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► To cite this version:

Emmanuelle Garrigues, Michael S. Corson, Christian Walter, Denis A. Angers, Hayo van Der Werf. Soil-quality indicators in LCA: method presentation with a case study. 8eme International Conference on LCA in the Agri-Food Sector, Oct 2012, Saint-Malo, France. 2012. hal-01461115

HAL Id: hal-01461115

<https://hal.science/hal-01461115>

Submitted on 3 Jun 2020

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Soil-quality indicators in LCA: method presentation with a case study

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ABSTRACT

Impacts on soil quality should be included in life cycle assessments because of the essential role that soils play in ecosystem functioning. We propose a method that integrates impacts on quality of agricultural soils (erosion, soil organic matter, and compaction) of each stage of an agricultural product as a function of the soil and climate contexts of its agricultural processes. Input data must be as site-specific and accurate as possible, but if measured data are missing, the method has a standardised framework of rules and recommendations for estimating or finding them. We present a case study focused on the soil-quality impacts of producing pig feed in Brittany, France. The framework allows for incremental improvement of the method through the inclusion of new soil-quality impacts.

Keywords: soil quality, life cycle assessment, indicators, site dependence

1. Introduction

Soils are an essential resource in both managed and natural systems, and maintaining soil quality is critical to the sustainable development of human activities, in particular agriculture. The difficulty in representing impacts on soil quality remains an unresolved problem in Life Cycle Assessment (LCA) because of soil's spatial and temporal variability and the complex interactions among soil properties. Current status of soil quality in LCA is presented in (Garrigues et al., 2012). It is crucial to consider soil quality in the environmental assessment of products, especially those with a majority of their life cycle in bio-based processes (such as agriculture and forestry).

Soil is defined herein as naturally occurring, unconsolidated mineral or organic material at least 10 cm thick that occurs at the earth's surface and is capable of supporting plant growth. In this definition "naturally occurring" excludes displaced materials such as gravel dumps and mine spoils, but "unconsolidated material" includes that compacted or cemented by soil-forming processes. Soil quality can be defined by its capacity to function (Karlen et al., 1997) and/or its fitness for use (Larson and Pierce, 1994; Letey et al., 2003).

The objective of this study was to establish a framework for quantifying indicator(s) of impact on soil quality in a life cycle perspective, valid for all soil and climate conditions, and considering both on-site and off-site agricultural soils. The method developed answers needs identified by Garrigues et al., (2012) for LCA indicators of impacts on soil quality. It includes the impact categories erosion, soil organic matter (SOM) and compaction. Erosion and SOM impacts already exist in LCA approaches (Milà i Canals et al., 2007; Nuñez et al., 2010), but compaction impacts have yet to be quantified in detail in LCA. Cowell and Clift (2000) provided some ideas but excluded soil compactibility of their indicator. We applied the method to a case study of soil-quality impacts of producing pig feed in Brittany, France.

2. Method Presentation

2.1. General framework

Integrating soil-quality impacts throughout the life cycle of an agricultural product requires a global approach to assess impacts on soil quality that can be adapted to individual soil and climate contexts. Input data must be as site-specific and accurate as possible, but if measured data are missing, the method has a standardised framework of rules and recommendations for estimating or finding them.

Soil-quality impact assessment within LCA is quantified with midpoint indicators describing processes that can degrade or improve the soil. Soil physical, chemical and biological properties and function are excluded as indicators because of the difficulty in determining how they influence the system functions reflected in the functional units. Pathways were selected to link elementary flows of the inventory (LCI) to the midpoint impact indicators, which result from the combination of soil, climate, and management characteristics (Fig. 1).

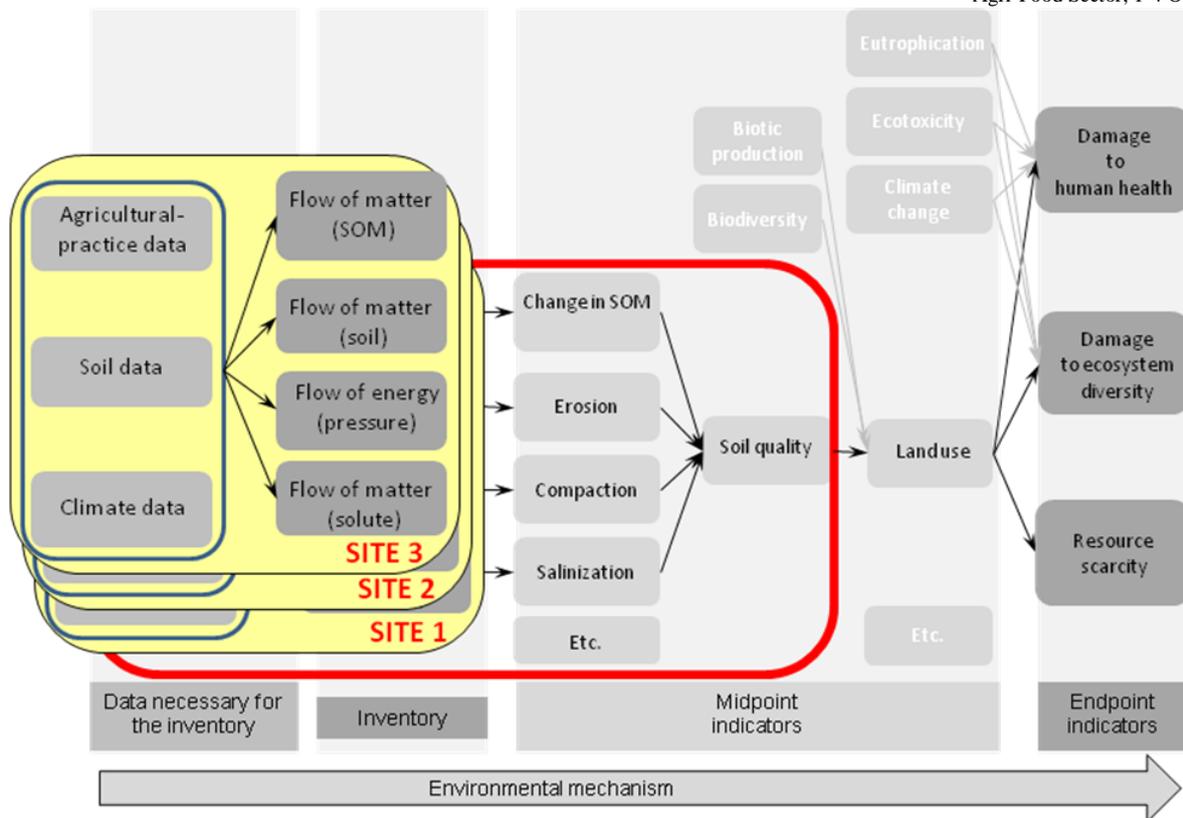


Figure 1. Steps for assessing impacts on soil quality (outlined) (adapted from Garrigues et al., 2012).

The LCI and impact assessment (LCIA) are based on simulation modelling, using models simple enough for use by non-experts, general enough to parameterise with available data at a global scale, and already validated: RUSLE2 for erosion (Renard and Ferreira, 1993); RothC for SOM (Coleman et al., 1997; Coleman and Jenkinson, 2008), and COMPSOIL for compaction (O'Sullivan et al., 1999). Most of the input data necessary for establishing the LCI are common to the three midpoint indicators. For each indicator, total impact is estimated by summing the impacts from individual upstream agricultural sites together. Thus, the method currently has no regionalised characterisation factors for LCIA, assuming that a given erosion, SOM, or compaction impact has equal impact regardless of location.

2.2. Inventory – input data requirements

2.2.1 Soil data

Soil characteristics such as texture, C content, bulk density, and slope are required. If necessary, national or international databases, such as the Harmonized World Soil Database (FAO et al., 2009), can provide the required data. In the future, the Global Soil Map project (<http://www.globalsoilmap.net>) will provide data at a finer resolution. Users can assume that agricultural processes in a region occur on its dominant soil type, a compromise between data precision and availability.

2.2.2 Agricultural-practice data

Crop data (e.g., yield, residues), management data, and vehicle characteristics (e.g., type and weight of vehicle, tyre size) are necessary.

2.2.3 Climate data

Monthly (erosion and SOM) and daily (compaction) temperature, precipitation, and potential evapotranspiration (PET) data are necessary. For SOM predictions, a time series up to 20 years is preferable. We used the TURC method (Federer, 1996) to estimate PET:

$$PET=0.313 T_m (R_s + 2.1)/(T_m + 15) \text{ with } PET=0 \text{ when } T_m < 0 \quad (1)$$

where T_m is mean daily air temperature ($^{\circ}C$) and R_s is daily solar radiation (MJ/m^2).

If climate data are not found from national sources, international climate databases exist (NASA, 2012).

2.3. Simulation models used

2.3.1 Erosion: *RUSLE2*

The *RUSLE2* (Revised Universal Soil Loss Equation) model (Renard and Ferreira, 1993) improves upon the original *USLE* model. The fundamental equation is:

$$A = R \times K \times LS \times C \times P \quad (2)$$

where *A* is the computed annual soil loss, *R* is the rainfall-runoff erosivity factor, *K* is the soil erodibility factor, *LS* is a topographic factor combining slope length (*L*) and steepness (*S*), *C* is a cover-management factor, and *P* is a supporting-practice factor. Three input databases are required that describe climate, crops and field operations.

2.3.2 Soil organic matter change: *RothC*

RothC (version 26.3) simulates the dynamics of organic carbon (*C*) in soil (Coleman and Jenkinson, 2008). The effects of soil type, temperature, moisture content and plant cover are considered in the turnover process. It uses a monthly time-step to calculate total organic carbon (*TOC*, t/ha) and microbial biomass carbon (t/ha) over one to hundreds of years. The method simulates 20 years of the same management practice and divides the total change in *SOM* by 20 to provide the rate over one year.

2.3.3 Compaction: *COMP SOIL*

COMP SOIL (O'Sullivan et al., 1999) predicts the effect of an agricultural machine on soil bulk density using readily available machine and tyre data. Topsoil and subsoil compaction are reported both separately (0-30 and 30-50 cm, respectively) and together. Initial dry bulk density comes from the *SOTWIS* database (ISRIC, 2012) from which soil texture is divided into five classes (coarse to very fine, according to the *FAO* texture triangle), each associated with an initial bulk density. Soil water content, a required input, is predicted from soil and precipitation data with the two-reservoir *BILHY* model (Jacquart and Choisnel, 1995). The method assumes uniform initial bulk density and water content profiles.

2.3. Indicators of impact on soil quality

The erosion indicator represents a loss of soil (t), while the *SOM* indicator represents an increase or decrease in the stock of soil *C* (t *C*). The compaction indicator represents a loss of soil porosity (m³/ha) and distinguishes topsoil from subsoil compaction because the former is more easily reversible. Estimates of these soil processes in an inventory level are already informative enough to serve as indicators impact without requiring characterisation factors. A single indicator of impact on soil quality has not yet been developed because of the difficulty in aggregating diverse impacts into a single measure.

2.4. Case study

The case study was selected to illustrate impacts of a composite product formed from crop-based ingredients produced with widely differing soils, climates, and crop-management practices. It focused on the global soil-quality impacts of producing pig feed in Brittany, France, with ingredients coming from Brittany, Brazil, and Pakistan (Table 1).

Table 1. Ingredient composition (by mass) and sources of representative pig feed produced in Brittany.

Ingredient	Maize	Wheat	Triticale	Barley	Pea	Rapeseed cake	Soya cake	Soya oil	Molasses
Soil type	Loam	Loam	Loam	Loam	Loam	Loam	Clay		Loam
Country	France (Brittany)	Brazil (Santa Catarina)		Pakistan					
Source crop	Maize	Winter wheat	Triticale	Barley	Pea	Rapeseed	Soya		Sugar-cane
Yield (t DM/ha)	9.0	7.0	7.0	6.5	4.2	3.3	2.8		35.0
Pig feed ingredient (%)	3.1	34.5	14.6	4.3	16.3	8.8	1.1	7.8	3.6
Economic allocation (%)	100	100	100	100	100	23.8	65.4	34.6	18.1

The system boundary for crop products used as feed ingredients was set at the farm gate, while that for feed ingredients was set at the factory gate. For each crop, the temporal boundary included the inter-crop

period (if any) that occurs just before the crop. Impacts were predicted per ha of each crop and then converted to impact per tonne of feed ingredient based on crop yields and economic allocation for rapeseed cake, cane molasses and soya oil and cake. Impacts per tonne of ingredient in pig feed were added together to calculate total impact per tonne of pig feed produced in Brittany.

3. Results and discussion

Table 2 shows predicted erosion, SOM change, and compaction impacts per t of feed; note that SOM change is the only indicator that can have a negative value.

Table 2. Erosion, change in soil organic matter (SOM), and compaction impacts per tonne of pig feed in Brittany.

EROSION	SOM CHANGE	COMPACTION
0.177 t soil/t feed	-0.026 t C/t feed	Topsoil: 17.6 m ³ /t feed Subsoil: 5.9 m ³ /t feed Total: 23.5 m ³ /t feed

For erosion, despite constituting only 9% (by mass) of pig feed (Fig. 2 left), soya-based ingredients (cake + oil) contributed 69% of the impact (Fig. 2 right). Agriculture-related erosion in Brazil tends to be higher than in Europe, especially in the location where we assumed soya to originate: Santa Catarina state, where precipitation and mean slopes are high. The erosion model used, RUSLE2, represents well the high sensitivity of erosion to precipitation and mean slope.

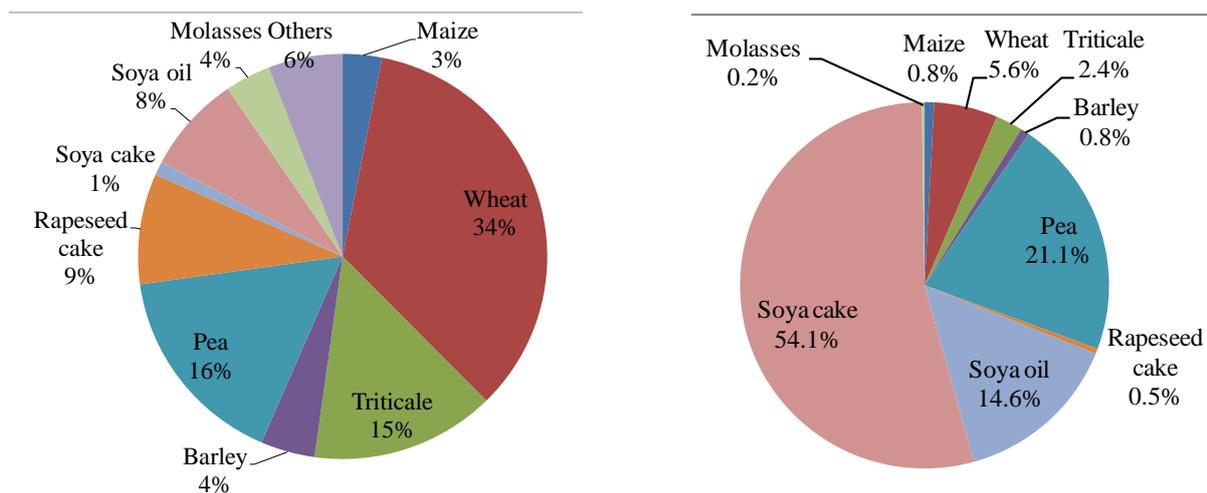


Figure 2. Left: Ingredient composition by mass of representative pig feed produced in Brittany. Right: Contribution of crop-based ingredients to erosion impact per tonne of pig feed in Brittany (total soil loss: 0.177 t soil/t feed).

For SOM change, rapeseed cake and pea contributed most to the net negative impact (Fig. 3). In Brittany pea is mostly cultivated with only mineral fertilisation and has few residues left on field. The C dynamics simulate by Roth C is sensitive to manure and plant-residues supplies. Furthermore, the soil of Brittany has a high C content (2.5% TOC), which requires high C input over the 20 years of simulation of pea cultivation to be able to maintain it.

For compaction, as crops grown in Brittany require similar agricultural practices, the relative impact of each ingredient is similar to its relative mass in the feed (Fig. 4). The impact of wheat is relatively higher because of the highest number of passes in field than the others crops. In Brazil, machines are heavy, but reduced-tillage practices result in fewer passes than in Brittany. Furthermore, Brazilian soils have high clay contents, which decrease their sensitivity to compaction (unlike the loamy soils of Brittany).

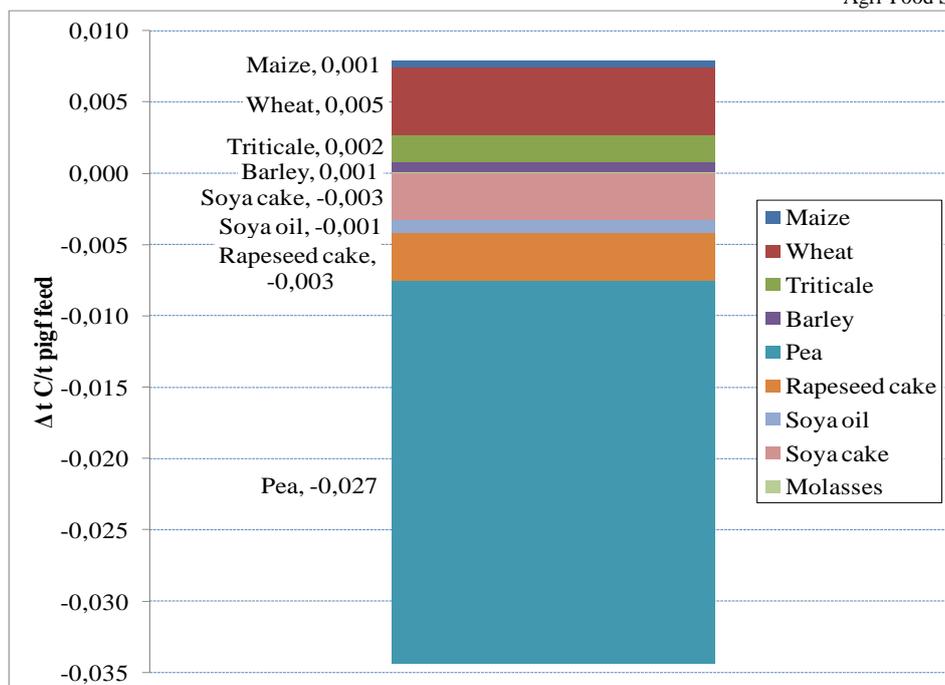


Figure 3. Contribution of crop-based ingredients to impact of change in soil organic matter (SOM) per tonne of pig feed in Brittany (net SOM change: -0.026 t C/t feed).

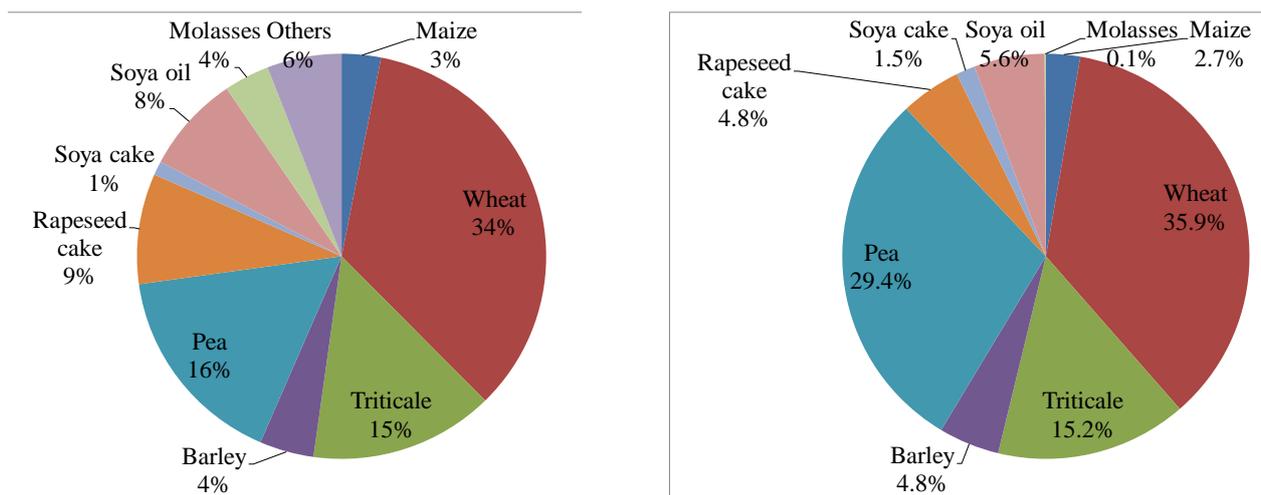


Figure 4. Left: Ingredient composition by mass of representative pig feed produced in Brittany. Right: Contribution of crop-based ingredients to compaction impact in the upper 50 cm of soil (topsoil + subsoil) per tonne of pig feed in Brittany (loss of porosity: 23.5 m³/t feed). The subsoil compaction is irreversible.

These soil-quality impact indicators can be used in LCAs of bio-based materials (e.g., plants, wood, food, industrial bio-based materials) for cultivation processes or for waste-management processes if considering composting. Although, the impact of non-cultivation processes on soil quality could be included, many of them, such as soil sealing with concrete, transform soil into nonsoil, which has zero soil quality. Thus, we believe that non-cultivation processes are better included with impacts of land use and land-use change.

In a life cycle perspective, soil-quality impact indicators can interact with other impact categories, such as climate change, in which SOM changes influence net C emissions into the atmosphere. Also, soil-quality impact indicators complement other impact categories, providing increased ability to identify “impact swapping” or trade-offs between transport distance and agricultural soil quality.

All the input data necessary for establishing the LCI (approximately 30 parameters) will be presented in the project report in late 2012 and can be found in the international databases cited. Most input data are common to the three indicators. As the framework allows for incremental improvement, the inclusion of new soil-quality impact indicators (such as salinisation) will increase input-data requirements little. A forthcoming users’ guide will describe each step of the method.

5. Conclusion

Impacts on soil quality should be taken into account into a life cycle perspective because of the essential role of soils in ecosystem functioning. We have developed a framework for quantifying indicators of impact on soil quality, valid for all soil and climate conditions, and considering both on-site and off-site agricultural soils. These indicators can be used in LCAs of bio-based materials or the waste-management stage when considering composting.

The first indicators developed represent the most prevalent threats on soil: erosion, SOM change and compaction. Overall impact estimates result from the combination of soil, climate, and management characteristics. Results to date can begin to fill a database of soil-quality impact indicators for crops and crop-based products from a several regions. Most of the input data necessary for establishing the LCI are common to the three midpoint indicators and can be found in existing databases.

The framework allows for incremental improvement of the method through the inclusion of new soil-quality impacts. Improvement efforts will focus first on developing robust impact indicators for individual soil processes before considering whether to aggregate them into a single indicator. Nonetheless, a variety of aggregation approaches can be explored (Garrigues et al., 2012).

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