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An approach to include soil carbon changes in life cycle assessments

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ABSTRACT

Globally, soil carbon sequestration is expected to hold a major potential to mitigate agricultural greenhouse gas emissions. However, the majority of life cycle assessments (LCA) of agricultural products have not included possible changes in soil carbon sequestration. In the present study, a method to estimate carbon sequestration to be included in LCA is suggested and applied to two examples where the inclusion of carbon sequestration is especially relevant: 1) Bioenergy: removal of straw from a Danish soil for energy purposes and 2) Organic versus conventional farming: comparative study of soybean production in China. The suggested approach considers the time of the soil CO_2 emissions for the LCA by including the Bern Carbon Cycle Model. Time perspectives of 20, 100 and 200 years are used and a soil depth of 0–100 cm is considered. The application of the suggested method showed that the results were comparable to the IPCC 2006 tier 1 approach in a time perspective of 20 year, where after the suggested methodology showed a continued soil carbon change toward a new steady state. The suggested method estimated a carbon sequestration for the first example when storing straw in the soil instead of using it for bioenergy of 54, 97 and 213 kg C t^{-1} straw C in a 200, 100 and 20 years perspective, respectively. For the conversion from conventional to organic soybean production, a difference of 32, 60 or 143 kg soil C ha^{-1} yr^{-1} in a 200, 100 or 20 years perspective, respectively was found. The study indicated that soil carbon changes included in an LCA can constitute a major contribution to the total greenhouse gas emissions per crop unit for plant products. The suggested approach takes into account the temporal aspects of soil carbon changes by combining the degradation and emissions of CO_2 from the soil and the following decline in the atmosphere. Furthermore, the results from the present study highlights that the choice of the time perspective has a huge impact on the results used for the LCA. For comparability with the calculation of the global warming potential in LCA, it is suggested to use a time perspective of 100 years when using the suggested approach for soil carbon changes in LCA.

1. Introduction

Climate change is increasingly regarded as a major problem and mitigation options are discussed (e.g. IPCC, 2007). Carbon sequestration, which is removal or temporary storage of carbon from the atmosphere for example in vegetation or soil, is seen as a way of mitigating climate change by temporarily avoiding some radiative forcing (Brandão et al., 2013). Soil carbon sequestration is the temporary storage (or release) of carbon in the soil and is in agricultural soils expected to hold a major potential for agriculture's global warming mitigation potential to reduce agricultural emissions and increase C sequestration. Thus, Smith et al. (2007) estimated soil C sequestration to contribute about 89% to the global mitigation potential from agriculture. However, the importance of soil C sequestration is poorly reflected in current LCA's (Koerber et al., 2009), since the majority of studies have not included soil C sequestration in the overall greenhouse gas estimations, mainly due to methodological limitations (Brandão et al., 2011). Though, recently a few LCA studies have attempted to include soil C changes – using mainly modeling and using time horizons of a few to 30 years (Hörtenhuber et al., 2010; Röös et al., 2010; Halberg et al., 2010; Hillier et al., 2009; Mila i Canals et al., 2008; Gabrielle and Gagnaire, 2008), although the time horizon used is not explicitly stated in all of the studies. Soil carbon changes are normally estimated by modeling since the full extent of the soil carbon changes caused by changes in agricultural practices will

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only appear when a new equilibrium of soil carbon content has been reached after at least 20 years. When the agricultural practice is changed, the level of soil C will increase/decrease more at the beginning of the period and then level out to reach a new equilibrium. Using a time perspective of 20 years, the estimates of annual soil C changes will be higher compared to a time perspective of 30 years or 100 years. Thus, the time perspective chosen to evaluate the C sequestration or the payback time is crucial. The subjects of these studies were mainly bioenergy (Hillier et al., 2009; Gabrielle and Gagnaire, 2008) or organic agricultural production (Hörtenhuber et al., 2010; Halberg et al., 2010), since C sequestration is especially relevant to include in these studies (Whitaker et al., 2010).Consequently, Brandão et al. (2011) states that '… clearly a systematic and harmonised method for considering SOC (soil organic carbon) changes in LCA is needed.' There is currently no consensus or standard procedure on how to account for temporary removals of carbon from or release to the atmosphere in LCA accounting (Brandão et al., 2013).

The British publicly available specification (PAS, 2050, 2008) for assessing product life cycle greenhouse gas emissions have not included soil C changes either, whereas agriculturally induced land use changes (e.g. forests to agricultural land) is included with a time perspective of 20 years (PAS, 2050, 2008). The EC Renewable Energy Directive (EC, 2009) includes soil C changes due to land use change in a 20 year's time perspective. The IPCC guidelines (IPCC, 2006) for national inventories includes a tier 1 approach on how to estimate changes in soil C stocks using a 20 years default time perspective, which can be included in LCA, as it has been done in Knudsen et al. (2010). However, the time perspective can be questioned for LCA purposes since this method was developed for national inventories and not for LCA. Furthermore, categorical estimates are used in the IPCC guidelines (IPCC, 2006) tier 1 approach for estimating the soil C stock changes. These are based on choices of four categories of land use, three categories of tillage and four categories of input with regard to crop residues and manure (IPCC, 2006). Thus, the specific amount of carbon added to the soil cannot be precisely accounted for.

Some main uncertainties and discussions with regard to including soil C changes in LCA's agricultural products would be: a) The spatial system boundary: optimal estimated depth in the soil profile, b) temporal system boundary: optimal time horizon (20, 30, 100 or 200 years), c) toward a new equilibrium: saturation of soils. Basically, a switch to a new agricultural practice such as conventional to organic or removal of straw instead of leaving it in the field will lead to a change toward either a higher or a lower level of soil C organic matter. C in soil organic matter is however not 'stable' but there is a constant turnover and the net changes in soil C will be a balance between deposited and emitted (Jenkinson, 1990). Normally the time of emissions is not given particular attention in the LCA, since the emissions normally are emitted within the analyzed time frame (e.g. a year). However, dealing with soil C changes, added C is released from the soil in different quantities over a longer period and needs to be taken into account (Reap et al., 2008; Levasseur et al., 2010)Brandão et al. (2013) summarizes six available methods for accounting for the potential climate impacts of carbon sequestration and temporary storage or release of biogenic carbon in LCA (relevant for both land use change and soil carbon sequestration). Cherubini et al. (2011) uses an approach that includes the Bern carbon cycle model, as in the suggested approach in the present paper, but with a forest growth curve for bioenergy from existing forests.

The aim of the present paper is to suggest a method to estimate the effect of soil C changes on CO_2 in the atmosphere to be included in LCA's with particular reference to the time related balance between carbon sequestered and the following release to the atmosphere. The method is applied to two examples where the inclusion of soil C changes is especially relevant: 1) Bioenergy: removal of straw from a soil in Denmark for energy purposes and 2) Organic versus conventional farming: comparative study of soybean production in China. The effect of soil C changes is estimated and it is shortly described how this could be included in a future LCA. Furthermore, the effect of different time horizons is illustrated. As a sensitivity analysis, the approach is compared to the IPCC 2006 tier 1 approach to estimate changes in soil C stocks (IPCC, 2006).

2. Materials and methods

2.1. Assessment of soil carbon changes in space and time

With regard to the spatial system boundary, the simple IPCC tier 1 guideline (IPCC, 2006) for estimating changes in the soil C stock only takes the topsoil into account. In contrast, a soil profile of 0–100 cm is considered in the C-TOOL model (Petersen, 2010) used in this study. The soil C model C-TOOL is further described in (Petersen, 2010; Petersen et al., 2002). The model consists of three C pools: FOM, which encompasses freshly added matter and soil biota; HUM, native soil organic matter or "humus"; ROM, very slowly decaying matter with a halving time under Danish conditions of approx. 1500 years. Each of these pools exhibit first-order decay. The model considers both the topsoil (0–25 cm) and the subsoil (25–100 cm). Transport of C from the topsoil to the subsoil is included. The difference between choosing 0–100 cm instead of only the topsoil is discussed further in the sensitivity analysis.

With regard to the temporal system boundary, every agricultural practice in theory reaches a certain 'steady state' level of soil C after a number of years (Jenkinson, 1990), as illustrated in Fig. 1. The C change rate will be highest in the first few years and then the gains/losses will decline over time.

Here, the consequences of choosing three time horizons of 20, 100 and 200 years were analyzed. The IPCC 2006 tier 1 approach, which has a time perspective of 20 years, was used in the sensitivity analysis (IPCC, 2006). This means that the total change in soil carbon stocks was divided on 20 years.

2.2. Estimation of CO_2 present in the atmosphere in a specific time perspective

When C (in the form of e.g. crop residues or manure) in one year is added to the soil, parts of the C will remain in the soil, while other parts will be released to the atmosphere dependent on time, as illustrated in Fig. 2. At the same time, however, when the C is released to the atmosphere in the form of CO_2, it will follow a decay pattern same as any other release of CO_2 to the atmosphere due to

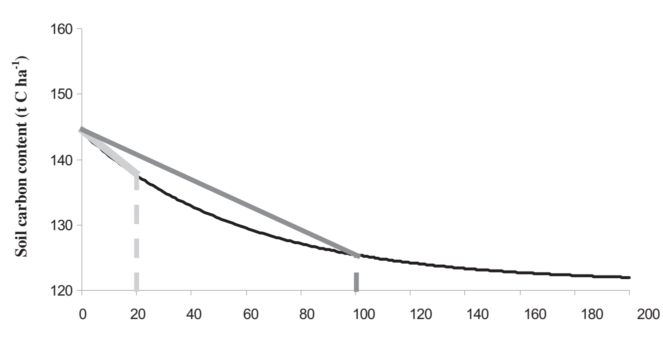

Fig. 1. Illustration of the impact of the chosen time perspective when estimating soil carbon changes.

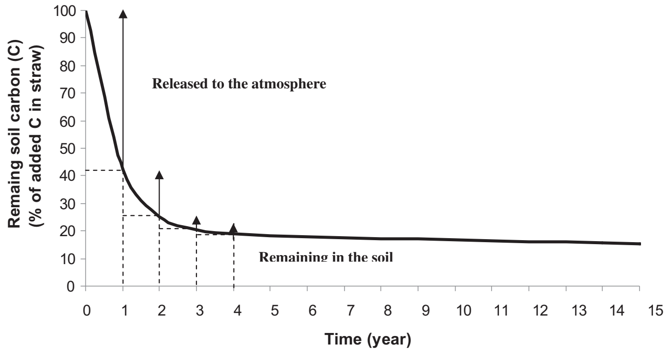

Fig. 2. Generic illustration of the decay of carbon (C) (e.g. crop residues or manure) added to the soil as a single event in the first year. The area below the graph is C retained in the soil and the arrows above the graph illustrate the C that is released to the atmosphere.

absorption in sinks (mainly the oceans). The decay pattern of CO_2 in the atmosphere is described by the Bern Carbon Cycle Model for which the following equation serves as a proxy (IPCC, 2007):

$$f(t) = 0.217 + 0.186\exp\left(\frac{-t}{1.186}\right) + 0.338\exp\left(\frac{-t}{18.51}\right) + 0.259\exp\left(\frac{-t}{172.9}\right) \quad (1)$$

Where $f(t)$ is the fraction of CO_2 left in the atmosphere dependent on time, t.

Fig. 3 shows this decay of a pulse of CO_2 released to the atmosphere, when it is transferred to other pools, such as terrestrial ecosystems and the oceans.

The area below the curve is the time-integrated mass load of CO_2 in the atmosphere in a specific time perspective:

$$A_T = \int_1^T f(t)\mathrm{d}t \quad (2)$$

where T is the time horizon and $f(t)$ is derived from Equation (1).

As illustrated in Fig. 3, the area below the curve (Equation (1)) in a 100-year perspective, for instance, is only 48% of the hypothetical value without sinks.

The above description of the fate of C (e.g. straw or compost) added to the soil, that – dependent on time – will end up in either

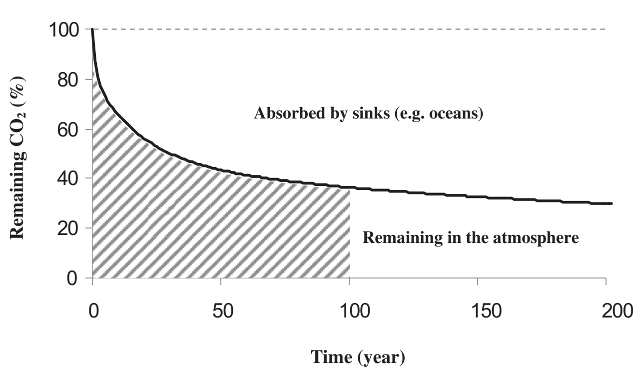

Fig. 3. Decay of CO_2 in the atmosphere, based on the **Bern** Carbon Cycle Model, f(t) (IPCC, 2007). The area under the curve is the time-integrated mass load of CO_2 in the atmosphere and is described by A_T (Equation (2)). An example of the time-integrated mass load of CO_2 in the atmosphere in a 100-year perspective, A_{100}, is given.

soil, atmosphere or C sinks is focused on a single years addition of C. However, this focus on a single year is fully additive if this event is repeated year after year. Fig. 4 is the sum of curves from Fig. 2 (where the area below the curve is the C remaining in the soil) for repeated annual additions of C to the soil. Fig. 4 illustrates the build-up of soil C from repeated annual additions of C and how the soil C approaches a new 'steady state' or equilibrium based on the sum of the C remaining in the soil from each year's addition of C.

On this basis we estimated the effect of soil C changes on CO_2 in the atmosphere to be included in LCA. The approach was applied to two typical LCA situations using a case study approach: I) the choice between removal of cereal straw for bioenergy or leaving it on the soil, II) comparison of two farming systems differing in their soil organic matter building practices.

2.3. Example I: straw removal from agricultural soils in Denmark for bioenergy purposes

The first example is focused on a case study of removing cereal straw for bioenergy purposes versus leaving it in the field in a typical crop rotation in Denmark. The case study area is characterized by a coastal climate with an annual average temperature of 7.7 °C (average for Denmark, 1961–90). The climate zone is according to IPCC guidelines (IPCC, 2006) cool, temperate, moist. The modeled soils are Alfisols with 12% clay and 62 t C ha^{-1} in the topsoil (0–25 cm). In this study, it was assumed that one t C ha^{-1} was removed for bioenergy instead of left in the field.

2.4. Example II: organic versus conventional production of soybeans in China

Example II is a case study of organic versus conventional soybean production in the Jilin province in China, which is further described in Knudsen et al. (2010). The case study area is characterized by a continental climate with a mean average temperature of 4.0 °C (in between climate station Changchun and Dunhua). The climate zone is according to IPCC guidelines (IPCC, 2006) cool, temperate, dry (on the border to moist). The soils are Mollisols with 14% clay and 3% C in the topsoil (Zhao et al., 2006). In the case study, 20 organic farms and 15 conventional farms producing soybeans were included. The main crops for both farm types were soybeans and maize. The main inputs and outputs relevant for the C balance from soybeans are given in Table 1.

The crop residues from the conventional soybean fields were burned, whereas in organic fields these were incorporated into the soil as compost. The organic farmers were using compost, whereas the conventional farmers were using mineral fertilizer. The two most important differences between organic and conventional soybean production affecting the soil C balance is the fertilization method and the crop residue management practice. The C assimilated in the crop and the C harvested in soybeans is assumed to be similar since there was no significant difference between organic and conventional soybean yields (Table 1). The relative changes in the organic and conventional soybean fields due to different fertilization and crop residue management practices are presented in Table 1.

3. Results

3.1. Changes in atmospheric CO_2 following a change in carbon added to soil

The suggested approach takes its point of departure in the description in Section 2.2 of the fate of the estimated change in CO_2 in the atmosphere caused by a balance between carbon added to

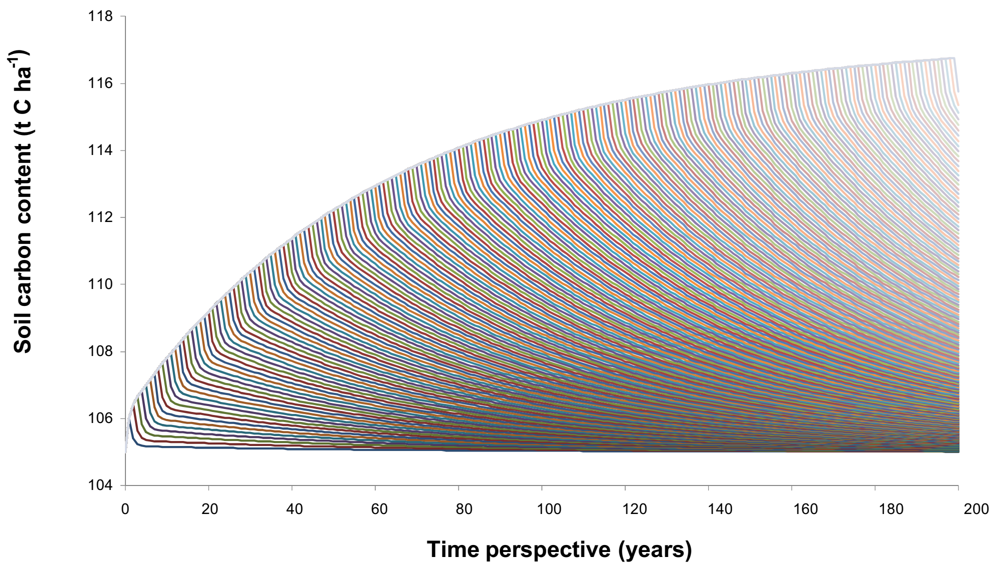

Fig. 4. Illustration of the build-up of soil carbon (C) toward a new steady state from repeated annual additions of C (e.g. straw or compost). The curve is based on the sum of decay curves of every single year's addition of C, where the area below each single curve is the C remaining in the soil from the annual addition of C (e.g. straw or compost) to the soil. The basic point of departure is a scenario where less C has been added to the soil.

the soil, the rate of subsequent release of carbon (Fig. 2), and the decay of carbon described by the Bern Carbon Cycle Model (IPCC, 2007) (Fig. 3).

By combining the two curves; Fig. 2 for decay of C in soil (and corresponding release of CO_2 to the atmosphere and Fig. 3 for the subsequent atmospheric 'decay' of the released CO_2 from the soil, Fig. 5 shows the net result (illustrated for the first four years after applying crop residues to the soil).

Table 1
Main inventory data (above) relevant to the partial carbon budgets[a] (below) for1 ha of organic and conventional soybeans in the Jilin province, China (2006).

	Organic	Conventional
Inventory data:		
Input		
Mineral fertilizer, N (kg Nha^{-1})	–	47
Organic fertilizer[b] (m^3 ha^{-1})	13	–
Organic fertilizer[b], N (kg Nha^{-1})	45	–
Output		
Soybean yield (kg ha^{-1})	2788	3083 ± 310
Crop residues[c]		
Left in field (%)	23	13
Burned (in kitchen) (%)	40	41
Removed for fodder (%)	4	5
Burned (in field) (%)	–	41
Removed for compost (%)	33	–
Partial carbon budget (kg C ha^{-1})[a]:		
Input		
Organic fertilizer[d]	675	0
Output		
Crop residues burned in kitchen	874	896
Crop residues removed for fodder	87	109
Crop residues burned in field	0	717
Crop residues removed for compost	721	0
Partial field balance	−1007	−1722

[a] Inputs from crop carbon assimilation during photosynthesis and output from harvested crops are not included, since organic and conventional soybean yields were not significantly different.
[b] Compost, which consists of cattle manure (60%), forest soil (20%) and soy/maize crop residues (20%).
[c] % represents the mass of the crop residues.
[d] The C:N ratio in the compost used is estimated to be 15:1 according to Tang et al. (2006), Eiland et al. (2001), Stamatiadis et al. (1999) & Evanylo et al. (2008).

From Fig. 5 it can be seen that the approx. 60% of added C to soil that are released to the atmosphere in the first year (Fig. 2) has a subsequent decay in the atmosphere according to the Bern Carbon Cycle Model. The second year an extra approx. 15% of the originally added C is released to the atmosphere (Fig. 2) following a decay pattern in the atmosphere (Fig. 5) and so forth. In Fig. 5 only the following four years after applying C to the soil is illustrated. However, all years are included in the summed curve illustrating the decay of the summed emissions from soil storage, illustrating that these processes reaches an equilibrium.

Thus, the area below the summed graph (Fig. 5) expresses the time integrated relative atmospheric load of CO_2 as influenced by soil storage and can be formulated in one-year step numerical integration as:

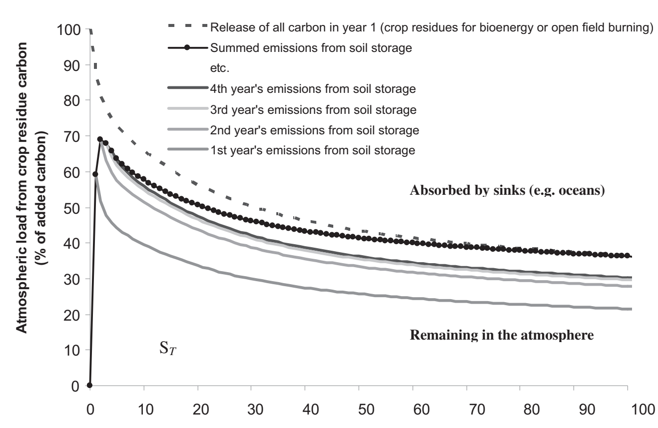

Fig. 5. Illustration of the atmospheric load from either soil storage or burning of crop residue carbon (C). The soil storage curves are a combination of the decay curve of a single event of carbon (C) added to the soil in the first year and the decay curve of CO_2 in the atmosphere (Bern Carbon Cycle Model) – shown on a yearly basis for the first four following years only as an illustration. The curve of the summed emissions from soil storage contain all the following years. The upper dotted line represents the scenario where the entire C in crop residues is released in the first year (as for bioenergy use or open field burning).

$$S_T = \sum_{i=1}^{T}\left(a(i)\sum_{j=1}^{T-i} f(j)\right) \tag{3}$$

where T is the time frame, $a(i)$ is the release of CO_2 in year i from a single addition of crop residues (as resulting from the decay of organic matter, and $f(j)$ is given by Equation (1).

In addition to the graph illustrating S_T, Fig. 5 also includes a graph (the upper dotted line) illustrating the atmospheric load of CO_2 if the entire C in straw was released in the first year (if crop residues were used for bioenergy purposes or burned in the field), which corresponds to A_T (Fig. 3; Equation (1)).

Thus, the area below the dotted line in Fig. 5 represents A_T, which is the atmospheric load if the entire C in crop residues was released in the first year. The area below the summed curve in Fig. 5 represents S_T, which is the atmospheric load if the straw was left in the soil.

The area between the two curves represents the total time-integrated atmospheric load of CO_2 avoided by storing the crop residue C in the soil (compared to releasing it to the atmosphere)(Fig. 5).

The soil storage effect equivalent to an avoided atmospheric load R_T over a T-year perspective is calculated as follows:

$$R_T = \frac{A_T - S_T}{A_T} \tag{4}$$

where R_T is the fraction of the straw C that is stored in a T-year perspective and thus comparable to an avoided atmospheric load compared to releasing all the C in crop residues in the first year. A_T is the atmospheric CO_2 load from crop residue C released to the atmosphere (e.g. for bioenergy) (the area below the Bern Carbon Cycle Model curve) and S_T is the atmospheric load from soil storage of the same amount of crop residues.

If the avoided atmospheric load, R_T, in a 100-year perspective was e.g. 10% through leaving 1 t of C in crop residues on the soil instead of releasing it all to the atmosphere in the first year, this would mean that a greenhouse gas (GHG) emission corresponding to 100 kg C is avoided in a 100-year time perspective for every t of C left in the field in a particular growing season.

As mentioned earlier, this approach furthermore focuses on the consequences of changing the C balance in a field in a single year, which will have an effect on CO_2 in the atmosphere. The resulting avoided atmospheric load (if e.g. crop residues were incorporated instead of burned) is assumed fully additive if this event is repeated year after year. This basic method for quantifying the consequences for CO_2 in the atmosphere of an activity that changes the soil C balance over a period was then applied to the two case studies.

3.2. Application of methodology to example I: straw removal for bioenergy in Denmark

The consequences for the C balance were based on one t of straw C added to the soil instead of using it for bioenergy. The soil C decrease and emissions over time from added straw C in a Danish soils using C-TOOL is shown in Fig. 6.

There was a relatively rapid decay of 80% of the added straw C during the first few years following the application and after 100 years up to 95% of the added C had been released to the atmosphere as CO_2.

When these emissions from the soil decay of straw C were combined with the Bern Carbon Cycle Model, as illustrated in Fig. 7, the net avoided load, R_T in atmospheric C from leaving straw C on the soil was shown to be 21.3% in a 20 years perspective and 9.7% in a 100 years perspective (Table 2). In a 20 years perspective, this corresponds to a carbon sequestration equivalent of 213 kg soil C t^{-1} straw C and a resulting CO_2 reduction of 781 kg CO_2 t^{-1} straw (when multiplying the carbon sequestration potential with 44/12).

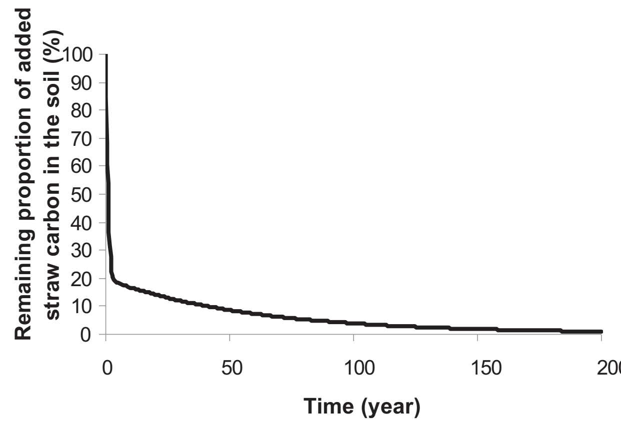

Fig. 6. Decay of one t straw carbon when added to the soil as a single event in the first year according to C-TOOL modelling.

Thus, when conducting an LCA study on straw for bioenergy in Denmark, an additional 781 kg CO_2 release should be added to the climate change impact per t straw C used for bioenergy if one uses a 20 year time perspective, due to soil C reduction in Denmark, or 198 kg CO_2 t^{-1} straw C if evaluated in a 100 year perspective.

3.3. Application of methodology to example II: organic versus conventional soybean production in China

The consequences for the soil C balance when converting from conventional to organic soybean production in the case study in China is presented in Table 1 that shows a difference of 715 kg C ha^{-1}.

The C-TOOL modelling of the decay and emissions of crop residue C in the Chinese soil over time using site-specific driving variables combined with the Bern Carbon Cycle Model resulted in a soil storage effect equivalent to an avoided load, R_T, of 20.0% and 8.4% in a time perspective of 20 and 100 years, respectively. Thus, of the 715 kg C ha^{-1} yr^{-1} that are added extra to the organic soils, 143 kg C ha^{-1} yr^{-1} are sequestered in a 20 years perspective and

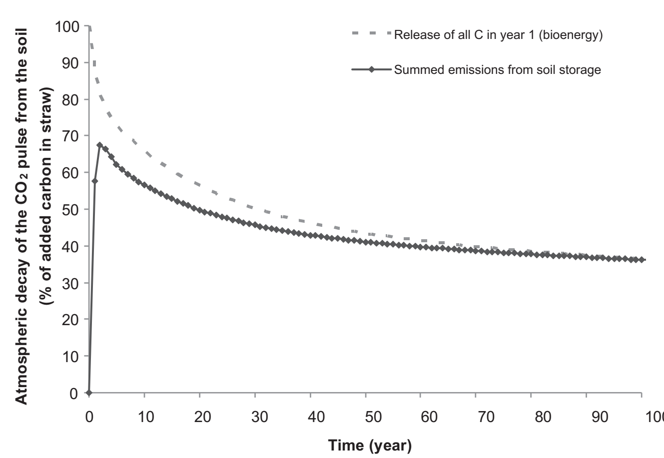

Fig. 7. Atmospheric CO_2 emission load from soil storage of straw carbon (C) added in the first year in relation to releasing the entire straw C in the first year (for bioenergy) – using C-TOOL combined with the **Bern** Carbon Cycle Model.

Table 2
Emission reduction, R_T, carbon (C) sequestration and CO_2 reduction when incorporating one t of straw C in a soil in Denmark instead of using it for bioenergy (Example I).

Time perspective (years)	Emission reduction, R_T (%)	Carbon sequestration equivalents (kg soil Ct^{-1} straw C)	CO_2 reduction[a] (kg CO_2 t^{-1} straw C)
20	21.3	213	781
100	9.7	97	356
200	5.4	54	198

[a] The carbon sequestration is multiplied by 44/12 to get the CO_2 reduction, based on the molecular weight of CO_2 to C.

60 kg C ha^{-1} yr^{-1} in a 100 years perspective (Table 3) in the soil. Table 3 furthermore presents the resultant extra C sequestration per area and reduction in CO_2 emissions per area and per crop unit caused by soil storage of crop residues instead of open field burning.

Thus, converting from conventional to organic soybean production practices in the case study in the Jilin province in China causes a removal of an extra emission load of 524 or 220 kg CO_2 ha^{-1} yr^{-1} from the atmosphere in a 20 or 100 years perspective, respectively. When conducting a comparative LCA of organic and conventional soybeans from this case study in China the difference in greenhouse gas emissions per crop unit should be widened by 188 kg CO_2 t^{-1} soybean, using a time perspective of 20 years. Taken into account that the total greenhouse gas emissions of the Chinese organic soybeans at farm gate excluding soil C changes was estimated to 156 kg CO_2 eq t^{-1} soybean (Knudsen et al., 2010), the inclusion of C sequestration plays a major role in determining the result. Even if a 100 year perspective was chosen the consequences of not burning straw equal 79 kg C ha^{-1} yr^{-1} corresponds to 51% of the total farm gate greenhouse gas emissions per t organic soybean.

3.4. Sensitivity analysis

A sensitivity analysis was performed on the suggested methodology. First of all, the methodology was compared to the IPCC 2006 tier 1 approach to estimate change in soil C stocks (IPCC, 2006), as presented in Box 1 and 2. SOC_{ref} is the default reference soil organic C stocks for mineral soils (under native vegetation) and F_{LU}, F_{MG}, F_I is the relative stock change factors related to land use, tillage and input, respectively.

The present C sequestration results (per t straw C) from Example I (Table 2) need to be converted to an area basis to be comparable to the IPCC results. Since the available cereal straw yield ha^{-1} in Example I is 1.56 t C ha^{-1} yr^{-1} (data not shown), the difference in C sequestration (based on Table 2) from removal of all available straw to leaving it in the field in a 20 years perspective will be 213 kg C t^{-1} C × 1.56 t C ha^{-1} yr^{-1} = 332 kg C ha^{-1} yr^{-1} as compared to the IPCC approach estimating 262 kg C ha^{-1} yr^{-1} (Box 1).

Table 3
Emission reduction, R_T, carbon (C) sequestration and CO_2 reduction when converting from conventional to organic soybean production practices and thereby incorporating 715[a]kg ha^{-1} yr^{-1}extra of soy residueCin a soil in the Jilin province, China instead of burning it in the field (Example II).

Time perspective (years)	Emission reduction, R_T (%)	Carbon sequestration equivalents (kg soil C ha^{-1} yr^{-1})	CO_2 reduction[b] per area (kg CO_2 ha^{-1} yr^{-1})	CO_2 reduction per crop unit (kg CO_2 t^{-1} soybean)
20	20.0	143	524	188
100	8.4	60	220	79
200	4.5	32	117	42

[a] From C balance (Table 1).
[b] The carbon sequestration is multiplied by 44/12 to get the CO_2 reduction, based on the molecular weight of CO_2 to C.

Box 1. IPCC, 2006 methodology applied to Example I:

Temperature zone: Cool temperate, moist.
$SOC_{ref,\ Alfisol\ (HAC\ soils)}$: 95 t C ha^{-1} (in 0–30 cm)
F_{LU}: 0.69 (long-term cultivated)
F_{MG}: 1.00 (full tillage)
$F_{I,\ no\ straw\ removal}$: 1.00 (medium input)
$F_{I,\ straw\ removal}$: 0.92 (low input)
No straw removal: 95 × 0.69 × 1.00 × 1.00 = 65.55.
Straw removal: 95 × 0.69 × 1.00 × 0.92 = 60.31.
Difference: 5.24 t C ha^{-1}
C sequestration, 20 years perspective:
5.24 t C ha^{-1}/20 yr = 262 kg C ha^{-1} yr^{-1}
CO_2 reduction:
262 kg C ha^{-1} yr^{-1} × 44/12 = 961 kg CO_2 ha^{-1} yr^{-1}

The IPCC estimate of a C sequestration of 100 kg C ha^{-1} year when converting from conventional to organic soybean production in the case study area in Example II (Box 2), is directly comparable to the estimate of 143 kg C ha^{-1} yr^{-1} in a 20 year time perspective in the present study (Table 3).

The IPCC estimates were thus lower than our new estimates, which is partly due to the deeper soil layers included in C-TOOL (0–100 cm) compared to the IPCC approach (0–30 cm). If C-TOOL is parameterized for 0–25 cm only, the comparative value for C sequestration in 20 years for Example I would be 195 kg C t^{-1} straw C and 305 kg Cha^{-1} yr^{-1}, as compared to the IPCC approach estimating 262 kg C ha^{-1} yr^{-1} and the suggested method using a soil profile of 0–100 cm estimating 332 kg C ha^{-1} yr^{-1}.

Fig. 8 illustrates for Example I, the soil carbon changes if all available straw carbon in the crop rotation is removed from the Danish field, using both the suggested approach with a soil depth of

Box 2. IPCC, 2006 methodology applied to Example II:

Temperature zone: Cool temperate, dry.
$SOC_{ref,\ Mollisol\ (HAC\ soils)}$: 50 t C ha^{-1} (in 0–30 cm)
F_{LU}: 0.80 (long-term cultivated)
F_{MG}: 1.00 (full tillage)
$F_{I,\ organic\ soybean\ production}$: 1.00 (medium input)
$F_{I,\ conventional\ soybean\ production}$: 0.95 (low input)
Organic: 50 × 0.80 × 1.00 × 1.00 = 40.
Conventional: 50 × 0.80 × 1.00 × 0.95 = 38.
Difference: 2.0 t C ha^{-1}
C sequestration, 20 years perspective:
2.0 t C ha^{-1}/20 years = 100 kg C ha^{-1} yr^{-1}
CO_2 reduction:
100 kg C ha^{-1} yr^{-1} × 44/12 = 367 kg CO_2 ha^{-1} yr^{-1}
367 kg CO_2 ha^{-1} yr^{-1}/2.788 t ha^{-1} yr^{-1} = 132 kg CO_2 t^{-1} soybean.

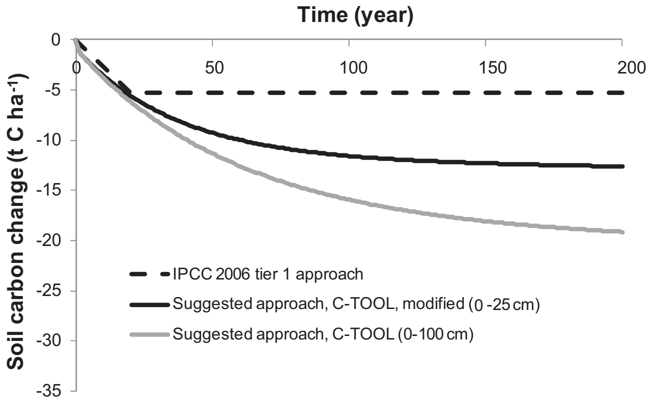

Fig. 8. Relative soil carbon change for example I, if all available cereal straw is removed year after year from the Danish field using either the suggested approach (incl. C-TOOL) with a soil depth of 0–100 cm, the IPCC 2006 tier 1 approach or the suggested approach modified to consider only 0–25 cm.

0–100 cm, the IPCC tier 1 2006 approach with a soil depth of 0–30 cm and a modified suggested approach where the estimated soil depth is reduced to 0–25 cm to be comparable to the IPCC approach.

According to the C-TOOL modelling in Fig. 8 it appears as if the IPCC tier 1 approach does not describe the entire soil carbon loss from straw removal in a long time perspective, but the magnitude of the yearly changes is comparable for the three different approaches for the first 20 years.

After 20 years, the C-TOOL simulation shows a continued soil C loss toward a new steady state where the yearly soil C losses are lower. Interestingly, the C-TOOL simulations show that a new steady state will be approached sooner when considering only the topsoil compared to considering 0–100 cm (Fig. 8).

Finally, the effect of possible future temperature increases on the modeling results is examined. As the soil C decay is affected by temperature, so is the avoided load, R_T.

Fig. 9 illustrates how R_T of Example I will decrease with increasing temperatures. Thus, for example compared with the results in Table 2, in a situation with 2 degrees temperature increase the carbon sequestration equivalent for 20 years would be reduced from 213 to 202 kg soil C t^{-1} straw C.

4. Discussion

The main difference of the present methodology as compared with other approaches to include soil C sequestration in LCA (e.g. Halberg et al., 2010; Hörtenhuber et al., 2010; Gabrielle and Gagnaire, 2008) is primarily that the time perspective of the CO_2 emission and the decay in the atmosphere is taken into account by including the Bern Carbon Cycle Model (IPCC, 2007) and that any time perspective can be chosen such as 20, 30, 100 or 200 years. Furthermore, the suggested method considers a soil depth of 0–100 cm enabling the method to capture a more precise estimate of the soil C changes in the soil depth. Finally, the suggested approach can account for actual estimated amounts of added C to the soil as opposed to the IPCC 2006 tier 1 approach where the estimates are based on four levels (categories) of C inputs to the soil (from mainly crop residues and manure).

The results derived from the suggested approach are comparable to the results of the IPCC approach (IPCC, 2006) when the soil C changes are estimated in a 20-year perspective. The slightly higher values in the suggested approach (Example I: 332 vs. 262 kg C ha^{-1} yr^{-1} Example II: 143 vs. 100 kg C ha^{-1} yr^{-1}) can partly be ascribed to the deeper soil horizon considered in the suggested approach (0–100 cm) than in the IPCC approach (0–30 cm). However, as shown in Tables 2 and 3, the chosen time perspective is crucial to the results. In the suggested methodology, the time perspective is not fixed to be 20 years as in the IPCC approach; since it can be discussed whether a 20 years time perspective is the more appropriate to use (Fearnside, 2002) when the global warming potential is normally estimated on the basis of a 100 year time perspective (IPCC, 2007). Furthermore, soil C changes toward a new steady state can take more than 20 years, as illustrated in Fig. 8, which is in accordance with long term field studies in Northern Europe (Jenkinson and Rayner, 1977; Jenkinson, 1990; Kirchmann et al., 1994), where the changes by contrasting residue management and manure application continue for at least 50–100 years. Trying to change the time perspective in the 2006 IPCC approach to 100 years (dividing by 100 years instead of 20), will underestimate the effect for the 100 year's perspective since the new steady state is not reached after the 20 years, as illustrated in Fig. 8. Assuming that a new steady state is reached after 20 years is perhaps more relevant for the tropics, where soil C changes are faster due to the high temperature.

The main challenge for using this method, is estimating the C deficit between the basis scenario and the new practice. The application of the Bern Carbon Cycle Model is straightforward so using Equation (4) depends mainly on an appropriate soil C model (such as e.g. C-TOOL and RothC) to estimate the turnover of C in the specific site, dependent on e.g. soil properties and climate data.

The assumption that the soil C turnover is independent on the C content of the soil is used by the majority of soil C models (Paustian et al., 1997) including the C-TOOL model. It should be mentioned that this assumption is challenged, see e.g. Six et al. (2002), Stewart

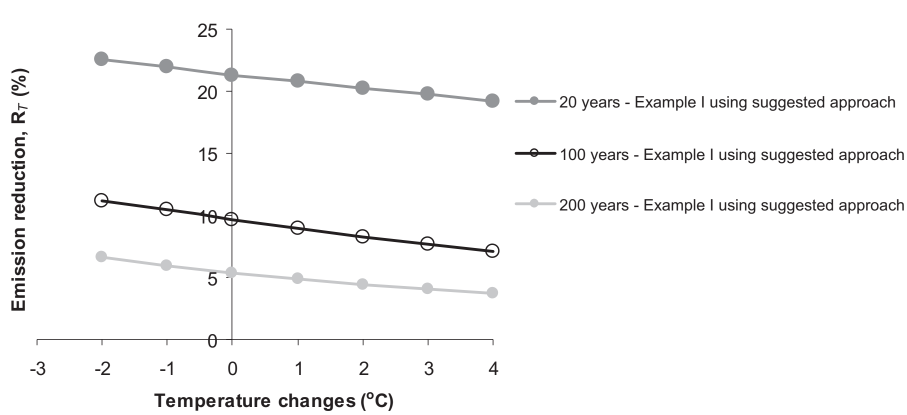

Fig. 9. Emission reduction, R_T, of example I (when leaving 1 t of straw C in the field instead of using it for bioenergy) as affected by temperature changes relative to the mean air temperature of 7.7 °C.

et al. (2008) and Kimetu et al. (2009). These studies suggest a saturation effect by high levels of soil C. Both the latter studies are based on comparisons between soils of different origin though. The Stewart et al. (2008) study compared soil from respectively the A and C horizon and the Kimetu et al. (2009) study compared forest soil with agricultural soil. The assumption of saturation at some point seems plausible, but arguably the comprehensive study demonstrating this effect and its quantitative implications on fully comparable soils is still lacking. However, within the changes caused by agricultural practices the assumption that soil C turnover is independent on the C content of the soil should be acceptable.

The present study highlights that the choice of time perspective is crucial to the results on soil carbon changes to be included in LCA. For e.g. soybeans, the CO_2 reduction per crop unit (to be included in the LCA calculations) varies from 188 to 79 kg CO_2 t^{-1} soybean in a 20 or 100 years perspective, respectively (Table 3). In this approach we calculate the avoided impact (in terms of avoided atmospheric load) caused by the temporary storage of CO_2 in the soil over a given time horizon. Thus, the results rely on the time horizon. For the use of the suggested approach to include soil carbon changes in LCA, where the global warming potential is estimated in a 100 years perspective, it is suggested also to estimate the soil carbon changes in a 100 years perspective.

5. Conclusions

The suggested approach takes into account the temporal aspects of soil carbon changes by combining the degradation and emissions of CO_2 from the soil and the following decline in the atmosphere using the Bern Carbon Cycle Model. Furthermore, the results from the present study highlights that the choice of the time perspective has a huge impact on the results used for the LCA. For comparability with the calculation of the global warming potential in LCA, it is suggested also to use a time perspective of 100 years when using the suggested approach for soil carbon changes in LCA.

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