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LAND USE IN LCA

Soil organic carbon as an indicator of land use impacts in life cycle assessment

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Abstract

Purpose Anthropogenic activities are a major driver of soil and land degradation. Due to the spatial heterogeneity of soil properties and the global nature of most value chains, the modelling of the impacts of land use on soil quality for application in life cycle assessment (LCA) requires a regionalised assessment with global coverage. This paper proposes an approach to quantify the impacts of land use on soil quality, using changes in soil organic carbon (SOC) stocks as a proxy, following the latest recommendation of the Life Cycle Initiative.

Methods An operational set of SOC-based characterisation factors for land occupation and land transformation were derived using spatial datasets (1 km resolution) and aggregated at the national and global levels. The developed characterisation factors were tested by means of a case study analysis, investigating the impact on soil quality caused by land use activities necessary to provide three alternative energy supply systems for passenger car transport (biomethane, ethanol, and solar electricity). Results obtained by applying characterisation factors at local, regional, and national levels were compared, to investigate the role of the level of regionalisation on the resulting impacts.

Results and discussion Global maps of characterisation factors are presented for the 56 land use types commonly used in LCA databases, together with national and global values. Urban and industrial land uses present the highest impacts on SOC stocks, followed by severely degraded pastures and intensively managed arable lands. Instead, values obtained for extensive pastures, flooded crops, and urban green areas often report an increase in SOC stocks. Results show that the ranking of impacts of the three energy systems considered in the case study analysis is not affected by the level of regionalisation of the analysis. In the case of biomethane energy supply, impacts assessed using national characterisation factors are more than double those obtained with local characterisation factors, with less significant differences in the other two cases.

Conclusions The integration of soil quality aspects in life cycle impact assessment methods is a crucial challenge due to the key role of soil conservation in ensuring food security and environmental protection. This approach allows the quantification of land use impacts on SOC stocks, taken as a proxy of soil quality. Further research needs to improve the assessment of land use impacts in LCA are identified, such as the ability to reflect the effects of agricultural and forestry management practices.

Keywords Land occupation · Land transformation · Land use impact · Characterisation factors · Soil organic carbon · Life cycle impact assessment (LCIA) · Regionalisation

1 Introduction

Increased pressures on land resources caused by land use and land use change, driven by the expansion and intensification of anthropogenic activities, are leading to soil quality degradation worldwide (MEA 2005). Soil quality has been

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defined as "the fitness of a specific kind of soil to function within its surroundings, support plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al. 1997). As soils contribute to several ecosystem services (e.g., freshwater provision, climate regulation, biomass production), soil conservation is key to achieving several Sustainable Development Goals by ensuring food security, carbon sequestration, biodiversity conservation and environmental protection (Lorenz et al. 2019). This was recently acknowledged by the

EU soil strategy for 2030,[1] as part of the EU biodiversity strategy (European Commission 2020), and the European Commission's proposal for a Soil Monitoring and Resilience Law, an initiative to address soil and land degradation in a comprehensive way (European Commission 2023).

To ensure that the methodological tools are in place to enable assessing the contribution of products and services to soil degradation, it is crucial to incorporate soil quality aspects in life cycle impact assessment (LCIA) methods (Brandão and Milà i Canals 2013; Koellner et al. 2013b; Morais et al. 2016; Teixeira et al. 2018). Such ambition is challenged by the complexity of soil processes, as well as the spatial and temporal variability of soil properties (Adhikari and Hartemink 2016; Li et al. 2007). Existing models, developed to account for impacts of land use activities on soil quality, addressed the following degradation processes: decline in soil organic matter (SOM) (Milà i Canals et al. 2007a, b) or soil organic carbon (SOC) stocks (Brandão and Milà i Canals 2013), soil erosion (Bos et al. 2016; Núñez et al. 2013; Sonderegger et al. 2020), salinisation (Payen et al. 2014), soil compaction (Sonderegger et al. 2020), reduction in groundwater regeneration potential, and mechanical and physicochemical filtration potential (included in the multi-indicator LANd use indicator value CAlculation (LANCA®) model (Bos et al. 2016; Saad et al. 2013). The LANCA® model was further used as a starting point for the development of a soil quality index (SQI), an aggregated index based on four of the LANCA® indicators applied in the EF method (EF3.0) (De Laurentiis et al. 2019). This decision resulted from an assessment of available models that not only considered the coverage of key soil functions but also their operationality, resulting from their compatibility with LCA's existing modelling frameworks and databases (Vidal Legaz et al. 2017; Sala et al. 2019).

An evaluation of existing models was performed by an expert taskforce established by the Life Cycle Initiative, hosted by the UN Environment Programme (UNEP), to identify promising indicators and models to assess the impacts of land occupation and transformation on soil quality, for further application and development in LCA. This resulted in the publication of the *Global Guidance for Life Cycle Impact Assessment Indicators 2* (UNEP 2019), with a dedicated chapter on land use impacts on soil quality (Grant et al. 2019). In this document, a recommendation was made to use changes in soil organic carbon stock as a proxy indicator for soil quality impacts in LCA. Albeit acknowledging that the level of SOC stocks does not fully represent all aspects of soil quality, the decision to focus on this indicator was taken as it is positively correlated with several

soil functions, including carbon transformations, nutrient cycling, soil structure maintenance, and the regulation of pests and diseases (Kibblewhite et al. 2008).

To assess the impacts of land use on SOC stocks, an interim recommendation was given on the use of the model developed by Brandão and Milà i Canals (2013). The following needs for further development and validation of the model were highlighted in the guidance, to ensure the operationality of the model in LCA applications and to allow more regionalised assessments:

– To expand the list of land use types[2] considered to include forests, permanent crops, and artificial areas (e.g., urban, industrial areas, mineral extraction sites)
– To better link the recommended characterisation factors with the land use nomenclature recommended by the Life Cycle Initiative and currently used by inventory databases, presented in Koellner et al. (2013a), by providing a correspondence table
– To test the characterisation factors recommended by means of case study analyses on relevant production systems, including annual and perennial agriculture and forestry
– To consider the potential update of the characterisation factors based on the revised IPCC (2019) guidelines, with updated management factors affecting the estimation of SOC stocks
– To provide characterisation factors at a smaller geographical scale (e.g., states, ecoregions within a country, or at a more refined resolution scale) than those provided in the guidance (i.e., at a national level).

Some of the limitations and needs for further development identified in the Life Cycle Initiative guidance reflect the limitations reported by Sala et al. (2019) when assessing the potential application of the model by Brandão and Milà i Canals (2013) in the EF method (i.e., the need to standardise the nomenclature used and to better grasp impacts on different soil properties).

The aim of this paper is to address the needs presented above by developing an operational set of characterisation factors for land occupation and transformation based on the model developed by Brandão and Milà i Canals (2013), using the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2019) for the calculation of SOC stock levels, and compatible with the land use nomenclature list by Koellner et al. (2013a).[3]

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[1] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12634-Healthy-soils-new-EU-soil-strategy_en

[2] The definitions of land-use types used in this article follow the classification provided by Koellner et al. (2013a)

[3] The work presented in this paper took shape during an expert workshop that was conducted in October 2018 on the European Commission's Joint Research Centre premises in Ispra (Italy), to which six

2 Methodology

This section introduces the conceptual framework applied to assess the impacts of land occupation and transformation activities on soil quality (Section 2.1). It then presents the methodological steps followed to derive SOC-based characterisation factors at grid, national, and global levels (Section 2.2), which were then tested through a case study analysis, described in Section 2.3.

2.1 Conceptual model to assess impacts of land occupation and land transformation on soil quality

Following the framework suggested by Koellner et al. (2013b) and Brandão and Milà i Canals (2013), occupation impacts, caused by a land use activity, are calculated as the area and time-integrated difference between the potential soil quality of the reference situation and the quality of the soil under the land use activity taking place. In this work, following the recommendations of UNEP (2019), SOC stock is used as an indicator of soil quality for its effects on soil fertility, biodiversity regulation, water retention, nutrient cycling, and soil structure maintenance.

The SOC stock of the reference situation is defined as the one present in native lands, such as non-degraded, unimproved lands under native vegetation (defined in Koellner et al. (2013b) as the quasi-natural land cover predominant in global biomes and ecoregions). The rationale behind the calculation of the SOC stock value induced by the studied land use i (LU_i) is presented in Section 2.2.1 for the different land use activities considered.

The characterisation factor (CF) for land occupation relative to LU_i—$CF_{occ,LUi}$—is hence calculated as the difference between the SOC stock of the reference situation (SOC_{ref}) and the SOC stock of the land use under study (SOC_{LUi}), as illustrated by Eq. (1). As the reference situation is here assumed to correspond to the native vegetation,[4] values of SOC_{ref} are derived from IPCC (2019), where the SOC stocks of the native vegetation are provided as function of the climate zone and soil type.[5]

$$CF_{occ,LUi} = SOC_{ref} - SOC_{LUi} \text{ [tonne C ha}^{-1}] \quad (1)$$

Reversible transformation impacts are calculated following Koellner et al. (2013b) as the area and time-integrated difference in SOC stock between the land use and the reference situation, considering that, if no further anthropogenic activity would follow a transformation, the area under study would naturally return to a quasi-natural state after some time (defined as regeneration time, t_{reg}), and assuming a linear recovery of soil quality. This entails that the CF for a land transformation to LU_i—$CF_{trans\ to\ LUi}$—is calculated as illustrated by Eq. (2).

$$CF_{trans\ to,LUi} = 0.5 \times t_{reg} \times (SOC_{ref} - SOC_{LUi}) = 0.5 \times t_{reg}$$
$$\times CF_{occ,LUi} \text{ [tonne C year ha}^{-1}]$$
$$(2)$$

The regeneration time depends on the intensity of the land use activity considered and on the ecosystem type (e.g., warm humid climates favour a faster regeneration in terms of biotic production) (Koellner et al. 2013b). Although there is limited knowledge on ecosystems' regeneration times (Bessou et al. 2020), a number of publications have proposed estimations of regeneration times (e.g. Müller-Wenk 1998; van Dobben et al. 1998; Koellner and Scholz 2008; Saad et al. 2013). IPCC's (2019) Tier 1 method assumes a regeneration time of 20 years for biotic land uses, although this is considered to be an underestimation of reality. Saad et al. (2013) suggest values of the regeneration time for different biomes, ranging from 52 years (for mangroves) to 138 years (for montane grassland and shrubland). Furthermore, transformations leading to SOC losses occur at shorter time scales than transformations leading to SOC accumulation, meaning that in case of transformation to land uses presenting SOC stock levels higher than the reference situation, the regeneration time should be shorter, as the subsequent regeneration would entail a SOC loss (Conant et al. 2001).

In LCA applications, the inventory flow for land occupation records the area occupied and the occupation time (ha year), whilst the inventory flow for land transformation records the area transformed (ha); therefore, the life cycle impact assessment (LCIA) results of land occupation and transformation are both measured with the unit "tonne C year" referring to the amount of additional SOC temporarily present or absent from the soil in the system under study compared to a reference system and are directly additional (Brandão and Milà i Canals 2013). Life cycle inventories (LCI) distinguish between two types of transformations: "transformation to LU_i" and "transformation from LU_y".

Footnote 3 (continued)

experts took part, all of which are co-authors of this article. During this event, the approach to calculate the new set of characterisation factors was defined, and the correspondence between the nomenclature list by Koellner et al. (2013a), and the IPCC nomenclature were agreed upon.

[4] It should be noted that this is a simplistic approach, also adopted by Brandão and Milà i Canals (2013); however, the debate on the selection of the reference situation is still open (Bessou et al. 2020).

[5] The IPCC (2019) defines 12 climate zones (polar moist, polar dry, cool temperate dry, cool temperate moist, boreal dry, boreal moist, warm temperate dry, warm temperate moist, tropical dry, tropical moist, tropical wet, and tropical montane) and six mineral soil types

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Footnote 5 (continued)

(high activity clay, low activity clay, sandy, spodic, volcanic, and wetland soils).

The former represents the impact caused by the hypothetical transformation from a reference situation to the land use under study (calculated according to Eq. (2)), whilst the latter represents the avoided impact caused by the hypothetical transformation from the previous land use to a quasi-natural state (assumed to present the same level of SOC stock as the reference situation). The CF for a transformation from LU_i—$CF_{trans\ from,LUi}$—is therefore calculated according to Eq. (3).

$$
\begin{aligned}
CF_{trans\ from,LUi} &= 0.5 \times t_{reg} \times (SOC_{LUi} - SOC_{ref}) \\
&= -0.5 \times t_{reg} \times (SOC_{ref} - SOC_{LUi}) \qquad (3) \\
&= -0.5 \times t_{reg} \times CF_{occ,LUi} \quad [\text{tonne C year ha}^{-1}]
\end{aligned}
$$

As can be seen by comparing Eqs. (2) and (3), the transformation to and from CFs referring to a given land use class presents the same absolute value but opposite signs, meaning that a transformation from LU_i to LU_i is associated with an impact on soil quality equal to zero.

2.2 Calculation of characterisation factors based on SOC stock
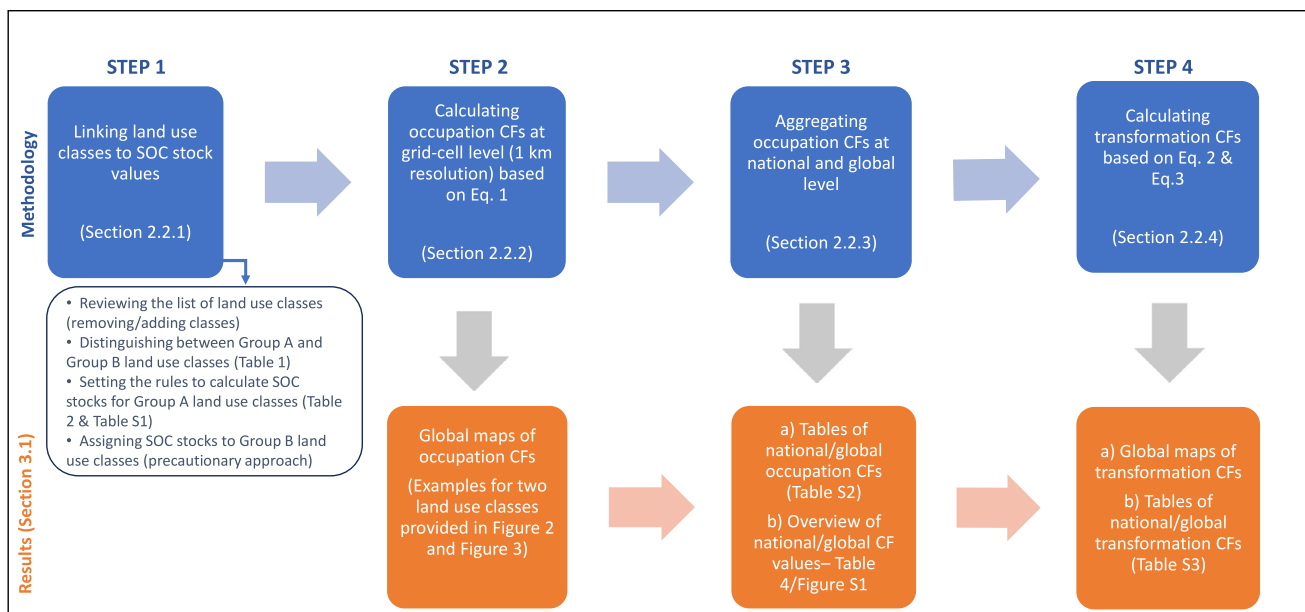
The methodology used to derive the SOC stock-based CFs is based on four main steps, an overview of each is provided in Fig. 1, linking them to the corresponding outputs presented in Section 3.

The first step (Section 2.2.1) involved defining a procedure to derive a value of SOC stock for each land use from the classification suggested by Koellner et al. (2013a). This is a hierarchical classification consisting of four levels of detail: at level 1, it includes 11 general land use and land cover classes, each of which is further divided into more detailed classes at the subsequent levels. We further refer to "land use classes" only as encompassing the various possible land covers, shall they be natural or not and the land actually used or not. Each land use class is assigned an identification code (ID), consisting of up to four digits, depending on the level of detail (e.g., agriculture, 5; arable, 5.1; arable non-irrigated, 5.1.2; arable non-irrigated extensive, 5.1.2.1). The classification presented in Koellner et al. (2013a) was analysed in detail, and a distinction was made between two groups of land uses: those presenting the highest level of detail in their group, i.e., sub-classes up to the fourth degree (group A), that were directly assigned a SOC stock value, and those assessed at a less detailed level (group B), for which we derived a value of SOC stock based on those assigned to the land use belonging to group A.

The second step (Section 2.2.2) was the calculation of occupation CFs, using the approach suggested in the previous step to calculate SOC stock values for each land use and by applying Eq. (1). As a result, maps of CFs for different land use activities were obtained.

To ensure the usability of the CFs in LCA applications and in LCA software environments, and in relation to background systems (where the LCA practitioner most likely will not be aware of the exact location where certain activities took place), national and global CFs were derived for each land use class by aggregating the grid-cell-level CFs calculated at the previous step (Step 3, Section 2.2.3).

Fig. 1 Overview of the methodological steps followed to derive soil organic carbon (SOC) stock-based characterisation factors (CFs) and corresponding outputs presented in Section 3
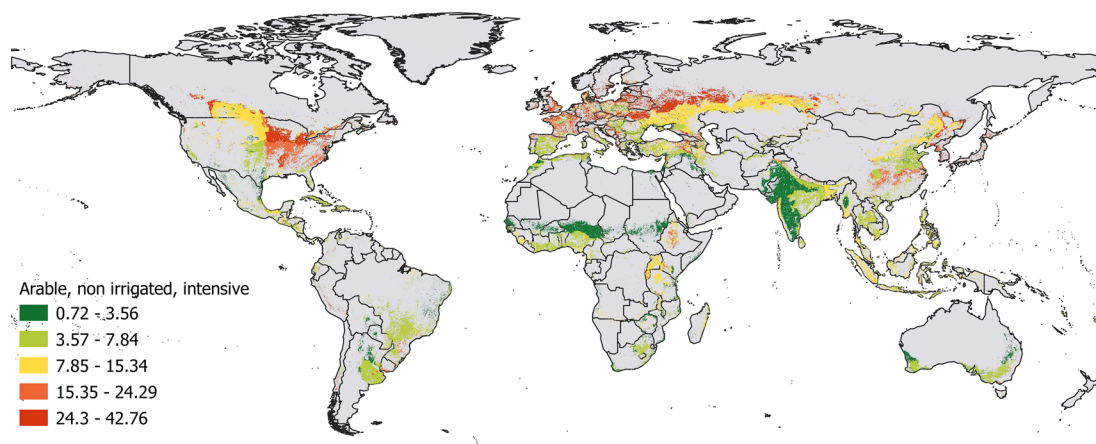
Fig. 2 Occupation characterisation factors for land use class "arable, non-irrigated, intensive" measured in tonne C ha^{-1}. Values are provided for all the locations where arable landcovers are reported according to the land use map by Kehoe et al. (2017). Each colour is associated with a quintile of the overall global distribution of grid-cell-level characterisation factors for this land use class

In the fourth and final step (Section 2.2.4) transformation CFs were calculated at the three resolution scales (grid-cell level, national level, and global level) from the occupation CFs obtained at the previous steps.

2.2.1 Step 1: setting the scene for the calculation of SOC stock values of land use classes
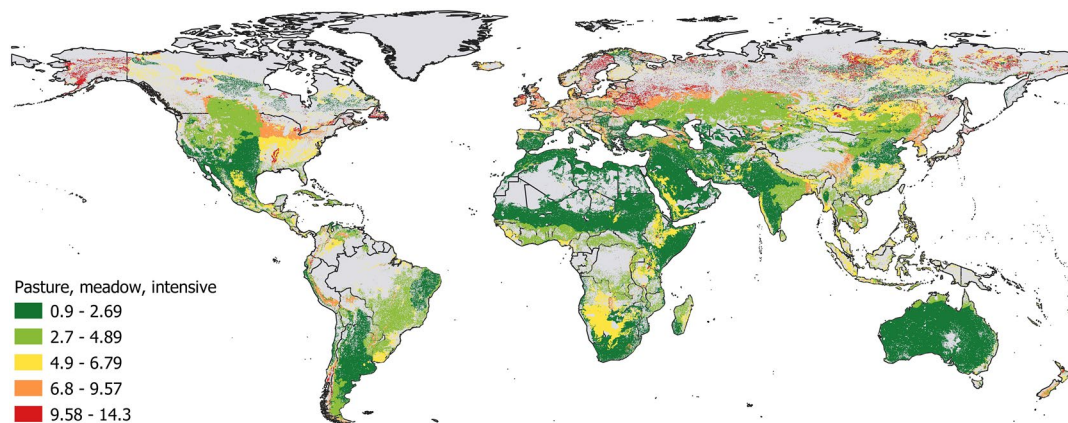
The land use classification provided by Koellner et al. (2013a) was analysed to derive a rationale to calculate a SOC stock value (depth 0–30 cm) and related CFs for occupation and transformation for each land use class.

All land use classes classified as natural references in the original publication (those identified with a (*) mark in Table 1 by Koellner et al. (2013a)) were assigned a SOC stock value equal to SOC$_{ref}$, meaning that the CFs for both occupation and transformation of those land use classes

would be equal to zero. As the classification of land uses presented in Koellner et al. (2013a) is done at four levels of detail, it was decided to calculate SOC stock values only for the land use activities presenting the highest level of detail in each group of land use classes (e.g., for pasture/meadows at level three—ID codes 4.2.1 and 4.2.2—whilst for agriculture at level four—ID codes 5.1.2.1, 5.1.2.2., 5.1.3.1, and 5.1.3.2). These land use classes were defined as belonging to group A, classifying under group B the remaining classes.

A precautionary approach was taken to assign SOC stock values to the land use classes belonging to group B, by assigning to a land use class presenting a lower level of detail the minimum SOC stock value amongst the ones calculated for its related land use classes belonging to group A, in other words, choosing the class associated with the largest impact as a proxy of a broader class. For instance, the SOC stock value attributed to land use class 4.2 (pasture/meadow)

Fig. 3 Occupation characterisation factors for land use class "pasture/meadow, intensive" measured in tonne C ha^{-1}. Values are provided for all the locations where pasture landcovers are reported according to the land use map by Kehoe et al. (2017). Each colour is associated with a quintile of the overall global distribution of grid-cell-level characterisation factors for this land use class

Table 1 Classification of land use classes in three main groups (land cover, land use group A, and land use group B) and approach to assign soil organic carbon (SOC) stock values to group B classes

ID	Land use class	Group	Rule for assigning SOC stock value (for group B classes)
0	Unspecified	B	MIN (all classes)
0.1	Unspecified, used	B	MIN (all classes, excluded land cover classes)
0.2	Unspecified, natural	Land cover (SOC = SOC$_{ref}$)	
1	Forest	B	MIN (1.1; 1.2)
1.1	Forest, natural	Land cover (SOC = SOC$_{ref}$)	
1.1.1	Forest, primary	A	
1.1.2	Forest, secondary	A	
1.2	Forest, used	B	MIN (1.2.1; 1.2.2)
1.2.1	Forest, extensive	A	
1.2.2	Forest, intensive	A	
2	Wetlands	Land cover (SOC = SOC$_{ref}$)	
2.1	Wetlands, coastal	Land cover (SOC = SOC$_{ref}$)	
2.2	Wetlands, inland	Land cover (SOC = SOC$_{ref}$)	
3	Shrub land	Land cover (SOC = SOC$_{ref}$)	
4	Grassland/pasture/meadow	B	MIN (4.1; 4.2)
4.1	Grassland	B	MIN (4.1.1; 4.1.2)
4.1.1	Grassland, natural	Land cover (SOC = SOC$_{ref}$)	
4.1.2	Grassland, for livestock grazing	A	
4.2	Pasture/meadow	B	MIN (4.2.1; 4.2.2; 4.2.3)
4.2.1	Pasture/meadow, extensive	A	
4.2.2	Pasture/meadow, intensive	A	
4.2.3	Pasture/meadow severely degraded**	A	
5	Agriculture	B	MIN (5.1; 5.2)
5.1	Arable	B	MIN (5.1.1; 5.1.2; 5.1.3; 5.1.4)
5.1.1	Arable, fallow	A	
5.1.2	Arable, non-irrigated	B	MIN (5.1.2.1; 5.1.2.2)
5.1.2.1	Arable, non-irrigated, extensive	A	
5.1.2.2	Arable, non-irrigated, intensive	A	
5.1.3	Arable, irrigated	B	MIN (5.1.3.1; 5.1.3.2)
5.1.3.1	Arable, irrigated, extensive	A	
5.1.3.2	Arable, irrigated, intensive	A	
5.1.4	Arable, flooded crops	A	
5.1.5	Arable, greenhouse	B	MIN (5.1.1; 5.1.2; 5.1.3; 5.1.4)
5.1.6	Field margins/hedgerows	Excluded	
5.2	Permanent crops	B	MIN (5.2.1; 5.2.2)
5.2.1	Permanent crops, non-irrigated	B	MIN (5.2.1.1; 5.2.1.2)
5.2.1.1	Permanent crops, non-irrigated, extensive	A	
5.2.1.2	Permanent crops, non-irrigated, intensive	A	
5.2.2	Permanent crops, irrigated	B	MIN (5.2.2.1; 5.2.2.2)
5.2.2.1	Permanent crops, irrigated, extensive	A	
5.2.2.2	Permanent crops, irrigated, intensive	A	
6	Agriculture, mosaic	Excluded	
7	Artificial areas	B	MIN (7.1; 7.2; 7.3; 7.4; 7.5; 7.6)
7.1	Urban	B	MIN (7.1.1; 7.1.2; 7.1.3; 7.1.4, 7.1.5)
7.1.1	Urban/industrial fallow	A	
7.1.2	Urban, continuously built	A	
7.1.3	Urban, discontinuously built	A	
7.1.4	Urban, green areas	A	
7.1.5	Urban, sparsely built**	A	

Table 1 (continued)

ID	Land use class	Group	Rule for assigning SOC stock value (for group B classes)
7.2	Industrial area	A	
7.3	Mineral extraction site	A	
7.4	Dump site	A	
7.5	Construction site	A	
7.6	Traffic area	B	MIN (7.6.1; 7.6.2, 7.6.3)
7.6.1	Traffic area, road network	A	
7.6.2	Traffic area, rail network	A	
7.6.3	Traffic area, rail/road embankment	A	
8	Bare area	Land cover (SOC = SOC$_{ref}$)	

MIN minimum value, *SOC$_{ref}$* SOC stock of the reference situation

**Suggested additional land use classes

would be the minimum between the two values calculated for class 4.2.1 (pasture/meadow, extensive) and 4.2.2 (pasture/meadow, intensive).

In this process, the list of land use classes was critically assessed to identify land uses that should be removed and others that should be added to the list based on updated SOC stock change factors from the revised IPCC guidance (IPCC 2019). First, land use classes classified under ID codes 9 and 10 (snow and ice and water bodies) were excluded as the focus was on terrestrial activities. Then, two land use classes (i.e., "field margins/hedgerows" and "agriculture, mosaic") were excluded from the analysis, and no further calculations were done for those classes. This decision was motivated by the fact that those classes were considered to refer to specific practices for which the SOC modelling remains challenging due to the spatial heterogeneity and no sufficient mechanistic knowledge. It was suggested that a new land use class might be introduced in the future to better reflect agroecological practices; in this case, the use of field margins and mosaic practices could be two of the criteria for selecting such a land use class. Moreover, two new land use classes were suggested. The first is "pasture/meadow severely degraded", as there was no land use class reflecting a major long-term loss of productivity and vegetation cover, due to severe mechanical damage to the vegetation and/or due to severe soil erosion, whilst this typology of land is available in the IPCC (2019) classification. The second is "urban, sparsely built", in addition to the existing class "urban, discontinuously built" to capture urban landscapes with different construction densities (defining the former as an area where less than 30% is sealed land and the latter as an area presenting between 30 and 80% of sealed land).

The list of land use classes considered and their classification into three main groups (i.e., natural, group A, group B) is presented in Table 1. For those belonging to group B,

the criteria followed to assign a SOC stock value in each case are also presented.

The procedure adopted to assign SOC stock values to group A land use classes is presented in Table 2. In the case of forest, grassland, and agricultural land use classes, this was done by linking a land use class to a set of SOC stock change factors taken from the IPCC (2019), in line with the method suggested by Brandão and Milà i Canals (2013).

The IPCC Tier 1 method provides stock change factors (unitless) to calculate the steady state SOC stock values associated with different types of land use, management and intensity from the value of SOC stock of the reference condition SOC$_{ref}$, as illustrated by Eq. (4). By steady state, it is meant that the SOC stock value of the land use under study (SOC$_{LU}$) is present in the soil starting from 20 years after a change in land use, management practice or input level has taken place. For the purpose of this exercise, and in line with Brandão and Milà i Canals (2013), it was assumed that the two situations compared were both at equilibrium, and therefore, the use of said stock change factors is considered appropriate.

$$SOC_{LU} = SOC_{ref} \times F_{LU} \times F_{MG} \times F_I \quad [\text{tonne C ha}^{-1}] \quad (4)$$

F_{LU} is a stock change factor for land use systems (e.g., cropland, long-term cultivated), F_{MG} is the stock change factor for management regime (e.g., no tillage), and F_I is a stock change factor for the input of mineral and organic amendments or N-fixing crop in rotation (e.g., high input with manure). Stock change factors are provided for cropland and grassland land uses and for different climate zones, considering 9 climate zones from the 12 defined in IPCC (2019)[6], as tropical most and tropical wet are aggregated, and polar moist and polar dry are excluded.

Cropland and grassland land use classes (belonging to group A) were assigned a set of stock change factors based

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[6] See footnote 5.

Table 2 Rationale for the calculation of soil organic carbon (SOC) stock values for group A land use classes

ID	Land use class	Basis for SOC stock calculation	Land use category (F_{LU})	Land use practice (F_{MG})	Land use intensity (F_I)
1.1.1	Forest, primary	IPCC factors	Forest		
1.1.2	Forest, secondary	IPCC factors	Forest		
1.2.1	Forest, extensive	IPCC factors	Forest		
1.2.2	Forest, intensive	IPCC factors	Forest		
4.1.2	Grassland, for livestock grazing	IPCC factors	Grassland	Nominally managed (non-degraded)	
4.2.1	Pasture/meadow, extensive	IPCC factors	Grassland	Improved grassland	Medium inputs
4.2.2	Pasture/meadow, intensive	IPCC factors	Grassland	High-intensity grazing	
4.2.3	Pasture/meadow, severely degraded	IPCC factors	Grassland	Severely degraded	
5.1.1	Arable, fallow	IPCC factors	Cropland—set aside		
5.1.2.1	Arable, non-irrigated, extensive	IPCC factors	Cropland—long-term cultivated	Reduced tillage	Medium inputs
5.1.2.2	Arable, non-irrigated, intensive	IPCC factors	Cropland—long-term cultivated	Full tillage	Medium inputs
5.1.3.1	Arable, irrigated, extensive	IPCC factors	Cropland—long-term cultivated	Reduced tillage	Medium inputs
5.1.3.2	Arable, irrigated, intensive	IPCC factors	Cropland—long-term cultivated	Full tillage	Medium inputs
5.1.4	Arable, flooded crops	IPCC factors	Cropland—paddy rice		
5.2.1.1	Permanent crops, non-irrigated, extensive	IPCC factors	Perennial/tree crop	No tillage	Medium inputs
5.2.1.2	Permanent crops, non-irrigated, intensive	IPCC factors	Perennial/tree crop	Reduced tillage	Medium inputs
5.2.2.1	Permanent crops, irrigated, extensive	IPCC factors	Perennial/tree crop	No tillage	Medium inputs
5.2.2.2	Permanent crops, irrigated, intensive	IPCC factors	Perennial/tree crop	Reduced tillage	Medium inputs
7.1.1	Urban/industrial fallow	80% sealed area (SOC=0); 20% severely degraded grassland (4.2.3)			
7.1.2	Urban, continuously built	90% sealed area (SOC=0); 10% grassland (4.1.2)			
7.1.3	Urban, discontinuously built	50% sealed area (SOC=0); 50% grassland (4.1.2)			
7.1.4	Urban, green areas	IPCC factors	Grassland	Improved grassland	Medium inputs
7.1.5	Urban, sparsely built	30% sealed area (SOC=0); 70% grassland (4.1.2)			
7.2	Industrial area	90% sealed area (SOC=0); 10% severely degraded grassland (4.2.3)			
7.3	Mineral extraction site	SOC=0			
7.4	Dump site	SOC=0			
7.5	Construction site	SOC=0			
7.6.1	Traffic area, road network	SOC=0			
7.6.2	Traffic area, rail network	SOC=0			

Table 2 (continued)

ID	Land use class	Basis for SOC stock calculation	Land use category (F_{LU})	Land use practice (F_{MG})	Land use intensity (F_I)
7.6.3	Traffic area, rail/road embankment	50% sealed area (SOC = 0); 50% nominally managed grassland (4.1.2)			

IPCC factors are taken from IPCC (2019). Additional definitions for some of the land use classes are provided in Table S1

on the description of the land use class provided in Koellner et al. (2013a) and the specification provided by the IPCC 2019 refinement (2019), in particular focusing on the decision trees provided in support to the choice of stock change factors. In this process, an additional definition was assigned to some of the land use classes, whenever this was considered necessary to explain the rationale for assigning the stock change factors to a land use class (i.e., in case the original definition was not enabling to choose a set of stock change factors and a value choice had to be made). The full list of land use classes, together with their original definition (from Koellner et al. (2013a)) and additional definition (when relevant), is provided in Table S1 of the SI.

According to the IPCC (2019), so far, it is not possible to include changes in SOC stock under different forest management systems, when adopting a Tier 1 method at a global level. Therefore, in line with what was done by Brandão and Milà i Canals (2013), for forestry land use, it is assumed that the SOC stock is equal to one of the reference situations (meaning that the resulting CFs will be equal to zero).

In the case of artificial land uses, the following assessment was made: in case the land use entails that the land is fully sealed, the value of SOC stock was assumed to be unavailable during occupation and thus set to zero; in all the other cases, the SOC stock value was calculated modelling the land use as a combination of sealed land and grassland (characterised by different levels of degradation and/or management), with the exception of "urban green areas", which was fully modelled as improved grassland. As a result of this exercise, it was possible to assign to each land use class belonging to group A either a combination of SOC stock change factors from IPCC 2019 refinement documents (2019) or a criterion to calculate the variation from the SOC_{ref} under that specific land use activity.

2.2.2 Step 2: calculating maps of characterisation factors

The calculation of occupation characterisation factors was performed using spatially explicit datasets. The calculation was done using R version 3.5.2 (2018-12-20) (R Core Team 2020) and the following packages: *raster*, *sp*, *rgdal*, *doParallel*, and *foreach* (Bivand et al. 2013, 2019; Calaway et al. 2017, 2018; Hijmans and van Etten 2012; Pebesma

and Bivand 2005). The visualisation of the results was done using ArcGIS version 10.5.1 (ESRI 2017).

A 1-km resolution map providing SOC stock reference values (expressed in tonne C ha^{-1}, 0–30 cm depth) by climate zone and soil type was derived, based on the IPCC default reference conditions SOC_{ref} values for mineral soils provided in IPCC 2019 refinement documents (2019), following the approach by Hiederer (2016).

Maps were then generated for each land use LU_i by assigning to each grid cell the factors needed to calculate the SOC_{LUi}, derived as explained in Section 2.2.1. As the factor assigned to each cell is multiplied by the SOC_{ref} value (following Eq. (4)), these maps are referred to as "multiplicator maps". For cropland and grassland land use activities, these factors depend on the climate zone; therefore, to derive such multiplicator maps, a map of global climate zones was used (taken from Hiederer et al. 2010).

Subsequently, the SOC_{ref} map was combined with the multiplicator maps to derive maps of SOC stock values under each land use considered. As the IPCC (2019) does not provide stock change factors for polar areas, no calculation of SOC stock values was performed in these areas. Then, for each individual land use map, the difference between the SOC_{ref} and the SOC_{LUi} was calculated (Eq. (1)), resulting in a map of occupation CFs for each land use type.

2.2.3 Step 3: aggregating characterisation factors at national and global level

The rationale chosen to calculate aggregated national CFs was the following: only those areas where the land use activity considered could feasibly take place would be included in the calculation of the aggregated CFs. To this end, for each land use class, aggregated national CFs were calculated as the average of the CFs obtained in each grid cell included in the national boundaries excluding those areas where the considered activity does not take place according to the land use map provided by Kehoe et al. (2017), similar to the aggregation approach proposed by Maier et al. (2019). Therefore, the land use map of Kehoe et al. (2017) was divided into the broad land use classes, namely cropland, pasture, urban, primary, and secondary vegetation, using the same matching approach of the land use classes of Newbold

et al. (2015). Global average CFs were derived following a similar approach, by calculating the average of the CFs obtained in each grid cell where a certain land use activity takes place according to the land use map considered. Areas where a given land use cannot take place (e.g., arable crops in the Sahara region) were excluded in order to avoid distorted results such as those identified in De Laurentiis et al. (2019) for the LANCA® model v2.0 (Bos et al. 2016). The approach here suggested for performing the aggregation is a refinement of the approach presented in De Laurentiis et al. (2019), which was applied to derive new national aggregated CFs for the LANCA® model v2.5 (Horn and Maier 2018).

2.2.4 Step 4: deriving transformation characterisation factors

As a final calculation step, CFs for land transformation were calculated from occupation CFs by means of Eqs. (2) and (3), assuming a regeneration time of 20 years for biotic land uses and 85 years for artificial land uses, following the suggestion of Brandão and Milà i Canals (2013). "Transformation to" and "transformation from" CFs were derived at all resolution scales: at the grid-cell level, at the national level, and at the global level.

2.3 Case study analysis

A case study analysis was developed to showcase the application of the CFs presented in this work at different geographical scales. For this specific application, an intermediate level of aggregation was adopted to derive additional CFs at the regional level on top of those calculated at the country level, with the purpose of exploring further the sensitivity of the CFs to the level of geographical aggregation. The aggregation approach adopted to derive regional CFs was the same as the one adopted for national CFs, the only difference being the geographical areas considered in the aggregation. Regions were defined as level 1 of countries' subdivisions in the Global Administrative Area Database (GADM 2021), which was used as the data source for the regional boundaries.

Three alternative energy supply systems for passenger car transport are considered and compared using as a common functional unit the annual travelling distance of an average EU passenger car, equal to 18,600 km (European Commission 2018). The selected examples of energy supply systems for passenger cars are solar photovoltaic (PV) electricity production in the federal state of Bayern, Germany; corn (Z*ea mays*) silage methane production in the federal state of Sachsen, Germany; and sugarcane (*Saccharum officinarum*) ethanol production in São Paulo, Brazil. Geographical locations were chosen as considered typical locations for these production activities (Uusitalo et al. 2022). These three energy supply systems for passenger car transport differ in terms of

land use classes and geographical locations of major land uses thus providing a suitable case for testing the developed CFs. Sugarcane and corn represent typical feedstocks for biofuel production. Germany and Brazil are examples of different climate conditions for feedstock production. Solar PVs are an example of an energy supply system which does not require biomass feedstock production. To develop the case study analysis, the following tank-to-wheel energy use data are considered: ethanol-operated flexi-fuel cars 1.9 MJ/km, gas-operated cars 1.8 MJ/km, and electric cars 0.69 MJ/km. Energy use values are presented considering an occupancy factor of 1.7 passengers, and assuming 27% street drive and 73% highway drive (Technical Research Centre Finland 2018).

This case example is carried out by calculating annual land occupation and related land transformation for the three energy supply systems including agricultural land use for corn and sugarcane cultivation, land occupation for solar PVs, land occupation of ethanol and biomethane production plants, and land occupation for refuelling and charging stations. Land use for inputs required in cultivation (e.g., for the production of fertilisers) or production is not included in the assessment. This is considered justifiable as the aim of the case study is to demonstrate the applicability of the method and not carry out a full life cycle assessment. According to Uusitalo et al. (2022), land use of biomass production in energy supply systems for passenger cars is dominating the total land use in comparison to, e.g., production sites or refuelling infrastructure.

According to Wang et al. (2012), ethanol productivity from sugarcane is 171 MJ/kg. Average Brazil sugarcane crops have a yield of approximately 75 t/ha (FAO 2021). This leads to land occupation of arable land of 0.078 m^2 over 1 year to produce 1 MJ of energy from sugarcane ethanol. It can be assumed that in Germany, 1 ha of arable land for corn silage production is able to produce 6400 m^3 biogas with 53% methane content (Lask et al. 2020). Therefore, this leads to an arable land occupation of 0.084 m^2 over 1 year to produce 1 MJ of energy from corn methane.

According to Global Solar Atlas (2021), direct normal irradiation in the Bavarian region in Germany is approximately 1100 kWh/m^{2}y. Efficiencies for solar PVs have been increasing, and a 20% efficiency has been used in this paper (Green et al. 2019), leading to an electricity production of 220 kWh/m^{2}y. PV constructions require additional land occupation for corridors between PVs. Based on satellite maps of example PV installations in Bavaria, it can be roughly assumed that PVs cover only 40% of total land use and corridors 60% (Google Maps 2021). There can be alternative land use options for corridors, e.g., sheep grazing (Al Mamun et al. 2023), but this has not been considered in the case analysis.

Table 3 Calculation of land occupation related to the production and refuelling/recharging of ethanol, biomethane, and electricity needed to provide a functional unit (FU) of 18,600 km yr^{-1} travelled by passenger car

	Unit	Ethanol car	Methane car	Electric car
Energy use	[MJ/FU]	35340	33480	
	[kWh/FU]			3565
Land occupation for cultivation	[m^{2}y/MJ]	0.078	0.084	
	[m^{2}y/FU]	1458	1567	
Production plant land occupation	[m^{2}y/MJ]	0.00002	0.0001	
	[m^{2}y/FU]	0.86	3	
Electricity produced by solar PV	[kWh/m^{2}y]			220
Area required for PVs	[m^{2}y/FU]			16.2
Land occupation for PV and corridors	[m^{2}y/FU]			40.5
Refuelling/recharging land occupation	[m^{2}y/FU]	0.28	0.28	0.033

Both ethanol production from sugarcane and methane production from corn silage require processing plants to convert biomass into fuel. Land occupations for production plants are calculated using example plants' annual fuel production capacities and land occupations measured from maps. An example ethanol production plant in Brazil produces annually 3.3 billion MJ of ethanol and 313,000 t of sugar, and it occupies approximately 200,000 m^2 of land (Industry About 2014; Google Maps 2021). The land occupation of the plant is economically allocated based on market prices for ethanol 0.4 US\$/l and sugar 0.3 US\$/kg (Trading Economics 2021a, b). This leads to 40% land occupation allocation for ethanol. Land occupation for ethanol plant is therefore 0.00002 m^{2}y/MJ. An example biomethane production plant in Germany produces annually 5.8 million m^3 of biomethane, and it occupies approximately 20,000 m^2 of land (Google Maps 2021; MVV Energia AG 2021). Land occupation for the biomethane plant is therefore 0.0001 m^{2}y/MJ.

Uusitalo et al. (2022) assessed that land occupation for charging electric cars is 0.03 m^{2}y and 0.28 m^{2}y for land occupation for refuelling ethanol and methane cars. Both values refer to the same functional unit as the one used in this current study. Table 3 provides an overview of the input data used in the calculation of land occupation and the resulting values.

Land transformation flows associated with the occupation of arable land in Brazil and Germany for the production of, respectively, sugarcane and corn were calculated using an updated version of the Blonk land use change tool (Blonk Consultants 2013), where the input land use data from FAOSTAT were updated to refer to the year 2018. Land transformation flows related to the occupation of land for solar PV installations in Germany were calculated by assuming that the entire area occupied was transformed from a different land use and allocating the transformation over 20 years. The allocation to the 20 years after the transformation has taken place was done as suggested in Koellner et al. (2013b). The resulting "transformation to" flow was equal to 2.03 m^2 per functional unit. The corresponding "transformation from" flows were calculated assuming the same proportions reported in the Blonk tool for Germany, based on trends in land use statistics (0% deriving from forest, 0% deriving from grassland, 6% deriving from perennial cropland, and 94% deriving from annual cropland). The low level of detail of the land use classes used for land transformation is related to the level of detail of the land use statistics underlying the calculations performed by the Blonk tool. The transformation of land linked to the land occupied by the industrial plants for both ethanol and biomethane production was assumed to be negligible, due to the very small entity of these land occupation flows (Table 3). The same was assumed for the land transformation connected to the occupation of land for the refuelling and recharging stations. Each land occupation and transformation value thus obtained was associated with a land use type following the classification considered in this study, the resulting inventory of land uses is presented in Table S4.

To assess how the level of aggregation of the CFs can affect the results of the analysis, the location-specific inventory data collected for the three alternative energy systems considered were combined with CFs calculated at three different spatial resolution scales: at the grid-cell level, at the regional level, and at the national level. The results of this analysis showing the impacts on soil quality linked to land use activities associated with the chosen functional unit in the three alternative systems are presented in Section 3.2.

3 Results

3.1 Characterisation factors based on SOC stock

As a result of the first two steps (Fig. 1), maps of occupation CFs were derived for each land use class belonging to group A[7] (as defined in Section 2.2.1). As an example, Fig. 2 presents the map of CFs obtained for the land use class "arable,

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[7] Available at: https://fordatis.fraunhofer.de/handle/fordatis/395.

non-irrigated, intensive", and Fig. 3 presents the map of CFs obtained for the land use class "pasture/meadow intensive". In both figures, CFs are shown only in areas where the land use activity considered can take place following the rationale presented in Section 2.2.3, which was used to aggregate CFs at national and global levels. CFs at the grid-cell level are also available for the remaining locations, to allow practitioners to assess alternative scenarios.

The occupation CFs obtained were then aggregated at national and global levels (Step 3, Fig. 1). These values are provided in tabular form for all land use classes considered in this work in Table S2 of the SI. In addition, Table 4 illustrates the variability of the country-aggregated occupation CFs obtained for all group A land use classes (a visualisation of the same data is provided in Fig. S1 of the SI). It is possible to see that, for some land use classes, the distribution of CFs is predominantly made of positive values (representing a loss of SOC), whilst for other classes (namely "pasture/meadow, extensive", "arable, flooded crops", and "urban, green areas"), the distribution is either fully or almost fully characterised by negative values (representing an increase in SOC stocks). This highlights how the correct identification of the most suitable land use class to describe an activity at the inventory stage is critical, as this choice drastically influences the final outcome of the LCA study (in terms of land use impacts). Focusing on the median values reported, as expected, artificial land uses (IDs from 7.1.1 to 7.6.3 in Table 2) are those presenting the highest impacts on soil quality (with the exception of urban green areas). They are followed by severely degraded

Table 4 Distribution of country-aggregated occupation characterisation factors and global average occupation characterisation factors for land use classes belonging to group A. Values are measured in tonne C ha^{-1}

ID	Land use class	Global average	Country aggregated characterization factors				
			Min	**1st quartile**	**Median**	**3rd quartile**	**Max**
1.1.1	Forest, primary	0.00	0.00	0.00	0.00	0.00	0.00
1.1.2	Forest, secondary	0.00	0.00	0.00	0.00	0.00	0.00
1.2.1	Forest, extensive	0.00	0.00	0.00	0.00	0.00	0.00
1.2.2	Forest, intensive	0.00	0.00	0.00	0.00	0.00	0.00
4.1.2	Grassland, for livestock grazing	0.00	0.00	0.00	0.00	0.00	0.00
4.2.1	Pasture/meadow, extensive	−6.32	−17.92	−8.90	−7.05	−4.98	−1.57
4.2.2	Pasture/meadow, intensive	4.26	0.92	3.17	4.31	5.67	12.80
4.2.3	Pasture/meadow severely degraded	12.78	2.77	9.50	12.94	17.01	38.40
5.1.1	Arable, fallow	6.23	0.68	3.27	7.00	9.47	21.02
5.1.2.1	Arable, non-irrigated, extensive	10.08	0.87	5.33	7.12	11.22	31.95
5.1.2.2	Arable, non-irrigated, intensive	10.74	0.78	6.20	8.43	11.45	35.18
5.1.3.1	Arable, irrigated, extensive	10.08	0.87	5.33	7.12	11.22	31.95
5.1.3.2	Arable, irrigated, intensive	10.74	0.78	6.20	8.43	11.45	35.18
5.1.4	Arable, flooded crops	−15.76	−41.16	−19.95	−15.06	−10.67	−3.40
5.2.1.1	Permanent crops, non-irrigated, extensive	6.26	−7.77	−4.22	0.59	8.93	25.37
5.2.1.2	Permanent crops, non-irrigated, intensive	8.16	−3.53	−1.78	1.82	10.57	29.60
5.2.2.1	Permanent crops, irrigated, extensive	6.26	−7.77	−4.22	0.59	8.93	25.37
5.2.2.2	Permanent crops, irrigated, intensive	8.16	−3.53	−1.78	1.82	10.57	29.60
7.1.1	Urban/industrial fallow	43.63	7.74	25.94	35.80	49.09	110.08
7.1.2	Urban, continuously built	45.66	8.10	27.15	37.47	51.37	115.20
7.1.3	Urban, discontinuously built	25.37	4.50	15.08	20.81	28.54	64.00
7.1.4	Urban, green areas	−7.34	−17.92	−9.02	−6.80	−4.46	−1.53
7.1.5	Urban, sparsely built	15.22	2.70	9.05	12.49	17.12	38.40
7.2	Industrial area	47.18	8.37	28.05	38.71	53.08	119.04
7.3	Mineral extraction site	50.73	9.00	30.16	41.63	57.08	128.00
7.4	Dump site	50.73	9.00	30.16	41.63	57.08	128.00
7.5	Construction site	50.73	9.00	30.16	41.63	57.08	128.00
7.6.1	Traffic area, road network	50.73	9.00	30.16	41.63	57.08	128.00
7.6.2	Traffic area, rail network	50.73	9.00	30.16	41.63	57.08	128.00
7.6.3	Traffic area, rail/road embankment	25.37	4.50	15.08	20.81	28.54	64.00
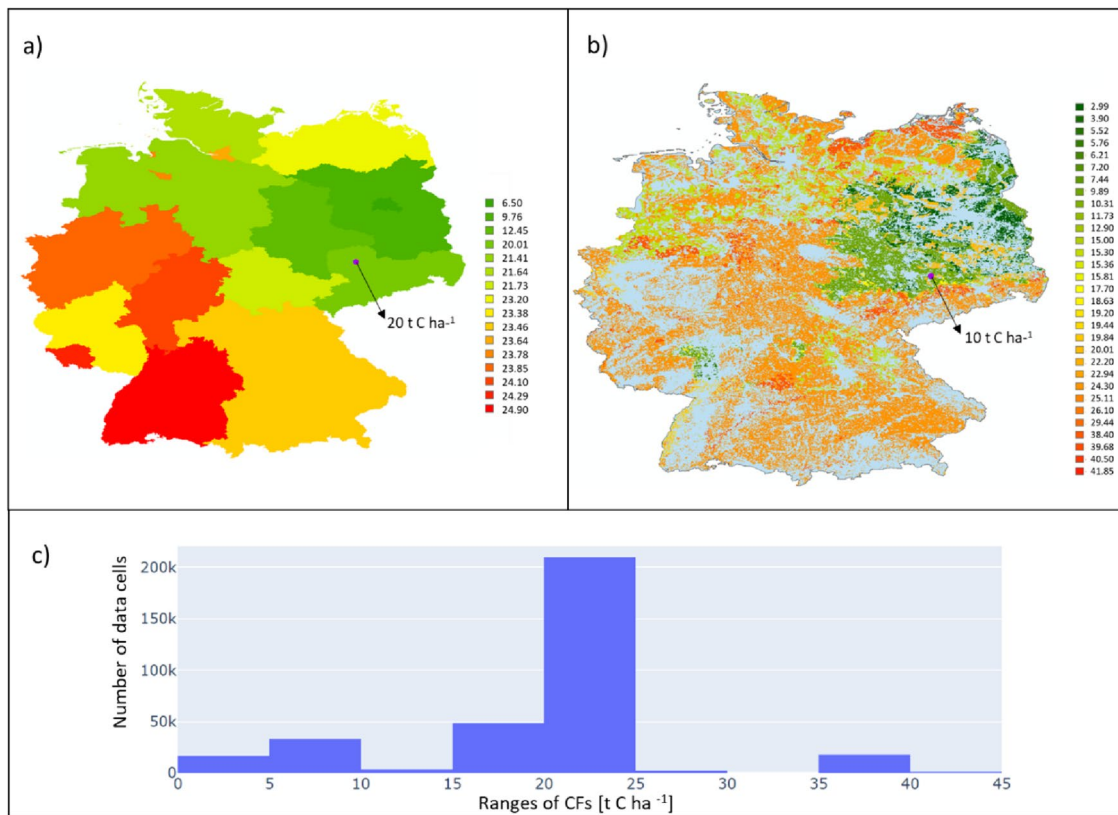
Fig. 4 Soil organic carbon (SOC)-based occupation characterisation factors (CFs) for the land use class "arable irrigated, intensive" for Germany at **a** regional aggregated level and **b** grid-cell level. **c** Distribution of characterisation factors displayed in **b**. All values are in tonne C ha^{-1}. The location where the cultivation of corn in the case study analysis takes place is marked with a purple dot in **a** and **b** and highlighted by a black arrow. Each value of characterisation factor is associated with a specific colour

pastures, intensive arable lands, other agricultural land uses, and high-intensity grazing pastures. Forest and nominally managed grassland presented a CF equal to zero, according to the IPCC (2019).

CFs for transformation impacts (calculated in Step 4, Fig. 1) are provided in the form of maps[8] for all the land uses belonging to group A and are reported in the SI in tabular form (Table S3) at national and global aggregated levels.

3.2 Case study analysis

To assess the sensitivity of the results to the level of aggregation of the CFs used, the case study analysis was performed by applying to the location-specific inventory data CFs calculated at three different spatial resolution scales: at a grid-cell level, at a regional level, and at a national level. The calculation of CFs at a grid-cell level and their aggregation at a national level are presented in Section 3.1. Instead, regional-level CFs were calculated specifically for

the case study analysis and only for the two countries considered: Germany and Brazil. Figure 4 shows as an example a comparison between the SOC-based CFs calculated at a regional level (Fig. 4a) and at a grid-cell level (Fig. 4b) for Germany. In both cases, the CFs are derived for the land use class "occupation, arable irrigated intensive". It can be seen that the regional aggregation and, even more so, the national aggregation entail a significant loss of detail as the CFs for the considered land use class for Germany vary between 3.0 and 41.9 tonne C ha^{-1} at grid-cell level (Fig. 4b), whilst at regional level, this variation is reduced to the interval 6.5 to 24.9 tonne C ha^{-1} (Fig. 4a) and becomes a unique value (equal to 21 tonne C ha^{-1}) at national level. Nevertheless, the distribution of CFs obtained at grid-cell level for Germany (Fig. 4c) shows that the largest share of grid cell-level CFs ranges between 20 and 25 t C ha^{-1}, a range to which belong also all the regional-level CFs excluded three (Fig. 4a). In the location where the cultivation stage of the case study analysis takes place (shown in Fig. 4a, b), the grid-cell CF is equal to 10 tonne C ha^{-1}. In case the LCA practitioner did not know the exact location, but only the region, they would use instead the regional-aggregated CF, which is equal to 20

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[8] Available at: https://fordatis.fraunhofer.de/handle/fordatis/395.

tonne C ha^{-1}. Finally, if the only information available was the country where the cultivation takes place, they would use the national CF, equal to 21 tonne C ha^{-1}. Therefore, in this specific case, the regional-aggregated value is only slightly closer to the grid-cell value than the national-aggregated value. Similarly, CFs at grid-cell, regional, and national levels were extracted considering the location where the cultivation of sugarcane takes place in the case study analysis and are reported in Table S4 of the SI.

The following land use types were associated with the different activities considered in the case study analysis: "arable, irrigated, intensive" was selected for the cultivation of corn in Sachsen (Germany), "arable, non-irrigated, intensive" for the cultivation of sugarcane in São Paulo (Brazil), "industrial area" for the biomethane and ethanol production plants (both assumed to be located in the same region as the ones considered for the cultivation phase), "urban" for the refuelling and recharging stations (assumed to be located in Baden-Württemberg, Germany), and "urban sparsely built" for the PV power station in Bayern (Germany). The choice of modelling the occupation of land for PV power stations with the land use class "urban sparsely built", caused by the lack of a specific land use class, is considered reasonable as this land-use class is described as a combination of grassland and sealed land. The land occupation and transformation flows and the associated CFs at grid-cell, regional and country levels are reported in Table S4 of the SI for all the considered land use types and locations.

The results of the case study analysis are presented in Fig. 5, comparing the impacts on soil quality due to land occupation and transformation associated with the considered functional unit in the three cases considered (biomethane, ethanol, and solar electricity powered passenger car) and performing the analysis at three different spatial resolution scales. The regional aggregation yielded results that were in-between the grid-cell level and the national level of aggregation, in two cases out of three (i.e., for the biomethane and the solar electricity), yet closer to the results obtained with national CFs. This limits the ground for adopting this level of aggregation in place of the national one, which in turn is less data-intensive both to derive the CFs and to implement them in LCA software. The differences between the results obtained at different levels of aggregation (Fig. 5a–c) are particularly significant for the case of biomethane (where the impact obtained with national CFs is more than double the one obtained using grid-cell level CFs), and less so for the ethanol and the solar electricity. It is interesting to notice the predominant role of occupation impacts over transformation impacts for biomethane and ethanol, due to significantly lower inventory values for land transformation than for land occupation in these two cases. Similar results were obtained by Milà i Canals et al. (2013), who argued that this might unveil a shortcoming in
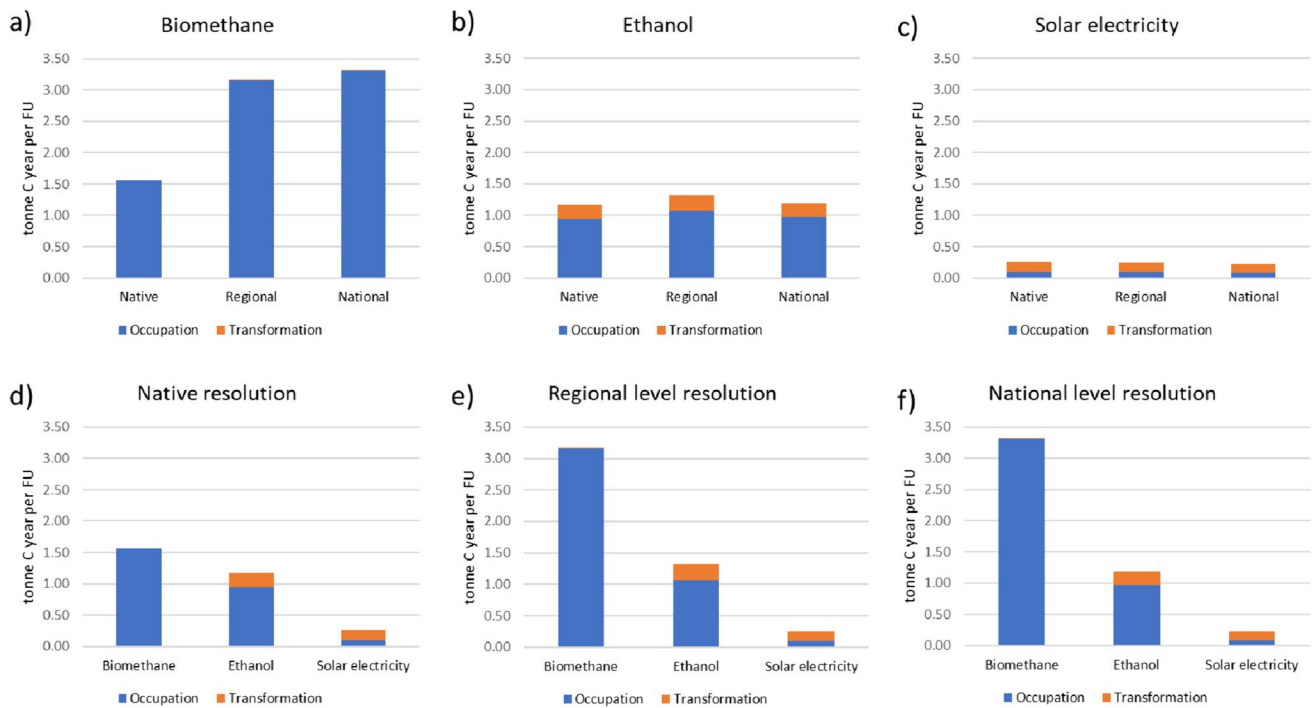
Fig. 5 Impacts on soil organic carbon (SOC) stocks from land occupation and transformation associated with the considered functional unit (FU) (energy used for a transport distance of 18,600 km by passenger car) for three alternative energy supply systems and at three different geographical levels

the approach adopted to model impacts from land use change in this framework. The reverse can be noticed in the case of solar electricity production. This is due to relatively higher inventory values for land transformation than in the other two cases (due to the assumption that all land occupied has been transformed in the 20 years prior to the occupation) and also to the higher values of regeneration times considered in the calculation of land transformation CFs for artificial land uses (85 years) compared to biotic land uses (20 years). Figure 5d–f presents the same trend, indicating that the highest impacts from land use are associated with the biomethane energy supply system, followed by the one based on ethanol and then on solar electricity, notwithstanding the level of aggregation of the CFs. This shows that, in the case analysed, the level of regionalisation of the analysis does not influence the ranking of the options considered.

4 Discussion

To derive an operational list of CFs that can be implemented in LCA software, the nomenclature adopted for land use types in this work is the one recommended by the Life Cycle Initiative and currently used by inventory databases, introduced by Koellner et al. (2013a). However, the chosen nomenclature system was not initially developed to be compatible with the definitions of land use classes adopted by the IPCC when providing SOC stock change factors. This means that to associate said factors to each land use class, value choices had to be made based on the additional information provided by the IPCC (2019), and the description of each land use class in Koellner et al. (2013a). An example is the case of the land use classes "arable, irrigated, intensive" and "arable, irrigated, extensive". From the description provided in the original classification, the level of intensity of these classes did not seem to correlate with the input level as defined in the IPCC; therefore, both classes were assigned input stock change factors connected to medium inputs and were differentiated by linking the extensive land use with reduced tillage and the intensive one with full tillage. To explain better the rationale behind these value choices and the link between the land use types as defined in inventory databases and their relative CFs suggested in this work, an additional definition was provided to complement the original one from Koellner et al. (2013a), when considered necessary. These additional definitions should be considered when building land use inventory models with the aim of characterising them with the CFs presented in this study. Despite the nomenclature harmonisation effort performed by Koellner and colleagues (2013a), inventory databases might use different nomenclature systems. In this case, to apply the CFs developed in this current study, mapping exercises are required, such as the ones presented in Sanyé-Mengual et al. (2022) and Scherer et al. (2021).

Moreover, this nomenclature system suffers from some limitations as it only partially captures different management regimes and intensities with highly varying levels of detail (for instance, not enabling to capture different management regimes in greenhouse agriculture). As a consequence, CFs were derived for an additional land use class, describing pasture and meadows that are severely degraded, which are covered by the land use practices considered by the IPCC (2019). However, this article could not cover all land uses considered by IPCC (2019). In particular, the current nomenclature system does not address the intensity of tillage, which affects the level of SOC (Ligthart and van Harmelen 2019). Furthermore, specific soil management options such as organic agriculture or conservation agriculture, are not distinguished in the CFs developed here. Given that one of the key goals of such forms of agriculture is to preserve and enhance soil quality, potentially resulting in higher levels of SOC than in conventional agriculture (Corbeels et al. 2019), the CFs provided so far cannot support comparisons with conventional agriculture. It is for this reason that the addition of a new land use class to better reflect agroecological practices, currently not considered in the nomenclature list, was suggested. Another land use that could not be assessed in this work is agroforestry, although it affects the level of SOC (Cardinael et al. 2018). Overall, it is here suggested that the classification of agricultural land uses should be expanded to better reflect the influence of agricultural practices, using as a starting point the practices considered in the management and input factors provided by the IPCC (2019) (e.g., reduced/no tillage, green manure, cover crops, use of perennial grasses in annual crop rotation).

As the model here presented is in general based on the IPCC (2019) Tier 1 method at the global level for measuring SOC stock changes in mineral soils, it was not possible to derive CFs for different forest management systems, which are currently all modelled as having an impact on SOC equal to zero, similarly to what is done by Brandão and Milà i Canals (2013). Whilst this assumption allows the use of a consistent data basis globally, its application to forestry systems is limited as it does not consider changes in SOC due to different forestry intensity levels, species, and management practices, which have been identified as relevant factors for forest soil carbon stocks (Grüneberg et al. 2014; Mayer et al. 2020). In particular, forest management practices may critically affect SOC stocks, both in terms of storage capacity but also in terms of risk prevention, e.g., against fire events (Hurteau et al. 2019).

Beyond the need to extend the current list of land use and land management types, there are also a number of limitations in current knowledge hindering the implementation of such refinement in a robust way. First, soil depth is

a key factor in assessing the long-term impact of agricultural or land use change practices on SOC (Balesdent et al. 2018). So far, CFs only refer to the first 30 cm, and further work is needed to provide evidence to account for the influence of land use activities on SOC stock at deeper depths. Second, many factors need to be accounted for to fit with the current land use framework in LCA. In particular, the natural reference and the regeneration times are very sensitive parameters that critically influence the final results (Bessou et al. 2020). More research is needed to model better the regeneration times depending on land use and practice change, and embedding larger depth and long-term changes. The choice of the natural reference to derive CFs has been much debated and may be related to the goal and scope of the LCA study (Milà i Canals et al. 2013). The reference state proved to be a very sensitive variable (Bessou et al. 2020), and in some cases, CFs may need to be adjusted manually depending on the LCA study, bearing in mind that this should not be allowed when LCA is adopted to perform comparative studies, such as in Environmental Footprint studies (European Commission 2013). A limitation of the aggregation approach adopted to derive national and global CFs is that it is influenced by the accuracy of the land use map providing information on where different land use activities take place. To take future potential changes in land use into account, this aggregation should ideally be periodically updated using newly published land use maps.

Although SOC stock represents a crucial indicator of the provisioning (e.g., biotic production) and regulating ecosystem services (e.g., climate regulation) and can be considered overall a good indicator of soil health, fertility, and quality (Lorenz et al. 2019), the risk related to adopting a model based on SOC as a standalone indicator when performing LCA studies is that impacts on other important soil functions are not directly assessed, e.g., soil resistance to erosion and filtration capacity, and some impacts are neglected, e.g., compaction and salinisation (Mattila et al. 2011; Vidal Legaz et al. 2017). Therefore, the approach presented in this work to assess the impacts of land use activities in LCA on soil, using SOC as a proxy of soil quality, should ideally be complemented by assessing additional impacts on soil properties.

Despite the discussed limitations and needs for further improvement, the added value of this work is to have advanced previous efforts to consistently derive SOC-based CFs from a single and authoritative data source at a global level (Brandão and Milà i Canals 2013) by (i) increasing the level of detail of the land use classification adopted, (ii) ensuring the operationality of the CFs by tailoring them to the nomenclature system and the spatial scale resolution commonly adopted by life cycle inventory databases, and (iii) additionally deriving them at a more refined spatial

resolution, useful for further investigating the relevance of using location-specific data when developing the foreground system. The case study application highlighted the relevance of the latter aspect, as, in one of the three cases investigated, the use of location-specific CFs led to impacts that were less than half of those obtained with national aggregated CFs, stressing the need to perform analyses at a finer spatial resolution to support decision-making.

5 Conclusion and outlook

The Global Guidance for Life Cycle Impact Assessment Indicators 2 (UNEP 2019) presented an interim recommendation to use the model developed by Brandão and Milà i Canals (2013) to assess the impacts of land use activities on soil quality, taking SOC as an indicator of soil quality. In the guidance document, a number of needs for further development and validation of the recommended model were highlighted, including improving the link between the characterisation factors and the land use nomenclature recommended by the Life Cycle Initiative and currently used by inventory databases; providing characterisation factors for forests, permanent crops, and artificial areas; testing the model by running case study analyses; updating the calculation of characterisation factors in line with the revised IPCC guidelines from 2019; and providing characterisation factors at more detailed geographical scales, beyond those available at country scale. This article aimed to address these needs by deriving a new set of CFs based on the model suggested by Brandão and Milà i Canals (2013), using the IPCC 2019 refinements for the calculation of SOC stocks, and compatible with the land use nomenclature list recommended by the Life Cycle Initiative. The characterisation factors were derived using spatial datasets (1-km resolution) and aggregated at national and global levels, by adopting an aggregation approach excluding those areas not suitable for a certain land use activity to avoid the introduction of bias. The new occupation and transformation characterisation factors were tested by means of a case study analysis, investigating the impact on SOC stocks caused by land use activities necessary to provide three alternative energy supply systems for passenger car transport. It is the authors' opinion that those requirements have now been fulfilled and that the present work may be the basis for an upgrade (from interim to full recommendation) of the Life Cycle Initiative's recommendation.

The case study analysis highlighted the relevance of conducting regionalised studies (at the foreground level) to better capture the spatial variability of soil types and climatic conditions and their influence on the resulting impacts. Further needs to improve the assessment of land use impacts in LCA based on changes in SOC stocks are a refinement

of the list of land use classes used at the inventory level to better capture the effects of management practices in agriculture and forestry, the introduction of a method to assess changes in SOC stocks induced by forestry activities, and better estimates of regeneration times. Further validation of the developed characterisation factors and application to different case studies are needed to evaluate the boundaries and potential weaknesses of the methods and theoretical framework employed, aiming to enhance trust in the reliability of the outcomes for the purpose of decision-making support.

Declarations

Conflict of interest The authors declare no competing interests.

References

Adhikari K, Hartemink AE (2016) Linking soils to ecosystem services - a global review. Geoderma. https://doi.org/10.1016/j.geoderma.2015.08.009

Al Mamun MA, Garba II, Campbell S, Dargusch P, deVoil P, Aziz AA (2023) Biomass production of a sub-tropical grass under different photovoltaic installations using different grazing strategies. Agric Syst. https://doi.org/10.1016/j.agsy.2023.103662

Balesdent J, Basile-Doelsch I, Chadoeuf J, Cornu S, Derrien D, Fekiacova Z, Hatté C (2018) Atmosphere–soil carbon transfer as a function of soil depth. Nature. https://doi.org/10.1038/s41586-018-0328-3

Bessou C, Tailleur A, Godard C, Gac A, de la Cour JL, Boissy J, Mischler P, Caldeira-Pires A, Benoist A (2020) Accounting for soil organic carbon role in land use contribution to climate change in agricultural LCA: which methods? Which impacts? Int J Life Cycle Assess. https://doi.org/10.1007/s11367-019-01713-8

Bivand R, Keitt T, Rowlingson B, Pebesma E, Sumner M, Hijmans R, Rouault E, Warmerdam F, Ooms J, Rundel C (2019) Package 'rgdal'. Bindings for the Geospatial Data Abstraction Library. https://www.rdocumentation.org/packages/rgdal/versions/1.6-7

Bivand RS, Pebesma E, Gómez-Rubio V (2013) Applied spatial data analysis with R, 2nd edn. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-7618-4

Blonk Consultants (2013) Direct land use change assessment tool. Version 2013.1. Gouda, Netherlands

Bos U, Horn R, Beck T, Lindner JP, Fischer M (2016) LANCA®- Characterization factors for life cycle impact assessment, version 2.0. Fraunhofer Verlag, Stuttgart, Germany

Brandão M, Milà i Canals L (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

Calaway R, Weston S (2017) Package "foreach". *R package*. https://cran.r-hub.io/web/packages/foreach/foreach.pdf

Calaway R, Weston S, Tenenbaum D (2018) Package 'doParallel'. *R Package*. https://cran.r-hub.io/web/packages/doParallel/doParallel.pdf

Cardinael R, Umulisa V, Toudert A, Olivier A, Bockel L, Bernoux M (2018) Revisiting IPCC tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems. Environ Res Lett. https://doi.org/10.1088/1748-9326/aaeb5f

Conant RT, Paustian K, Elliott ET (2001) Grassland management and conversion into grassland: effects on soil carbon. Ecol Appl. https://doi.org/10.1890/1051-0761(2001)011[0343:GMACIG]2.0.CO;2

Corbeels M, Cardinael R, Naudin K, Guibert H, Torquebiau E (2019) The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. Soil Tillage Res. https://doi.org/10.1016/j.still.2018.02.015

De Laurentiis V, Secchi M, Bos U, Horn R, Laurent A, Sala S (2019) Soil quality index: Exploring options for a comprehensive assessment of land use impacts in LCA. J Clean Prod 215:63–74. https://doi.org/10.1016/j.jclepro.2018.12.238

ESRI (2017) ArcGIS desktop: release 10.5.1. Environmental Systems Research Institute, Redlands, CA

European Commission (2013) 2013/179/EU: Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations Text with EEA relevance. OJ L 124, 4.5.2013. pp 1–210

European Commission (2018) Statistical pocketbook. EU transport in figures. https://transport.ec.europa.eu/facts-funding/studies-data/eu-transport-figures-statistical-pocketbook/statistical-pocketbook-2018_en

European Commission (2020) COM/2020/380: COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS EU Biodiversity Strategy for 2030 Bringing nature back into our lives

European Commission (2023) 2023/0232/COD: Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Soil Monitoring and Resilience (Soil Monitoring Law)

FAO (2021) Food and Agriculture Organization of the United Nations (FAO). FAOstat – food and agriculture data. http://www.fao.org/faostat. Accessed 4 May 2021

GADM (2021) Global administrative area database. https://gadm.org/index.html

Global Solar Atlas (2021). https://globalsolaratlas.info/. Accessed 4 May 2021

Google Maps (2021). https://www.google.com/maps. Accessed 4 May 2021

Grant T, Bessou C, Mila i Canals L, Grann B, De Laurentiis V, Ugayav C, De Souza D (2019) Land use impacts on soil quality. In: Global guidance for life cycle impact assessment indicators, vol 2. Life cycle initiative

Green MA, Dunlop ED, Levi DH, Hohl-Ebinger J, Yoshita M, Ho-Baillie AWY (2019) Solar cell efficiency tables (version 54). Prog Photovoltaics Res Appl. https://doi.org/10.1002/pip.3171

Grüneberg E, Ziche D, Wellbrock N (2014) Organic carbon stocks and sequestration rates of forest soils in Germany. Glob Chang Biol. https://doi.org/10.1111/gcb.12558

Hiederer R (2016) Processing a soil organic carbon C-stock baseline under cropland and grazing land management. EUR 28158 EN. Publications Office of the European Union, Luxembourg. https://doi.org/10.2791/64144

Hiederer R, Ramos F, Capitani C, Koeble R, Blujdea V, Gomez O, Mulligan D, Marelli L (2010) Biofuels: a new methodology to estimate GHG emissions from global land use change, EUR24483 EN – scientific and technical research series – ISSN 1018-5593. Publications Office of the European Union, Luxembourg. https://doi.org/10.2788/48910

Hijmans RJ, van Etten J (2012) Raster: geographic analysis and modeling with raster data. R package version 2.0–12

Horn R, Maier SD (2018) LANCA®- characterization factors for life cycle impact assessment, version 2.5. http://publica.fraunhofer.de/documents/N-379310.html. Accessed 4 May 2021

Hurteau MD, North MP, Koch GW, Hungate BA (2019) Managing for disturbance stabilizes forest carbon. Proc Natl Acad Sci USA. https://doi.org/10.1073/pnas.1905146116

Industry About (2014) Raizen – Costa Pinto sugar refining mill. https://www.industryabout.com/country-territories-3/529-brazil/sugar-industry/3267-raizen-costa-pinto-sugar-refining-mill. Accessed 4 May 2021

IPCC (2019) Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. In: Buendia EC, Tanabe K, Kranjc A, Baasansuren J, Fukuda M, Ngarize S, Osako A, Pyrozhenko Y, Shermanau P, Federici S (eds). Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE (1997) Soil quality: a concept, definition, and framework for evaluation (a guest editorial). Soil Sci Soc Am J. https://doi.org/10.2136/sssaj1997.03615995006100010001x

Kehoe L, Romero-Muñoz A, Polaina E, Estes L, Kreft H, Kuemmerle T (2017) Biodiversity at risk under future cropland expansion and intensification. Nat Ecol Evol. https://doi.org/10.1038/s41559-017-0234-3

Kibblewhite MG, Ritz K, Swift MJ (2008) Soil health in agricultural systems. Philos Trans R Soc B Biol Sci. https://doi.org/10.1098/rstb.2007.2178

Koellner T, Baan L, Beck T, Brandão M, Civit B, Goedkoop M, Margni M, Canals LM, Müller-Wenk R, Weidema B, Wittstock B (2013a) Principles for life cycle inventories of land use on a global scale. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-012-0392-0

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

Koellner T, Scholz RW (2008) Assessment of land use impacts on the natural environment. Int J Life Cycle Assess. https://doi.org/10.1065/lca2006.12.292.2

Lask J, Martínez Guajardo A, Weik J, von Cossel M, Lewandowski I, Wagner M (2020) Comparative environmental and economic life cycle assessment of biogas production from perennial wild plant mixtures and maize (Zea mays L.) in southwest Germany. GCB Bioenergy. https://doi.org/10.1111/gcbb.12715

Li G, Chen J, Sun Z, Tan M (2007) Establishing a minimum dataset for soil quality assessment based on soil properties and land-use changes. Acta Ecol Sin. https://doi.org/10.1016/S1872-2032(07)60059-6

Ligthart TN, van Harmelen T (2019) Estimation of shadow prices of soil organic carbon depletion and freshwater depletion for use in LCA. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-019-01589-8

Lorenz K, Lal R, Ehlers K (2019) Soil organic carbon stock as an indicator for monitoring land and soil degradation in relation to United Nations' sustainable development goals. Land Degrad Dev. https://doi.org/10.1002/ldr.3270

Maier SD, Lindner JP, Francisco J (2019) Conceptual framework for biodiversity assessments in global value chains. Sustain. https://doi.org/10.3390/su11071841

Mattila T, Seppälä J, Nissinen A, Mäenpää I (2011) Land use impacts of industries and products in the Finnish economy: a comparison of three indicators. Biomass Bioenerg. https://doi.org/10.1016/j.biombioe.2011.02.052

Mayer M, Prescott CE, Abaker WEA, Augusto L, Cécillon L, Ferreira GWD, James J, Jandl R, Katzensteiner K, Laclau JP, Laganière J, Nouvellon Y, Paré D, Stanturf JA, Vanguelova EI, Vesterdal L (2020) Influence of forest management activities on soil organic carbon stocks: a knowledge synthesis. For Ecol Manage. https://doi.org/10.1016/j.foreco.2020.118127

MEA (2005) Ecosystems and human well-being synthesis. World health. Island Press, Washington, DC, USA

Milà i Canals L, Muñoz I, McLaren S, Brandão M (2007a) LCA methodology and modelling considerations for vegetable production and consumption. University of Surrey, Surrey, UK. Centre for Environmental Strategy

Milà i Canals L, Rigarlsford G, Sim S (2013) Land use impact assessment of margarine. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-012-0380-4

Milà i Canals L, Romanyà J, Cowell SJ (2007b) Method for assessing impacts on life support functions (LSF) related to the use of "fertile land" in life cycle assessment (LCA). J Clean Prod. https://doi.org/10.1016/j.jclepro.2006.05.005

Morais TG, Domingos T, Teixeira RFM (2016) A spatially explicit life cycle assessment midpoint indicator for soil quality in the European Union using soil organic carbon. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-016-1077-x

Müller-Wenk R (1998) Land use—the main threat to species. How to include land use in LCA. University of St, Gallen, Switzerland

MVV Energia AG (2021) Our Kelin Wanzleben biomethane plant. https://www.mvv.de/en/about-us/group-of-companies/mvv-umwelt/renewable-energies/biogas/klein-wanzleben-biomethane-plant. Accessed 4 May 2021

Newbold T, Hudson LN, Hill SLL, Contu S, Lysenko I, Senior RA, Börger L, Bennett DJ, Choimes A, Collen B, Day J, De Palma A, Díaz S, Echeverria-Londoño S, Edgar MJ, Feldman A, Garon M, Harrison MLK, Alhusseini T, Ingram DJ, Itescu Y, Kattge J, Kemp V, Kirkpatrick L, Kleyer M, Correia DLP, Martin CD, Meiri S, Novosolov M, Pan Y, Phillips HRP, Purves DW, Robinson A, Simpson J, Tuck SL, Weiher E, White HJ, Ewers RM, MacE GM, Scharlemann JPW, Purvis A (2015) Global effects of land use on local terrestrial biodiversity. Nature. https://doi.org/10.1038/nature14324

Núñez M, Antón A, Muñoz P, Rieradevall J (2013) Inclusion of soil erosion impacts in life cycle assessment on a global scale: application to energy crops in Spain. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-012-0525-5

Payen S, Basset-Mens C, Follain S, Grünberger O, Marlet S, Montserrat N, Perret S (2014) Pass the salt please! From a review to a theoretical framework for integrating salinization impacts in food LCA. In: 9th International conference on life cycle assessment in the agri-food sector (LCA Food)

Pebesma EJ, Bivand RS (2005) Classes and methods for spatial data in R. R news

R Core Team (2020) R: a language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. Available online: https://www.r-project.org/. Accessed 4 May 2021

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. https://doi.org/10.1007/s11367-013-0577-1

Sala S, Benini L, Castellani V, Vidal-Legaz B, De Laurentiis V, Pant R (2019) Suggestions for the update of the environmental footprint life cycle impact assessment. Impacts due to resource use, water use, land use and particulate matter. EUR 28636. ed. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/78072. ISBN 978-92-79-69335-9

Sanyé-Mengual E, Valente A, Biganzoli F, Dorber M, Verones F, Marques A, Ortigosa Rodriguez J, De Laurentiis V, Fazio S, Sala S (2022) Linking inventories and impact assessment models for addressing biodiversity impacts: mapping rules and challenges. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-022-02049-6

Scherer L, De Laurentiis V, Marques A, Michelsen O, Alejandre EM, Pfister S, Rosa F, Rugani B (2021) Linking land use inventories to biodiversity impact assessment methods. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-021-02003-y

Sonderegger T, Pfister S, Hellweg S (2020) Assessing impacts on the natural resource soil in life cycle assessment: methods for compaction and water erosion. Environ Sci Technol 54:6496–6507. https://doi.org/10.1021/acs.est.0c01553

Technical Research Centre Finland (2018) Lipasto unit emissions database. http://lipasto.vtt.fi/yksikkopaastot/indexe.htm. Accessed 4 May 2021

Teixeira RFM, Morais TG, Domingos T (2018) Consolidating regionalized global characterization factors for soil organic carbon depletion due to land occupation and transformation. Environ Sci Technol. https://doi.org/10.1021/acs.est.8b00721

Trading Economics (2021a) Ethanol. https://tradingeconomics.com/commodity/ethanol. Accessed 4 May 2021

Trading Economics (2021b) Sugar. https://tradingeconomics.com/commodity/sugar. Accessed 4 May 2021

UNEP (2019) Global guidance for life cycle impact assessment indicators, vol 2. https://www.lifecycleinitiative.org/training-resources/global-guidance-for-lifecycle-impact-assessment-indicators-volume-2/2019. Accessed 4 May 2021

Uusitalo V, Horn R, Maier SD (2022) Assessing land use efficiencies and land quality impacts of renewable transportation energy systems for passenger cars using the LANCA® method. Sustainability 14:6144

van Dobben H, Schouwenberg E, Nabuurs G, Prins A (1998) Biodiversity and productivity parameters as a basis for evaluating land use changes in LCA—annex 1. In: Lindeijer E, van Kampen M, Fraanje P, van Dobben H, Nabuurs G, Schouwenberg E, Prins A, Dankers N, Leopold M (eds) Biodiversity and life support indicators for land use impacts in LCA. Dienst Weg- en Waterbouwkunde (Publication series raw materials 1998/07), Delft

Vidal Legaz B, Maia De Souza D, Teixeira RFM, Antón A, Putman B, Sala S (2017) Soil quality, properties, and functions in life cycle assessment: an evaluation of models. J Clean Prod. https://doi.org/10.1016/j.jclepro.2016.05.077

Wang M, Han J, Dunn JB, Cai H, Elgowainy A (2012) Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. Environ Res Lett. https://doi.org/10.1088/1748-9326/7/4/045905

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