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Global characterisation factors to assess land use impacts on biotic production

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Abstract
Purpose The inclusion of land-use activities in life cycle assessment (LCA) has been subject to much debate in the LCA community. Despite the recent methodological developments in this area, the impacts of land occupation and transformation on its long-term ability to produce biomass (referred to here as biotic production potential [BPP]) — an important endpoint for the Area of Protection (AoP) Natural Resources — have been largely excluded from LCAs partly due to the lack of life cycle impact assessment methods.
Materials and methods Several possible methods/indicators for BPP associated with biomass, carbon balance, soil erosion, salinisation, energy, soil biota and soil organic matter (SOM) were evaluated. The latter indicator was considered the most appropriate for LCA, and characterisation factors for eight land use types at the climate region level were developed.
Results and discussion Most of the indicators assessed address land-use impacts satisfactorily for land uses that include biotic production of some kind (agriculture or silviculture). However, some fail to address potentially important land use impacts from other life cycle stages, such as those arising from transport. It is shown that the change in soil organic carbon (SOC) can be used as an indicator for impacts on BPP, because SOC relates to a range of soil properties responsible for soil resilience and fertility.
Conclusions The characterisation factors developed suggest that the proposed approach to characterize land use impacts on BBP, despite its limitations, is both possible and robust. The availability of land-use-specific and biogeographically differentiated data on SOC makes BPP impact assessments operational. The characterisation factors provided allow for the assessment of land-use impacts on BPP, regardless of where they occur thus enabling more complete LCAs of products and services. Existing databases on every country's terrestrial carbon stocks and land use enable the operability of this method. Furthermore, BPP impacts will be better assessed by this approach as increasingly spatially specific data are available for all geographical regions of the world at a large scale. The characterisation factors developed are applied to the case studies (Part D of this special issue), which show the practical issues related to their implementation.

Keywords Biotic production potential · Ecosystem services · Land use · Life Cycle Impact Assessment (LCIA) · Midpoint indicators · Soil organic carbon (SOC) · Soil organic matter (SOM)

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1 Introduction

Ecosystems provide humans with a variety of goods and services that are essential for our survival. These are collectively known as ecosystem services and include the provision of food, fibre and energy; the regulating and supporting of processes (air, water and nutrient cycles; climate; erosion; pests and diseases; pollination; soil formation; photosynthesis); and, even, provision of non-material services, such as cultural diversity and spiritual and religious values (Millennium Ecosystem Assessment 2005). The importance of these services (which can be considered endpoints[1] in the life cycle assessment (LCA) framework (Chapman 2008; Bare and Gloria 2008) implies that LCA — as an environmental systems analysis tools aiming at being holistic and comprehensive — must include the environmental impacts on ecosystem services that product systems cause. In the first phase of the United Nations Environment Programme-Society for Environmental Toxicology and Chemistry (UNEP-SETAC) Life Cycle Initiative Programme on Life Cycle Impact Assessment (LCIA), key elements in a framework for land use impact assessment were identified, including three impact pathways: biodiversity, ecological soil quality (ESQ) and biotic production potential (BPP) (Milà i Canals et al. 2007a).

For the benefit of harmonising the LCA land use impact assessment framework (Milà i Canals et al. 2007a) with the Ecosystem Services framework developed by the Millennium Ecosystem Assessment (2005), ESQ can be said to be associated with the *supporting* and *regulating* types of ecosystem services, whereas BPP is associated with *provisioning* services.[2] It must be noted that ecosystem services are highly interlinked and interdependent. As a result, it is likely that midpoints for any of these degradation paths could serve as indicators for BPP. For example, the midpoints erosion, compaction, salinisation, contamination, loss of organic matter have an impact on the potential for biotic production. Supporting and regulating services include filter and buffer capacity, substance cycling (such as carbon, other nutrients and water), and climate regulation. While Saad et al. (2012) address impacts on filter and buffer capacity, water cycling and erosion resistance, and Müller-Wenk and Brandão (2010) suggest an approach for carbon sequestration, this paper is concerned with BPP. This paper aims at identifying the methods that have been put forward for assessing the impacts of land use on BPP (or some variation of it) and at developing characterisation factors (CF) from the indicator deemed most appropriate.

BPP refers to the conditions of land that determine its short, medium and long-term inherent ability to produce and sustain biomass (food, feed, fodder, wood, fibre, energy, medicines, ornamentals) at current productivity levels, through the provision of water, nutrients, air and a stable physical support place for plants to fix their roots. Land or ecosystem productivity is measured in biomass produced per unit area per unit time (e.g., kg m^{-2} $year^{-1}$). Because biotic production is a flow and not a stock, impacts refer to those impairing the potential or capacity of ecosystems for biotic production. BPP does not refer to the present biomass production foregone as a result of a particular land use (this would be reflected by changes in Net Primary Production [NPP]), but to the change in the productive capacity or the ability of the ecosystem to sustain future biomass production (under potential for biotic production — Area of Protection (AoP) Natural Resources).

BPP depends to a large extent on aspects such as climate (temperature and precipitation), soil type, slope, vegetation cover, history of land use, management practices, and biological activity. These aspects determine soil quality, i.e., the emergent property arising from the presence of those attributes without which supporting ecosystem services cannot be delivered. As a consequence, impacts on BPP depend not only on the particular land use, but also on the sensitivity of the ecosystem where the activity is located. The aim of this paper is to propose CF based on models and literature that reflect both land use type and ecosystem, in line with the inventory principles in (Koellner et al. 2012a).

This paper briefly reviews indicators that have been put forward to represent impacts on BPP (Section 2), and justifies the election of an indicator for BPP. Subsequently, Section 3 describes the model following the guidelines proposed by Koellner et al. (2012b), including the calculation procedure for CF which are calculated for a variety of land uses and climate regions based on SOC; a comprehensive list of CF is provided in the Electronic Supplementary Material. Finally, Section 4 discusses how the new CF may inform better the decisions based on LCA of land-based systems in particular, and Section 5 provides conclusions and recommendations for further research.

2 Review of indicators for impacts on BPP at midpoint and endpoint levels

Impact indicators should be sensitive to variations in management, and accessible to many users (Kennedy and Smith 1995). An array of different land quality indicators have been suggested for use in LCA in several reports, including those presented by Baitz et al. (1999), Cowell (1998), Lindeijer et al. (1998), Lindeijer (2000), Mattsson et al. (1998), Koellner and Scholz (2007, 2008), Michelsen (2008), Milà i Canals (2003), Milà i Canals et al. (2007c), Schmidt (2008), Wagendorp et al. (2006), Weidema and Lindeijer (2001), as reported by Milà i Canals et al.

[1] While midpoint modelling refers to the modelling of impacts (e.g., Climate Change) at a middle point in the cause–effect chain or environmental mechanism, endpoint modelling refers to that at the end of the cause–effect chain (i.e., damage to Human Health, Ecosystems or Natural Resources).

[2] BPP is also referred to the conditions responsible for biological/biomass/ecosystem productivity. It is a life support function that is included in the Ecosystem Services Framework as a provisioning ecosystem service, and includes food, fibre, fuel, genetic resources, biochemicals, natural medicines and pharmaceuticals, ornamental resources and fresh water (Millennium Ecosystem Assessment 2005).

(2007a). These, however, refer to general soil quality/life support functions, and/or biodiversity, and not to BPP specifically. Because soil quality in general is affected by many factors, many indicators are possible and an index that includes the many aspects of soil quality has been developed (e.g., Baitz et al. 1999). The potential of the different soil quality indicators to incorporate impacts from land use on BPP in LCA varies and is presented in Table 1, which expands on the review made by Milà i Canals et al. (2007c). Table 1 aims to summarise the pros and cons of the indicators that have been used for BPP. Further details are given by Brandão (2011).

In addition to the review presented in Table 1, the Joint Research Centre of the European Commission led a review of impact assessment methods for 11 impact categories developed for the International Reference Life Cycle Data System (ILCD) handbook (European Commission 2010) and recommends SOC for land-use impacts at midpoint level (European Commission 2010). In this paper, we suggest using changes in SOM (SOC)[3] as an indicator for impacts on BPP.

Before the invention and use of synthetic fertilisers, SOM was at the core of soil fertility for biomass production, which is still the case for low-input agriculture, forestry and organic/ecological agriculture (Van-Camp et al. 2004). Because SOM affects, either directly or indirectly, most of the chemical, physical and biological properties of soil, it is thought to be a good measure of changes in biological productivity, since its presence determines the conditions necessary for it. The anthropogenic causes of SOM loss include land conversion, tillage, overgrazing, soil erosion, and forest fires (Van-Camp et al. 2004).

Even though no conclusive quantitative relationship has been established between the two variables in a ceteris paribus way, there seems to be a positive correlation within certain thresholds. Long-term experiments at Askov (Denmark) and Rothamsted (England), from 1894 and 1843, respectively, have shown that SOM has a significant impact on yields. Indeed, “irrespective of the amount of N applied, yields … were larger on soils with extra SOM resulting from applications of FYM since 1843” (Christensen and Johnston 1997). The mechanisms through which SOM can affect the yield of arable crops include nutrient release, improved soil structure, and improved waterholding capacity, “but these cannot be readily separated and quantified” (Christensen and Johnston 1997).

[3] Soil organic matter (SOM) is best measured as soil organic carbon (SOC), according to Reeves (1997). SOM content is measured as density of SOC, and SOC is usually considered to be 58% of SOM, giving a conversion factor of 1.72:1 (SOM/SOC) (Brady and Weil 1999). SOC is chosen in this paper as indicator for BPP.

3 Description of the model to assess impacts on BPP from land use

In this section, the approach suggested by Milà i Canals and co-workers (2007c) and further detailed by Milà i Canals et al. (2007b), is presented in the context of the guidelines recommended by Koellner et al. (2012b).

3.1 Spatial model

The model presented in this paper addresses the impact pathway linking land occupation and transformation flows to effects on soil physical, chemical and biological fertility as expressed by soil organic carbon (SOC). The model aims at global coverage of all land use types identified by Koellner et al. (2012a) at the first land use classification level. For those land uses that involve biotic production, further refinement is desirable in order to capture differences in the land management (e.g., intensive vs. extensive agriculture; permanent crops vs. annuals), and thus this paper goes a level deeper in the land use types classification for agricultural land uses. On the other hand, “artificial” land use types (e.g., those sealing the soil surface or heavily impairing its properties) may be modelled in a coarser way, and simplifying assumptions are presented to cover them at the most aggregate level suggested by Koellner et al. (2012a) (e.g., “artificial areas”).

The biogeographical differentiation that can be achieved in the calculation of CF depends very much on the data available. This paper suggests differentiation at a climate region level for the background system; however, higher resolution (e.g., country, soil type) may actually be achieved with currently existing data provided in this paper (see Section 3.2).

As recommended by Koellner et al. (2012b), the SOC present in (quasi-)natural land cover predominant in global biomes and ecoregions is used as a reference against which SOC levels induced by the studied land use are assessed. The SOC content is influenced by soil type, climate region (or temperature regime), land-use type and land management. In order to determine the average reference SOC in the different biomes or climate regions, a weighted average is applied to the values associated with the different soil types within each climate region (Table 2), which reflects the share of those soil types in each climate region. This is done with reference to GIS datasets, and results in the values shown in Table 3.

3.2 Data collection

3.2.1 Inventory data required to model BPP

In this proposed model, the impact of land use on BPP is a function of three parameters: change in SOM content, area

Table 1 Review of indicators for BPP in LCA

Indicator	Relationship to BPP	Applicability in LCA/Has it been used in LCA?	Relevant references
Back-up technology (endpoint)	Alternative and artificial way for restoring the same productivity levels of BPP (e.g., by fertiliser use)	Yes, but mainly related to non-land resources (e.g., desalinisation for water use impacts)	Stewart and Weidema (2005)
Net Primary Production (NPP)	NPP refers to actual biomass production	Appropriate for non-biotic production life cycle stages. The limitation with NPP is that it may be completely determined by the particular management regime to which the land is subjected to (e.g., high crop yields sustained by fertiliser use) and/or short-term natural factors. The long-term and inherent ability of the ecosystem itself to produce biomass is, therefore, bypassed.	Weidema and Lindeijer (2001)
Human Appropriation of Ecosystem Carbon Stock (HAPECS)	Refers to the carbon exported from the system in the form of biomass and CO_2	Yes, as an aggregate indicator of impacts on ecosystem services and biodiversity.	Brandão et al. (2010)
Erosion	Physical loss of soil undermines and decreases the potential of soil to perform its functions, including biotic production.	This indicator may not be fully compatible with a whole life cycle approach, being more suitable to the agricultural phase of the life cycle.	Cowell and Clift (2000)
Salinisation	The increase in concentrations of salts in soil due to poor irrigation and other agricultural practices and extensive land clearing cause soil degradation and may inhibit biotic production by reducing the ability of plant roots to uptake water and nutrients.	As in the case of erosion, the choice of this indicator might not be meaningful for sealed soils or stages of the life cycle outside the agricultural stage. On the other hand, when salinisation occurs other indicators for BPP will be less relevant.	Feitz and Lundie (2002)
Energy/exergy	Energy and carbon balances are closely related (see NPP and HAPECS).	Whilst it may be useful in the assessment of industrial systems, indicators based on energy/exergy are less suitable for the assessment of biotic systems. Its applicability in LCA is limited to the post land-use stages of the life cycle.	Wagendorp et al. (2006)
Microbial biomass and diversity	Soil organisms are crucial in the ecological functioning of the soil due to their role in mineralisation and cycling of SOM and nutrients, degrading pollutants, controlling pests, improving soil structure, fixing CO_2 and producing SOM.	It helps the soil perform its functions. Rosado et al. (2006) found that soil bacterial communities were extremely sensitive to land management. This indicator is closely related to SOC as soil biota is sustained mainly by organic matter. However, this indicator is limited by difficulty of measurement.	Peixoto et al. (2006)
Soil organic matter (SOM)/Soil organic carbon (SOC)	SOM affects most of the chemical, physical and biological properties of soil. Despite the relatively minor quantity in soil, SOM plays an important role as a soil constituent and as source of food and energy for soil biota. Therefore, SOM is a keystone for soil functioning. It influences soil texture and soil structure, which together determine the general productivity of cropping systems by influencing the availability of nutrients. Before the invention and use of synthetic fertilisers, SOM was at the core of biomass production.	SOM is recognised as the best stand-alone indicator for soil quality, despite not considering all aspects of soil functioning. Indeed, SOM is probably the most cited indicator of soil quality within soil science research. The reason for this is that not only does it influence soil fertility but also a range of indicators of soil and environmental quality. As an indicator, SOC has been widely used outside the LCA methodology, and even within it, it has already been suggested. SOM is best measured by SOC. The value of this indicator lies in the fact that it is closely related to other soil quality indicators, such as cation-exchange capacity, soil biota, and structure. However, not all aspects of soil quality are captured by the SOM indicator. These include build-up of toxic substances, acidification and salinisation.	Milà i Canals et al. (2007c)

Table 2 Soil organic carbon stocks under native vegetation (tonnes C ha^{-1} in 0–30 cm depth) (IPCC 2006)

Climate Region	High activity clay soils	Low activity clay soils	Sandy soils	Spodic soils	Volcanic soils	Wetland soils
Boreal	68	NA	10	117	20	146
Cold temperate, dry	50	33	34	NA	20	87
Cold temperate, moist	95	85	71	115	130	87
Warm temperate, dry	38	24	19	NA	70	88
Warm temperate, moist	88	63	34	NA	80	88
Tropical, dry	38	35	31	NA	50	86
Tropical, moist	65	47	39	NA	70	86
Tropical, wet	44	60	66	NA	130	86
Tropical montane	88	63	34	NA	80	86

and time. The latter refers to both the duration of occupation and the rate of recovery. The change in organic matter from occupation depends on the land use, soil type, location and management; this change may be calculated by the LCA practitioner for foreground systems, and expected average changes are provided as CF for the background system in this paper. Figure 1 illustrates the impact on BPP as indicated by SOC change (shaded areas) in changing land use, followed by occupation.

The impact is measured as a carbon deficit (or credit, expressed by negative values) with the unit "kg Cyear", referring to the amount of extra carbon temporarily present or absent from the soil due to the studied system compared to a reference system (Milà i Canals et al. 2007c). In order to estimate the change in SOC caused by land use, the default values suggested by IPCC for a large variety of soil types, climatic conditions and management options may be used in a first instance. The CF developed are derived from the SOC values in Tables 2, 3, 4, 5 and 6 (extrapolated from IPCC 2003, 2006).

3.2.2 Regeneration time

The IPCC (2003, 2006) assumes that the regeneration time is 20 years between biotic land uses, i.e., that it takes 20 years following the environmental intervention in land use and management to reach a new equilibrium, although longer regeneration times are used for sealed land uses (see Section 3.2.2). In order to determine the steady-state SOC values associated with the different types of land use and management, the reference values are calculated by multiplying the reference SOC with the IPCC factors (see Tables 4, 5 and 6). The CF for both land transformation and land occupation reflect the SOC deficit associated with each land-use intervention relative to the Native SOC (see Fig. 1). The carbon stock changes associated with land-use changes are assumed to happen instantly, so that the transformation impact can be fully ascribed to transformation processes, instead of occupation processes (see Koellner et al. this issue (b)).

Table 3 Soil organic carbon stocks under native vegetation by Climate Region and Land Use Type (extrapolated from IPCC 2006)

CLIMATE REGION	AREA (km^2)	Relative (%)	Permanent grassland (tonnes C ha^{-1} in 0–30 cm depth)	Long-term cultivated	Native ecosystem	Set-aside	Paddy rice
Tropical, wet	9,408,767	7.0	58.0	56.6	57.4	53.3	58.5
Tropical, moist	17,451,444	13.0	56.2	58.4	54.1	59.0	62.0
Tropical, dry	30,553,142	22.8	36.4	37.1	37.2	36.4	38.7
Tropical montane	7,351,295	5.5	65.0	76.3	70.9	72.7	74.8
Warm temperate, moist	5,528,026	4.1	79.2	81.4	78.0	77.4	80.9
Warm temperate, dry	12,631,558	9.4	36.9	38.1	37.2	37.5	37.7
Cool temperate, moist	11,808,612	8.8	91.3	94.3	95.0	96.0	96.6
Cool temperate, dry	12,221,975	9.1	49.1	51.4	49.2	50.3	50.3
Boreal, moist	13,770,293	10.3	84.1	70.9	85.1	73.8	66.1
Boreal, dry	3,808,837	2.8	74.9	72.7	81.8	74.1	71.8
Polar, moist	7,565,826	5.6	42.7	36.4	46.4	36.6	25.5
Polar, dry	1,975,716	1.5	47.5	45.8	53.5	46.6	45.2
Total (without Antarctica)	134,075,489	100.0					

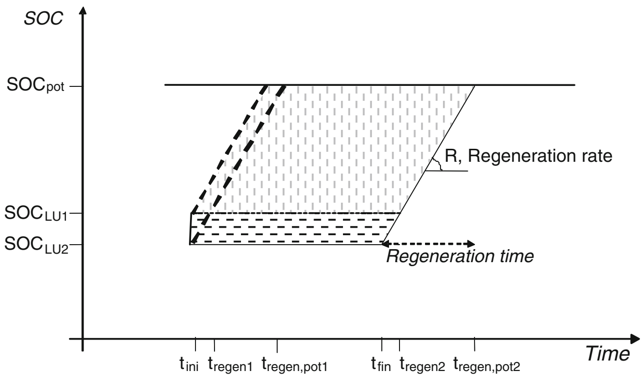

Fig. 1 Calculation of impacts on BPP measured by SOC (adapted from Milà i Canals et al. 2007b)

In biotic land uses (e.g., agriculture and forestry), the average time required to get to new steady state levels of SOC is assumed to be 20 years, as suggested by the IPCC (2003, 2006). This time is clearly too short in many occasions, and particularly for transformations from low SOC land uses (e.g., arable land) to high SOC land uses (e.g., forest) the build-up of SOC may take considerably longer (WBGU 1998). In addition, agricultural soils seem to be almost always far from equilibrium (e.g., Ceschia et al. 2010). However, for the time being this simplification has been considered to be valid for land uses where the soil is functioning. For artificial land use types (sealed land), where soil has been removed or significantly impaired, the regeneration times are estimated based on Lindeijer et al. (1998) (see Saad et al. 2012; de Baan et al. (2012).

3.2.3 Calculation of impacts on BPP

The method developed by Milà i Canals et al. (2007c) has been slightly modified to follow the considerations discussed by Milà i Canals et al. (2007a) and Koellner et al. (2012b). The general formula used to calculate CF for land transformation flows is shown in Eq. 1, and that for land occupation flows is shown in Eq. 2 (see Fig. 1 for an illustration of the formula's parameters).

$$\Delta C\left[\mathrm{kg\,C\,year\,m^{-2}}\right] = \left(\mathrm{SOC_{pot}} - \mathrm{SOC_{LU1}}\right) \times \left(t_{\mathrm{regen1}} - t_{\mathrm{ini}}\right) + \frac{1}{2}\left(t_{\mathrm{regen1}} - t_{\mathrm{ini}}\right) \times \left(\mathrm{SOC_{LU1}} - \mathrm{SOC_{LU2}}\right) \quad (1)$$

where $\mathrm{SOC_{pot}}$ is the potential level of SOC if land is left undisturbed (i.e., Native SOC); $\mathrm{SOC_{LU1}}$ the SOC level in the land use prior to the transformation/occupation studied; $\mathrm{SOC_{LU2}}$ is the SOC level in the subsequent land use; t_{ini} is the moment when the transformation and subsequent occupation takes place (assumed to be simultaneous); at t_{fin}, the occupation period ends; at t_{regen}, SOC has reverted to the level prior to land transformation; and $t_{\mathrm{regen,pot}}$ is the time when the system reaches its potential quality (Native SOC). t_{regen} may be calculated from the regeneration rate (R) if known; see above for the considerations used in this study for the generic CFs. The equation assumes a linear evolution of SOC, as suggested by Milà i Canals et al. (2007a). The first component of the numerator refers to the impacts due to the postponed regeneration of the system, whereas the second component refers to the impacts due to the change SOC following transformation. The denominator serves to express the CF in $\mathrm{m^{-2}\,year^{-1}}$ (all the SOC values are expressed per square meter), which applies to occupation CFs only.[4]

$$\Delta C\left[\mathrm{kg\,C\,year\,m^{-2}\,year^{-1}}\right] = \frac{\left(\mathrm{SOC_{pot}} - \mathrm{SOC_{LU2}}\right) \times \left(t_{\mathrm{fin}} - t_{\mathrm{ini}}\right)}{\left(t_{\mathrm{fin}} - t_{\mathrm{ini}}\right)} \quad (2)$$

The following example shows how to calculate the changes in SOC due to land-use change effects for a conversion of set-aside land in the UK for annual crop production:

Climate Region: Cold temperature
Moisture Regime: Moist
Soil type: High activity clay soils
Land use 1: Set-aside (<20 years)
Land use 2: Long-term cultivated
Land management: Full tillage, high input without manure
Original carbon stock=95×0.82=77.9 tonnes of carbon/ha (see Tables 2 and 4)
Final carbon stock=95×0.69×1.00×1.11=72.8 tonnes of carbon/ha (Tables 2, 4, and 5)
Change in carbon stock=−5.1 tonnes carbon/ha

The characterisation factor for this land transformation is therefore:

$$\Delta C\ \left[\mathrm{kg\,C\,year\,m^{-2}}\right] = (9.50 - 7.79) \times (4.6 - 0) + \frac{1}{2}(4.6 - 0) \times (7.79 - 7.28) = 9$$

The characterisation factor that would be considered for each year of land occupation as annual crop production in the UK after this transformation would be:

$$\Delta C\ \left[\mathrm{kg\,C\,year\,m^{-2}\,year^{-1}}\right] = \frac{(9.50 - 7.28) \times (1 - 0)}{(1 - 0)} = 2.2$$

Generic CF for the first level of land use classification and spatial differentiation as suggested by Koellner et al. (2012a) are offered in the electronic Appendix.

[4] The only difference between the equation for calculation CFs for transformation from that for occupation is that the latter is not expressed per $\mathrm{m^2}$ and year and therefore excludes the denominator in Eq. 1.

Table 4 IPCC Land use factors, unitless (IPCC 2006)

Land use	Temperature regime	Moisture regime	IPCC defaults	Error (±)
Long-term cultivated	Temperate/Boreal	Dry	0.80	9%
		Moist	0.69	12%
	Tropical	Dry	0.58	61%
		Moist/Wet	0.48	46%
	Tropical montane	n/a	0.64	50%
Permanent grassland	All	All	1.00	
Paddy rice	All	Dry and Moist/Wet	1.10	50%
Perennial/tree crop	All		1.00	50%
Set-aside (<20 years)	Temperate/boreal and tropical	Dry	0.93	11%
		Moist/Wet	0.82	17%
	Tropical montane	n/a	0.88	90%

3.2.4 Allocation of land transformation impacts

As suggested by several authors, legislation and greenhouse gas accounting schemes (EU 2010; BSI 2011; Koellner et al. 2012b; Flynn et al. 2011), we have equally allocated land transformation impacts to the first 20 years of land occupation. In the above example, the land use impacts on BPP attributed to any of the first 20 years of cropping in a m^2 following transformation would therefore be 9/20+2.2= 2.7 kg C year m^{-2} $year^{-1}$. Other approaches to allocation, not used in this paper, include a consequential approach (e.g., Schmidt 2008) or allocating all land transformation to the total current amount of land used, e.g., in a country (e.g., Pfister et al. 2010; Milà i Canals L et al. 2012).

Table 5 IPCC Land management factors for cropland, unitless (IPCC 2006)

Land-use management	Temperature regime	Moisture regime	IPCC defaults	Error (±) (%)
Full tillage	All	Dry and Moist/Wet	1.00	NA
Reduced tillage	Temperate/Boreal	Dry	1.02	6
		Moist	1.08	5
	Tropical	Dry	1.09	9
		Moist/Wet	1.15	8
	Tropical montane	n/a	1.09	50
No tillage	Temperate/Boreal	Dry	1.10	5
		Moist	1.15	4
	Tropical	Dry	1.17	8
		Moist/Wet	1.22	7
	Tropical montane	n/a	1.16	50
Low input	Temperate/Boreal	Dry	0.95	13
		Moist	0.92	14
	Tropical	Dry	0.95	13
		Moist/Wet	0.92	14
	Tropical montane	n/a	0.94	50
Medium input	All	Dry and Moist/Wet	1.00	NA
High input without manure	Temperate/boreal and tropical	Dry	1.04	13
		Moist/Wet	1.11	10
	Tropical montane	n/a	1.08	50
High input with manure	Temperate/boreal and tropical	Dry	1.37	12
		Moist/Wet	1.44	13
	Tropical montane	n/a	1.41	50

Table 6 IPCC Land management factors for permanent grassland, unitless (IPCC 2006)

Land-use management	Temperature regime	IPCC defaults	Error (±) (%)
Nominally managed (non-degraded)	All	1.00	NA
Moderately degraded	Temperate/Boreal	0.95	13
	Tropical	0.97	11
	Tropical Montane	0.96	40
Severely degraded	All	0.70	40
Improved grassland	Temperate/Boreal	1.14	11
	Tropical	1.17	9
	Tropical Montane	1.16	40
Land management (for improved grassland only)			
Medium	All	1.00	NA
High	All	1.11	7%

3.3 Land use impacts calculation

The regeneration times considered for SOC are always shorter than the suggested modelling period for land use impacts (500 years; see Koellner et al. 2012b). Therefore, no provision for the calculation of permanent impacts is made in Eq. 1. It is possible, particularly for land uses where soil is completely removed and there is no active restoration after the land use that recovery of SOC would actually take longer than 500 years. In such cases, the recommendations by Koellner et al. (2012b, Fig. 2) should be followed to calculate the CF for BPP.

In terms of uncertainty, the values for SOC evolution provided by IPCC (2003, 2006) suggest the order of magnitude for the expected error. This addresses partially the large uncertainties expected in the assessment of BPP. In addition to the statistical uncertainty for the aspects that are known (e.g., SOC levels in specific soils or regions), there are sources of uncertainty in ascribing specific climatic regional values to specific biomes; the actual location of the studied land uses (which may vary between regions/climates according to the time of the year or the supplier); soil management practices; etc.

4 Discussion

A couple of recent case studies used earlier versions of the SOC-based CF, and provide an indication of their usefulness. Milà i Canals L et al. (2008) studied several supply chains providing vegetables in the UK but based around the world. Their main findings in relation to soil quality as indicated by SOC were that “stages different than cropping (e.g., mining for kerosene production) may dominate the impacts related to land use, even if cropping still dominates the amount of m^2 year”. Thus, in that case, SOC as an indicator was useful to distinguish between very differentiated production systems (one based on local production vs. one reliant on air freight). Brandão et al. (2011) offer a recent case study of LCA of bioenergy production from land in the UK. In that work, the estimates are all derived from values from different literature. They find that estimates of changes in SOC are highly dependent on the input data for the initial SOC and on the reference system used for comparison; and that SOC evolution depends strongly on management practices and location, and so any decision to use a particular input value instead of another should be properly justified. Therefore, while the results obtained in that study are plausible, they should also be interpreted as broad comparisons only, even though the differences found between different land uses are so large that they may be considered significant. The added value of the present paper is to have consistently derived CFs from a single and authoritative data source, the IPCC, covering the entire globe.

Milà i Canals L et al. (2012) apply for the first time the CF developed in this paper in a case study of margarine production. They find that the impacts on BPP are largely dominated by the agricultural phases (growing of several oil crops for the margarine), and by occupation rather than transformation flows. Due to this, those crops with lower yields tend to show larger impacts on BPP. One limitation of the CF provided here that is highlighted by Milà i Canals L et al. (2012) is the poor differentiation of permanent crops (plantations); at the moment the same CF as forests (0) are used for permanent crops, which is likely to underestimate the impacts of such crops.

Because the factors affecting BPP are complex and vary across the different regions of the world, it is challenging to model BPP accurately. It may indeed be argued that SOC is too limited to represent BPP properly; other authors (e.g., Pfister et al. 2010) suggest combining biodiversity and BPP indicators (NPP) to provide CF for “ecosystem quality” at the damage level. While we accept the value of combining different aspects of land quality such as biodiversity and productivity, assessing such impacts at the midpoint level has the advantage of making trade-offs between such aspects evident. In addition, and despite the multitude of interconnected ecosystem properties that determine BPP, the adoption of SOC as a single indicator is a reasonable simplification supported by evidence that SOC is closely related to BPP (Christensen and Johnston 1997).

The rationale for suggesting SOC as an indicator for BPP lies in the fact that SOM is a common link between them, therefore being a good candidate for a stand-alone indicator. However, even though many researchers accept the paramount importance of SOC in soil fertility and thus BPP, it needs to be stressed that the link between SOC and BPP needs to be further tested in a variety of soils and regions.

The relevance of SOC in life-cycle stages other than biotic production (agriculture, forestry) is not straightforward. Particularly where soil has been removed (e.g., in a quarry) or sealed (e.g., road), it may be confusing to express impacts on BPP by SOC deficit. The strength of LCA lies in the fact that all stages related to a product or service are included in the assessment. Therefore, it is vital to communicate the effects on BPP in all these stages properly.

Further to published case studies where CF for land use impacts have been applied, the new CF develop further the work existing so far on SOC as an indicator for soil quality by providing a first degree of spatial differentiation at the climate region level. This will allow some further differentiation in the impact assessment phase; the significance of this differentiation will need to be tested in further case studies. Increasingly refined data for SOC in many regions are continuously being produced, which ensures continuity and environmental relevance in the use of SOC as indicator for land use impacts on BPP.

5 Conclusions and needs for further research

The importance of land in providing biomass is widely acknowledged, as is its susceptibility to degradation induced by human activities. This paper has reviewed indicators for BPP and, building on previous references advocating for the use of SOC and collating new data sources for SOC in different land use types and ecosystems, provided operational CF to include impacts on BPP on a global scale. The variability in CF induced by, e.g., climatic conditions, soil types, specific management, results in a wide difference of capacities to support biomass production; this is addressed with CF covering this wide range of conditions. The latest case studies (this issue) show how the new level of refinement both in terms of land use types and spatial differentiation are relevant in driving the results of impacts on BPP, although more work is required particularly in further differentiating and assessing biotic land uses (e.g., permanent crops, forestry) and in estimating regeneration times.

New case studies to test the sensitivity of the CF are also required. In particular, complex product systems combining bio-based production and "artificial land uses" would be helpful to identify less obvious hotspots.

The approach presented in this paper is built on the assumption/evidence that SOC is closely linked to BPP; further evidence of this link is required in order to prove the validity of this indicator in different soils across the globe.

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