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Soil quality, properties, and functions in life cycle assessment: an evaluation of models

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ABSTRACT

Soils provide essential ecosystem services for supporting both human and ecosystem needs and has been under pressures resulting from the intensification and expansion of human activities. In the last 15 years, substantial efforts have been made to quantify the impacts on soils derived from production systems and their related supply chains. In this study, a systematic, qualitative evaluation of up-to-date models connecting land occupation and land transformation to soil impact indicators (e.g., soil properties, functions, and threats) is performed. The focus is on models that may be applied for assessing supply chains, namely in the context of life cycle assessment (LCA). A range of eleven soil-related models was selected and evaluated against different criteria, including scientific soundness, stakeholders' acceptance, reproducibility, and the applicability of models from the perspective of LCA practitioners. Additionally, this study proposes a new land use cause-effect chain to qualify the impacts of land use on soils. None of the models is fulfilling all the criteria and includes comprehensively the cause-effect impact pathways. Notably, trade-offs were most frequent between the relevance of the modeled impact processes and the models' applicability. On the one hand, models proposing multi-indicators cover several drivers of impacts and have a broader scope. On the other hand, several models just focus on one driver of impact, but may provide more relevant impact characterization. Our results provide common ground for the development and identification of models that provide a comprehensive and robust assessment of land use change and land use impacts on soils. Indeed, to ensure both a comprehensive and relevant characterization of impacts, the study identifies several research needs for further models' developments, namely: 1) adopting a common land use cause-effect chain and land use classification; 2) accounting for different land management and land use intensities; 3) expanding the inventory data beyond the accounting of the area related to a certain land use; 4) assessing the added value of multi-indicators compared to single indicators, including the reduction of possible redundancies in the impact evaluation; 5) improving consistency from midpoint to endpoint characterization, especially the link with biodiversity; 6) guiding the calculation of normalization factors; and 7) assessing systematically model's uncertainty.

1. Introduction

Soil quality is defined as the "capacity of a living soil to: function, within natural or managed ecosystem boundaries; to sustain plant and animal productivity; to maintain or enhance water and air quality; and to promote plant and animal health" (Doran, 2002). This concept is closely related to soils capacity to deliver essential ecosystem services such as freshwater purification and regulation (Garrigues et al., 2012), food and fiber production, and the

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maintenance of global ecosystem functions. Ensuring the maintenance of high quality standards for the state of soils is, therefore, a fundamental requirement for global sustainability (Doran, 2002). The intensification and expansion of human activities have placed increasing pressure on land resources, resulting in soil quality degradation, particularly linked to land use and land use change (MEA, 2005). A report on the status of world's soil resources (FAO, 2015) shows the majority of soils are in fair, poor, or very poor conditions. Some of the most worrisome conditions are characterized by advanced degrees of erosion, leading to crop losses, and increased soil acidity with a lack of soil nutrients, constraining food production (Blum, 2005; Menon et al., 2014). For instance, the condition of soils in the Middle East and North Africa is generally considered to be very poor as a result of advanced soil erosion, sealing, and contamination; while in Europe, soils are considered poor as a result of poor nutrient balance, acidification, soil sealing, contamination, and salinization. The trend towards soil degradation is expected to continue, with projected increases in livestock production (Bouwman et al., 2013), deforestation rates, poor water and nutrient management, and large-scale applications of pesticides (FAO and ITPS, 2015). The FAO report also identifies the need to understand the spatial and temporal variations in soil functions as well as monitor soil changes. Accordingly, attention has been given to the development of indicators for monitoring pressure on soil due to human activities (Van Oudenhoven et al., 2012; Niemi et al., 2015). Consequently, there is a clear need to assess the extent to which soil quality is affected by current human interventions (Jandl et al., 2014), and to detect hotspots along supply chains as well as possible “sustainable land management” options (Liedtke et al., 2010; Del Borghi et al., 2014). Even so, quantifying impacts on soil functions is challenging given the complexity of soil processes and the spatial and temporal variability of soil properties (Lauber et al., 2013; Vereecken et al., 2014). Accounting for this variability determines the adequacy of a soil quality model to represent local conditions (Doran and Parkin, 1996).

In the literature, three main quantitative approaches to the land footprinting, i.e. the impact assessment of human pressures on land, were identified: 1) mere land accounting, which reports the area of land use associated with certain activities/crops (e.g. expressed in m^2); 2) weighted accounting, which estimates the amount of land standardized to factors as the productivity of the land, e.g., the ecological footprint (Wackernagel, 2014); and 3) the quantification of the change of a specific soil feature resulting from land interventions, e.g., soil organic matter (Milà i Canals et al., 2007a, 2007b).

In light of these approaches, an integrated assessment method is needed to assess and allocate the impacts of specific production systems (at the product level) on natural resources like soil. Life Cycle Assessment (LCA) (ISO, 2006a, 2006b) is considered one of the best approaches to quantify the potential impacts of production from a life cycle perspective (Hellweg and Milà i Canals, 2014). In LCA, potential impacts can be assessed by two types of indicators. On the one hand, endpoint or damage indicators address aspects to safeguard, denominated Areas of Protection (AoP) in an LCA context, i.e., the natural environment (e.g. biodiversity), natural resources (e.g. resource availability), and human health (e.g. life expectancy of humans). On the other hand, LCA might also include midpoint indicators, which are intermediate aspects between the life cycle inventory (LCI) —e.g., the amount of pollutants emitted, resources used, or land use associated with production processes— and the endpoints.

In the last 15 years, in the LCA community, substantial efforts have been made to improve the assessment of impacts due to land use. However, due to the challenges of quantifying these impacts (Li et al., 2007), soil properties and functions have been incorporated in a very limited way. Midpoint indicators have usually consisted of the sum of the area of land occupied and/or transformed for the production of a certain amount of product. This type of data is generally available in LCA software and inventories. However, data on only the amount of land used is an inappropriate basis for comparisons of products (Helin et al., 2014), and the assessment of land use impacts needs to be more inclusive (Koellner et al., 2013a). Indeed, according to the United Nations Environmental Programme—Society of Environmental Toxicology and Chemistry (UNEP-SETAC) Life Cycle Initiative LCA, land use models should focus both on soil quality, biotic production, and biodiversity. Several endpoint indicators have generally focused on the damage to biodiversity caused by land use (e.g. loss in species' richness as in De Baan et al., 2013; Souza et al., 2015). However, a consensus on the best available model for impact on biodiversity due to land use is difficult to be achieved (Teixeira et al., 2016), as demonstrated in a parallel review conducted by the UNEP-SETAC Life Cycle Initiative task force on land use impacts on biodiversity (Curran et al., 2016).

Regarding midpoint indicators, so far efforts to select a model to be widely applied has been made mainly by the European Commission, which in 2011 assessed several models and recommended the model developed by Milà i Canals et al. (2007a; 2007b) within the International Reference Life Cycle Data System handbook (ILCD handbook) (EC-JRC, 2010; 2011). This has been further adopted also as model for the product environment footprint (PEF) (EC, 2013). This model was selected as a result of an evaluation of land use models (developed up to 2009) against defined criteria (inspired by those of ISO, 2006b and related to: environmental relevance, applicability, robustness, etc). Specifically, the recommended model adopts soil organic matter (SOM) as a stand-alone indicator for the assessment of land use impacts at the midpoint level. Notably, important soil functions are disregarded in this model, even though SOM is considered one of the most important indicators for the sustainability of cropping systems (Fageria, 2012) and plays a crucial role in provisioning (e.g. biotic production) and supporting services (e.g. climate regulation). Examples of these ignored functions include resistance to erosion, compaction, and salinization (Mattila et al., 2011). Therefore, the model was considered not fully satisfactory and was recommended to be applied with caution (EC-JRC, 2011).

Internationally, scientific efforts of the UNEP-SETAC Life Cycle Initiative have resulted in a harmonized classification of land use/cover types (Koellner et al., 2013b) to guarantee a better coverage of land use typologies and improve the comparability of modeling results.

In spite of these efforts, several issues are still critical and may affect modeling assumptions and results (Allacker et al., 2014). First, a clear and consistent cause-effect chain, also called *impact pathway*, is still missing. The impact pathway should depict systematically the causal relationships from the inventory data (amount and typology of land use) to the mid- and endpoint indicators and areas of protection. Second, current models that could be applicable in LCA are unable to comprehensively depict the multiple impacts derived from land use and land use change. Moreover, many of these models are originally based on site-specific studies (and data) and require additional effort for their adaptation to other locations and spatial scales. Finally, the reference state used to assess the potential environmental impacts often differs among models, making results incomparable.

As a result of this lack of inclusiveness in the nuances of soil quality in models, there is a need to improve the available models, ensuring their wider applicability in LCA and their comprehensiveness in modeling the key drivers of impacts on soil quality. To fill this gap in research, this paper reviews the models that assess potential land use impacts on soils at midpoint level. Specifically,