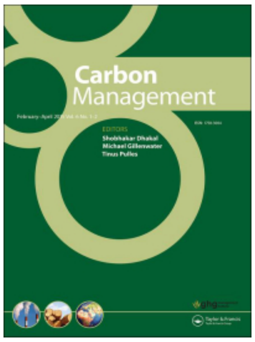

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Higher carbon sequestration on Swedish dairy farms compared with other farm types as revealed by national soil inventories

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ABSTRACT

Small changes in the large stock of soil organic carbon (SOC) can have a substantial influence on the climate impact of agriculture. We used information from a Swedish soil monitoring program, in combination with farm census data, to analyze decadal SOC concentrations and SOC stock changes on dairy farms compared with other farm types, and to quantify the climate impact of these changes on dairy farms. Soil monitoring data included topsoil samples from two inventories on 159 dairy farms, 86 beef farms, 318 arable farms, and 13 pig farms, taken at the same locations in 2001–2007 and 2011–2017. Concentrations of SOC on dairy farms (3.0%) were significantly higher than on arable farms (2.3%) and pig farms (2.4%), but not significantly different from beef farms (3.1%). SOC concentration was correlated with proportion of ley at farm scale. SOC stocks in the upper 20 cm increased significantly on dairy, beef, and arable farms, by 0.38, 0.14, and 0.21 Mg C ha^{-1} $year^{-1}$, respectively, between 2001–2007 and 2011–2017. For dairy farms, this corresponded to -1.4 Mg CO_2 ha^{-1} and approximately -0.22 kg CO_2 kg^{-1} energy-corrected milk, demonstrating that SOC changes could have a substantial influence on the climate footprint of milk.

KEYWORDS
Soil organic carbon; milk production systems; climate impact; soil and crop monitoring program

Introduction

Globally, soils contain approximately 1500 Pg organic carbon (C) in the top 100 cm, which is more than the C stored in vegetation and atmosphere combined [1, 2]. The magnitude of the global soil C pool means that even a small relative change can have a significant effect on atmospheric carbon dioxide (CO_2) concentrations. Soil organic carbon (SOC) also promotes several soil quality functions related to fertility and resilience such as erosion resistance, water-holding capacity, and nutrient delivery to plants and microorganisms [3].

There is strong interest in increasing global SOC stocks to mitigate climate change, because increased C storage in soil is considered more cost-effective than other methods creating negative emissions [4–6]. For example, the "4 per 1000" initiative was launched at the 2015 United Nations Climate Change Conference (COP 21) in Paris, supported by many different actors in the public and private sector [4, 7]. The rationale behind the initiative is that increasing C stocks in the top 40 cm of agricultural soils globally by 4‰ per year would significantly counteract the climate impact of total greenhouse gas emissions. Changes in land use and management are associated with changes in both the quantity and quality of inputs, which affects the soil C balance. For example, transition from cropland to grassland and increased frequency of perennial forage crops are generally expected to increase SOC stocks [8, 9]. However, the magnitude of actual SOC sequestration achieved depends on both management and pedoclimatic site characteristics, and can therefore vary considerably between farms [10]. Developing knowledge about SOC stocks and stock changes in different agricultural production systems is critical in order to increase SOC stocks or avoid losses of previously built-up stocks.

Cultivation of perennial grass, often in combination with clover, is fundamental in cattle production, both for grazing and as silage, and roughage provides a high proportion of the feed [11]. Dairy

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farming has been the core of Swedish agriculture for a long time, but the dairy sector has undergone dramatic structural changes during the past century, affecting the location of dairy farms, average farm size, and feed rations [12]. In particular, there has been a transition from smallholder farms with diverse production towards fewer, but much larger and more specialized, farms. Since the 1960s, the proportions of grain and feed concentrate in feed rations have also increased [12]. This has led to higher milk yield per cow, but has also affected crop rotations, both on-farm and on other farms producing the purchased feed. These changes may have affected SOC stocks and SOC dynamics in arable soil on different farm types.

Dairy products contribute to negative environmental impacts caused by Swedish food consumption, but the climate impact can be partly counteracted by SOC sequestration [13, 14]. Including SOC changes in environmental assessments of dairy products has been shown to influence the conclusions when comparing different management options such as feed strategy [14, 15]. Accurate estimates of SOC changes on dairy farms are therefore important for comparisons of the environmental performance of different dairy production systems or different types of farms, and for comparisons of dairy to other products [16, 17]. Despite this, SOC dynamics are often neglected in environmental assessments of agricultural products, mainly due to their high uncertainty [18].

Due to the high spatial variation in SOC content, many soil samples are usually required to quantify the relatively small SOC changes over time brought about by specific land use or land management [19]. National soil monitoring programs, with repeated systematic determination of soil properties at different sites or areas, are a valuable resource for examining spatial and temporal variations [20]. The number of samples taken and sampling strategy vary considerably in European soil monitoring networks, but Saby *et al.* [21] suggest that at least a 10-year period is necessary to determine temporal changes in SOC. In combination with information on management at each sampling point from census data or interviews with farmers, it is possible to establish the influence of factors such as the proportion of different crop types in the rotation, tillage, or organic amendments on observed SOC changes over time [22–24]. The Swedish soil and crop monitoring program (Mark- och grödoinventeringen) has been ongoing since the late 1980s. Concentration of SOC in the topsoil has been one of the variables measured and this information can be used for estimating changes in SOC stocks at a large number of sites over time. A previous study based on the data available at that time, concluded that SOC concentrations in Swedish arable topsoils had increased since monitoring began [25]. An increasing area used for leys was identified as the main driver for this trend. Eriksson *et al.* [26] and Eriksson [27] showed that SOC concentrations differed between farm types, based on data from the Swedish soil and crop monitoring program, but did not assess the changes over time.

The full dataset from the last inventory has not previously been used for analyzing the trends in SOC over time from the perspective of different farm types and in particular, the effect of field-based measurements of changes in SOC stocks have not been included in climate impact assessments for Swedish dairy farms. In this study, we used data from the last two inventories, to analyze SOC in arable mineral topsoil (0–20 cm depth), in order to address the following research questions:

- What is the SOC concentration in arable fields on different farm types in Sweden, and how does it relate to the proportion of ley in the crop rotation, selected soil characteristics, and geographical region?
- Is it possible to detect changes in SOC concentration in arable fields on different farm types in Sweden over a decade? If so, how does it differ between dairy farms and other types of farm?
- What is the climate impact of the SOC change occurring on an average Swedish dairy farm?

Material and methods

Data sources

The Swedish soil and crop monitoring program has the task of describing the conditions in Swedish agricultural soils and the quality of crops on existing farms. To date, the program has included three inventories, conducted between 1988 and 1995 (Inventory I), 2001 and 2007 (Inventory II), and 2011 and 2017 (Inventory III). The samples for Inventory I and II were not taken at the same locations. The sites in Inventory II were selected by generating random geographical locations within Sweden and then filtering out sites located on arable land. Geographical regions

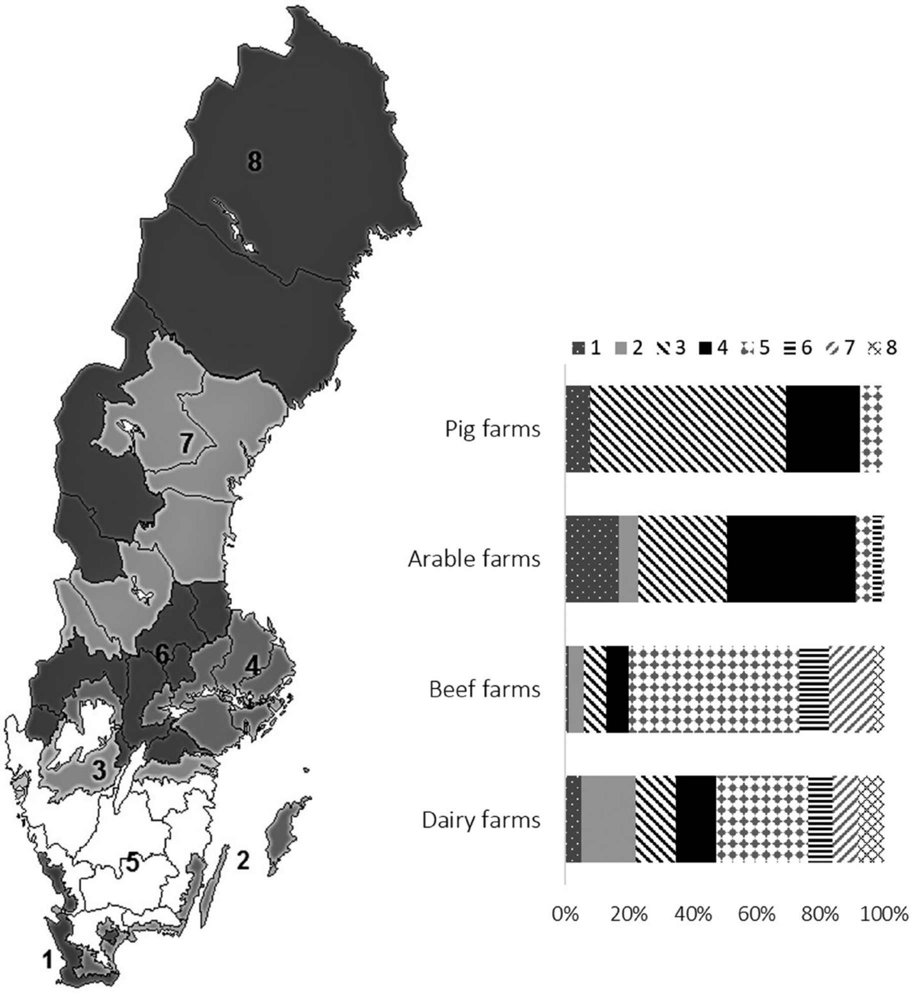

Figure 1. **(Left) Location of the eight production areas (1–8) used in Swedish agricultural statistics. These production areas are designated according to pedoclimatic condition, i.e. similarities in soil type, topography, and climate. Production areas 1–4 are characterized by plains while 5–8 are dominated by forest. (Right) Distribution of the different farm types in production areas 1–8, based on the 576 sampling points included in this study (see section 2.2).**

with more arable land thus appear more frequently in the inventories. Inventory III primarily involved revisiting sampling points from Inventory II, but also included new sampling points in order to replace points that had lapsed since Inventory II, e.g. due to land use change [27]. In this study, we considered only data from the sampling points included in both Inventory II and III, which comprised 1821 locations. The exact sampling points in Inventory II and III were located at a maximum distance of 1 m from each other, based on the accuracy of the positioning equipment [27].

At each sampling site during both Inventory II and III, nine core samples were taken from the topsoil (0–20 cm) within a 3-m radius from the sampling point [27]. These nine samples were combined into one composite sample, which was analyzed for a wide range of soil characteristics and trace elements during both Inventory II and III [25, 27]. Soil texture was only analyzed for Inventory II. Apart from SOC content, we selected three additional variables, clay content, total soil nitrogen (N_{tot}) content, and pH, for statistical testing (see section 2.2). A thorough description of the sampling procedure and sample analysis is provided in Swedish in Eriksson [27] and is summarized in English by Poeplau *et al.* [25].

To complement the sampling data from the soil and crop monitoring program, we used data from the Swedish Farm Register [28]. Each sampling point was connected to a farm in the Swedish Farm Register by comparing geographic coordinates, and data was extracted for the sampled farms during the years when samples were taken. These data included farm type (i.e. the main production enterprise), number of dairy cows that delivered milk during that year, total area of arable land, and amount of arable land used for ley cultivation. The data in the Farm Register are based on information on land use and number of animals reported by farmers to the Swedish Board of Agriculture. The farm type classification is based on standardized estimation of the amount of labor needed to manage the reported land use and animals [28].

Data analysis

The Swedish soil and crop monitoring program covers arable land all over Sweden and includes both mineral and organic soils. Soils with SOC content higher than 7%, considered organic soils [29], were excluded from our analysis, since SOC changes in organic soils cannot be quantified by simply measuring the SOC concentration at a certain soil depth. To detect changes in organic soils, the height of the organic layer has to be monitored over time, which was not done in the inventories. This criterion eliminated almost 10% of the sampling points (leaving 1651 points). Information from the Swedish Farm Register was available for 1563 of these locations. From this dataset, we removed data points for farms that had different farm type classifications at the time of Inventory II and III. This criterion further reduced the dataset by 53%, resulting in a dataset with 733 data points. We then selected data points for farms classified specifically as dairy farms, beef farms, arable farms, or pig farms, which resulted in 621 data points in total (i.e. farms that did not belong to any of these categories were excluded from the analysis).

Grouped data points were then analyzed for outliers by linear regression between observed SOC concentrations from Inventory II and III. Sites where the residual (difference between observed SOC concentration and that modeled by linear regression) exceeded 10 mg C g^{-1} soil were removed from the dataset. This excluded 7% of the data and resulted in a dataset with 159 data points for dairy farms, 86 for beef farms, 318 for arable farms, and 13 for pig farms. These 576 data points are hereafter referred to as "all farms." The different farm types are unevenly distributed across the country (Figure 1). Arable and pig farms are concentrated to the coastal and plain districts (production areas 1–4) while dairy and in particular beef farms to larger extent are found in production areas 5–8 dominated by forest and mountains.

R Studio 1.4.1717 [30] was used to analyze the data. Data handling was done using the *openxlsx* [31] and *plyr* [32] packages, and diagrams were created using *ggplot* (*ggplot2* package [33]). Differences between inventories were determined by Wilcoxon rank sum test (function *wilcox.test*). Differences between farm types, and between production areas, were determined by the non-parametrical Kruskal–Wallis test (function *kruskal.test*) and pairwise Wilcoxon test (function *pairwise.wilcox.test*) with *p*-value correction after Benjamini and Hochberg [34] (argument *p.adjust.method* = *"BH"*) as post-hoc test. We used linear regression analysis (function *lm()*) to determine relationships between observed SOC concentration in Inventory III and selected soil and management parameters (proportion of ley, clay content, silt content, soil N_{tot} content, and pH). We also determined the relationships between SOC concentration change (between Inventory II and III) and the following parameters: clay content, silt content, change in proportion of ley, change in N_{tot} content, change in pH, and SOC concentration in Inventory II ("initial SOC concentration").

In order to calculate SOC stocks and related changes over time, we estimated soil bulk density for each sampling point *f* using one of the pedotransfer functions derived from a Swedish database, which explained 52% of the variation in 337 topsoil samples [35]. The model estimated the soil bulk density ρ_f (Mg m^{-3}) as a linear function of the organic C content $C_{org,f}$ (%) according to:

$$\rho_f = 1.6384 - 0.0945 * C_{org,f} \quad (1)$$

SOC stocks in Mg C ha^{-1} were calculated for each sampling point in both inventories *i* by combining data on SOC concentration with data on bulk density and soil volume in the top 20 cm of the soil *V* (m^3 ha^{-1}) according to:

$$SOC\ stock_{f,i} = \rho_f * C_{org,f,i} * V \quad (2)$$

Climate impact calculations for SOC changes on dairy farms

We calculated the climate impact of SOC changes on dairy farms and estimated the climate impact per kg energy-corrected milk (ECM), in order to compare the climate impact of on-farm SOC changes with published data on the total climate impact (expressed as CO_2-equivalents) of dairy production. ECM is commonly used as a unit to normalize milk yields in relation to their quality, e.g. in statistics and life cycle assessments of the environmental footprint of dairy products [36, 37].

We calculated annual SOC change in Mg C ha^{-1} $year^{-1}$ for each sampling point using the difference in SOC stocks between Inventory II and Inventory III and the number of years between sampling occasions on each farm ($t_3 - t_2$, approximately 10 years):

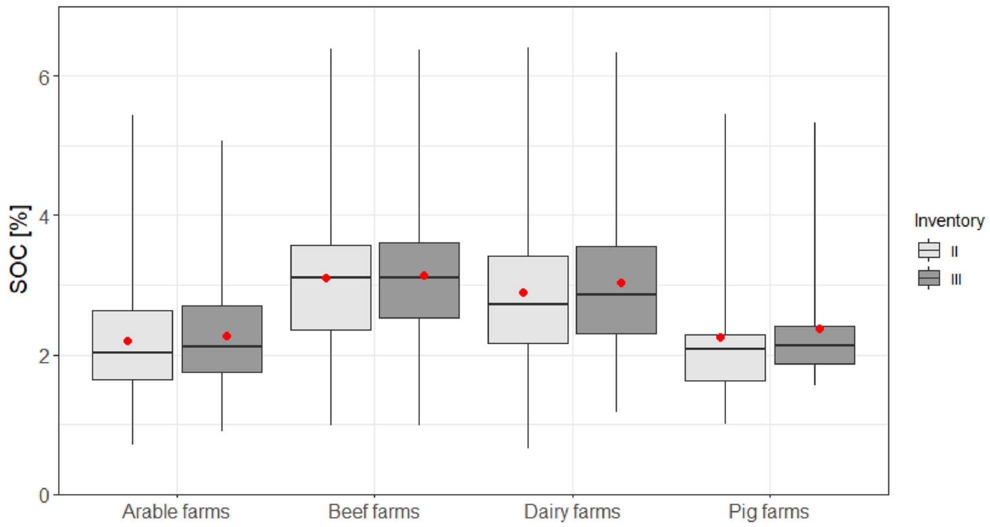

Figure 2. Soil organic carbon (SOC) concentration (% dry matter C) on different farm types in Inventory II and III. The average interval between the two inventories was 10 years. Each boxplot shows the median (black horizontal line), 25th percentile (lower end of the box), 75th percentile (upper end of the box), minimum, and maximum. The mean is indicated by red dots.

$$Annual\ SOC\ change_f = \frac{\Delta SOC\ stock_f}{t_3 - t_2} \quad (3)$$

We calculated annual SOC change per kg milk using the area of arable land on each farm (*AL*, ha), number of dairy cows (*DC*), and milk production per dairy cow (*M*, kg ECM (dairy cow)$^{-1}$ year^{-1}). This was done using data from Inventory III, since those best represent the current situation. A value of 9721 kg ECM per dairy cow was used, based on statistics on the average milk production of a dairy cow in 2014 (the average year of Inventory III sampling) [37].

$$Annual\ SOC\ change\ per\ kg\ milk_f = \frac{Annual\ SOC\ change_f * AL_f}{DC_f * M} \quad (4)$$

Finally, we calculated the climate impacts of SOC changes by using the mass fraction of C in CO_2. In the main results, the climate impact of SOC change is allocated fully to the milk.

Results

SOC concentrations, stocks, and stock changes on different farm types

Mean SOC concentration was significantly higher on dairy farms than on arable farms and pig farms in both Inventory II and III ($p < 0.05$) (Figure 2, Figure S1). In Inventory III, mean SOC stocks (0–20 cm) on dairy farms were 16.7 Mg C ha^{-1} higher than on arable farms, and 14.9 Mg C ha^{-1} higher than on pig farms (Table 1). The mean SOC concentration on dairy farms was lower than that on beef farms, but the difference between these farm types was not statistically significant for either of the inventories.

The mean SOC concentration significantly increased between Inventory II and III for all farm types except pig farms (Table 1). The largest increase in mean SOC concentration was observed on dairy farms (from 2.90 to 3.03%, corresponding to 0.38 Mg C ha^{-1}year^{-1} or about 5‰ annual increase), while the smallest change was observed on beef farms (from 3.10 to 3.14%, corresponding to 0.14 Mg C ha^{-1}year^{-1} or about 2‰ annual increase) (Figure 2 and Figure S2; Table 1).

Relationships between SOC and soil parameters and site

Comparison of SOC concentrations on all farms against different site characteristics showed statistically significant positive relationships between SOC concentration in Inventory III and proportion of ley (Figure 3a) and soil N_{tot} content (Figure 3b). There was only a weak negative relationship between SOC concentration and soil pH (R^2=0.09; Figure S3). No correlation was found with clay or silt content (Figure S3). However, there were statistically significant differences in mean SOC concentration and Swedish production area (1–8) for all farms (Table 2).

Changes in SOC concentrations between Inventory II and III across all farms decreased significantly with the initial SOC concentration in Inventory II (Figure 4a), and increased significantly with changes in soil N_{tot} content (Figure 4b). A very weak correlation with changes in pH was found (R^2 = 0.01; Figure S4). No correlation was

Table 1. Estimated mean soil organic carbon (SOC) stocks (Mg C ha^{-1}) on different Swedish farm types in Inventory II and III, mean annual SOC change (Mg C ha^{-1} $year^{-1}$), number of observations for each farm type, and average time between sampling in Inventory II and III.

	Mean SOC stock Inventory II	Mean SOC stock Inventory III	Mean annual SOC change	Number of observations	Average number of years between Inventory II and III
Dairy farms	76.8	80.8	0.38	159	9.7
Beef farms	81.3	82.8	0.14	86	9.7
Arable farms	62.0	64.1	0.21	318	10
Pig farms	62.0	65.9	n.s	13	10

n.s = not significant.

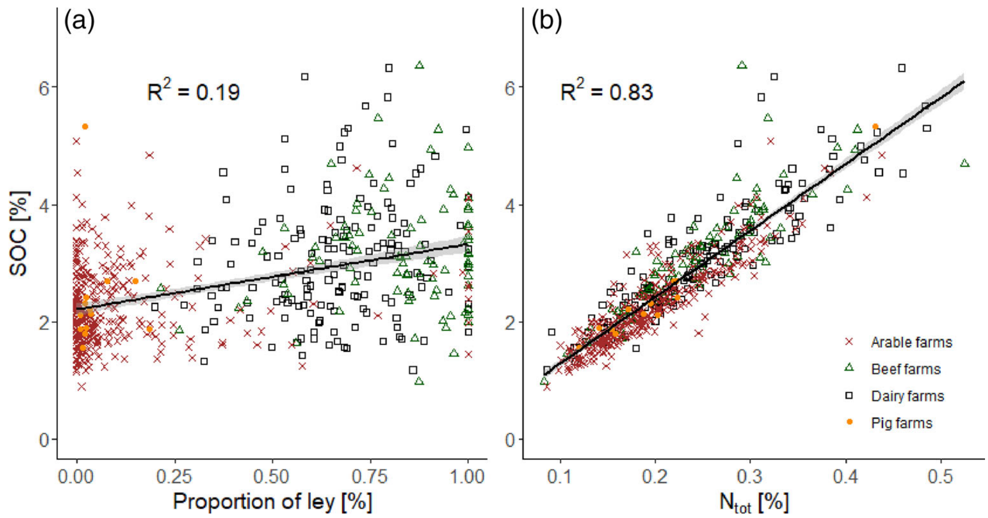

Figure 3. Results of regression analysis on soil organic carbon (SOC) concentration in Inventory III (y-axis) against (a) proportion of ley on the farm and (b) total nitrogen (N_{tot}) content in soil.

Table 2. Mean soil organic carbon (SOC) concentrations (% dry matter C) on all farms in each Swedish production area (1–8, see Figure 1) and results from the Kruskal-Wallis test comparing SOC concentrations in Inventory III between the eight Swedish production areas.

Production area	1	2	3	4	5	6	7	Mean SOC concentration (%)	Number of farms
1								2.04	63
2	*							2.57	51
3	*	n.s						2.39	122
4	*	n.s	n.s					2.46	157
5	*	*	*	*				3.12	110
6	*	n.s	n.s	n.s	n.s			2.76	29
7	*	*	*	*	n.s	n.s		3.39	28
8	*	n.s	*	*	n.s	n.s	n.s	3.14	16

An asterisk signifies statistically significant differences between mean SOC concentrations in the respective production areas and n.s signifies no significant difference.

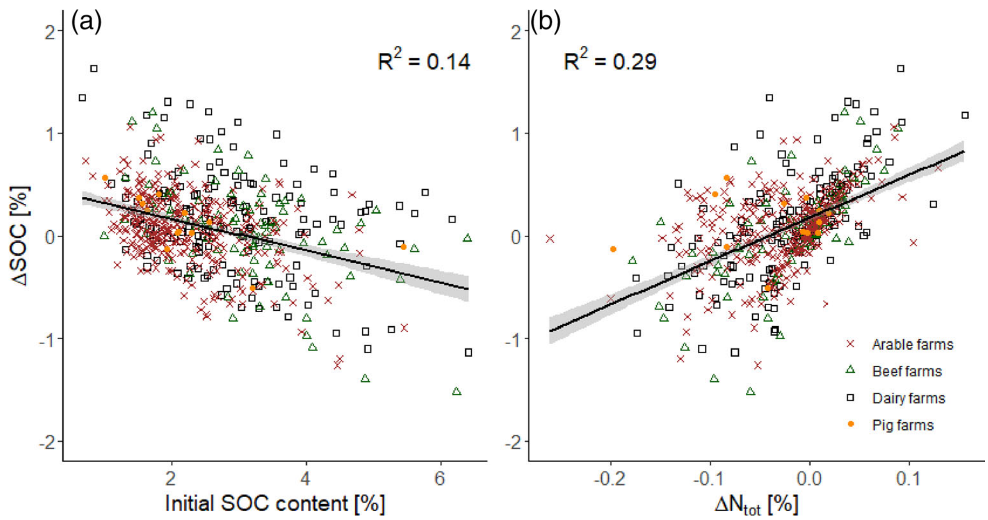

Figure 4. Regression analysis of changes in soil organic carbon (SOC) concentration (y-axis) against (a) initial SOC concentration (Inventory II) and (b) changes in total nitrogen (N_{tot}) content in soil.

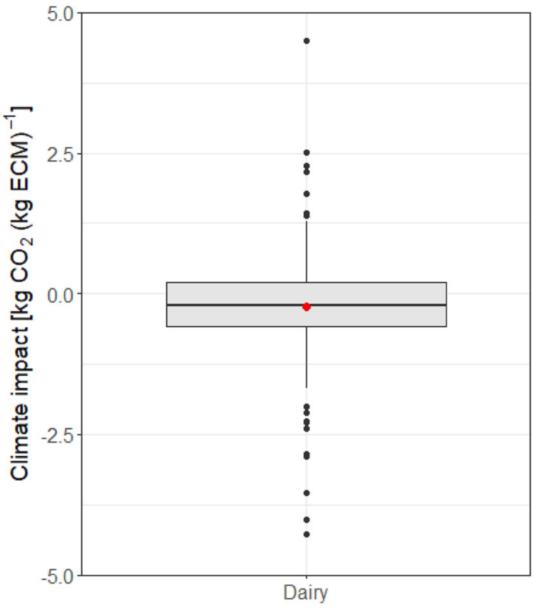

Figure 5. Climate impact of soil organic carbon (SOC) changes [kg per kg energy-corrected milk, ECM] on dairy farms in Inventory III when all changes were allocated to the milk. The boxplot shows the median (black horizontal lines), 25th percentile (lower end of the box), 75th percentile (upper end of the box), minimum (lower whisker), and maximum (upper whisker), as well as outliers (black dots), and the mean (red dot).

found between changes in SOC concentration and clay or silt content, or changes in the proportion of ley on the farm (Figure S4). There were also no significant differences between Swedish production areas 1–8 regarding the changes in SOC concentration between Inventory II and III (data not shown).

Climate impact of SOC changes on dairy farms

There was a statistically significant SOC change on dairy farms between Inventory II and III of 1.3 mg g^{-1} soil. Using the estimated bulk density values to convert concentrations to stocks for each site resulted in a mean net increase of 3.9 Mg C ha^{-1} in the top 20 cm on dairy farms between the two inventories. This corresponded to uptake of 0.38 Mg C ha^{-1} $year^{-1}$, or 1.4 Mg CO_2 ha^{-1} $year^{-1}$. The average area of arable land on each farm at the time of Inventory III was 157 ha and the average number of dairy cows per farm was 107. Thus the estimated mean climate impact was −2.33 kg CO_2 dairy cow^{-1} $year^{-1}$ and −0.24 kg CO_2 (kg $ECM)^{-1}$ when the entire climate impact of SOC change was allocated to the milk (Figure 5). However, the impacts for the individual dairy farms ranged from −1.67 to 1.28 kg CO_2 (kg $ECM)^{-1}$, with some farms even having values as low as −4.28 and as high as 4.49 kg CO_2 (kg $ECM)^{-1}$ (marked as outliers in Figure 5).

Discussion

Differences in SOC concentration between farm types

Dairy farms had higher mean SOC concentrations in the topsoil than arable farms and pig farms (Figure 2). Beef farms had slightly higher SOC concentrations than dairy farms, but the difference was not statistically significant. This is in agreement with findings by e.g. Capriel [23] that soils on farms with livestock generally have higher SOC content than soils on farms without livestock. The average proportion of ley crops on dairy, beef, arable, and pig farms during Inventory III was 67, 82, 11, and 5%, respectively. An increasing proportion of perennial forage crops in crop rotations is generally expected to increase SOC stocks [8, 9] and SOC concentration was found to correlate with the proportion of ley in Inventory III in this study (Figure 3). The higher proportion of perennial ley crops is therefore most likely an important reason for the higher SOC concentrations on dairy and beef farms. Compared with arable farms in particular, greater use of manures could also have contributed to the higher SOC concentration on dairy and beef farms. Field trials on crop rotations with perennial crops and manure have shown that both these factors have positive effects on SOC stocks, to varying extents [9, 38–40].

It remains difficult to disentangle the effects of proportion of ley and carbon input from manure, since these two variables are interrelated and since manure input can be expected to correlate with the proportion of leys. On analyzing 25 years of data from well-defined monitoring sites on Swiss cropland, Gubler *et al.* [24] found that manure input (together with initial SOC:clay ratio) was more important than the presence of leys *per se*. The variation in SOC concentration between Swedish farm types shows that other factors also have a large influence on SOC stocks, e.g. factors related to soil management and inherent characteristics of the site. In addition to the correlation with proportion of ley, soil nitrogen concentration showed a strong positive correlation with SOC concentration (Figure 4), which is not surprising considering the narrow stoichiometric C:N ratio in soil in general [41].

There were significant differences in mean SOC concentrations between different geographical regions of Sweden, and SOC concentrations were higher in production areas 5–8 compared to production areas 1–4 (Table 2). Although these mean concentrations were only determined on a subsample from Inventory III, they reflect the regional differences determined in a previous study using all the data from Inventory I [29]. This is also in line with previous findings that SOC dynamics depend on conditions at the site, such as inherent soil characteristics and climate [10, 42]. Pedoclimatic conditions affect plant growth, and thereby C inputs to the soil, and also SOC decomposition rate. However, our data did not show significant correlations between SOC concentration and clay or silt content, despite the ability of clay to protect organic matter from decay [43]. One explanation for this is that farm types are not evenly distributed within the country and soil types and proportion of perennial crops in crop rotations also vary across Sweden, thus these factors may counteract each other. For example, clay content is highest in production area 4 [44], which is dominated by arable farms, and arable farms turned out to have a lower SOC concentration than beef and dairy farms (Figure 2). Furthermore, the relationships between SOC and soil texture in soil-monitoring studies are highly variable, sometimes they are present [24] but not always [23]. This is also true when assessing changes in SOC stocks in long-term field experiments [9].

Changes in SOC concentration between inventories

The mean SOC concentration increased with time on all farm types, although the increase was not statistically significant for pig farms, likely due to the much more limited number of sampling points for that farm type. The average increase was highest for dairy farms (1.3 mg C g^{-1} soil), followed by arable farms (0.7 mg C g^{-1} soil) and beef farms (0.4 mg C g^{-1} soil) (Figure 2). A previous analysis using the Swedish soil and crop monitoring program indicated that the increase in SOC could be explained by an increase in ley cultivation [25], since perennial forage crops build up SOC stocks by allocating more C to roots compared with annual crops, and root-derived C has a longer turnover time than aboveground crop residues [45, 46]. Despite the significant correlation between total SOC concentration and proportion of ley (Figure 3a), there was no significant correlation between the SOC change (ΔSOC) and change in the proportion of leys for all farms in the present study (Figure S4d). This may be because in our analysis we only assessed a decadal change, while the previous analysis assessed these relationships over two decades including data from Inventory I. Although that study only included about half of the data from Inventory III that were available at the time, it was shown that the proportion of leys increased slightly more between Inventory I and II than between Inventory II and III [25].

In addition to differences in ley cultivation, there are several other potential explanations for the increases in SOC across farm types and the particularly high increase on dairy farms. For instance, land use history can significantly influence current SOC changes [47]. Swedish agriculture has undergone substantial structural changes and technological development during the past century, which means that production and agricultural management at many of the sampled sites have changed over time. Furthermore, yields per hectare of spring cereals and winter wheat increased slightly between 2005 and 2015 [48]. Higher yield results in higher C inputs from above- and belowground crop residues, and is probably one of the reasons for the increase in mean SOC concentrations on all farm types. The area of winter wheat increased during the same period, mostly at the expense of spring barley and oats. Compared with spring cereals, winter wheat has much higher yield and net primary production potential, and thereby leaves more crop residues in the field. For winter rapeseed, another crop leaving an important amount of crop residues, both the area and yield increased in the same period.

A contributing factor for the differences in ΔSOC between farm types could be that farm types are not equally distributed within the production areas in Sweden (Figure 1). Dairy farms are more evenly distributed between the production areas than the other farm types, e.g. the majority of beef farms were located in production area 5, which has a high SOC content in general (Table 2). The majority of arable farms were located in production areas 3 and 4, which have a lower SOC content. In general, that means that due to the regional differences in SOC, higher C inputs would be needed on the beef farms in production area 5 to achieve the same SOC increase as on the arable farms in production areas 3 and 4. This is also reflected in the negative relationship between SOC change and initial SOC concentration (Figure 5a; [40]). However, more research is needed to explain how different combinations of pedoclimatic conditions, geographical location, and previous and present land use affect the current SOC changes observed.

The mean increase in SOC in the top 20 cm of soil on dairy farms corresponded to about 0.38 Mg C ha^{-1} $year^{-1}$ (Table 1), which is within the range of SOC stock changes (0.36–0.66 Mg C ha^{-1} $year^{-1}$ to 20 cm depth) reported in long-term field experiments comparing ley-dominated rotations with continuous annual cereal cropping [40, 49]. However, the SOC change on individual dairy farms included in our analysis also varied, from a 3.9 Mg C ha^{-1} $year^{-1}$ decrease to a 5.1 C ha^{-1} $year^{-1}$ increase, so it is difficult to compare results from individual sites since local factors like climate, soil type, and previous land use influence the net SOC loss or gain [40, 50]. The mean SOC stock increase on dairy farms between Inventory II and III corresponded to an approximately 5‰ annual increase over the 10-year period. This means that the topsoils (0–20 cm) on Swedish dairy farms on average exceeded the goal set by the "4 per 1000" initiative, although that goal is based on increases in the top 40 cm of soils. The SOC increases in the top 20 cm of soils on beef farms and arable farms were smaller than 4‰, and were not significant for pig farms.

Climate impact of SOC change and stocks on dairy farms

The SOC increase on dairy farms resulted in a mean climate impact of −1.4 Mg CO_2 ha^{-1} and −0.24 kg CO_2 kg^{-1} ECM. However, that is without accounting for the fact that the dairy farms could deliver several products. If we instead allocate only 93% of this climate impact to the milk, assuming allocation of the remaining 7% to the meat based on Moberg *et al.* [51], the mean climate impact was −0.22 kg CO_2 kg^{-1} ECM. According to Moberg *et al.* [51], Swedish milk has a climate impact of 1.27 kg CO_2-equivalents kg^{-1} ECM (excluding SOC change), so uptake of 0.22 kg CO_2 kg^{-1} ECM would correspond to 17% of the climate impact. Trydeman Knudsen *et al.* [14] evaluated the potential effect of including SOC changes when assessing the climate impact of milk in Denmark, the UK, and Austria, using models to estimate the SOC change, and concluded that SOC changes could contribute between −0.05 and −0.19 kg CO_2 kg^{-1} ECM. Moberg *et al.* [51] calculated potential SOC changes for Swedish milk using a simpler model, which gave a climate impact of −0.04 kg CO_2 kg^{-1} ECM. The SOC changes found in the present study are therefore higher or even considerably higher than previously estimated contributions of SOC changes to ECM for dairy production. However, we did not account for SOC changes induced by the dairy production elsewhere than on the arable soils on the farm, e.g. in pasture soils or in soils used to produce feeds imported to the farm. This means that the net climate effect of SOC changes induced by dairy production could be different than quantified here. Nevertheless, Swedish arable farms in the present study on average also showed an increase in SOC (Figure 2), and SOC changes in Swedish pastures are reported to show a slightly positive trend [52]. On the other hand, the dairy farms could use feeds imported from locations where land use change like deforestation is a substantial problem, causing large SOC losses [11]. Overall, the results in this case study indicate that it is important to account for SOC changes when assessing the climate impact of dairy production, and that the climate impact of SOC increases on dairy farms may be larger than estimated in previous studies.

In addition to the climate benefit of net increases in SOC, temporary storage of C in products and in the soil also influences the climate by delaying emissions, possibly contributing to avoiding climate system tipping points [53]. Thus, there is also a climate benefit of the higher SOC stocks on dairy farms compared with, e.g. arable farms, but this is much more difficult to quantify than the climate impact of net annual SOC change since it requires assumptions on alternative land use and longevity of the temporary storage [53, 54]. Apart from keeping CO_2 out of the atmosphere, high SOC stocks also enhance soil quality and biotic production potential, which can increase yields and thereby decrease the climate impact per unit of crop produced [55, 56].

Using the Swedish soil and crop monitoring program to detect changes in SOC

Soil inventories are an important resource for tracking changes in SOC stocks and other soil characteristics over time [21]. The present study demonstrated that the Swedish soil and crop monitoring program can provide important information about the current state of SOC on different types of farms in Sweden, which could be useful in the quest to reduce the climate impact of Swedish agriculture.

In the Swedish soil and crop monitoring program, Inventory II was conducted as a restart, i.e. it became an investigation with resampling of soils at the same sites at different times. This means that our analysis was based on only two sampling occasions, and it is therefore important that the monitoring program continues to follow up on regional and national carbon accounting schemes. Furthermore, inclusion of the subsoil in carbon accounting systems has been suggested [57]. For example, the Danish program has shown that temporal changes in the subsoil (25–50 cm) can be important, varying with climate, soil texture, and management, with, e.g. grass leys contributing storage of 0.58 Mg C $ha^{-1} yr^{-1}$ in the subsoil [58]. With the exception of a special investigation during Inventory II [26], where about 25% of the sites were sampled in three depth increments (0–20, 20–40, and 40–60 cm), the Swedish program has so far conducted analysis for SOC only in topsoils. Results from Swedish long-term experiments indicate that organic amendments and crop rotations may actually further increase SOC stocks in layers below 20 cm by up to 39% [49, 59]. Therefore, the total actual SOC changes are probably even larger than reported in the present study. However, these subsoil effects can be site-specific or even absent [49, 60], and there is a need for further studies documenting the quantity of changes in subsoil carbon and the regulating factors involved.

The present study also excluded organic soils, for reasons explained in the Materials and Methods section. Thus samples from sites that probably have a significant loss of SOC were excluded, which should be considered when interpreting the results. In addition, only arable fields were sampled, which means that SOC changes in e.g. semi-natural pastures were not included in the assessment. The results in this study should therefore not be interpreted as a complete assessment of SOC stocks and changes in all soils on Swedish farms.

When assessing the climate impact of a product or production chain, soil inventories give both advantages and disadvantages in estimating SOC stock changes compared with more commonly used approaches based on SOC models or long-term field trials. The samples in the Swedish soil and crop monitoring program are taken on farms, which should mean that they are representative of the actual situation, both in terms of management and site characteristics. Long-term field trials are usually less representative of the average situation on actual farms, e.g. a commercial farmer would adjust the crop choice and make other management decisions depending on, e.g. weather forecasts, pest conditions, and new technology. While soil and crop management in long-term field trials applies agricultural practices commonly used at the time when the experiments were established, these are usually kept relatively constant, sometimes over several decades. Modeling is more flexible, since it can be designed to represent any system, which helps in analyzing and identifying factors contributing most to SOC changes. In contrast to field trials and soil inventories on existing farms, properly calibrated models can also be used to assess the influence of future events and conditions. Future land use and climate can have a large influence on the actual climate benefit of current SOC increases, since the SOC can be re-emitted as CO_2 if conditions change [61]. However, SOC models are always an approximation of reality, and accurate assessment of climate variability and the influence of disruptions like drought, pests, and disease can be difficult. Overall, all these approaches provide valuable information that can be used to increase knowledge about SOC dynamics. Data from the Swedish soil and crop monitoring program are useful for detecting overall trends in SOC on different types of farms over time, and thereby complement the knowledge gained from other types of assessment.

Conclusions

In this study, we used a sub-sample from the two latest inventories (II and III) in the Swedish soil and crop monitoring program to assess SOC stocks and stock changes on arable land on Swedish farms, with the focus on dairy farms. The dataset consisted of 576 sampling points at identical locations covering approximately a 10-year period. The mean SOC concentration on dairy farms in Inventory III was 3.0%, which was higher than that on arable farms (2.3%) and pig farms (2.4%), but not significantly different from that on beef farms (3.1%). The SOC concentration on all farms was correlated with proportion of on-farm ley, indicating that the higher SOC concentrations on dairy and beef farms is probably due to a higher proportion of perennial leys in the crop rotations on these farm types.

The mean change in SOC concentration between Inventory II and Inventory III was statistically significant for dairy farms, beef farms, and arable farms, corresponding to an increase of 0.38, 0.14, and 0.21 Mg C ha^{-1} $year^{-1}$, respectively. There was a correlation between initial SOC concentration and change in SOC concentration, which may partly explain the difference between dairy farms and beef farms. There was no correlation between changes in SOC concentration and changes in the proportion of leys, likely because these changes were less pronounced during the decade between the two inventories. This highlights the importance of maintaining the Swedish soil and crop monitoring program with identical sampling coordinates, both for confirming the current overall increases in SOC in Swedish arable soils and for improving identification of contributing factors.

The mean climate impact of the SOC change on dairy farms was −1.4 Mg CO_2 ha^{-1} and −0.22 kg CO_2 (kg ECM)$^{-1}$ when the climate benefit was allocated between the milk (93%) and meat (7%) from the dairy cows. This is greater than the climate impact of SOC derived by modeling in previous studies and corresponds to about one-sixth of all greenhouse emissions from typical Swedish milk production. Consequently, it is important to account for on-farm SOC changes when assessing the climate impact of Swedish dairy production systems.

Disclosure statement

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