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Research article

Introduction of a natural resource balance indicator to assess soil organic carbon management: Agricultural Biomass Productivity Benefit

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ABSTRACT

The rising demand for feed and food has put an increasing pressure on agriculture, with agricultural intensification as a direct response. Notwithstanding the higher crop productivity, intensive agriculture management entails many adverse environmental impacts. Worldwide, soil organic carbon (SOC) decline is hereby considered as a main danger which affects soil fertility and productivity. The life cycle perspective helps to get a holistic overview when evaluating the environmental sustainability of agricultural systems, though the impact of farm management on soil quality aspects is often not integrated. In this paper, we introduce an indicator called Agricultural Biomass Productivity Benefit of SOC management (ABB_SOC), which, relying on natural resource consumption, enables to estimate the net effect of the efforts made to attain a better soil quality. Hereby the focus is put on SOC. First, we introduce a framework to describe the SOC trend due to farm management decisions. The extent to which remediation measures are required are used as a measure for the induced SOC losses. Next, ABB_SOC values are calculated as the balance between the natural resource consumption of the inputs (including remediation efforts) and the desired output of arable crop production systems. The models RothC and EU-Rotate_N are used to simulate the SOC evolution due to farm management and the response of the biomass productivity, respectively. The developed indicator is applied on several rotation systems in Flanders, comparing different remediation strategies. The indicator could be used as a base for a method to account for soil quality in life cycle analysis.

1. Introduction

The global population is projected to reach 8.6 billion in 2030 and swell to an expected 9.8 billion in 2050 (United Nations, 2017). A growing population will require increased crop production for food and feed, which will give rise to a further intensification of the agricultural sector (Pradhan et al., 2015). Traditional techniques related to intensive agriculture have resulted in spectacular increases in productivity over time, while also generating adverse environmental impacts and land degradation (Almagro et al., 2016). Agricultural land subject to intensive management is namely prone to soil and groundwater contamination, soil erosion, soil compaction and soil organic matter (SOM) decline (Almagro et al., 2016; D'Hose et al., 2014).

Worldwide, SOM decline is considered as an environmental risk entailing far-reaching consequences. SOM affects biological, chemical and physical soil parameters, and consequently has an impact on many soil processes and characteristics (e.g., erosion, soil biodiversity, and control of plant diseases and pests) (Brady et al., 2015; D'Hose et al., 2014). Soil organic carbon (SOC), which is used to measure SOM and is usually considered to be 58% of SOM, is thus considered a key feature in soil health and crop productivity (Brady et al., 2015; Brandão and Milà I Canals, 2013).

The importance of maintaining or increasing SOC content is emphasized by the European Commission in its Seventh Environmental Action Programme (2014) (European Commission, 2016). In Europe, around 45% of the mineral soils are characterized by a low SOC content

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Table 1
Percentage distribution of the SOC content of arable land samples and percentage occurrence in Flanders (2012–2015) (based on Tits et al. (2016)).

	Sand (42%)[a]	Sandy loam (46%)[a]	Clay (12%)[a]
LOW			
%OC	< 1.2	< 0.9	< 1.5
% cropland	9	19	47
MEDIUM[b]			
%OC	1.2–1.9	1.0–1.5	1.6–2.1
% cropland	52	62	22
HIGH			
%OC	2.0–4.5	1.6–3.0	2.2–4.5
% cropland	39	18	31
MINIMUM THRESHOLD[c]			
%OC	1.0	0.9	1.2

[a] % cultivated area of cereals, fodder and industrial crops per soil texture in Flanders. Reference year 2015 (ADS, 2017).

[b] Optimum range defined by Ghent University (LNE, 2014).

[c] Minimum values for SOC content based on the Common Agricultural Policy (VITO, 2015).

(0–2%). Although changes in SOC levels resulting from agricultural intensification are rather slow, studies suggest that the SOC level in European agricultural land is clearly decreasing (Jones et al., 2012). For example, surveys of arable land in Northern Belgium (where 210 000 soil samples were taken between 1989 and 1999) revealed widespread decreasing SOC stocks in cropland (Sleutel et al., 2003). In Flanders (northern region of Belgium) in 2015, 9, 19 and 47% of samples of arable sand, sandy loam and clay textured soils, respectively, contained suboptimal SOC levels as defined per texture (Table 1) (LNE, 2014; Tits et al., 2016). Accordingly, the Flemish government's Common Agricultural Policy defines minimum values for SOC content according to soil texture (Table 1) (LNE, 2014).

To improve SOC content, several options are available (1) adapted land cover (e.g., cultivation of intercrops): and residue management, (2) low impact tillage practices to minimize alteration of soil composition, structure and biodiversity (e.g., reduced tillage), (3) adapted soil cover (e.g., alternative crop rotations), and (4) input of exogenous organic matter (Louwagie et al., 2009). The quantity and the quality of the SOC inputs are key factors for controlling the SOC content, which is in turn the key to long-term fertility in agricultural systems (Oberholzer et al., 2014).

The extent to which SOM stock changes as a result of land use and agricultural management is mainly investigated by long-term field trials, whereas the sustainability of the management practices is often indicated by crop yields (Oberholzer et al., 2014). However, according to Brandão and Milà I Canals (2013), a decisive establishment of a quantitative relationship between yield and SOC level has not yet been determined, although there seems to be a positive correlation between both variables within certain thresholds. For example, Mikanová et al. (2012) found a statistically significant correlation between SOC content and grain yield. Based on a field experiment, they found that for winter wheat, a rise of 0.5% SOC content in the topsoil induces an increase of more than 2 tons of grain yield per hectare, when applying reduced tillage or no tillage. Furthermore, long-term experiments have shown that larger crop yields are often obtained on soils with a higher SOC level compared to those on soils with a lower SOC content, regardless of the amount of N fertilizer applied (Johnston et al., 2009).

Sustainable agricultural intensification relies in large part on efficient exploitation of the available land. Alvarenga et al. (2013a) have developed a natural resource balance indicator allowing comparison of the land use efficiency of terrestrial biomass production systems (including agricultural systems). This indicator, called 'Overall Net Annual Exergy Production' (ΔEP), weighs the total biomass production (main product, its above- and below-ground residues and weed) against the cumulative consumption of local (e.g., nutrients, CO_2) and non-local resources (e.g., pesticides, mineral fertilizers), expressed in exergy (Alvarenga et al., 2013a). Exergy is based on the second law of thermodynamics and accounts for both the amount and quality of material and energy flows in one common unit, i.e. joules of exergy (J_{ex}) (Dewulf et al., 2008). To get a more holistic view, Alvarenga et al. (2013a) used a life cycle perspective to perform a so called cradle-to-gate analysis (International Organization for Standardization (ISO), 2006). Life cycle analysis (LCA) is a tool commonly used to quantify the potential environmental impacts due to human activities, linked to a certain product or service (Taelman et al., 2016). To perform the exergetic LCA, the resource-accounting method known as Cumulative Exergy Extraction from the Natural Environment (CEENE) is used (Dewulf et al., 2007).

Although this indicator offers an interesting way to account for the use efficiency of available land, one important aspect is not covered: the dependence of biomass production on soil quality (Boone et al., 2016), i.e., the legacy effect of a biomass production system on soil quality (Schrama et al., 2016). For example, decline of SOM can limit the soil's future ability to provide nutrients, which may compromise the possibility to maintain highly productive systems (Brandão and Milà I Canals, 2013; Louwagie et al., 2009).

Soil quality impacts must be accounted for in sustainability assessments of production systems in relation to the biomass provisioning capacity (Griffiths et al., 2010). This provisioning capacity is an important endpoint for the Area of Protection (AoP) (i.e. safeguard subjects we like to protect) natural resources (Taelman et al., 2016). Biomass is a renewable fund, but due to human activities affecting the soil quality, we may deplete the production capacity of the ecosystem (Dewulf et al., 2015). Although it is relevant, there is not yet a standardized method to evaluate the impact of land use (and corresponding changes in soil quality) on the long-term ability to produce biomass.

Therefore, in this study we introduce a framework to compare the sustainability of agricultural crop production systems in terms of biomass productivity by accounting for changes in soil quality. To account for the soil quality loss, we quantify the extent to which corrective actions are required to restore soil quality with reference to a baseline level. However, soil quality not only must be returned to the desired level but must also be maintained.

This results in the following research question "How to assess changes in soil quality (with the focus on SOC stock) arising from different agricultural management options, and include legacy effects (i.e. changes in crop yield) in environmental sustainability assessments?". To answer this question, we introduce the indicator '*Agricultural Biomass Productivity Benefit of SOC Management*'. This indicator is based on a resource accounting approach and has been applied to several scenarios in Flanders (Belgium).

2. Framework to assess SOC management

2.1. Influence of farm management on SOC level and biomass productivity

To study the impact of farm management decisions (e.g., crop rotation, choice of fertilizer) on the SOC level of agricultural soils over time, we introduce the framework illustrated in Fig. 1. The slope of the curve representing the SOC trend depends on the carbon input (by fertilization, crops) and carbon export by removal of crops (and crop residues) and natural OC degradation. First, we investigate what would happen if a chosen rotation system (corresponding with a certain fertilization scheme) was applied unmodified for 20 years. This corresponds to the average time required to get a new steady state level of OC as suggested by the IPCC (2006). Then the situation is evaluated as follows: if the resulting SOC level is higher than a well-defined threshold, the situation is labeled as adequate while otherwise remediation techniques are applied. In the latter case, the period under study lasts from year 20 up to year 40, assuming that from an agricultural point of view it is desirable to restore the soil in 20 years (half