lifecycle maintenance, habitat and gene pool protection	9. Habitat and gene pool maintenance *
	Pest and disease control	10. Pest and disease control
	Regulation of soil quality	11. Soil quality *
	Water conditions	12. Water conditions *
	Atmospheric composition and conditions	13. Atmospheric composition and conditions regulation
	Maintenance of physical, chemical, abiotic conditions	14. Maintenance of abiotic conditions
Cultural (Biotic and abiotic)	Physical and experiential interactions with natural environment	15. Aesthetic value, cultural/educational/scientific value. Use of sea or landscapes *
	Physical and experiential interactions with natural abiotic components of the environment	
	Intellectual and representative interactions with abiotic components of the natural environment	NA
	Intellectual and representative interactions with natural	NA
	environment	
	Spiritual, symbolic and other interactions with the abiotic components of the natural environment	NA
	Spiritual, symbolic and other interactions with natural environment	NA

Table 2
Ranks (highest to lowest) of categories of the optimal state missing from ReCiPe2016 based on economic valuation estimates. The monetary values by de Groot et al. (2012) in standardized units of International dollars per hectare per year (2007 price levels), were used to rank the categories and the ecosystem services within these categories. The group of "Mediation of smell, noise and visual impacts" and "Maintenance of abiotic conditions" did not match the ES types studied by de Groot et al. (2012) and therefore were not assigned any economic value within the ranking.

Rank #	ES categories proposed for optimal state	ES used by de Groot et al. (2012)	Monetary value (int.$/ha/year, 2007 price levels)
1	Regulation of flows and protection of extreme events	Erosion prevention	185.195
		Disturbance moderation	25.394
		Regulation of water flows	5.948
2	Mediation of wastes, toxics nuisances/Water conditions	Waste treatment	165.500
3	Aesthetic value	Recreation	105.336
		Esthetic information	12.849
		Cognitive development	1.168
4	Habitat and gene pool maintenance	Genetic diversity	26.155
		Nursery service	13.418
		Pollination	61
5	Genetic material resources	Genetic resources	33.071
6	Biomass provision	Raw materials	22.819
		Food	6.728
		Medicinal resources	1.905
		Ornamental resources	618
7	Soil quality	Nutrient cycling	1.854
8	Pest and disease control	Biological control	1.194
	Mediation of smell, noise and visual impacts	NA	NA
	Maintenance of abiotic conditions	NA	NA

of natural capital to 'life on Earth' and therefore excludes abiotic resources such as mineral resources (Lele et al., 2013; MA, 2005)). CICES does account for mineral resources as a provisioning service and is therefore one of our proposed categories for the optimal state. To improve the robustness of an optimal state, the analysis could be repeated using different classification systems or by using a harmonized classification system. However, since most classification systems differ only slightly in what they consider a service or a benefit, and in how they categorize and aggregate ES types, we think the differences would be only minor.

4.2. Prioritization results and robustness

To help bridging the gap between the current and optimal state we conducted a prioritization analysis. The results of this prioritization can be used to make fast steps forward in the inclusion of ES in LCA. The results of this analysis indicated that ecosystem services related to regulation of flows and protection of extreme events ranked as the highest priority. Ecosystem services that provide mediation of wastes/water conditions and aesthetic value were ranked as second and third in the prioritization ranking, respectively.

Two aspects should be considered when examining the results obtained from this analysis. First, the robustness of the monetary values used from de Groot et al. (2012) should be considered. The estimated values of global averages of ecosystem services per ha can vary across time depending on the changes in the average functionality of ecosystem service per ha and the possible changes in environmental and social capital (Costanza et al., 2014; de Groot et al., 2012). Furthermore, the estimates of monetary values of ES are highly dependent on the valuation methods used, the socio-economic context of the studied ES and even the type of values used (e.g. market value, present value, etc.). For example, Costanza et al. (2014) compared global average values of ecosystem services from an earlier study by Costanza et al. (1997) with those published by de Groot et al. (2012). The values obtained for de Groot et al. (2012) appeared to be approximately eight times higher than those obtained for Costanza et al. (1997). One of the main reasons for this difference was the increased number of valuation studies that had become available, in combination with a different suite of valuation techniques applied. The monetary values used by de Groot et al. (2012) were last updated in 2011 and we can assume with high certainty that the monetary values of ecosystem services have changed from 2011 to present, due to the fast degradation caused by anthropogenic activities. The use of updated unit values would therefore lead to different global average estimates per ha and potentially also to different prioritization ranking results if degradation has affected services differently. Moreover, monetary valuation may be more appropriate for e.g. provisioning services than for cultural services, causing an underestimate of e.g. cultural services (Schild et al., 2017). Also, not all ecosystem services have been valued and supported with enough data to be included in databases such as the Ecosystem Service Valuation Database, from where the monetary estimates were obtained. This means there is an underrepresentation of ecosystem services. As a result thereof, the priority of including aesthetic value might actually be higher than proposed by our analysis.

The second aspect to consider includes the decisions made during the prioritization to match the ES types from de Groot et al. (2012) with our proposed ES categories (See description in SI3). For example, the category "Raw materials" used by de Groot et al. (2012), which is based on the TEEB classification, contains estimates of biomass materials as well as minerals and ore based materials. However, the specific values for each type were not available, and therefore we attributed all monetary values of the "raw materials" category to our "Biomass provision" category, which results in a slight overestimation of this category within our ranking. Another consideration regards the ecosystem services categories of "water conditions" and "mediation of wastes, toxics and nuisances". They are ranked at the same level since they are presented together in the category "waste treatment and water purification" by the TEEB (Van der Ploeg et al., 2010). Finally, the prioritization was done entirely based on the monetary valuation, whereas ideally a ranking of ES according to those most impacted by the technosphere could also have been considered. Unfortunately, the lack of comprehensive data on impacted ES hampered including this in the analysis.

Despite the limitations of ecosystem services economic valuation, it also has several advantages. For example, monetary valuation data of ES is available and easily accessible (for example the Ecosystem Services Valuation database by Van der Ploeg et al. (2010)), and the use of monetary units can facilitate the communication of economic benefits that, for example, would be lost if ES were destroyed. Therefore, we propose using economic valuation studies to support the decision making process regarding the prioritization of ES for inclusion in LCA, as was exemplified in this study.

4.3. Aggregation of the optimal coverage

Given that our analysis shows that the majority of ecosystem services categories (11 out of 15) that may be impacted by the technosphere are not yet considered in LCAs, creating the proposed optimal state will imply a need to develop a large number of midpoint indicators. Our prioritization analysis can serve as a guide for future research by indicating the ES categories that present the "highest priority" based on available monetary data. In addition, a high number of indicators may be considered difficult to handle in decision-making processes (Cucurachi et al., 2016). The weighting step in LCA has the explicit intention to address this problem by further aggregating the indicator results using normative weights and thus facilitate decision-making (Cucurachi et al., 2017). While this weighting process is sometimes debated within LCAs, for ES this method is well-developed ensuring that all ecosystem services are expressed in the same units through e.g. monetary valuation. Given that comprehensive databases are available for monetary valuation (such as de Groot et al., 2012), this process may be facilitated by a cross-fertilization between the fields of LCA and ES. Before weighting can be performed, the various indicator results will first need to be transposed into the same units, for which normalization is one possibility (Guinée et al., 2002). Therefore, normalization factors may have to be developed for new ES impact categories. For instance, if a new impact category such as "*Biomass consumption*" or "Decrease on biomass production" is included in LCA, a normalization factor needs to be provided, such as "*total biomass produced*" in the world at a certain year. Some inherent problems of normalization will have to be taken into consideration such as normalization bias, compensation, magnitude insensitivity, etc. (Cucurachi et al., 2017; Heijungs et al., 2007; Prado et al., 2017). Another option is to aggregate or model mid-point indicator results into endpoint indicator results. However, also this requires weighting. As an example of this, Cao et al. (2015) proposed the aggregation of six mid-point land use indicators into an endpoint representing the loss of ecosystem services captured by human society. Ultimately, this could lead to an endpoint on "ecosystem services impact" which captures all impacts of the technosphere on ecosystem services.

4.4. Implementation of future indicators

Ecosystem services depend on natural properties and functions that differ across the globe due to biogeographical variations, making spatial differentiation a crucial aspect for their assessment. If impacts to ES are to be included in LCA, it is essential that their estimation is done by taking into account biogeographical variations (Koellner et al., 2013; Maes et al., 2012). As described previously, several indicators have been proposed in the literature for the assessment of ES in LCA (Beck et al., 2010; Brandão and I Canals, 2013; Cao et al., 2015; Koellner et al., 2013; Langlois et al., 2015; Maes et al., 2016; Milà i Canals et al., 2007b; Núñez et al., 2013; Saad et al., 2013; Taelman et al., 2016; Vidal Legaz et al., 2017), through the incorporation of new impact categories in impact assessment methods and newly developed characterization factors. Geographical specificity has been attempted for some of the indicators by developing characterization factors at a diverse range of spatial scales (Saad et al., 2013). However, their use is limited due to practical complications involving spatial compatibility with inventory flows of background processes, and has been restricted mainly to foreground processes in the case of LCA. As described by Heijungs (2012), most background processes lack the precise geographical information to connect the emissions with highly site-specific characterization factors. Furthermore, pursuing a hyper-regionalization of the impact assessment phase in LCA would lead to "a complete breakdown of the feasibility of matrix-based LCA" (Heijungs, 2012).

To reach a compromise between the need for spatial differentiation for ES and the practical limitations of LCA, we propose further research to focus around the use of archetypes (see for example Gandhi et al., 2011b, 2011a; Kounina et al., 2014) to develop spatially differentiated characterization factors that can be linked with background processes. Most background processes are categorized at a maximum geographical resolution of country level. However, biographical variations can be reflected with the use of archetypes by assigning each country to an archetype category, and therefore reducing the number of spatial categories needed for the assessment of ES. Archetypes can take into account environmental and socioeconomic factors to have a more accurate representation of the studied system (Kounina et al., 2014; Václavík et al., 2013). The use of archetypes would allow estimating impacts on ES also for background processes, increasing the applicability of newly proposed indicators.

5. Conclusion

Our study proposes an optimal state for the coverage of ecosystem services in LCA composed by fifteen ES categories derived from CICES V5.1 (2018). The categories that are still missing from the assessment of LCA, and specifically from ReCiPe2016, should be integrated in the most explicit way possible to prevent and avoid double counting of overlapping categories. Our prioritization of ES categories missing can be used (and improved) as an indication of which ES require more attention and rapid integration in impact assessment methods to avoid their continuing degradation and loss of benefits to human well-being. The list of ES categories provided in this study helps shedding a light on the increasing number of impact categories needed for incorporation in LCA. The incorporation of impact categories and characterization factors will require interdisciplinary cooperation to develop models that can be used in LCA and that can remain representative of the (spatial differentiation in) natural processes and effects that are desired to assess.

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Appendix A. Supplementary data

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