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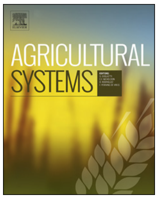

Accounting for long-term soil fertility effects when assessing the climate impact of crop cultivation

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ABSTRACT

Soil organic carbon (SOC) dynamics influence the climate impact of crop cultivation, both through affecting net carbon exchange between the soil and the atmosphere and through affecting soil fertility. Higher soil fertility can enhance yield, and consequently make more plant residues available for carbon sequestration in the soil. This feedback mechanism between SOC and yield is commonly not included when assessing the environmental impact of crop production using system analysis tools like life cycle assessment (LCA). Therefore, this study developed a modelling framework where the SOC-yield feedback mechanism is included in climate impact assessment of crop cultivation, and which could be applied in LCAs. The framework was constructed by combining a model for SOC dynamics, yield response to SOC changes in a Swedish long-term field experiment and climate impact assessment. The framework employs a dynamic approach, with a time-distributed emissions inventory and a time-dependent climate impact assessment model, complemented by the most common climate metric, global warming potential (GWP). A case study applying the framework to barley cultivation was performed to explore the quantitative effect of including the feedback mechanism on the calculated climate impact. The case study involved simulating a fertiliser-induced 10% yield increase during one year and assessing the climate impact over 100 years. The effect of solely including SOC dynamics without the yield response to SOC decreased climate impact per kg barley by about three-fold more than only accounting for the 10% temporary yield increase. When the feedback mechanism was included, the estimated climate impact decreased five-fold more than when SOC changes were not included. These results show that SOC changes affect the climate impact of cultivation, not only through affecting net CO_2 exchanges between soil and atmosphere, as previously acknowledged by other studies, but also through changing the system performance. The quantitative results obtained in this study show that this could be an important aspect to include in order to avoid introducing systematic error when assessing the long-term climate impact of crop management changes that affect yield or SOC dynamics.

1. Introduction

The atmospheric concentration of carbon dioxide (CO_2) and other greenhouse gases has increased rapidly since the industrialisation age, causing climate change which has increasingly detrimental effects on the earth's ecosystems and societal activities. Historically, loss of biogenic carbon in biomass and soils through land use change and poor soil management has been a substantial contributor to CO_2 emissions, and is still estimated to be a net source of CO_2 (IPCC, 2013). Loss of soil organic matter can also decrease soil quality and agricultural productivity (Lal, 2004b). Soil organic matter has several positive effects on soil functioning, such as being a nutrient resource, enhancing water-holding capacity, improving aggregate stabilisation and providing sites for ion exchange (Lal, 2004b). The yield response to soil organic matter content in cultivated soils varies with factors such as climate, cropping system and soil characteristics (Blanco-Canqui and Lal, 2009; Zhang et al., 2016), but positive yield responses to increased levels of soil organic matter have been reported for a range of soils in different climates (Lal, 2010).

Increasing plant production increases the amount of plant residues available for soil organic matter formation, and can therefore also increase the soil organic carbon (SOC) levels (Snyder et al., 2009). High crop yields and appropriate crop residue management are important for maintaining or increasing SOC levels in cultivated soils, especially when organic carbon is not provided from external sources (e.g. manure) (Follett, 2001; Matson et al., 1997). Carefully designed

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strategies to increase crop yield also provide an opportunity for increased resource efficiency and decreased environmental impact of agricultural production systems (Burney et al., 2010). Increasing crop yield is also a way to prevent land use change that involves clearing new land to provide food for a growing global population (Kätterer et al., 2012). However, poorly designed strategies to increase crop yield can also lead to negative environmental effects, such as nutrient- and carbon-depleted soils, biodiversity loss and increased use of inputs, ultimately resulting in increased environmental impact and reduced ability to deliver ecosystem services (Matson et al., 1997). The pressure to increase agricultural output while minimising the environmental impact of agriculture calls for appropriate methods to account for long-term soil productivity when assessing the environmental impact of agricultural products.

One method for assessing the environmental impact of a product or a process is using the system analysis tool life cycle assessment (LCA). LCA was originally designed for industrial processes, but its area of application has expanded and it has been used for evaluating the environmental impact of agricultural processes for decades (Garrigues et al., 2012). However, soil functions and processes are frequently not included in LCA contexts (Brandão et al., 2011; Renouf et al., 2014), even though LCA studies have shown that changes in SOC can have a substantial impact on the overall greenhouse gas emissions of crop cultivation (e.g. Brandão et al., 2011; Korsaeth et al., 2012; Tidåker et al., 2014). Published research on this topic primarily focuses on the effects of land use and management change on SOC stocks and the associated climate impact (e.g. Brandão et al., 2013), or on soil as a resource which can be affected by human activity (e.g. Milà i Canals et al., 2007). However, the influence of SOC on soil production potential has been recognised in previous LCA research on a few occasions, for example in studies proposing SOC as an indicator of impact on biotic production potential (Brandão and Milà i Canals, 2013), or as an elementary flow for loss of net primary production (Wiloso et al., 2014).

A motive for broadening the inclusion of soil function aspects in LCA is that changes in soil properties such as SOC content also affect the output of the system, i.e. the yield. Changed yield will then not only affect the distribution of environmental burden between outputs, but also the input of SOC to the soil, and thereby both the net carbon exchange between the soil and the atmosphere and the soil fertility. Thus, there is a feedback mechanism between yield and SOC, and disregarding this in LCAs may introduce a systematic error when assessing the environmental impacts of cultivation practices that affect yield. In the present study, we expanded on inclusion of this feedback mechanism by incorporating its effect in climate impact assessment.

The overall aim of the study was to develop a modelling framework that includes long-term SOC dynamics and its legacy effect on soil fertility and which can be integrated into LCAs when assessing the climate impacts of cereal cultivation. Another aim was to explore the significance of including these secondary effects on the overall calculated climate impact of crop cultivation. This was done by implementing the modelling framework in a case study on barley (*Hordeum vulgare*) cultivation in Sweden.

2. Methods

An integrated framework for incorporating long-term soil fertility in climate impact assessment of crop cultivation was developed (Section 2.1). The framework consists of three main modules, all with annual time steps. The main interactions between these modules are described in Fig. 1. The quantitative effect of including SOC-yield feedback on assessed climate impact was then modelled for a case study on barley cultivation in Sweden (Section 2.2). This was done through simulating enhanced yield during one year and then running the framework for 100 years. The difference in climate impact between not including any SOC dynamics, including SOC dynamics without yield feedback and including SOC dynamics with yield feedback was then calculated.

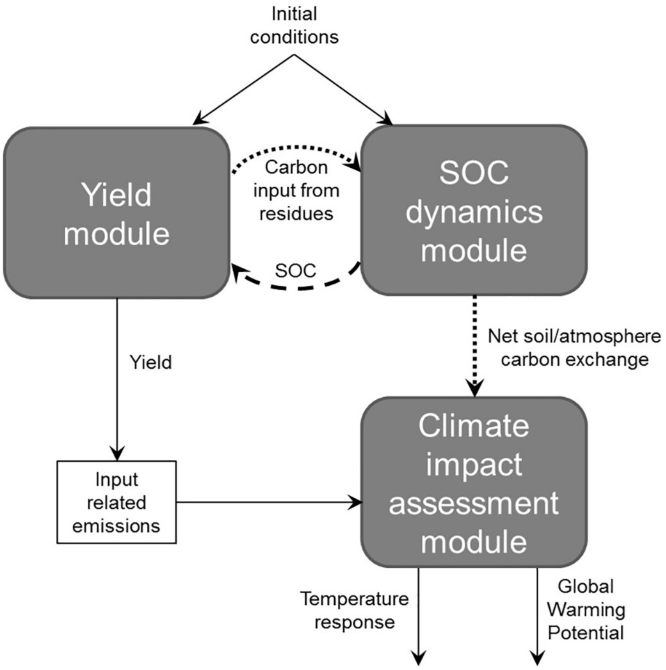

Fig. 1. Illustration of the modelling framework, including the information flow to, from and between the model modules. Dotted lines indicate that the information flow is only used in approaches that include SOC dynamics (A2 and A3), and the dashed line indicates that information flow is only used in the approach where yield response to SOC is included (A3). See also Section 2.2.4 for a full description of the approaches.

2.1. Modelling framework set-up

2.1.1. Soil organic carbon dynamics

Soil organic carbon dynamics were estimated using the introductory carbon balance model (ICBM), first described by Andrén and Kätterer (1997). ICBM calculates SOC in the topsoil (0–25 cm) based on data on crop carbon inputs and parameters that depend on soil type, crop and climate (Andrén et al., 2004; Andrén et al., 2008). It has previously been used to estimate SOC dynamics in agricultural LCAs (e.g. Tidåker et al., 2016; Korsaeth et al., 2012). It is a process model based on first-order kinetics and allocates SOC into two dynamic carbon pools, young (*Y*) and old (*O*). We used the regional ICBMr version of ICBM, with data dependent on regional conditions. The ICBMr model describes SOC dynamics according the following equations (Andrén et al., 2004):

$$Y_t = (Y_{t-1} + i_{t-1})e^{(-k_Y r_e)} \tag{1}$$

$$O_t = \left(O_{t-1} - h\frac{k_Y(Y_{t-1} + i_{t-1})}{k_O - k_Y}\right)e^{(-k_O r_e)} + h\frac{k_Y(Y_{t-1} + i_{t-1})}{k_O - k_Y}e^{(-k_Y r_e)} \tag{2}$$

where Y [Mg ha^{-1}] and O [Mg ha^{-1}] are the young and old soil carbon pools, respectively, t is the year, i [Mg ha^{-1}] is the carbon input from plant residues, straw and roots, k_Y [year^{-1}] and k_O [year^{-1}] are the decomposition rates constants of Y and O, respectively, $r_e[-]$ is a parameter representing region-specific external conditions depending on soil type, crop and climate, and h $[-]$ is the humification coefficient, which is the fraction of carbon in Y that enters O. The total SOC stock [Mg ha^{-1}] is then obtained by adding the two pools.

2.1.2. Yield development

Crop yield [kg ha^{-1}] was calculated from a reference yield [kg ha^{-1}], SOC changes and yield response [-]. Yield response is a parameter that describes how yield changes with SOC, and may vary between sites. In our case study, we assumed that the yield would