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Effect of ley inclusion in crop rotations on soil carbon stocks in a life cycle perspective
Effekter av fleråriga grödor på markkolslager i ett livscykelperspektiv

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The overarching vision of the programme Mistra Food Futures is to create a science-based platform to enable transformation of the Swedish food system into one that is sustainable (in all three dimensions: environmental, economic and social), resilient and delivers healthy diets. By taking a holistic perspective and addressing issues related to agriculture and food production, as well as processing, consumption and retail, Mistra Food Futures aims to play a key role in initiating an evidence based sustainability (including environmental, economic and social dimensions) and resilience transformation of the Swedish food system. This report is a part of Mistra Food Future's work to identify agricultural systems with potential to make agriculture net-zero, one of the central issues within Mistra Food Futures.

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Abstract

Carbon sequestration in agricultural soils has been proposed as an important climate change mitigation strategy. Carbon stocks in soils can be increased by different cropland management options, one of which is greater inclusion of perennial crops in crop rotations. This study compared the climate impact in a life cycle perspective of continuous ley-dominated rotations and continuous cereal rotations at two different sites (loam, clay) in Sweden. Effects of these systems on carbon content in topsoil and subsoil over 35 years were assessed based on data from two ongoing long-term field trials. The continuous cereal rotations led to a decrease in soil organic carbon stocks at both sites, resulting in an increase in overall climate impact of 8-19%. The ley-dominated rotations increased soil organic carbon stocks at both sites over time, contributing to a decrease in overall climate impact of 7% (clay) and 18% (loam). The high soil carbon accumulation in the ley rotation at the site with loamy soil, where soil carbon stocks increased in both topsoil and subsoil, was possibly due to more roots entering the subsoil than at the site with clay soil.

Keywords: perennial crops, soil organic carbon sequestration, climate mitigation, subsoil

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1. Introduction

Large amounts of carbon are stored in soils globally and increasing carbon sequestration in agricultural soils through improved cropland management is an important climate mitigation strategy (IPCC, 2020). One of the most promising management strategies is to use more perennial forage crops in crop rotations (Kätterer and Bolinder, 2022). For example, literature reviews show that compared with annual crops alone, using perennial forage crops can increase soil organic carbon stocks by 0.5 Mg C ha^{-1} yr^{-1}. This is higher than the increase achieved with other management strategies, such as leaving aboveground crop residues in the field or reduced tillage operations. Cropping systems maintaining higher soil organic carbon content may also be beneficial for soil nitrogen conservation through changes in the microbial community. For example, it has been hypothesised that promoting bacteria capable of DNRA (dissimilatory nitrate reduction to ammonium) could help reduce nitrous oxide (N_2O) emissions from denitrification under anaerobic conditions (Putz et al., 2018).

The reason why perennial forage crops are particularly efficient in sequestering soil organic carbon relates to high belowground (root) biomass production (Bolinder et al., 2007). Compared with an annual crop such as small-grain cereals or oilseed rape, the amount of roots is up to 10-fold higher for a well-established perennial forage crop (i.e. 10 Mg ha^{-1} compared with 1 Mg ha^{-1} of dry root biomass). Furthermore, roots contribute around 2- to 3-fold more to the formation of stable soil organic carbon than aboveground crop residues, which explains why a perennial forage crop-based management strategy is more efficient than, for example, leaving aboveground crop residues in the field (Kätterer et al., 2011).

Empirical data on soil organic carbon changes due to different management strategies in agriculture are mainly available for the topsoil, while measurements of soil organic carbon changes in the subsoil are rarely performed (Bolinder *et al.*, 2020). However, some Swedish studies have shown that inclusion of perennial crops in the crop rotation can also affect the carbon content in the subsoil (Börjesson *et al.*, 2018; Kirchmann *et al.*, 2013). Consequently, including effects on carbon content in the subsoil could affect the overall estimated climate impact of certain management practices.

This study assessed the overall climate impact of agricultural production systems using a life cycle perspective that included the effect of soil carbon changes in both topsoil and subsoil. Specifically, an almost continuous perennial forage cropping system (ley insown in spring barley, followed by three years of ley) was compared with a continuous cereal crop rotation at two different locations in Sweden.

Life cycle assessment (LCA) is a useful method for assessing the environmental impact of a product or service throughout its life cycle. In the present study, a life cycle perspective was applied in climate impact assessment to analyse the importance of soil organic carbon changes in relation to other life cycle steps, such as fertiliser manufacture and spreading and the use of agricultural machinery.

2. Aim and objectives

The overall aim of the study was to analyse the effect of soil carbon stock changes in the topsoil and subsoil on the overall climate impact of agricultural production systems for two crop rotations, one ley dominated and one continuous cereal rotation, at two locations in Sweden.

3. Materials and methods

3.1. System description

The assessment was mainly based on data from ongoing long-term field trials in Sweden. Two different sites in southern Sweden were chosen (Lönnstorp (55.67°N, 13.10°E) and Lanna (58.35°N, 13.13°E)), at which field trials were initiated in 1980 and 1981, respectively. The soil at the Lönnstorp site is a loam with a clay content of 15% in the topsoil, whereas the Lanna topsoil has a clay content of 43% (Poeplau *et al.*, 2015). At both sites, two contrasting crop rotations were compared: a continuous cereal monoculture including barley and oats and a ley-dominated rotation with ley insown in spring barley followed by three years of ley. The ley was a mixture of meadow fescue, timothy and red clover (Börjesson *et al.*, 2018).

3.2. Scope

3.2.1. Functional unit

Two different functional units were studied: 1 ha and 1 kg product (dry matter for ley and 14% moisture content for grains). One hectare was considered suitable as a basis for analysis of the influence of site and management options on greenhouse gas (GHG) emissions. To analyse the amount of product delivered by each system and the possibilities of the systems to deliver food and feed, per kg was considered suitable to include as an additional functional unit.

3.2.2. System boundaries

The system boundaries were set at the farm gate, which included the following processes:

- Production of seeds, fertilisers (N-P-K) and pesticides
- Soil emissions due to fertilisation, crop residues left in the field and nitrogen leaching
- Changes in soil organic carbon
- Emissions from use of machinery for field operations, drying of grain and silage production from the ley
- Production of capital goods
- Production of silage.

3.2.3. Climate metrics used for impact assessment

The climate impact of GHG emissions arising from the two agricultural systems was assessed using the GWP_{100} factors from the 6^{th} Assessment Report by the IPCC (Forster *et al.*, 2021).

3.3. Life cycle inventory

The original field experiments included different nitrogen fertiliser application rates. In this study, assessments of the climate impact of the two agricultural systems were made for a nitrogen fertiliser application rate of 120 kg N per ha and year for the cereal rotation and 150 kg N per ha and year for the ley rotation. The assessment also included data on straw retention in the cereal monoculture, whereas ley biomass was removed at harvest in the ley rotation. Average yield (dry matter per hectare) was calculated for the rotations during the experimental period 1980-2015 for Lönnstorp and 1981-2015 for Lanna. For the cereals in both rotations, 200 kg/ha yield were subtracted from yield of cereals to account for seed production, based on Andersson (1992). Seed production was excluded for the forage ley, as the impact was assumed to be negligible (Flysjö *et al.*, 2008).

Data on soil carbon changes over the study period were derived from Börjesson *et al.* (2018), who quantified the effects of soil carbon changes in the two specific rotations studied through sampling of the topsoil and subsoil at the two different sites in 2015.

Inventory data for emission sources that were not available for the field trials were taken from official statistics reported by Statistics Sweden or from reports (Johnsson *et al.*, 2019; Baky *et al.*, 2010; Flysjö *et al.*, 2008). For nitrogen in crop residues left in the field and for direct and indirect emissions of N_2O, calculations were carried out based on IPCC (2019) with the general emission factor 1% of the added nitrogen and the nitrogen in crop residues. With regard to nitrogen mineral fertiliser, 60% was assumed to be ammonium nitrate produced with Best Available Technology (BAT), (based on Swedish Agency for Public Management, 2010) and with corresponding emission factors from Yara International (2010). Emission factors for N-P-K fertiliser (26-15-15) production and pesticide production were obtained from the Ecoinvent database (Ecoinvent Centre, 2020) as European averages. Emission factors for fuels and electricity were taken from Gode *et al.* (2011). The Nordic electricity mix was assumed to be representative for the calculations. Production of capital goods was included in the calculations as a fixed value of 0.03 kg CO_2/kg output, based on Frischknecht *et al.* (2007). A summary of inventory data used in the study is presented in Table 1.

Table 1. Inventory data used in climate impact assessment of the agricultural systems in Lönnstorp and Lanna

	Share of crop in rotation	Yield (kg/ha)[1]	N mineral fertiliser application (kg N/ha)[2]	P mineral fertiliser application (kg P/ha)[3]	K mineral fertiliser application (kg K/ha)[3]	Pesticide application (kg active ingredient/ha)[4]	Soil organic carbon change (kg C/ha/year, 0-20 cm/20-50 cm)[5]	Nitrogen in crop residues (kg N/ha)[6]	Nitrogen leaching (kg N/ha)[7]	Diesel use in machinery (L/ha)[8]
Lönnstorp										
Cereal monoculture	1.0	5000					190/190			
Barley	0.33	4918	120	5.5	12.2	0.65		66	29.9	68.4
Oats	0.67	5041	120	7.3	12.7	0.35		62	29.9	68.6
Ley rotation	1.0	7803					-350/-130			
Ley	0.25	8857	150	2.0	6.0	0.25		44	29.9	49.0
Ley	0.25	9322	150	2.0	6.0	0.25		47	29.9	49.0
Ley	0.25	8128	150	2.0	6.0	0.25		41	29.9	49.0
Barley	0.25	4905	150	5.5	12	0.65		66	29.9	68.4
Lanna										
Cereal monoculture	1.0	4185					150/-10			
Barley	0.33	4048	120	5.5	12.2	0.65		55	18.6	68.4
Oats	0.67	4253	120	7.3	12.7	0.35		52	18.6	68.6
Ley rotation	1.0	7503					-170/-10			
Ley	0.25	9270	150	2.0	6.0	0.25		46	18.6	49.0
Ley	0.25	9140	150	2.0	6.0	0.25		46	18.6	49.0
Ley	0.25	8568	150	2.0	6.0	0.25		43	18.6	49.0
Barley	0.25	3234	150	5.5	12	0.65		44	18.6	68.4

[1]Yield levels for grass-clover leys are given as 100% dry matter (DM). Yield levels for cereals are given in 15% moisture content. For the cereals in both rotations, 200 kg/ha was subtracted from the yield to compensate for seed production. Yield levels for individual crops in the rotations were retrieved from Börjesson *et al.* (2018) and a weighted average of the whole rotation for the whole study period (1980-2015 for Lönnstorp, 1981-2015 for Lanna) was then calculated.
[2]Nitrogen mineral fertiliser application rate from Börjesson *et al.* (2018).
[3]Phosphorus and potassium mineral fertilizer application rates from SCB (2020); SCB (2017); SCB (2014).
[4]Pesticide application rate from SCB (2018); SCB (2011).
5Soil organic carbon changes in topsoil and subsoil from Börjesson *et al.* (2018), positive values represent soil carbon loss and negative values soil carbon gain.
[6]Nitrogen in crop residues calculated based on IPCC (2019).
[7]Region-specific data on nitrogen leaching obtained from Johnsson *et al.* (2019).
[8]Diesel use in machinery from Baky *et al.* (2010)

4. Results and discussion

4.1. Climate impact per hectare

The overall climate impact per ha, including the contributions from different GHG, for the two different crop rotations in Lanna and Lönnstorp is shown in Figure 1, while the contribution of different system processes to the overall climate impact is shown in Figure 2.

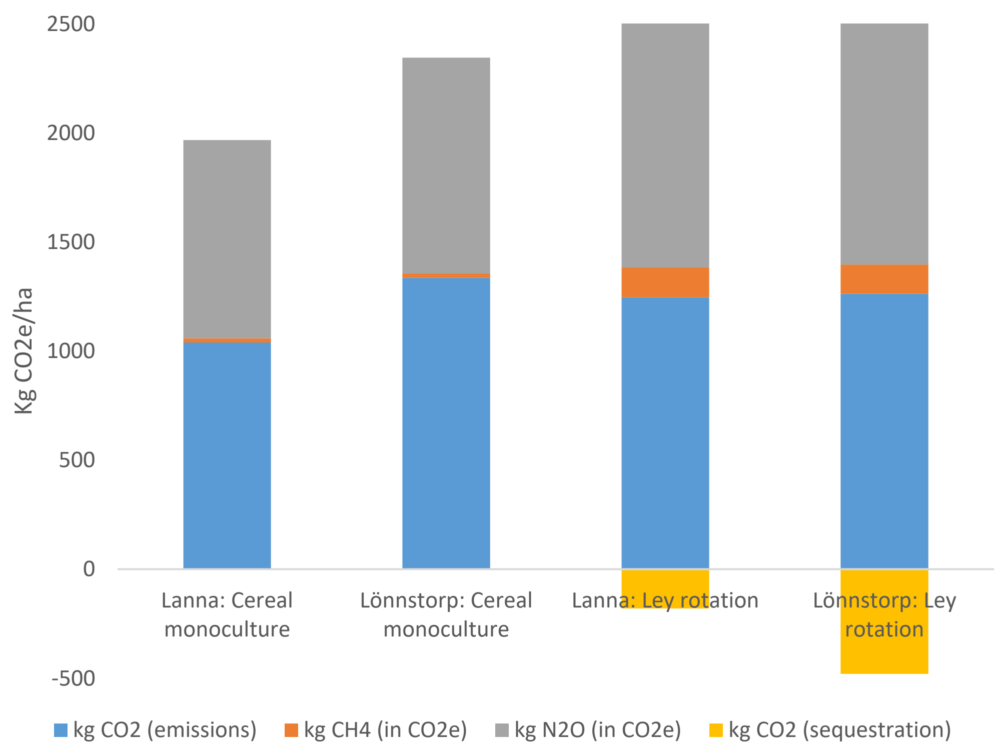

Figure 1. Climate impact per ha, including the contribution of different greenhouse gases, of the two different crop rotations (cereal monoculture, ley-dominated) in Lanna and Lönnstorp.

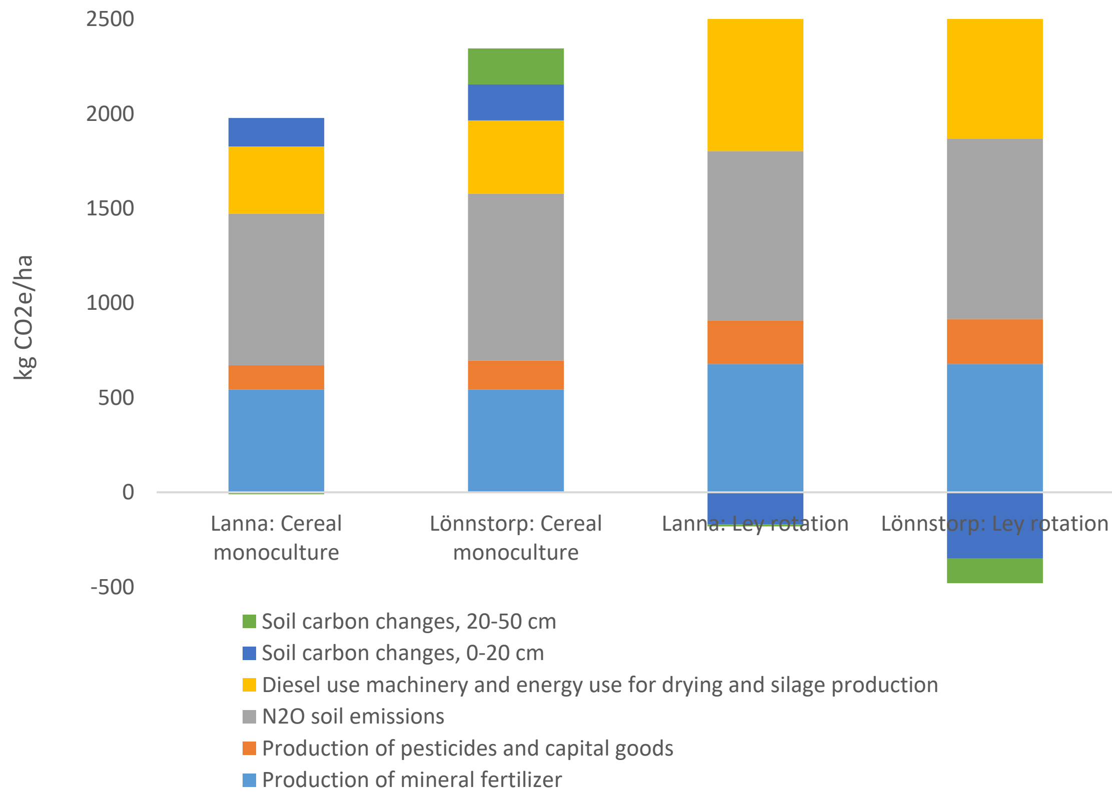

Figure 2. Contribution of different system processes to the overall climate impact of the different crop rotations (cereal monoculture, ley-dominated) in Lanna and Lönnstorp.

In the ley rotation at both locations, emissions of N_2O were important for the climate impact, contributing around 50-60% of the overall impact (Figure 1). These emissions was mainly explained by soil emissions and production of mineral fertiliser (Figure 2). For the cereal monocultures at both locations, emissions of N_2O constituted about 40-45% of the emissions, with the rest deriving from mineral fertiliser production and soil carbon changes. Field N_2O emissions are variable and depend on management, soil type, fertilization rates in relation to crop demand etc. (Wallman, 2021; Shcherbak *et al.*, 2014). Impacts from production of pesticides and capital goods were found to make a minor contribution to the overall impacts. The overall climate impact of the agricultural systems ranged between approximately 2000 and 2400 kg CO_2e/ha, with the highest climate impact observed in the ley rotation at Lanna (Figure 2). In the ley rotations, about 30% of the climate impact was due to production of silage. However, these results build on data taken from a report by Flysjö *et al.* (2008), which may contain outdated values.

The effects of soil carbon changes on climate impacts differed considerably between the rotations and sites and showed contrasting results between topsoil and subsoil. First, the effects of carbon changes were much greater at Lönnstorp than at Lanna for both rotations (Figure 2). Overall, soil carbon changes in the ley rotation resulted in sequestration of carbon, whereas the cereal monoculture was a source of GHG emissions due to soil carbon change. The climate effects of topsoil carbon change in the cereal monoculture and ley rotations at Lönnstorp were 1.3-fold and 2.1-fold greater, respectively, than the effects at Lanna. Second, there was little climate impact of the subsoil carbon changes at Lanna, while those at Lönnstorp had effects of comparable magnitude to those of topsoil carbon change. For example, emissions of 190 kg CO_2e/ha and sequestration of 130 kg CO_2e/ha were recorded with the subsoil carbon changes in the cereal monoculture and ley rotation, respectively, at Lönnstorp. However, the potential for reducing climate impact through soil carbon changes was relatively small in comparison with the overall emissions from the agricultural systems at both sites.

4.2. Climate impact per kilogram

The overall climate impact per kg, including the contributions from different GHG, for the two crop rotations in Lanna and Lönnstorp is shown Figure 3, while the contribution of different system processes to the overall climate impact per kg is shown in Figure 4.

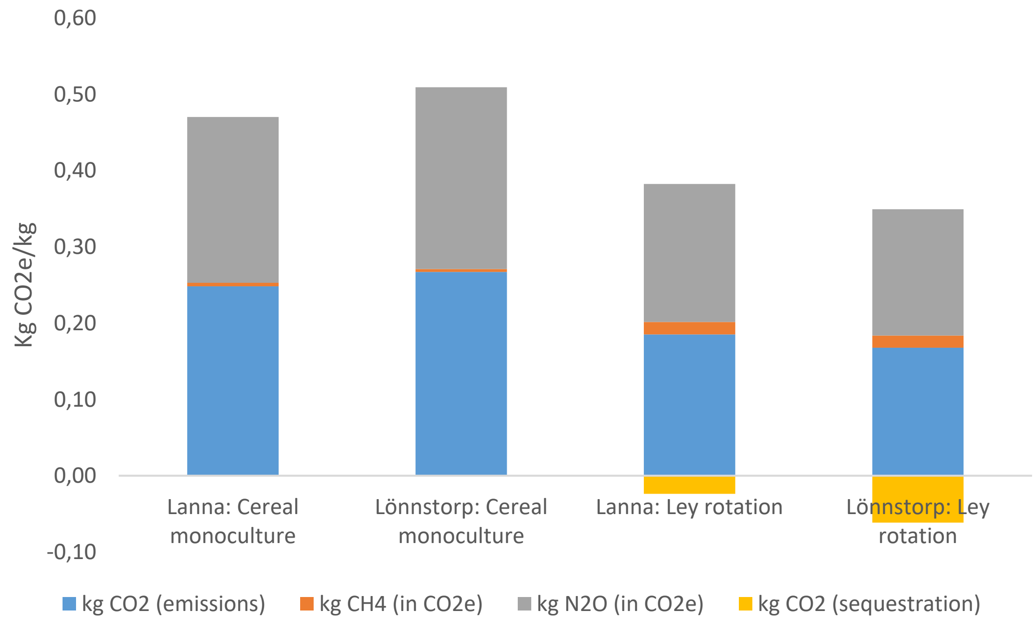

Figure 3. Climate impact per kg including the contributions from different greenhouses gases, of the two different crop rotations (cereal monoculture, ley-dominated) in Lanna and Lönnstorp.

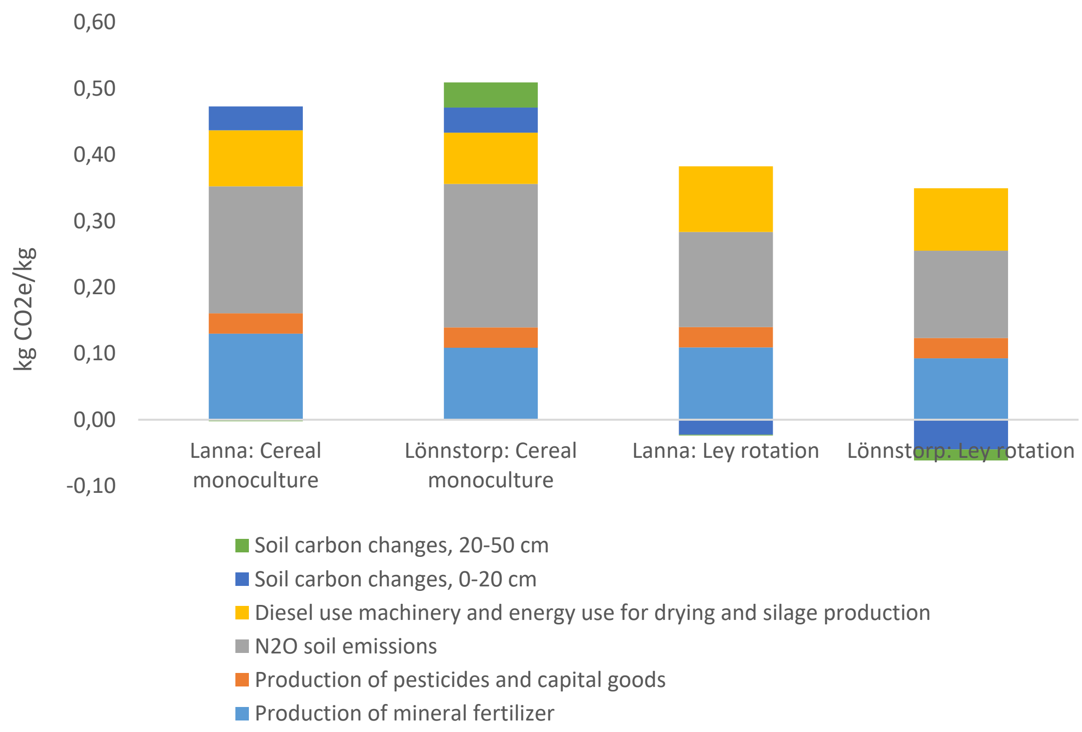

Figure 4. Contribution of different system processes on the overall climate impact of the different crop rotations (cereal monoculture, ley-dominated) in Lanna and Lönnstorp.

The impact per kg of output was similar for the Lanna monoculture and the Lönnstorp monoculture (about 0.5 kg CO_2e/kg). The ley rotations showed lower climate impact, 0.3-0.4 kg CO_2e/kg, which was mainly explained by their higher output in terms of yield.

4.3. Soil carbon changes during the study period

As reported by Börjesson *et al.* (2018), the soil organic carbon stock was considerably higher in the ley rotation than in the cereal monoculture at both Lanna and Lönnstorp. The annual accumulation of soil organic carbon decreased the overall climate impact of the ley rotation at Lanna and Lönnstorp by 6 and 19%, respectively.

For the cereal monoculture rotations, soil organic carbon stock decreased over the study period at both sites, which resulted in an increase in the overall climate impact of 6-15%. For cereals, the carbon input to soil was dominated by straw, whereas in ley rotations roots dominated the input, as the ley biomass was removed from the field after harvest. At the loamy Lönnstorp site, changes in soil organic carbon were observed in both the topsoil and subsoil. In the ley rotation at the Lönnstorp site, 27% of all soil carbon changes were due to changes in the subsoil, whereas up to 50% of the changes resulting from the cereal monoculture at Lönnstorp were due to changes in the topsoil. At the clayey Lanna site, the majority of soil organic carbon changes were observed in the topsoil. Börjesson et al. (2018) tentatively attributed these site-specific differences to a higher proportion of roots entering the subsoil in the loamy soil, in both the cereal and ley rotations. One explanation for the absence of significant changes in subsoil organic carbon at the clayey Lanna site could be restricted root growth in the subsoil because of high bulk density. As discussed by Börjesson et al. (2018), an estimated bulk density of 1.49 g cm^{-3} would be the critical limit for root growth at Lanna, whereas the measurements in the topsoil at this site was 1.46 g cm^{-3}, with higher values exceeding 1.49 g cm^{-3} found in the subsoil. Hence, the differences in subsoil carbon changes between the two sites can be partly attributed to differences in soil texture and structure.

Only a limited number of studies have been performed to date on changes in subsoil carbon content. However, within an ongoing project, (CarboSeq, which is part of an EJP SOIL research programme addressing agricultural soil management contributing to key societal challenges, including climate change), we are conducting a review of all publications on subsoil carbon for temperate regions (Parvin et al., in preparation). In the review, we are using meta-analysis techniques following the standardised mean difference (SMD) calculated between pairwise observations of improved management compared with a reference management practice. To date, we have compiled results from 35 long-term field studies on soil organic carbon (kg/ha) in topsoil (0-30 cm) and subsoil (30-60 cm) and the effect of perennial forage crops. Preliminary results comparing inclusion of perennial forage crops in the rotation with continuous cropping of cereals (reference treatment) indicate that forage crops have an overall significant positive effect on soil organic carbon concentration in the topsoil. For the subsoil, the results show greater variability (heterogeneity exceeding 50%) and are still undergoing detailed investigation, but some of the factors contributing to this variability have been identified. These are: fertilisation (Hu and Chabbi, 2022; Drury et al., 1998), age of the forage crop (Slessarev et al., 2020) and irrigation (Acharya et al., 2022). However, 10 of the studies reviewed show a high positive effect (SMD >0.8) of inclusion of forage crops in the rotations (e.g. Drury et al., 1998; Slessarev et al., 2020; Mikhailova et al., 2000), even higher in some cases than the effect observed at the Lönnstorp site in this study. It also emerged from the meta-analysis that soil organic carbon content is significantly and positively correlated with the proportion of forage crops in the rotation, in particular when the proportion exceeds 75%.

4.4. Impact of geographical location

There is no absolute limitation on where ley inclusion in crop rotations can be implemented. However, it is likely that regions which already have a very high proportion of leys on arable land (around 80%), such as the northernmost regions in Sweden, may not be able to include much more ley in their rotations. The southern and central forestland regions of Sweden have a slightly lower proportion of ley (around 60%), whereas the southeast, central east and southwest coastal regions have a much lower proportion of arable land under ley (15-35%). As shown in the present case study, the potential for carbon accumulation in the subsoil can be site-specific, depending on soil type and other physical conditions (e.g. soil texture and structure). In the topsoil, all other conditions (soil texture, climate, productivity, soil organic matter decomposition rate) being equal, the effect of leys on soil organic carbon content will likely be more important for soils with lower initial soil organic carbon content.

4.5. Implementation potential

The potential for implementation of this measure in practice is expected to depend largely on economic aspects of including more ley in the crop rotation. In regions with cash crop rotations, the economic outcome of introducing leys will depend on the market and demand for the forage biomass produced. However, the aboveground biomass does not necessarily have to be exported from the field and leys can be used solely for improving degraded soils with very low soil organic matter content, for example to improve poor soil structure and increase water-holding capacity. Soils with low soil organic carbon content are generally more common in southern Sweden, while in northern Sweden soil organic carbon content is usually higher. A more even distribution of cows in Sweden would imply that leys would become more common in lowland areas.

4.6. Time perspective of the measure

It is difficult to foresee any time limit on implementing the measure. Further, changes in soil organic carbon have not stabilised in 35 years of field trials in the case described here, suggesting that the crop rotation effect on soil carbon is likely to continue in future.

4.7. Impacts on other sustainability parameters

Including a ley in the crop rotation provides a permanent soil cover while the ley is in place and prevents water and wind erosion. Leys also start growing early in spring and continue growing during a significant period in late autumn, thereby helping to reduce the risk of phosphorus and nitrogen leaching. The residual soil effects of leys can have a positive influence on yield of the following crop (e.g. winter wheat or spring cereal) and may allow nitrogen fertiliser application rates to be lowered. However, this effect depends on the proportion of leguminous species (in mixed leys) and when the ley is ploughed (spring or autumn), which in turn depends on soil type and climate conditions. Further, Leys are also beneficial for crop protection, supressing weeds and fungal pathogen.

A drawback is that increased cultivation of ley would decrease production of cereals regionally, which in turn would increase the demand for cereal imports from other regions.

The indirect climate effects of changes in crop production were not analysed in the present study, but it is important to consider these effects in more comprehensive climate impact assessments of the Swedish agriculture sector in future.

5. Conclusions

This study analysed the effects of carbon stock changes in topsoil and subsoil on the overall climate impact of agricultural production systems for two crop rotations (cereal monoculture, ley-dominated) in two different locations in Sweden. The overall climate impact of the agricultural systems ranged from 2000 to 2400 kg CO_2e/ha, with the highest climate impact observed in one of the ley rotations. On taking into account outputs in yield, lower climate impact was found in both ley rotations (0.3-0.4 kg CO_2e/kg), a difference explained by higher yield levels in those rotations. In comparison, the cereal rotations had a climate impact of about 0.5 kg CO_2e/kg. In the cereal monoculture rotations, soil organic carbon stock decreased over the 35-year study period, which resulted in an annual increase in the overall climate impact of 8-19%. In the ley rotations, annual accumulation of soil organic carbon occurred, which decreased the overall climate impact at the two sites by 7% and 18%, respectively. The largest effect of soil carbon accumulation was observed in the ley rotation at the loamy Lönnstorp site, where soil carbon accumulation was observed in both the topsoil and subsoil, possibly due to a higher proportion of roots entering the subsoil than at the clayey Lanna site. The ley-dominated rotation in this study had a higher climate impact from field operations and agricultural inputs and it was only on the Lönnstorp site with the highest soil organic carbon accumulation where the overall climate impact including the effect from carbon sequestration was lower than the cereal rotation.

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MISTRA
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