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Integrated earth system dynamic modeling for life cycle impact assessment of ecosystem services

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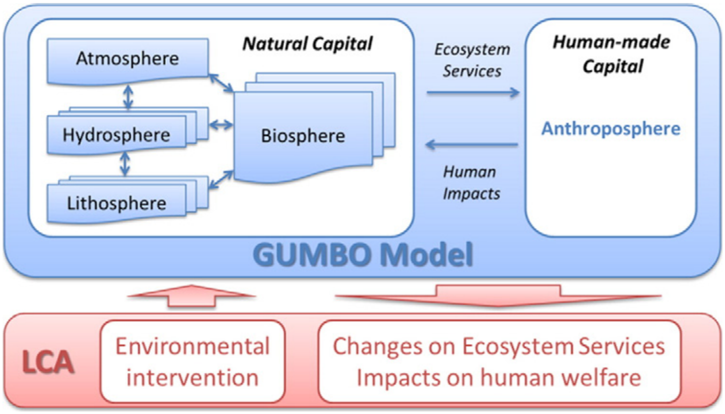
HIGHLIGHTS

- Current LCIA models do not fully consider Ecosystem Services.
- The use of integrated dynamic modeling is investigated to overcome this limitation.
- Preliminary results retrieved from the metamodel GUMBO are presented.
- Outcomes and limitations are discussed and a roadmap is elaborated.

GRAPHICAL ABSTRACT



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ABSTRACT

Despite the increasing awareness of our dependence on Ecosystem Services (ES), Life Cycle Impact Assessment (LCIA) does not explicitly and fully assess the damages caused by human activities on ES generation. Recent improvements in LCIA focus on specific cause–effect chains, mainly related to land use changes, leading to Characterization Factors (CFs) at the midpoint assessment level. However, despite the complexity and temporal dynamics of ES, current LCIA approaches consider the environmental mechanisms underneath ES to be independent from each other and devoid of dynamic character, leading to constant CFs whose representativeness is debatable. This paper takes a step forward and is aimed at demonstrating the feasibility of using an integrated earth system dynamic modeling perspective to retrieve time- and scenario-dependent CFs that consider the complex interlinkages between natural processes delivering ES. The GUMBO (Global Unified Metamodel of the Biosphere) model is used to quantify changes in ES production in physical terms – leading to midpoint CFs – and changes in human welfare indicators, which are considered here as endpoint CFs. The interpretation of the obtained results highlights the key methodological challenges to be solved to consider this approach as a robust alternative to the mainstream rationale currently adopted in LCIA. Further research should focus on increasing the granularity of environmental interventions in the modeling tools to match current standards in LCA and on adapting the conceptual approach to a spatially-explicit integrated model.

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1. Introduction and goals

Ecosystem Services (ES) result from ecosystem functions (Burkhard et al., 2012; de Groot et al., 2012; Costanza et al., 1997; Daily, 1997), which are 'the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly' (de Groot et al., 2002). Over the last 15 years, scientific studies flourished in the economic and biophysical valuation of ES (e.g. Gómez-Baggethun et al., 2010; TEEB, 2010). In particular, the Millennium Ecosystem Assessment (MEA) classified four categories of ES (MEA, 2005): provisioning, regulating, cultural and supporting services. The MEA has represented the consensual umbrella for all the ES valuation approaches developed afterwards. For example, The Economics of Ecosystems and Biodiversity (TEEB) approach, which is one of the most recommended frameworks to target ES and pursuing their benefits, especially at the country scale, incorporates many of the concepts, classification schemes and criteria developed by MEA (TEEB, 2010). However, valuing the contribution of ES to human welfare demands robust methods to define and quantify ES (Crossman et al., 2013), especially if the accounting perspective aims to address both economic, environmental and social (triple-bottom-line) aspects (Crossman et al., 2013; Cardinale et al., 2012; de Groot et al., 2010; Haines-Young et al., 2012; Maes et al., 2013).

Focusing on the environmental dimension, the growing interest for ES valuation has permeated the larger environmental assessment field, and namely Life Cycle Assessment (LCA), which is a widely accepted methodology to evaluate the environmental impacts of a product or service throughout its life cycle (ISO, 2006). Within LCA, the Life Cycle Impact Assessment (LCIA) step translates the elementary flows (resources consumed and pollutants emitted) into environmental impacts, which are either problem-oriented (midpoint approach) or damage-oriented (endpoint approach) (European Commission, 2010a). To this aim, so-called characterization factors (CFs) are developed using impact assessment models, reflecting the values associated with three main Areas of Protection (AoP): Human Health (HH), Natural Resources (NR), and Natural Environment (NE). Whereas there is scientific consensus on the scope of HH, the evaluation of NR and NE remains debatable, because of the intrinsic cross-linkages between the two areas (de Baan et al., 2013; European Commission, 2010b). The AoP of NR should cover the damage associated with the exploitation of natural resources, which can affect the delivering of ES. However, LCIA indicators (and related CFs) have essentially been developed with regard to the usefulness of natural resources for human purposes (see e.g. European Commission, 2010b, for a comprehensive list and analysis). Most of the indicators focus on the assessment of mineral and fossil resource scarcity, by evaluating the future marginal cost of extraction/use of these resources. With regard to the AoP of NE, the aim is to quantify the negative effects on the function and structure of natural ecosystems as a consequence of the exposure to chemicals or other physical interventions (European Commission, 2010b).

Recent researches have addressed the link among elementary flows of Life Cycle Inventory (LCI) (mainly land occupation and land transformation) and novel LCIA midpoint impact categories called 'potential damage on Ecosystem Services' (Koellner et al., 2013). Accordingly, spatially differentiated CFs were developed to assess potentials of e.g. biodiversity damage (de Baan et al., 2013) climate regulation (Müller-Wenk and Brandão, 2010), biotic production (Brandão and Milà i Canals, 2013), erosion and freshwater regulation and water purification (Saad et al., 2013), and water supply from groundwater (van Zelm et al., 2011). The assessment of functional diversity within the different taxonomic groups of mammals, birds and plants was recently proposed as a complement to the assessment of species richness (de Souza et al., 2013). While highlighting the lack of completeness of existing LCI databases, one of the main objectives reached is the definition, harmonization and ranking of a large set of land use and land use change elementary flows created as a common inventory database for both global and local (regionalized) assessments of ES, which can be directly used in the LCIA practice. Other research streams have tried to integrate LCA with the emergy concept and method (Odum, 1996), providing an explicit LCIA of ES that underlies a pure ecological orientation (Marvuglia et al., 2013; Rugani et al., 2013). However, this approach is not fully operational yet because of some computational and system boundary constraints associated with the combination of the two methods, further hampered by a lack of consensus on emergy in the LCA community (Arbault et al., 2013; Raugei et al., in press).

The insufficient coverage of ES in the current LCIA practice (Zhang et al., 2010; Curran et al., 2011; de Baan et al., 2013) is hampering the consistent application of LCA to a number of sectors which are very concerned by ES, e.g. agriculture. Despite the significant breakthrough of the recently developed methods, four aspects were identified deserving further attention.

First, cause–effect chains originating from land occupation and transformation are modeled independently (Koellner et al., 2013), i.e. without considering the interconnections between the mechanisms of natural processes. It is widely recognized that natural processes influence each other in many complex and indirect ways and that indirect effects can be delayed in time and widespread over the globe (Folke et al., 2011). This is therefore a significant simplification, as for instance an increased terrestrial acidification is likely to alter the biological properties of soil, thus changing local biodiversity, which in turn may change the sensitivity of ecosystems to toxic substances. CFs should thus not be constant, but time dependent as a function of all emitted inventoried substances over time.

Second, environmental mechanisms are investigated up to the midpoint level, whose impacts are expressed in physical units (Koellner et al., 2013). However, ES is a user-oriented concept, which has been developed to assess the benefits that human societies yield from nature. Although the health of ecosystems can be measured in physical terms, benefits are commonly expressed in terms closer to human values, such as economic development or contribution to welfare (MEA, 2005; de Groot et al., 2002; Costanza et al., 1997; TEEB, 2010). As a result, the investigation should include also endpoint targets.

Third, the potential damages in LCIA are usually assessed by adopting a marginal and short time perspective (Goedkoop et al., 2009). The focus is therefore on how the current state of ecosystems would be altered, in the short term, by a perturbation, usually defined at local scale and in a simplistic manner, because of the granularity of LCI databases. An example could be the assessment of the effects of occupying a small piece of land on the local species diversity during a short period. As a result, only marginal effects occurring right after the perturbation are included. Such an approach misses the holistic perspective, in which environmental mechanisms are influencing each other at various spatial scales and with both short-term and long-term effects. A more comprehensive analysis should therefore include, for instance, the effects on global climate change to local water regulation and soil erosion during the next decades.

Fourth, nature and mankind interact in many complex ways. Human-driven systems use natural resources and generate waste and emissions that can affect the ecosystems. The production of ES occurs at a limited pace. Over-exploitation of renewable resources may lead to a complete collapse of the local ecosystem. In turn, a degradation of the natural environment may challenge human welfare, so that in order to sustain our living standards we may need to extract more renewable resources, leading to even higher degradation of the environment. Such vicious circle already occurred in the past (Diamond, 2006) and still happens at present time (Steffen et al., 2007; Folke, 2010). On the contrary, when the benefits of preserving this natural capital are evaluated against the long-term costs of destroying it, the trend may change. While nowadays there is not enough empirical evidence that comparing benefits of preserving natural capital (in monetary terms) against the long-term costs of destroying it (also in monetary terms) may necessarily lead to a virtuous circle, the precautionary principle of preservation underlies the ES concept and the rationale behind their valuation in economic terms (TEEB, 2010). Therefore,