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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.

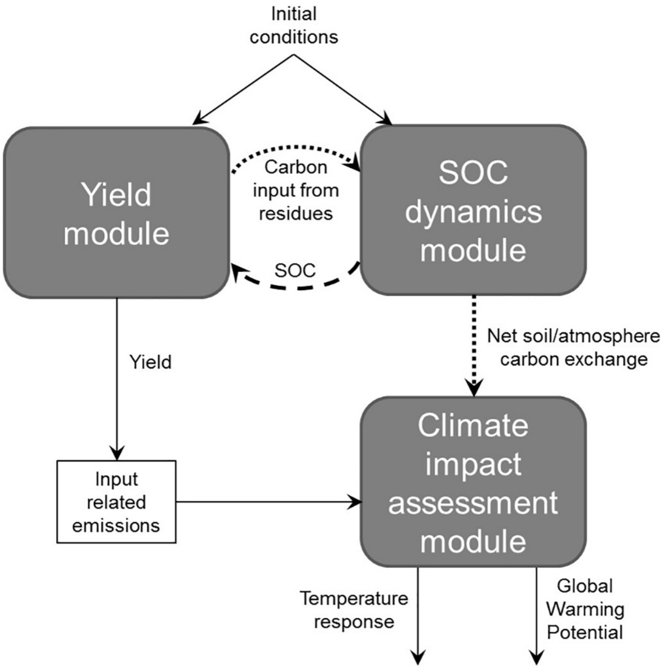

Fig. 1. Illustration of the modelling framework, including the information flow to, from and between the model modules. Dotted lines indicate that the information flow is only used in approaches that include SOC dynamics (A2 and A3), and the dashed line indicates that information flow is only used in 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 increase linearly with SOC (Eq. (3)), but other response behaviours could also be modelled with this framework.

$$\text{yield} = (1 + (\text{yield response} * \Delta\text{SOC\%}) * \text{reference yield} \tag{3}$$

where $\Delta SOC\%$ [-] is the difference in SOC concentration in the soil between the present and the reference state. The yield in each year was used to calculate annual carbon input from crop residues i, which was then fed back into the ICBM model, creating an iterative feedback loop between the SOC dynamics and yield calculations (Fig. 1).

2.1.3. Climate impact assessment

Recent global guidance on life cycle impact assessment indicators recommends using several climate metrics to account for both short-term and long-term climate impacts (Levasseur et al., 2016). Therefore, two different metrics for assessing climate impact were included in the modelling framework. One was global warming potential during 100 years (GWP_{100}), which is the most common method to represent climate impacts in LCA (Brandão et al., 2013). In this study, GWP_{100} characterisation factors from the IPCC's Fifth Assessment Report were used (30 kg CO_2-eq kg^{-1} fossil methane (CH_4) and 265 kg CO_2-eq kg^{-1} nitrous oxide (N_2O)) (Myhre et al., 2013). GWP accumulates the radiative forcing effect of the respective greenhouse gases over a certain time horizon (in this case 100 years) and normalises the effect of the respective gases to a reference gas (in this case CO_2) (Myhre et al., 2013). The other metric used was absolute global temperature change potential (AGTP), according to the methodology described in the IPCC's Fifth Assessment Report (Myhre et al., 2013). AGTP is an absolute and instantaneous metric that indicates the climate impact over time, expressed as the global mean surface temperature change at a point in time (ΔT_s; measured in Kelvin, K; hereafter referred to as temperature response) caused by a unit emission of a greenhouse gas (Myhre et al., 2013).

2.2. Case study

2.2.1. Cultivation system, system boundaries and functional unit

The theoretical cultivation system in the case study was located in Uppsala County, Sweden (59-60° N, 16-18°E). A monoculture with annual spring barley was assumed and all crop residues, including straw, were assumed to be incorporated into the soil. The initial yield was set at the average spring barley yield in Uppsala County in 2007–2016, which was 4310 kg ha^{-1} at 14 wt% moisture content[1] (SCB, 2015). Soil bulk density was considered constant at 1.21 Mg m^{-3} (Kätterer et al., 2011) throughout the whole simulation period, since the changes in SOC during the simulation period were small. Seeds were accounted for by subtracting 180 kg from the yield output after drying.

The processes included in the system model were: SOC dynamics (as described in Section 2.1), field operations, pesticides, fertilisers, direct and indirect field N_2O emissions, production and maintenance of machinery, and crop drying. Assumed amounts of inputs and emissions related to these inputs can be found in Appendix 1. The SOC dynamics, yield development and climate impact assessment were simulated over 100 years. The study included the three major greenhouse gases CO_2, CH_4 and N_2O. Carbon in living biomass was not included as carbon storage for this annual crop, because the storage time is shorter than the time step used (1 year). The functional unit was 1 kg grain at 14 wt% moisture content.

2.2.2. Model parameters

Carbon inputs through above-ground and below-ground crop residues, i_t, were estimated from grain yield in the previous year, according to Andrén et al. (2004):

$$i_{t,j} = (a_j + s_j H_{t-1}) * 10^{-3} \tag{4}$$

where $i_{t,\,j}$ is the carbon input from plant fraction j (roots, straw and other residues) in year t, H_{t-1} [kg ha^{-1}] is the carbon mass in the yield in year t-1, and a and s are crop-specific parameters for fraction j. The values of a and s were set according to data for spring cereals from Andrén et al. (2004). The decomposition rates k_Y and k_O in Eqs. (1) and (2) were set according to Andrén and Kätterer (1997) and r_e was chosen to represent the conditions in Uppsala County according to Andrén et al. (2008).

The yield response was derived from the Ultuna continuous soil organic matter field experiment in Uppsala, which started in 1956 (for more information about the experiment, see Kätterer et al. (2011)). In this study we compared crop yields and SOC in the experimental treatment "+N + straw", where both mineral nitrogen (N) fertiliser (calcium nitrate; 80 kg N ha^{-1} $year^{-1}$) and cereal straw (about 4 Mg carbon ha^{-1}applied every second year) are added, with those in the N-fertilised treatment "+N-straw", receiving N fertiliser (80 kg N ha^{-1} $year^{-1}$) but no organic amendments. In 2015, average SOC concentration in the upper 25 cm of the soil was 0.59 percentage points higher in "+N + straw" than in "+N-straw" (Fig. 2). The difference between the two data series in Fig. 2 is described by the linear regression function:

$$\Delta SOC\% = 0.0115x \tag{5}$$

where x represents years after 1956. Correspondingly, crop yield ratio between the "+N + straw" and "+N-straw" treatments increased with time (Fig. 3):

$$\text{yield ratio}(x) = 1 + 0.0044x \tag{6}$$

Ascribing this yield difference between treatments over time to changes in SOC by substituting x in Eq. (5) gives the relationship:

$$\text{yield ratio}(x) = 1 + 0.38\ \Delta\text{SOC\%} \tag{7}$$

The slope of the *yield ratio* over ΔSOC% (0.38 in our case) corresponds to the yield response described in Section 2.1.2 and was consequently used for calculation of yield in the case study, according to Eq. (3).

2.2.3. Application of modelling framework in the case study

The initial SOC stock was set by a spin-up of ICBM, through running the model with inputs corresponding to the initial yield and parameters as described in Section 2.2.2, until an approximate SOC equilibrium (SOC stock change $< 10^{-8}$ ton ha^{-1} $year^{-1}$) was reached. Thereafter, a yield impulse was simulated in year 1 to initiate the SOC-yield feedback mechanism. This 10% temporary higher yield was assumed to be achieved by increasing fertiliser rate from 81 to 90 kg N ha^{-1}, following national recommendations for fertilization (Albertsson et al., 2015; see also Appendix 1). Thereafter, yield and SOC dynamics were simulated for 100 years using the modelling framework described in section 2.1. Only the emissions associated with inputs added to the cultivation system in year 1 were included in the LCA and climate and cultivation practices were assumed to be constant during the simulation period (with the exception of year 1, when additional fertiliser was added). The annual net change in SOC stocks estimated with the ICBM model, after conversion to CO_2, was interpreted as annual pulse emission in a time-distributed inventory. The emissions were allocated to the output during the year when the management deviation occurred (year 1). The rationale behind this procedure is that since the soil is in SOC equilibrium before this disturbance, all net SOC changes occur due to the change in management in year 1. The impacts of SOC changes should therefore be allocated to the crop management change.

2.2.4. Modelling approaches

The quantitative effect of including SOC-yield feedback on assessed climate impact was analysed through modelling the case study with

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[1] Statistics Sweden http://www.scb.se/en/finding-statistics/statistics-by-subject-area/agriculture-forestry-and-fishery/agricultural-production/standard-yields/

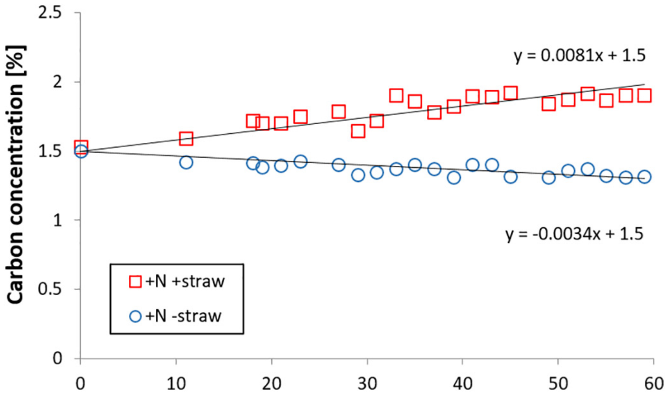

Fig. 2. Topsoil (0–25 cm) carbon concentration in two treatments with different straw management practices in the Ultuna continuous soil organic matter field experiment in Uppsala.

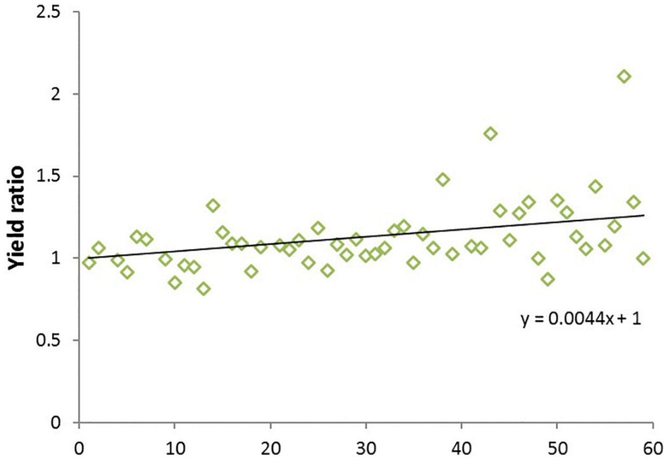

Fig. 3. Ratio between yield in the straw-amended treatment and in the non-amended treatment in the Ultuna continuous soil organic matter field experiment in Uppsala.

Table 1
Attributes included in approaches A1-A3.

Approach	Input-related emissions	SOC dynamics	Yield change due to SOC changes
A1	X		
A2	X	X	
A3	X	X	X

three different approaches. One of these (A3) included the SOC-yield feedback mechanism, while the other two (A1 and A2) followed currently used LCA approaches (Fig. 1 and Table 1).

- Approach 1 (A1) represents a standard LCA modelling strategy, where only the emissions related to the inputs during the cultivation of the crop are included.
- Approach 2 (A2) represents a modelling strategy where the net CO_2 flux associated with SOC changes during the simulation period is also included in the assessment. This has not been common LCA practice in the past (Brandão et al., 2013), but is now adopted by a growing number of LCA studies on agricultural products (e.g. Karlsson et al., 2015; Korsaeth et al., 2012). However, this approach does not assume that the SOC content will affect yield, and thus yield response is set to 0.
- Approach 3 (A3) represents a modelling strategy where the impact of SOC content on yield is included in the simulation. CO_2 fluxes due to subsequent SOC changes are included, and the extra yield achieved due to the SOC-yield feedback during the simulation period is also considered. The latter is implemented through assuming this yield occurs due to the inputs in year 1, which in practice is achieved through adding this extra yield to the outputs. The results from applying approaches A1-A3 were then compared against a reference case where the yield was assumed to remain at the initial level throughout the whole simulation period.

2.3. Sensitivity analysis

A sensitivity analysis was performed to test the robustness of the results to changes in the parameters impulse magnitude and yield response to SOC, and the assumed time frame. The parameters were separately varied by ± 50%, and thereafter simulations were run according to the same procedure as for the base scenario. For testing the sensitivity to time frame, a 20-year perspective was adopted, which meant that only SOC dynamics and yield changes (only in A3) up until year 20 were accounted for, and characterisation factors for GWP_{20} (85 kg CO_2-eq kg^{-1} fossil CH_4 and 264 kg CO_2-eq kg^{-1} N_2O) (Myhre et al., 2013) were used. The first result observed in the sensitivity analysis was the ratio between climate impact reductions (compared with the reference case) for A2 and A3 and the corresponding reduction for A1. The second result observed was the SOC increase per kg additional N added to achieve the impulse. The first result was chosen because it indicates the importance of the systematic error when not accounting for soil fertility and the second was chosen because it indicates the importance of the SOC dynamics for achieving the climate impact reduction.

3. Results

3.1. Climate impact assessment

Applying the modelling framework to the case study showed that approach A2 and, in particular, A3 consistently had lower climate impact than A1, regardless of impact assessment metric used (Table 2 and Fig. 4). After 100 years the reduction in climate impact, expressed as relative difference to the reference case, was approximately three-fold higher when only including SOC (A2), and five-fold higher when the SOC-yield feedback was also included (A3), compared with not including SOC or yield response (A1) (Table 2). These relationships were similar for both climate metrics. However, the difference between approaches, i.e. the magnitude of the systematic error when not including the SOC-yield feedback, varied over time (Fig. 5). The systematic difference between the approaches depended on both the SOC accumulation due to higher crop residue input and the higher output in terms of yield (Fig. 5).

Table 2
Climate impact of modelling approaches A1-A3 after 100 years, presented as temperature response and Global Warming Potential per kg barley.

Approach	Temperature response (year 100)		Global warming potential GWP_{100}	
	Impact [$\times 10^{-17}$ K kg^{-1}]	Relative difference to reference case	Impact [g CO_2-eq kg^{-1}]	Relative difference to reference case
Reference case	14.8	–	301	–
A1	14.5	−1.88%	296	−1.80%
A2	14.0	−5.52%	285	−5.33%
A3	13.4	−9.74%	273	−9.29%

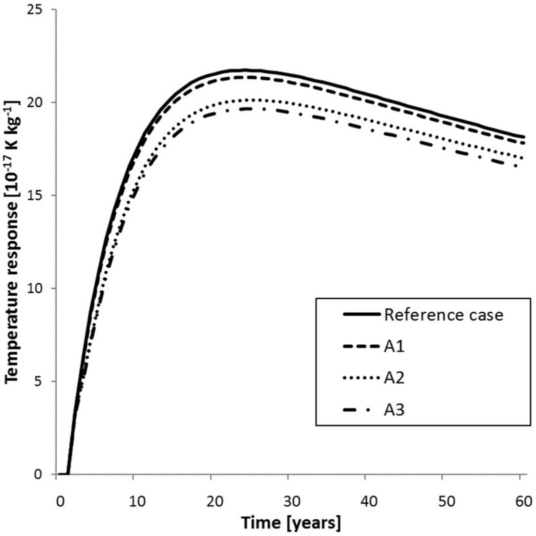

Fig. 4. Climate impact expressed as temperature response of barley cultivation during year 1. Reference case represents a situation where the yield stays at the initial level, while A1-A3 represent a situation where the yield is enhanced by adding extra fertiliser and where the yield and SOC dynamics are calculated with different modelling approaches.

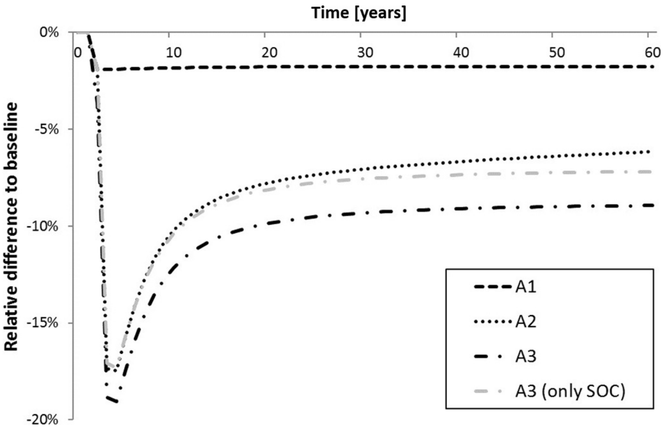

Fig. 5. Relative difference in temperature response between modelling approaches A1-A3 and the reference case, and approach A3 when the accumulated excess yield during year 2–100 is excluded.

3.2. Soil organic carbon changes and yield development

The accumulated excess yield from including the yield response to SOC equated to 126 kg ha^{-1} after 100 years, corresponding to 2.8% of the yield in year 1. Due to this extra yield, input-related emissions attributed to each kg of yield were lower in A3 than in A1 and A2. The SOC concentration increased after the impulse yield deviation in year 1 and showed a net annual decline each year after the peak in year 2 (Fig. 6). However, there was a net gain in SOC concentration over the whole simulation period, regardless of whether the SOC-yield feedback mechanism was included or not (Fig. 6). The net SOC gain after 100 years was equivalent to 13.2 and 18.7 kg carbon ha^{-1}, or 1.47 or 2.08 kg carbon kg^{-1} additional N applied in year 1, depending respectively on whether the SOC-yield feedback was included or not. This corresponds to 10.6 and 14.6 g CO_2 kg^{-1} barley, respectively.

3.3. Sensitivity analyses

The sensitivity analysis showed that the ratio between climate impact reductions of the different approaches, expressed as the relative difference to the reference case, was relatively independent of the magnitude of the impulse (Table 3). However, the ratio was somewhat sensitive to the magnitude of the yield response for the A3 approach, since the yield response parameter influenced both the yield and SOC dynamics in approach A3, but not in approach A1 (Table 3). The sensitivity of the ratio between SOC increase and additional kg N added was similar to the sensitivity of the climate impact reduction ratio for both impulse and yield response magnitude. The A2 results were more sensitive than the A3 approach to the choice of temporal system boundary (Table 3). This was due to a larger decline in SOC between year 20 and year 100 when the SOC-yield feedback mechanism was not included (Fig. 6), and to less additional yield accumulating over 20 years to compensate for the higher total SOC increase in the A3 approach. The changes in climate impact ratios were very similar for both climate metrics, and therefore only results for GWP are shown in Table 3.

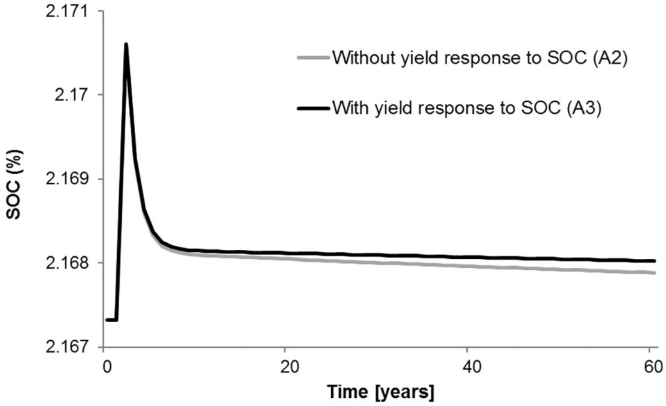

Fig. 6. Simulated changes in soil organic carbon (SOC) in a soil over the 100 years following a 10% impulse yield increase in year 1, with (A3) and without (A2) the SOC-yield feedback mechanism included.

4. Discussion

In this study we demonstrated how a modelling framework for including long-term fertility effects in assessment of the climate impact of crop cultivation can be constructed. The results obtained in testing the modelling framework on a temporary yield increase in a Swedish barley cultivation suggested that even a small management change may result in SOC and yield changes large enough to affect the long-term climate impacts of a crop cultivation (Table 2 and Fig. 4).

4.1. Influence of modelling approach on estimated climate impact

The three different modelling approaches employed in this study use different system boundaries in terms of inclusion of future effects on the system. A1 is the conventional LCA approach that only considers emissions directly related to the inputs to the system, whereas A2 and A3 include future effects on SOC dynamics. While the A1 approach avoids the extra work required and additional uncertainties involved with SOC modelling, ignoring SOC dynamics can give misleading results. Our results indicated that the estimated climate benefit of increasing yield can be several-fold larger if SOC and future yield effects are included (Table 2), compared with just accounting for the direct yield increase. The relative difference in climate benefit between approaches also proved to be relatively independent of the magnitude of the yield impulse, i.e. the amount of additional plant residues available for soil organic matter formation (Table 3). The difference in estimated climate impact between A2 and A3 is due not only to the extra yield added to the output, but also to the greater carbon sequestration that comes with the increased amount of carbon inputs from residues of this

Table 3
Influence of selected parameters on ratio of GWP reduction compared to A1 and SOC increase per kg additional N added in year 1.

Approach	Measurement	Base scenario	Impulse		Yield response	Temporal system boundary	
		10% impulse, yield response 0.38, 100 years	5% impulse	15% impulse	−50% yield response	+50% yield response	20 years
A1	Difference in GWP compared with reference case	−1.80%	−0.94%	−2.85%	−1.80%	−1.80%	−1.80%
A2	Difference in GWP compared to reference case	−5.33%	−2.78%	−7.92%	−5.33%	−5.33%	−7.71%
	Ratio of GWP reduction compared with A1 (change compared with base scenario)	2.97 (−)	2.96 (−0.37%)	2.78 (−6.43%)	2.97 (0.00%)	2.97 (0.00%)	4.29 (+44.7%)
	kg SOC increase per kg additional N added in year 1 (change compared with base scenario)	1.47 (−)	1.46 (−0.56%)	1.53 (+4.04%)	1.47 (0.00%)	1.47 (0.00%)	2.44 (+66.2%)
A3	Difference in GWP compared with reference case	−9.29%	−4.92%	−13.44%	−7.17%	−11.75%	−8.89%
	Ratio of GWP reduction compared with A1 (change compared with base scenario)	5.18 (−)	5.23 (+0.99%)	4.71 (−8.98%)	3.99 (−22.9%)	6.54 (+26.4%)	4.95 (−4.36%)
	kg SOC increase per kg additional N added in year 1 (change compared with base scenario)	2.08 (−)	2.07 (−0.46%)	2.16 (+4.01%)	1.75 (−16.0%)	2.48 (+19.4%)	2.68 (+28.7%)

extra yield (Fig. 6). In fact, the carbon sequestration obtained per unit N added was about 40% larger when the SOC-yield feedback was included (A3) than when only the carbon sequestration from the yield impulse in year 1 was included (A2). Accounting for future effects on soil fertility could thus potentially affect the preferred alternative when assessing the environmental consequences of increasing yield or in other ways altering the carbon input to the soil.

It is recommended practice to include SOC dynamics (Goglio et al., 2017) and including SOC in a similar fashion as the A2 approach has previously been shown to substantially affect the calculated climate impact in LCAs of crop cultivation (e.g. Tidåker et al., 2016; Korsaeth et al., 2012). However, the results in the present study indicate that under conditions where an effect of SOC on yield is present, this may also have a non-negligible effect on the climate impact of the crop cultivation (Table 2 and Fig. 4). The effect of SOC on yield should therefore also be included in the LCA, in addition to conventional SOC accounting.

4.2. Representing soil quality in LCA

In this study, soil was assumed to be a system characteristic used for deciding the output of the system given certain inputs. In LCA terms, soil was regarded as part of the technosphere supporting the production of output. Considering soil part of the technosphere is common practice in agricultural LCAs and, according to Notarnicola et al. (2017), this is one of the reasons that impacts on soil fertility are not included in most food LCA studies. However, using the approach presented in this study, we showed how one of the key soil fertility indicators can be incorporated into the LCA process while still regarding soil as part of the technosphere. In contrast, existing LCA approaches related to soil productivity have developed indicators for soil fertility by considering soil as a recipient of environmental stress (e.g. Oberholzer et al., 2012; Brandão and Milà i Canals, 2013; Wiloso et al., 2014). An advantage of relating soil fertility to emissions-related impacts by predicting its effect on future yields, as done in this study, is that the implications of soil fertility changes are considered without increasing the number of impact categories that need to be interpreted. However, it also introduces more uncertainty into the assessment, since the additional models included in the simulation are associated with their own uncertainties. Goglio et al. (2015) recommended that SOC changes are included in both the climate impact and the soil quality indicator. The representation of soil quality presented in this study does not exclude the possibility of also assessing the impact on soil as a separate impact category. In fact, the framework presented here can be used to improve SOC projections too, as can be seen from the differences in projected carbon content depending on whether the feedback mechanism is included or not (Fig. 6).

4.3. Influence of time horizon and site

LCA was originally a site- and time-independent tool, but methods for dealing with spatial and temporal aspects have been developed over time (Dyckhoff and Kasah, 2014; Garrigues et al., 2012). However, there is no consensus on the appropriate time horizon when assessing impacts on soil carbon dynamics (Goglio et al., 2015). The IPCC Tier I method suggests a 20-year time horizon as a default value for reaching SOC equilibrium after land use or land management change (IPCC, 2006), while a time horizon of up to 100 years is recommended by others, especially for colder climates (Goglio et al., 2015). The changes in SOC concentration in the present study (Fig. 6) and the results from the sensitivity analysis (Table 3) also indicated that a time horizon longer than 20 years is needed to differentiate between the A2 and the A3 approach, which in this case can be attributed to the feedback mechanism rather than the slower biomass decay in a colder climate. Some of the bias introduced when choosing a specific time horizon can be avoided using a time-distributed inventory and time-dependent impact assessment, as done in the present study. However, an issue with the modelling framework presented in the present study is that even though it uses a dynamic approach, the assessment is still dependent on the chosen time frame due to the inclusion of yield changes. Fig. 5 shows that a significant part of the difference in climate impact between A2 and A3 is due to the direct effect of adding extra yield to the output and thus allocating the same climate impact of input related emissions to a larger output. This output increased with longer time horizons, which is why the impact at year 20 in Figs. 4 and 5 did not correspond to the results obtained for the 20-year perspective in the sensitivity analysis (Table 3).

Cropping systems are site-dependent, both in terms of crop management and inherent characteristics such as soil type and climate (Garrigues et al., 2012). This means that the response of a crop management change affects cropping systems differently (Zhang et al., 2016). The sensitivity analysis showed that the quantitative difference in climate impact between A3 and the A1 approach is dependent on the magnitude of the yield response to SOC (Table 3). This is to be expected, since this parameter is the driver of the difference and since inclusion of the mechanism affects both SOC accumulation and the change in yield (Fig. 5).

To implement the modelling framework presented in this study, data on crop response to SOC content need to be available for the specific case, as well as a relevant model for soil carbon response to biomass input. Yield response to SOC has previously been reported for a range of soils and sites (Lal, 2004a; Wang et al., 2008), and simple soil carbon models such as ICBM have been adapted to represent management practices at different sites (e.g. Lemke et al., 2010; Karlsson et al., 2015). Thus, lack of data and relevant models could still limit the possibility to apply this framework. Although our data from the long-term field experiment exhibited a linear effect of SOC on yield for the SOC concentration and other conditions present at the site, this is not always the case. There may be a lower SOC limit under which yield declines significantly (Loveland and Webb, 2003), and similarly an upper SOC concentration where additional SOC does not improve the soil production capacity (Zhang et al., 2016), or even decreases it (Lal, 2010). For the sake of demonstrating the quantitative importance of including yield response to SOC, it was necessary to assume that the soil in the case study was in SOC equilibrium for the initial yield. Therefore, we chose to apply the yield response at a slightly different SOC concentration than at the field experiment site (Fig. 2 and Fig. 6). However, we generally recommend validating the yield response to SOC for the SOC concentration existing at the site when including the framework in future LCAs.

4.4. Applications of the modelling framework

The applicability of the framework was demonstrated for a temporary yield increase induced by additional fertiliser. This simple management change was chosen mainly to facilitate interpretation of results, as it enabled isolation of the effects of the feedback mechanism. However, the principles of the framework can be applied for more complex management changes that affect more parameters, and for management changes that persist for longer than one year. Appropriate areas of application of the framework include all cases where SOC levels can be expected to change due to a disturbance to the system, and where this SOC change can be expected to affect the output of the system. Apart from changes directly affecting crop yield, as assumed in this study, potential applications include cropping system changes such as altered crop rotation or tillage practices, introducing catch crops, crop residue management change, addition of organic amendments or use of new crop varieties with different harvest index. It should be noted that this also includes management change that decreases the SOC levels, and for declining yields. It is important that all relevant processes and mechanisms are included when assessing the climate impact of a product, in order to develop proper guidance on the best actions for minimising the environmental impact of agriculture.

5. Conclusions

This study demonstrated how the feedback mechanism between SOC and yield can be included in LCA of crop production by combining models for SOC dynamics, yield response to SOC and climate impact assessment into a dynamic modelling framework. Results for a case study where a temporary yield increase in barley cultivation in Sweden was simulated using the modelling framework showed that including SOC changes and its feedback effects on yield gave a five-fold climate impact reduction compared with only accounting for the temporary yield increase. The corresponding reduction when only including SOC changes was three-fold. These results strongly indicate that the feedback between SOC and yield should be included in LCAs assessing the environmental impact of different crop management practices where such an effect can be expected, to avoid introducing a systematic error in the results. Not including this effect may over- or under-estimate the difference in climate impact of crops cultivated under different crop management regimes, and may even give misleading conclusions on the best alternative from a climate perspective.

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Appendix A. Supplementary data

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