

## Soil carbon under arable and mixed dairy cropping in a long-term trial in SE Norway

Hugh Riley, Trond Maukon Henriksen, Torfinn Torp & Audun Korsæth

To cite this article: Hugh Riley, Trond Maukon Henriksen, Torfinn Torp & Audun Korsæth (2022) Soil carbon under arable and mixed dairy cropping in a long-term trial in SE Norway, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 72:1, 648-659, DOI: 10.1080/09064710.2022.2047770

To link to this article: <https://doi.org/10.1080/09064710.2022.2047770>



© 2022 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group



Published online: 10 Mar 2022.



Submit your article to this journal [↗](#)



Article views: 531



View related articles [↗](#)



View Crossmark data [↗](#)

RESEARCH ARTICLE



## Soil carbon under arable and mixed dairy cropping in a long-term trial in SE Norway

Hugh Riley, Trond Maukon Henriksen, Torfinn Torp and Audun Korsæth

Norwegian Inst. Bioeconomy (NIBIO), Nylinna 226, 2849 Kapp, Norway

### ABSTRACT

Soil organic carbon (SOC) was studied at 0–45 cm depth after 28 years of cropping with arable and mixed dairy rotations on a soil with an initial SOC level of 2.6% at 0–30 cm. Measurements included both carbon concentration (SOC%) and soil bulk density (BD). Gross C input was calculated from yields. Averaged over all systems, topsoil SOC% declined significantly ( $-0.20\%$  at 0–15 cm,  $p = 0.04$ ,  $-0.39\%$  at 15–30 cm,  $p = 0.05$ ), but changed little at 30–45 cm ( $+0.11\%$ ,  $p = 0.15$ ). Declines in topsoil SOC% tended to be greater in arable systems than in mixed dairy systems. Changes in BD were negatively related to those in SOC%, emphasizing the need to measure both when assessing SOC stocks. The overall SOC mass at 0–45 cm declined significantly from 98 to 89 Mg ha<sup>-1</sup>, representing a loss of 0.3% yr<sup>-1</sup> of the initial SOC. Variability within systems was high, but arable cropping showed tendencies of high SOC losses, whilst SOC stocks appeared to be little changed in conventional mixed dairy with 50% ley and organic mixed dairy with 75% ley. The changes were related to the level of C input. Mean C input was 22% higher in mixed dairy than in arable systems.

### ARTICLE HISTORY

Received 25 November 2021  
Accepted 24 February 2022

### KEYWORDS



Arable; bulk density; C input; cropping system; dairy; organic agriculture

### Introduction

Soil organic matter is recognised as a prime determinant of soil quality, affecting a wide range of chemical, physical and biological properties essential for sustainable agriculture (Bronick and Lal 2005; Diacono and Montemurro 2010; Johnston et al. 2009), whilst the soil organic carbon (SOC) content of agricultural soils is widely recognised as being of importance in relation to atmospheric carbon dioxide levels (Lal 2004). Declines in SOC are likely to contribute to further climate change, whilst increases may help to mitigate them. As a result of increased soil temperatures, large declines in SOC have been predicted in Europe between 1990 and 2080, (Jones et al. 2009; Smith et al. 2005; Wiesmeier et al. 2016). Land use change is widely recognised as being a further major cause of global SOC decline worldwide (Smith 2008). Amongst measures to counteract SOC decline in a European context, Freibauer et al. (2004) identified the use of organic inputs on arable land rather than grassland, the introduction of perennials on arable set-aside land, promotion of organic farming, raising the water table in farmed peatland and (with restrictions) zero or conservation tillage.

In south-eastern and central Norway, where much of the country's agricultural area is found, a considerable increase in arable cropping took place after 1950, due

to government policy to encourage cereal growing in the climatically best-suited areas and animal production in more marginal regions. In a long-term field trial on clay soil in SE Norway Uhlen (1991) studied how cereal rotations including various proportions of grass ley, with and without manure application and straw retention, affected SOC levels over 30 years in the topsoil. The SOC concentration increased slightly in a 2:4 year cereal:ley rotation that included the use of cattle manure, whilst it remained stable in such a rotation without manure. SOC declined slightly in a 4:2 year cereal:ley rotation, more so without the use of manure. In a cereal monoculture, it declined from 3.8% to ca. 3.4% (10% loss), even with straw residues retained. Further declines were found 30 years later in all three rotations, on average ca. 0.3%, 0.6% and 0.8% SOC in rotations with ley proportions of 2/3, 1/3 and zero, respectively (M.A. Bleken, pers. comm.). Using data from eleven long-term field experiments on cropland and permanent grassland in Switzerland, with treatments including mineral or organic fertilisation and soil management, Keel et al. (2019) found that topsoils lost C at an average rate of 0.29 Mg C ha<sup>-1</sup> yr<sup>-1</sup>, although many of the investigated treatments were expected to lead to SOC increases. The SOC change rates were driven by C inputs to soil (harvest residues and organic

**CONTACT** Hugh Riley  [hugh.riley@nibio.no](mailto:hugh.riley@nibio.no)  Norwegian Inst. Bioeconomy (NIBIO), Nylinna 226, 2849 Kapp, P.O. Box. 115, 1431 Ås, Norway

© 2022 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group  
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

fertiliser), soil cover and initial SOC stocks, whilst the type of land use or soil tillage had no significant effect.

Monitoring programmes of SOC levels in agricultural soils have been performed in many European countries. The results vary between countries, and even within the same country, as illustrated in the review of Gubler et al. (2019). Bellamy et al. (2005) reported declines in SOC throughout England and Wales in recent decades, whilst Skinner and Todd (2006) found that average SOC levels for all crops and grass had remained static during roughly the same period. In Scotland, Chapman et al. (2013) reported losses in SOC for the period up to around 1980, but Lilly et al. (2020) found no further change after partial resampling in 2017. Changes in SOC were found to vary between production systems in both the Netherlands (Hanegraaf et al. 2009) and Belgium (Goidts and van Wesemael 2007), indicating that grassland was less prone to decline than arable land. In the Belgian study, the arable soils had declined annually by 0.016–0.052% SOC over 10 years, whereas grassland soils showed annual gains of 0.051–0.068% SOC. Monitoring in south Germany suggested a decrease of SOC content in cropland as well as in grassland between 1986 and 2007. Crops and organic fertilisers were together with the initial SOC content considered the main causes of the observed changes, whilst a climatic effect could be neither proved nor excluded (Capriel 2013). In Switzerland, Gubler et al. (2019) found no overall decline, despite some divergent trends. In France, Saby et al. (2008) showed an average loss of 0.026% SOC per year in a 15-year study of 23,000 topsoil records. In Norway, considerable declines in topsoil SOC concentration were reported on arable land, both from a research station in the period 1952–2002 and from a survey of ca. 300 fields over a 10-year period (Riley and Bakkegard 2007). The average relative declines were ca. 1% annually of the soil's initial SOC content. As in other studies, the magnitude of the decline was positively related to the initial level of SOC in the soil, thus confirming that the rate of change of SOC is dependent on the distance from steady state level (Andr n et al. 2004).

Changes in SOC depend on the balance between C input and loss, with photosynthesis products as the primary source of C input (Kuzyakov and Domanski 2000). Thus, in the discussion of SOC stock change, reliable estimates of net primary production (NPP) are needed. In agroecosystems, annual NPP and C input to soil can be calculated from yield levels and equations for harvest index, shoot:root and root:exudate ratios. Keel et al. (2017) stated that such equations should be based on relevant agricultural conditions. They tested five sets of allometric equations on a Swiss dataset and

found large variations in calculated C input. Measured changes in SOC stock were best described using equations proposed by Bolinder et al. (2007), who collected data mainly from Canada. Poeplau et al. (2015) also based C input on these equations, with some modifications, when using the ICBM-model to evaluate the role of catch crops on C stock change in Sweden. No nationally derived equations exist for C input based on crop yields in Norway.

Long-term field trials provide opportunities for studying the effects of management factors, such as crop rotation, fertiliser use, tillage intensity, etc., on both soil quality and soil carbon (Jenkinson 1991). A long-term field experiment was established in 1988–1989 at Apelsvoll Research Centre in SE Norway, in response to concern about the environmental consequences of large inputs of fertiliser and plant protection chemicals. Many scientists advocated the adoption of an 'integrated' approach, using appropriate amounts of input to secure satisfactory yield levels, but with the additional aim of reducing environment impacts. Further, the adoption of organic farming practices, without mineral fertiliser and synthetic chemical inputs, has attracted political support, notably in Scandinavia. In Norway, a national strategy for organic farming 2018–2030 now exists (Norwegian Government 2018).

The Apelsvoll Cropping System Experiment (APSE) provides a basis for comparing arable and mixed dairy systems at a whole-system level, including both conventional and organic practices, as described by Eltun (1994) and Kors eth and Eltun (2000, 2008). The state of soil properties before the start of the experiment was characterised by Riley and Eltun (1994), showing that variation in SOC concentration had important effects on soil moisture storage. A later study (Riley et al. 2008) revealed that topsoil concentrations of SOC and the stability of soil aggregates had declined after 15 years of arable management with autumn ploughing and straw removal, whilst under shallow spring tillage with the use of catch crops and straw retention, both parameters had been maintained at levels similar to those in mixed dairy systems including the use of animal manure.

Management practices such as reduced tillage may affect the stratification of SOC, as shown by Hermle et al. (2008) in Switzerland and by Riley (2014) in Norway, resulting in increased concentrations near the surface and reductions at greater depth. Both these studies showed a negative correlation between SOC concentration and soil bulk density (BD), implying that the mass of SOC within the soil is affected by the management regime to a lesser extent than is the SOC concentration. Whilst the latter is of importance for soil

structure, it is the total amount of carbon in the soil that is of importance in relation to climate change. This requires the measurement of both the SOC concentration and BD.

Total amounts of SOC in the APSE have not been calculated previously. Further soil sampling of the same plots was performed in 2016, after 28 years of contrasting management. The present study compares SOC and BD in 2016 with the initial values in 1988. The aims of this paper are (1) to monitor changes in SOC concentration over time under contrasting cropping systems, (2) to calculate the total amounts of SOC carbon stored within the soil profile over time, taking into account any changes in BD that have occurred and (3) to compare such changes with calculated carbon inputs to the various systems.

## Methods and materials

### Site description and cropping systems

The APSE is located at Apelsvoll Research Station, Norwegian Institute for Bioeconomy, 60°42'N, 10°51'E, altitude 250 m. The region has a humid continental climate, with 600 mm annual precipitation and a mean annual temperature of 3.6°C (12°C in the growing season). The experiment covers three hectares of loam soil with imperfect or poor natural drainage, derived from moraine material. The topsoil contains 47% sand, 35% silt and 18% clay, with some gravel and stones. The major soil groups are classified as Aquic Fragiudept and Typic Epiaquept (Soil Survey Staff 1998), Endostagnic Cambisol and Haplic Stagnosol (FAO 1998) and Gleyed Melanic Brunisol and Orthic humic gleysol (CSSC 1998).

The site had formerly been in agricultural use with mixed arable and dairy systems. The experimental area was mainly used as pasture from 1935 to 1975. During the following 10 years the field was cropped uniformly with a rotation including 10% root crops, 40% small grains and 50% ley, using an average of 10 Mg cattle slurry ha<sup>-1</sup> yr<sup>-1</sup> (containing ca. 50 kg total-N Mg<sup>-1</sup>) plus regular amounts of mineral fertiliser. The field lay fallow in 1986 and 1988 and was cropped with winter wheat in 1987 and spring barley in 1989. The cropping systems described below were started in the autumn of 1989.

The experimental area is divided into twelve 30 × 60 m main plots, separated by 7.5 m grass borders, in two rows of six. Six cropping systems (arable CS1–CS3 and mixed dairy CS4–CS6) are randomly distributed on main plots within each row. Each main plot contains four 15 × 30 m sub-plots, individually drained at 1 m

depth with 7.5 m spacing. The site had previously been tile-drained, but with greater drain spacing. Each system has a 4-year crop rotation, with each crop present every year on separate sub-plots within each main plot. The arable crops include spring cereals (wheat *Triticum aestivum* L., barley *Hordeum vulgare* L., oats *Avena sativa* L.) and potatoes (*Solanum tuberosum*) and oats with peas (*Pisum sativum* L.). Fodder crops include grass–clover leys (timothy *Phleum pratense* L. and meadow fescue *Festuca pratensis* Huds. with red clover *Trifolium pratense* L.) and, until 1999, swedes (*Brassica napus* L.). Catch crops of Italian ryegrass (*Lolium multiflorum* Lam.) are grown as appropriate in all but the reference arable system (CS1).

Cropping systems CS1–CS3 represent arable production typical for the region, whilst CS4–CS6 represent fodder production typical of mixed dairy farming, with 50–75% ley in the rotation. CS1 is a reference system that reflects arable practices that are common when little attention is paid to non-point source losses of nutrients or to the maintenance of SOC levels. CS2 and CS4 are optimised arable and mixed dairy systems incorporating perceived system improvements related to such factors. CS3 is an organic arable system with green manuring and until 2011 mulch was left on the surface after cutting. The CS5 and CS6 systems are organic mixed dairy systems with different proportions of ley. CS1 is ploughed in autumn, whilst in CS2 ploughing is replaced by rotor harrowing in spring. In the remainder of the systems, the soil is ploughed in spring in all but ley years. Leys and catch crops are undersown in cereals in spring. Straw residues are removed from undersown leys, but otherwise retained except in CS1. Until 2000, cattle slurry was used in amounts as commonly used in agriculture in CS4, CS5 and CS6 until 2000, and thereafter in amounts calculated from grass yields and estimated use of concentrates. In CS3, biogas digestate was introduced in 2012 and two out of three grass cuttings were removed thereafter. Mineral fertilisers are only applied in CS1, CS2 and CS4. Less mineral fertiliser is used in CS2 than in CS1. Soil acidity is buffered with lime when necessary. The main management features of each system are summarised in Table 1. More details of the fertiliser and slurry rates used, as well as of crop yields, nutrient runoff, etc. are given in Korsæth and Eltun (2000), Eltun et al. (2002) and Korsæth (2008).

### Soil sampling

Core sampling was carried out in the autumns of 1988 and 2016 in a grid network of 24 soil profiles arranged at ca. 30 × 35 m within four rows and six columns. There were two profiles on each main plot, giving four profiles per

**Table 1.** Main management features of the six cropping systems (CS1–CS6).

	System name	Crop rotation	Tillage (arable)	Slurry use	Mineral fertiliser	Straw removal	Catch crops
CS1	Reference arable	Wheat, oats, barley, potato	Autumn plough	None	Yes NPK	Yes	No
CS2	Optimised arable	Wheat, oats, barley, potato	Spring harrow	None	Yes NPK	No	Yes
CS3	Organic arable	Wheat, oats/pea, barley, ley	Spring plough	Some	None	No	Yes
CS4	Optimised dairy	Wheat, barley, ley, ley	Spring plough	Annual	Yes NPK	No	Yes
CS5	Organic dairy (50%)	Wheat, barley, ley, ley	Spring plough	Annual	None	No	Yes
CS6	Organic dairy (75%)	Barley, ley, ley, ley	Spring plough	Annual	None	No	Yes

cropping system. The same plots within main plots were used at both samplings, avoiding previously disturbed soil. Results from three 15 cm depth layers are presented here (0–45 cm). In 1988, two small cylinders (100 cm<sup>3</sup>, 63 mm diameter) were used per depth in each profile, permitting analysis of soil pore distribution. Larger cylinders (535 cm<sup>3</sup>, 87 mm diameter) were used in 2016, thus providing more soil, with two cylinders in each profile at 0–15 and 15–30 cm and one cylinder at 30–45 cm. Cylinders were hammered into the soil and excavated by hand with minimally disturbed soil structure. They were taken from the centre of each depth layer (e.g. ca. 5–10 cm for layer 1 in 1988 and 3–12 cm in 2016). Additional (disturbed) samples were taken in 2016 from all 48 sub-plots in the trial at three depths (ca. 0–25 cm, 30–45 cm, 45–60 cm), using a hydraulic auger (3 cm diameter). Samples contained soil from 5 to 8 augerings per plot. Bulk density was not measured in these samples.

Soil texture and bulk densities measured at the start of the trial are shown in Table 2, based on the data of Riley and Eltun (1994). No significant differences in soil texture were found between the cropping systems, except for the sand and silt contents in the topmost layer, in which CS1 (Reference arable) had slightly lower sand and higher silt contents. Such differences were unlikely to affect other studied parameters (SOC and BD). The variability in gravel content was high (CV > 40%), compared to that in other soil properties. As stones and gravel in the soil were considered to be randomly distributed, and because we found the percentage of gravel to positively affect bulk density (BD = 1.26 + 0.025\*gravel%, n = 72, R<sup>2</sup> = 0.34), BD was expressed on a fine earth basis (see next section) in the following presentation of results. BD rose to >1.8 kg dm<sup>-3</sup> below 45 cm depth (not shown),

indicating low porosity, whilst the subsoil texture was similar to that of the topsoil.

### Soil analyses and calculations

Soil in cylinders was dried to constant weight at 105°C, then weighed for determination of dry bulk density (BD) of the whole sample. The fine earth (material < 2 mm) was sieved, and weights of stones and gravel were recorded. The specific gravity of the latter was found to be 2.65 kg litre<sup>-1</sup>. The BD of fine earth was calculated using Equation 1.

$$BD_{(\text{fine earth})} = \frac{BD_{(\text{whole sample})} * (100 - \text{gravel}\%)}{(100 - (BD_{(\text{whole sample})} * \text{gravel}\% / 2.65))} \quad (1)$$

In 1988, loss-on-ignition (LOI) of ca. 25 g soil per sample of fine earth was measured by combustion at 550°C for 3 hours, following Norwegian Standard NS-EN 15935 (2012). SOC was measured using a LECO CNS analyser at NIBIO Holt Research Station (Tromsø). In 2016, LOI was measured in the same way and converted to SOC using Equation 2, obtained from a dataset of 145 samples, 120 of which were from the Apelsvoll site in 1988 and the remainder from similar soils in the region.

$$\text{SOC}\% = \text{LOI}\% * 0.4665 - \text{Clay}\% * 0.0257 - 0.356 \quad (2)$$

(n = 145, R<sup>2</sup> = 0.95 S = 0.24).

This equation gave good coverage of SOC in the range from zero up to ca. 4%. All terms in the equation were significant at P < .001. A similar function was cited for Danish soils by Jensen et al. (2018), but with a slightly greater correction for clay than that found

**Table 2.** Gravel percentage, soil texture and bulk density measured at 0–45 cm depth in 1988. Means and standard deviations of all 24 profiles.

Layer	Gravel <sup>1</sup>		Sand <sup>2</sup>		Silt <sup>2</sup>		Clay <sup>2</sup>		Bulk density <sup>1</sup>	
	>2 mm		0.06–2 mm		2–60 µm		< 2 µm		Mg m <sup>-3</sup>	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd	Mean	sd
0–15 cm	7	3	47	5	35	3	18	3	1.32	0.07
15–30 cm	7	5	48	6	35	4	17	3	1.35	0.12
30–45 cm	13	6	51	7	37	6	12	3	1.73	0.09

<sup>1</sup> Based on weight of whole sample <sup>2</sup> Weight percentage of fine earth < 2 mm.

here. We considered the use of LOI to be suitable, particularly as it allows the use of a far greater quantity of soil than used in SOC dry combustion analysis (ca. 25 and 0.2 g subsamples, respectively). The initial clay contents measured at each profile location were used to calculate SOC from LOI in 2016, as we considered it unlikely that the cropping systems had any effect on soil texture.

The mass amounts of SOC ( $\text{kg m}^{-2}$ ) in the fine earth fraction of each 15 cm layer were calculated by multiplying the SOC concentrations with the respective BD values (Equation 3).

$$\text{SOC mass in depth}_{(i)} = \frac{\text{SOC}\%_{(i)} * \text{BD}_{(i)} * 1.5 * (100 - \text{gravel volume})}{100} \quad (3)$$

Adjustment for the mean volumes of gravel content was made with values found in the large cylinders used in 2016, averaged over cropping systems. Large cylinders were thought to represent the true gravel content better than small cylinders, and average values of all systems were used, thus achieving the same gravel contents in all systems. The values used were 17.5% and 21.5% gravel by weight, for topsoil and subsoil layers, respectively. With the average  $\text{BD}_{(\text{whole sample})}$  values measured in 2016, the corresponding gravel volumes were 9.3% and 14.3%, and these volumes were used in all cases in the calculations of SOC mass. The SOC masses were summed for the three depths sampled in both 1988 and 2016 (0–45 cm). In order to take account of variation in BD between systems and sampling times, further calculations were made to obtain equivalent soil mass, as described by Hermle et al. (2008). This involved adjusting the amount of soil included in the lowest layer in order to obtain a uniform BD of  $1.6 \text{ Mg m}^{-3}$  (Equation 4) for the whole profile. The latter BD value was chosen as it was close to the mean BD measured at 30–45 cm in both 1988 and 2016.

$$\text{SOC}_{\text{total}}(\text{at BD } 1.6) = \sum \text{SOC}_{\text{mass}(0-45 \text{ cm})} + \text{SOC}\%_{(30-45 \text{ cm})} * (1.6 - \sum \text{BD}_{(0-45 \text{ cm})} / 3) * 3. \quad (4)$$

This correction implies that when the mean measured BD is  $< 1.6$ , more SOC is added to the sum of the three layers, based on the SOC% of the lowest layer, and vice-versa when the mean BD is  $> 1.6$ . The added/subtracted value was also here adjusted for the gravel volume (though not shown in Equation 4).

## Calculation of C input

Carbon inputs to each cropping system were based on crop yields measured from 1990 to 2016, using the allocation coefficients described in Bolinder et al. (2007) and Bolinder et al. (2015). The catch crop yield was only measured in CS3 in 2006 ( $0.38 \text{ Mg ha}^{-1}$ ) and was elsewhere set to 50% of this figure. C input with seeds and organic additives was included. We assumed C concentrations of 45% of DM in all plant tissues, 42% in manure and 33% in biogas digestate, the two latter based on the mean of measurements.

## Statistical analyses

Data used for statistical analyses were means of core samples at each depth in each profile. Means, standard errors and simple regressions were performed in Excel. Multiple regression, paired *t*-tests and covariance analyses were performed with Minitab 18. The latter used the Mixed Effects procedure, with the following statistical model (5):

$$z_{ijk} = y_{ijk}^{(2)} - y_{ijk}^{(1)} = \mu\alpha + \alpha_i + B_j + (\alpha\beta B)_{ij} + y_{ijk}^{(1)} + \varepsilon_{ijk}. \quad (5)$$

where:

$i$  = cropping system ( $= 1-6$ );  $j$  = model farm ( $= 1,2$ );  $k$  = row ( $= 1,2$ );  $y_{ijk}^{(2)}$  = observed SOC mass in 2016 in row  $k$ , model farm  $j$  and cropping system  $i$ ;  $y_{ijk}^{(1)}$  = observed SOC mass in 1988 in row  $k$ , model farm  $j$  and cropping system  $i$ ;  $z_{ijk}$  = difference between SOC mass in 2016 and 1988 ( $k, j$  and  $i$  as above);  $\mu$  = constant,  $\alpha_i$  = main effect of cropping system  $i$ ,  $B_j$  = main effect of model farm  $j$ ;  $(\alpha\beta)_{ij}$  = interaction between cropping system  $i$  and model farm  $j$ ;  $\beta$  = slope coefficient for the linear relation between  $y_{ijk}^{(1)}$  and  $z_{ijk}$ ;  $\varepsilon_{ijk}$  = general error term;  $B_j$ ,  $(\alpha\beta)_{ij}$  and  $\varepsilon_{ijk}$  are random variables.

## Results

### Measurements made with core cylinders in 1988 and 2016

Mean carbon concentrations (SOC%) in each cropping system are presented for 1988 and 2016 in Tables 3 and 4, respectively, together with associated BD values. In 1988, the SOC% and BD varied only slightly between cropping systems, and the differences were not statistically significant, as indicated by the standard errors shown. SOC% levels below 45 cm depth (not shown) were in all systems  $< 0.3\%$ .

In 2016, the reference system CS1 had the lowest SOC % of all systems in the topsoil and the highest BD values,

**Table 3.** Mean concentrations of soil organic C and bulk densities (BD) of fine earth < 2 mm, measured at 0–45 cm depth in 1988 ( $n = 4$ ), 1 year before the cropping systems started.

System	CS1	CS2	CS3	CS4	CS5	CS6
Depth	Reference arable	Optimised arable	Organic arable	Optimised dairy	Organic dairy	Organic dairy
SOC %						
0–15 cm	2.60 ± 0.33	3.02 ± 0.30	2.58 ± 0.12	2.75 ± 0.19	2.20 ± 0.25	2.80 ± 0.17
15–30 cm	2.63 ± 0.35	2.07 ± 0.62	2.85 ± 0.21	2.27 ± 0.43	2.50 ± 0.31	2.90 ± 0.16
30–45 cm	0.30 ± 0.04	0.27 ± 0.05	0.60 ± 0.24	0.35 ± 0.03	0.33 ± 0.02	0.38 ± 0.02
BD Mg m <sup>-3</sup>						
0–15 cm	1.24 ± 0.02	1.23 ± 0.03	1.28 ± 0.03	1.29 ± 0.04	1.30 ± 0.04	1.28 ± 0.02
15–30 cm	1.26 ± 0.05	1.37 ± 0.06	1.29 ± 0.04	1.33 ± 0.06	1.26 ± 0.08	1.26 ± 0.02
30–45 cm	1.59 ± 0.03	1.64 ± 0.06	1.61 ± 0.08	1.67 ± 0.04	1.70 ± 0.06	1.64 ± 0.03

Note: ± se of mean. The systems are presented in table 1.

**Table 4.** Mean concentrations of soil organic C and bulk densities (BD) of fine earth < 2 mm, measured in autumn 2016 ( $n = 4$ ), after 27 years with six cropping systems.

System	CS1	CS2	CS3	CS4	CS5	CS6
Depth	Reference arable	Optimised arable	Organic arable	Optimised dairy	Organic dairy	Organic dairy
SOC %						
0–15 cm	1.99 ± 0.26	2.56 ± 0.08	2.37 ± 0.12	2.67 ± 0.14	2.44 ± 0.14	2.71 ± 0.11
15–30 cm	1.85 ± 0.42	2.06 ± 0.22	1.93 ± 0.32	2.46 ± 0.08	2.25 ± 0.09	2.30 ± 0.18
30–45 cm	0.50 ± 0.12	0.41 ± 0.04	0.37 ± 0.20	0.56 ± 0.11	0.39 ± 0.09	0.69 ± 0.19
BD Mg m <sup>-3</sup>						
0–15 cm	1.33 ± 0.06	1.26 ± 0.02	1.29 ± 0.01	1.22 ± 0.03	1.19 ± 0.02	1.19 ± 0.05
15–30 cm	1.43 ± 0.06	1.28 ± 0.05	1.33 ± 0.05	1.28 ± 0.02	1.19 ± 0.02	1.29 ± 0.06
30–45 cm	1.68 ± 0.03	1.57 ± 0.05	1.70 ± 0.03	1.56 ± 0.07	1.54 ± 0.08	1.59 ± 0.08

Note: ± se of mean. The systems are presented in table 1.

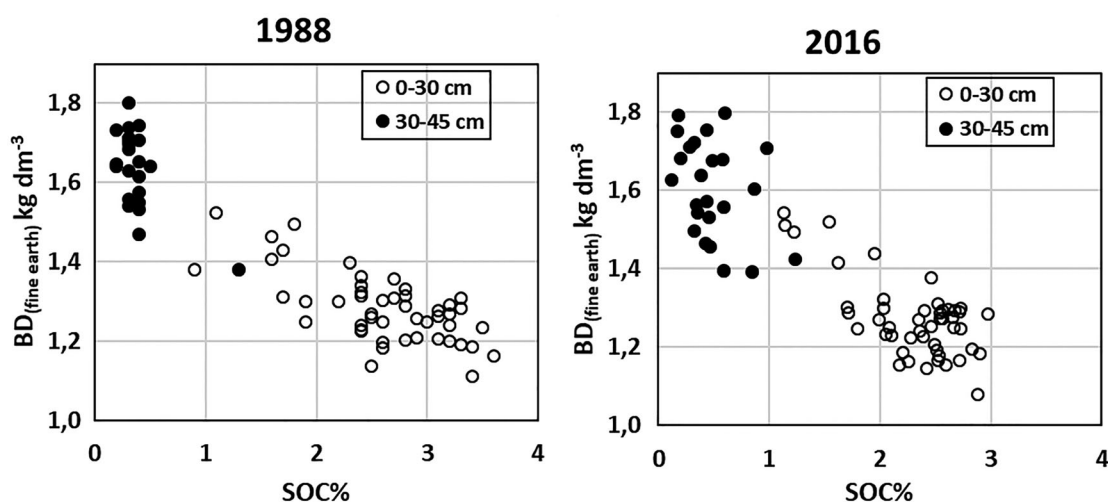
in agreement with findings in 2003 (Riley et al. 2008). The SOC% values in the upper topsoil layer were similar in all other systems, whilst in the lower topsoil layer, they were slightly higher in the mixed dairy systems than in the arable systems. SOC% in the subsoil layer (30–45 cm) was higher in 2016 than in 1988, except in CS3. The highest values at this depth were found in the optimised dairy system (CS4) and the organic dairy system with 75% leys. Bulk densities were generally lower in the mixed dairy systems than in the arable systems, particularly in the topsoil layers.

At both sampling times,  $BD_{(\text{fine earth})}$  declined significantly with increasing SOC% in both topsoil and

subsoil (Figure 1). The overall decline in BD with increasing SOC% was similar at both sampling times (regressions:  $BD_{(0-45 \text{ cm})} = 1.68 - 0.150 * \text{SOC}\%$ ,  $n = 72$ ,  $R^2 = 0.85$  in 1988 and  $BD_{(0-45 \text{ cm})} = 1.69 - 0.179 * \text{SOC}\%$ ,  $n = 72$ ,  $R^2 = 0.78$  in 2016).

#### Measurements made with auger machine in 2016

The auger samples showed a similar pattern of differences in SOC% between cropping systems (Table 5) as that seen in the core samples. As in the latter, the reference system CS1 had the lowest values, followed by CS3


**Figure 1.** Bulk density<sub>fine earth</sub> versus SOC% measured in 1988 and 2016.

**Table 5.** Mean concentrations of soil organic C, measured with soil auger at three depths on all 48 trial plots in autumn 2016, after 27 years with six cropping systems.

System Depth	CS1 Reference arable	CS2 Optimised arable	CS3 Organic arable	CS4 Optimised dairy	CS5 Organic dairy	CS6 Organic dairy
0–25 cm	2.12 ± 0.22	2.63 ± 0.10	2.33 ± 0.11	2.83 ± 0.09	2.68 ± 0.23	2.79 ± 0.18
25–45 cm	0.70 ± 0.08	0.88 ± 0.15	0.61 ± 0.10	0.96 ± 0.10	0.79 ± 0.06	0.97 ± 0.14
45–60 cm	0.41 ± 0.10	0.49 ± 0.11	0.46 ± 0.08	0.55 ± 0.08	0.41 ± 0.06	0.61 ± 0.05

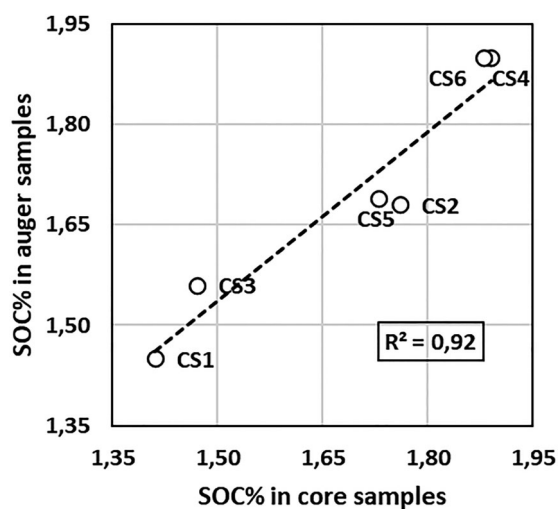
Note: The systems are presented in table 1.

(organic arable), whilst CS4 (conventional mixed with 50% ley) and CS6 (mixed organic with 75% ley) had the highest values. Precise comparison between core and auger samples is difficult as the measurement depths were not identical. Some soil mixing may have occurred between depths in the auger samples.

Other uncertainties were that the auger samples were from all 48 sub-plots in the trial, whilst the core samples were from only 24 sub-plots, and that soil compression often occurs within the auger, particularly in the topsoil layer, meaning that the actual depth sampled may be slightly different. Nevertheless, the means of the auger samples within the depth interval 0.45 cm corresponded closely with those of the cylinder samples within the same depth interval. There was close agreement between these mean SOC% values in all systems, irrespective of the sampling method (Figure 2). The overall mean values of all systems were almost identical. The core samples are therefore considered to be representative of the whole model farm from which they were taken.

### Changes over time in SOC concentrations, bulk density and total mass of soil carbon

Paired t-tests revealed that the overall SOC% had declined significantly between 1988 and 2016 in both

**Figure 2.** Mean SOC% in auger samples taken from 0 to 45 cm depth plotted against mean SOC% in core samples taken within the same depth interval.

topsoil layers (Table 6, above). At the individual system level, the declines were significant at 0–15 cm in the reference system CS1 and at 15–30 cm in the mixed organic system CS6. In the subsoil layer (30–45 cm) all systems except CS3 had small but nonsignificant increases in SOC%. There was relatively little overall change over time in BD values at any of the depths (Table 5, below). At the individual system level, BD had increased significantly at 15–30 cm in CS1 and declined significantly at 30–45 cm in CS4 and CS5. The changes in SOC% and BD were related significantly to their original levels before the start of the trial ( $R^2 = 0.61$  and  $0.51$  for topsoil and subsoil SOC% respectively, both  $p < .001$  and  $R^2 = 0.34$  and  $0.31$  for topsoil and subsoil BD respectively, both  $p < .01$ ). Topsoil SOC% had declined when the level in 1988 was greater than ca. 2.25%, whilst at levels lower than this it had increased over time. Subsoil SOC% had increased over time in most cases when the original level was  $< 0.5\%$ , but a large decline was found in one case when the original level was  $> 1\%$ . BD had decreased over time when the original level in the topsoil was greater than ca.  $1.3 \text{ kg dm}^{-3}$ , whilst in the subsoil the same was found when the original level was greater than ca.  $1.6 \text{ kg dm}^{-3}$ . The annual changes in BD

**Table 6.** Mean changes between 1988 and 2016 in SOC% and BD density<sub>fine earth</sub> at three depths and probability levels<sup>1</sup> of paired t-tests between dates of sampling.

SOC%	0–15 cm		15–30 cm		30–45 cm	
	Change	<i>P</i> -level	Change	<i>P</i> -level	Change	<i>P</i> -level
CS1	–0.61	.03	–0.77	ns	+0.20	ns
CS2	–0.47	.15	–0.01	ns	+0.14	.08
CS3	–0.20	ns	–0.92	.17	–0.23	ns
CS4	–0.08	ns	+0.18	ns	+0.21	ns
CS5	+0.24	ns	–0.25	ns	+0.06	ns
CS6	–0.09	ns	–0.60	<.01	+0.31	.19
Mean	–0.20	.04	–0.39	.05	+0.11	.15
BD Mg m <sup>–3</sup>	Change	<i>P</i> -level	Change	<i>P</i> -level	Change	<i>P</i> -level
CS1	+0.09	ns	+0.17	.02	+0.09	ns
CS2	+0.02	ns	–0.09	ns	–0.07	ns
CS3	+0.02	ns	+0.04	ns	+0.09	ns
CS4	–0.07	.12	–0.06	ns	–0.10	.05
CS5	–0.11	.07	–0.07	ns	–0.16	.03
CS6	–0.10	.16	+0.03	ns	–0.06	ns
Mean	–0.03	ns	±0.00	ns	–0.03	ns

<sup>1</sup>Significance at  $p < .05$  is shown in bold type,  $p$ -levels up to .20 are also shown,  $ns = p > .20$ .

Note: The systems are presented in table 1.



were negatively related with those in SOC% ( $\Delta BD = -0.12 \cdot \Delta SOC\% - 0.0014$ ,  $R^2 = 0.36$ ,  $P < .001$ ), implying that BD increased when the annual SOC% decline was greater than  $-0.01\% \text{ yr}^{-1}$ , and otherwise decreased. This confirms the importance of including changes in BD when calculating changes in SOC mass.

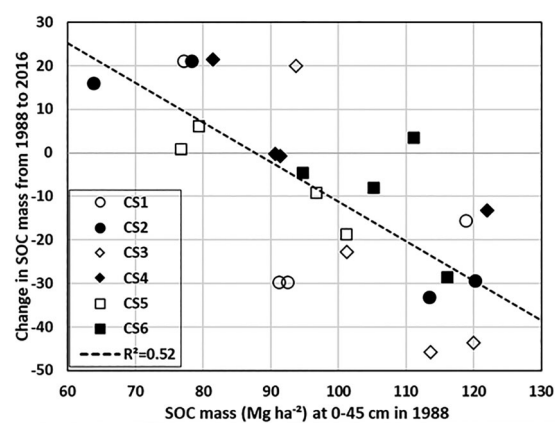
The amounts of SOC mass, expressed both as sums at 0–45 cm and levels corrected to equivalent bulk density, are shown in Table 7, together with paired t-tests of the changes. There was a significant overall decline in SOC mass, equivalent to ca. 0.3% per year of the amount present in 1988. Correction to equivalent soil mass slightly increased the SOC mass in all systems and lowered the significance of the overall decline. None of the changes were significant at the individual system level, but the mean SOC decline of the three arable systems ( $-14.3 \text{ Mg ha}^{-2}$ ) was close to significance at  $p = .09$ , whilst the mean decline of the three mixed dairy systems ( $-4.2 \text{ Mg ha}^{-2}$ ) was far from significant.

The SOC mass levels measured in 1988 accounted for about half of the variation in the declines of SOC mass found in 2016 from individual soil profiles of each system (Figure 3). SOC mass had increased over time when the initial SOC mass was less than ca.  $90 \text{ Mg ha}^{-2}$ , whereas it had declined at initial SOC mass above that level. Further analysis using the initial SOC mass as a covariate was thus considered to be justified, using Equation 5. This gave models with adjusted  $R^2$  values of 84% and 81%, for the SOC sum and adjusted total mass respectively. The modified mean values for the cropping systems are shown in Table 8. Compared with the unmodified declines (Table 7), this analysis increased the significance of the overall declines, without changing their magnitude. However, at the individual system level, the changes

**Table 7.** SOC mass<sup>1</sup> at 0–45 cm depth and total values adjusted to equivalent soil mass in 1988 and 2016, with probability levels of paired t-tests of changes between these dates.

System	CS1	CS2	CS3	CS4	CS5	CS6	Mean
SOC sum 0–45 cm							
1988	95 ± 9	94 ± 14	107 ± 6	96 ± 9	88 ± 6	107 ± 5	98 ± 3
2016	82 ± 11	88 ± 5	84 ± 10	98 ± 5	83 ± 2	97 ± 6	89 ± 3
Change	-13 ± 12	-6 ± 14	-23 ± 15	+2 ± 7	-5 ± 5	-10 ± 7	-9 ± 4
P-level	.34	.69	.23	.82	.42	.26	.04
SOC total mass corrected							
1988	97 ± 9	95 ± 14	111 ± 7	98 ± 9	90 ± 6	109 ± 5	100 ± 4
2016	83 ± 12	90 ± 4	86 ± 11	102 ± 4	86 ± 2	102 ± 8	92 ± 3
Change	-14 ± 13	-5 ± 14	-25 ± 17	+4 ± 8	-4 ± 6	-7 ± 8	-8 ± 5
P-level	.37	.73	.24	.63	.59	.47	.08

<sup>1</sup>Mean mass ± se in  $\text{Mg SOC ha}^{-1}$ , corrected for gravel content. Note: The systems are presented in table 1.



**Figure 3.** Declines in SOC mass at 0–45 cm in 2016 relative to the initial levels in 1988

**Table 8.** Changes in SOC mass<sup>1</sup> at 0–45 cm depth mean ± se between 1988 and 2016 in six cropping systems, after adjustment by covariance analysis with their initial levels of SOC

System	CS1	CS2	CS3	CS4	CS5	CS6	Mean
SOC sum 0–45 cm							
Change	-16 ± 11	-10 ± 11	-15 ± 11	±0 ± 11	-13 ± 11	-2 ± 11	-9 ± 2
P-level	.18	.39	.22	.97	.26	.89	<.001
SOC total mass corrected							
Change	-16 ± 11	-9 ± 11	-15 ± 11	+2 ± 11	-13 ± 11	+1 ± 11	-8 ± 2
P-level	.19	.43	.24	.85	.30	.90	<.001

<sup>1</sup>Mean mass ± se in  $\text{Mg SOC ha}^{-1}$ , corrected for gravel content. Note: The systems are presented in table 1.

were still not significant, and there were large standard errors associated with all mean SOC changes. The declines seen in the arable systems CS1 and CS3 were those closest to significance, whilst the changes in the mixed dairy systems CS4 and CS6 were those farthest from significance. The mean decline in the two first-mentioned systems was  $0.55 \text{ Mg ha}^{-2} \text{ yr}^{-1}$ , equivalent to ca. 0.5% of the initial amount. In the latter two systems, the mean increase was  $0.18 \text{ Mg ha}^{-2} \text{ yr}^{-1}$ , about 0.2% of the initial amount.

### Estimation of carbon inputs to the cropping systems

Estimated total NPP was higher in the mixed dairy systems ( $6.2 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ) than in the arable systems ( $4.8 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ). Estimated total inputs to the soil of C from the various sources (after export of products) are shown in Table 9 for the whole period 1990–2016. Mean input to soil was higher in mixed dairy systems ( $3.6 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ) than in arable systems ( $2.9 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ). The ratio of C from belowground (roots + exudates) to aboveground residues was much higher in systems with ley (1.9) than in arable systems

**Table 9.** Estimated total inputs of C to soil  $\text{Mg ha}^{-1}$  from various sources from 1990 to 2016.

System	Aboveground	Roots	Exudates	Manure	Seeds	Total
CS1	29.3	18.9	12.4	0.0	3.4	64.0
CS2	47.1	17.9	11.7	0.0	3.4	80.1
CS3	47.7	25.3	16.5	2.6	2.1	94.2
CS4	34.7	27.6	31.1	15.9	1.8	111.1
CS5	27.1	22.6	25.1	11.0	1.8	87.7
CS6	23.1	21.5	32.2	14.0	1.4	92.2

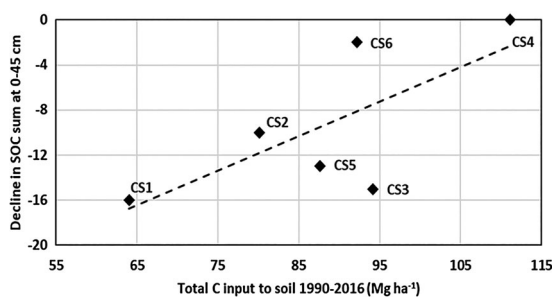
Note: The systems are presented in table 1.

(0.8). This shows the importance of including C allocated belowground. The use of manure in the dairy systems contributed 14% of total C input, while the amount with seeds was almost negligible (1–5%). Inputs of C in the two cropping systems that appeared to be close to steady state with regard to SOC (CS4 and CS6), were 4.1 and 3.4  $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ , respectively.

Regression of the mean declines in SOC mass at 0–45 cm (from Table 8) against the total C input to soil gave an  $R^2$  value of 0.50 ( $P = .07$ ) in the former. Systems with largest and smallest declines, CS1 and CS4 respectively, were placed close to the regression line (Figure 4), at opposite ends, but the organic arable system CS3 deviated far from this line. Omission of this system from the regression increased the  $R^2$  value to 0.77 ( $P = .02$ ). About half of the total C input in this system was aboveground material, much of which came from surface mulch, from which C may have been lost directly to the atmosphere (see discussion). Declines in SOC mass were in general related more strongly to the sum of belowground residues plus manure ( $R^2 = 0.60$ ,  $P = .05$ ) than with aboveground residues plus manure ( $R^2 = 0.10$ , ns).

## Discussion

Despite high soil variability at the experimental site, our results revealed a relatively large decline in SOC% between 1988 and 2016. The mean decline was ca.  $-0.021 \text{ SOC\% yr}^{-1}$  at 030 cm depth. This value is similar to that found by Riley and Bakkegard (2007) in a 10-year survey of 290 arable fields in SE Norway, and



**Figure 4.** Declines in SOC mass at 0–45 cm  $\text{Mg ha}^{-1}$  in relation estimated total C inputs to soil.

that found over 59 years of cereal monocropping on a clay loam in SE Norway (M.A. Bleken, pers.com.).

Measurements of changes in SOC% are often used to assess management effects on soil organic matter levels. However, our results clearly emphasise the need for measurements of changes in BD in order to assess changes in SOC storage, as BD was negatively related to SOC% at both sampling times, and changes over time in both parameters were affected by their initial levels. Such effects may account for the lower statistical significance of changes in SOC mass than in those of SOC%. Although changes in SOC mass were not statistically significant at the individual CS level, the overall decline amounted to a significant loss of 0.30  $\text{Mg C ha}^{-1} \text{ yr}^{-1}$  between 1988 and 2016. This loss is almost identical to the average loss reported by Keel et al. (2019) using Swiss data from eleven long-term field experiments with a range of treatments. In our case, the assessment of changes in SOC mass was also strongly affected by the initial level of SOC mass (Figure 4). Our results give a tentative indication that SOC mass was at a steady state only in a conventional mixed dairy system (CS4), while it declined on arable systems under the specific conditions at this site. This result is in line with those of Bolinder et al. (2010), who studied the effects of management regimes on SOC stocks at three sites with differing initial SOC in northern Sweden. At their site with the lowest initial SOC (82  $\text{Mg ha}^{-1}$  at 0–25 cm) SOC stocks increased over 50 years under continuous forage with manure use, whilst they were at steady state with forage crops in 4 of 6 years and declined in systems with less forage and manure. At two sites with higher initial SOC (ca. 125  $\text{Mg ha}^{-1}$  at 0–25 cm), SOC stocks declined over 30 years irrespective of the management regime. In the present study, part of the decline in SOC mass which we found in CS3 (organic arable) was probably attributable to its high initial SOC stock, and covariance analysis brought this decline into line with that of CS1. On the other hand, CS5 (organic dairy) had low initial SOC mass, and covariance analysis indicated a larger decline than that measured directly.

In a comprehensive analysis of organic versus nonorganic studies, Gattinger et al. (2012) found that organic farming has the potential to accumulate soil carbon. In

Denmark, however, Hu et al. (2018) were unable to detect differences in measured SOC between organic and conventional systems, despite consistently higher estimated C inputs in the former. In our study clover ley is used in the organic arable system (CS3), to fix nitrogen for use by later crops. This ley was mown regularly and left on the surface as mulch until 2011, whereafter two out of three cuttings has been removed and 'replaced' with biogas digestive. This mulch material was estimated to contribute 19% of the 3.5 Mg ha<sup>-1</sup> yr<sup>-1</sup> carbon input to soil. Despite such considerable input, SOC stocks appeared to decline substantially in this system. This may have been a random effect due to field variability, although both the core samples and auger samples from this system showed almost as low SOC% as the reference arable system (CS1). It may be that easily-degradable residues left as mulch throughout summer possibly contribute less to C sequestration than do roots and material that is more intimately mixed in the soil. In a greenhouse study of the fate of carbon in grass mulch on the soil surface, Flessa et al. (2002) found that 75% of the applied carbon was emitted as CO<sub>2</sub> within 50 days. The importance of carbon input from roots was stressed by Pausch and Kuzyakov (2018). This was confirmed in our study by the closer correlation of SOC decline with belowground input than with aboveground input to soil.

In the case of CS2, our results indicate that the omission of ploughing maintained the SOC level somewhat, relative to that of CS1 with autumn ploughing. However, a global meta-analysis has shown that whilst reduced tillage has a marked effect on SOC distribution within the soil profile it does not change SOC stocks (Luo et al. 2010). This conclusion is supported by results from long-term tillage trials in Norway (Riley 2014 and unpublished data). We, therefore, consider that the lower loss of SOC in CS2 is more likely due to the inclusion of catch crops and retention of straw residues. A meta-analysis by Poeplau and Don (2015) suggested that cover crops have a high potential for increasing SOC stocks, but Uhlen (1991) found that only 7% of the applied carbon remained in the soil in two long-term trials with straw incorporation.

The SOC stock in system CS4 (optimised mixed dairy with 50% ley) appeared to be close to steady state both when measured directly and after covariance adjustment for initial level, whilst that of C6 (organic dairy with 75% ley) appeared close to steady state after such adjustment. Our calculations of C input suggest that ca. 3.5–4 Mg C ha<sup>-1</sup> yr<sup>-1</sup> was added in these systems, which is equivalent to ca. 4% of the mean total SOC (0–45 cm). This implies that high annual inputs of plant DM are needed to maintain SOC levels under the conditions found at our experimental site. A recent simulation study by Nilsson et al. (2020) using data from Swedish grassland trials,

suggested that SOC increases little when the initial level is high. Their results also show that higher N-fertiliser levels have a marked effect on SOC, which may account for the superiority of CS4 over CS5 in our study.

The effect of manure use is also important, although only a relatively small proportion of C applied in manure remains in the soil in the long-term. In a global meta-analysis of 49 sites, Maillard and Angers (2014) estimated that 12% of cumulative C inputs were retained in SOC after an average of 18 years, whilst in Norway Uhlen (1991) calculated a figure of 17% after 30–50 years. We suggest that including leys in the rotation is more important for maintaining SOC than is the use of manure alone, in accordance with the findings of for example Goidts and van Wesemael (2007) in Belgium. Nevertheless, in a century-old fertiliser trial on soil similar to the present study, with a crop rotation including leys in 3 out of 7 years, SOC data for the past ~55 years indicate that the SOC% level has remained almost constant with manure use, whilst it has declined slightly with the use of balanced NPK fertiliser, despite higher crop production with the latter treatment (Riley 2016 and unpublished data).

## Conclusions

- Overall SOC concentrations declined significantly at 0–30 cm between 1988 and 2016, with trends towards greater declines in a conventional arable system with autumn ploughing and in an organic arable system, than in mixed dairy systems.
- Soil bulk densities were negatively related to SOC concentrations on both sampling dates, as were their changes over time, emphasising the need for measuring both parameters.
- The SOC mass had declined significantly at 0–45 cm depth by 10% between 1988 and 2016, with similar trends for arable and mixed dairy systems as mentioned for SOC%
- C input to soil was higher in mixed dairy than in arable systems. SOC mass appeared to be unaltered with an input of 4 Mg C ha<sup>-1</sup> yr<sup>-1</sup> but to decline when inputs were lower.
- An organic arable system with surface mulching appeared to have a large decline in SOC mass despite its high C input. Possible reasons for this finding require further study.

## Acknowledgements

The study was funded by the Norwegian Institute of Bioeconomy (NIBIO) and Yara International ASA.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Notes on contributors

**Hugh Riley** is a retired research scientist at NIBIO Division of Food Production and Society who worked for many years with research in the field of soil management, including soil tillage and soil structure assessment, crop fertilization and irrigation studies.

**Trond Maukon Henriksen** is a research scientist at NIBIO Division of Food Production and Society who has worked on many topics related to soil microbiology and nutrient turnover in crops. He is currently involved in several projects related to climate change.

**Torfinn Torp** is a senior adviser in NIBIO Department of Research assisting in the correct use of statistical methods.

**Audun Korsaaeth** is Director of NIBIO Division of Food Production and Society, who has worked on many aspects of nutrient turnover, including soil and crop modelling. For many years he was responsible for running the Apelsvoll Cropping System Experiment.

## References

- Andrén O, Kätterer T, Karlsson T. 2004. ICBM regional model for estimations of dynamics of agricultural soil carbon pools. *Nutr. Cycling Agroecosyst.* 70:231–239.
- Bellamy PH, Loveland PJ, Bradley RI, Lark MR, Kirk GJD. 2005. Carbon losses from all soils across England and Wales 1978–2003. *Nature.* 437:245–248.
- Bolinder MA, Janzen HH, Gregorich EG, Angers DA, VandenBygaart AJ. 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. *Agric. Ecosyst. Environ.* 118:29–42.
- Bolinder MA, Kätterer T, Andrén O, Ericson L, Parent LE, Kirchmann H. 2010. Long-term soil organic carbon and nitrogen dynamics in forage-based crop rotations in northern Sweden (63–64°N). *Agric. Ecosyst. Environ.* 138:335–342.
- Bolinder MA, Kätterer T, Poeplau C, Börjesson G, Parent LE. 2015. Net primary productivity and below-ground crop residue inputs for root crops: potato (*Solanum tuberosum* L.) and sugar beet (*Beta vulgaris* L.). *Can. J. Soil Sci.* 95:87–93.
- Bronick CJ, Lal R. 2005. Soil structure and management: a review. *Geoderma.* 124:3–22.
- Capriel P. 2013. Trends in organic carbon and nitrogen contents in agricultural soils in Bavaria (south Germany) between 1986 and 2007. *Eur. J. Soil Science.* 64(4):445–454.
- Chapman SJ, Bell JS, Campbell CD, Hudson G, Lilly A, Nolan AJ, Robertson AHJ, Potts JM. 2013. Comparison of soil carbon stocks in Scottish soils between 1978 and 2009. *Eur. J. Soil Sci.* 64:455–465.
- CSSC. 1998. The Canadian system of soil classification, 3rd ed. Ottawa: Agriculture and Agri-Food Canada Publication 1646.
- Diacono M, Montemurro F. 2010. Long-term effects of organic amendments on soil fertility. A review. *Agron. Sustain. Dev.* 30:401–422.
- Eltun R. 1994. The Apelsvoll cropping system experiment I background, objectives and methods. *Norw. J. Agric. Sci.* 8:301–315.
- Eltun R, Korsaaeth A, Nordheim O. 2002. A comparison of environmental, soil fertility, yield, and economical effects in six cropping systems based on an 8-year experiment in Norway. *Agric. Ecosyst. Environ.* 90:155–168.
- FAO. 1998. World reference base for soil resources. Rome: FAO.
- Flessa H, Potthoff M, Loftfield N. 2002. Greenhouse estimates of CO<sub>2</sub> and N<sub>2</sub>O emissions following surface application of grass mulch: importance of indigenous microflora of mulch. *Soil Biol. Biochem.* 34:875–879.
- Freibauer A, Rounsevell MDA, Smith P, Verhagen J. 2004. Carbon sequestration in the agricultural soils of Europe. *Geoderma.* 122:1–23.
- Gattinger A, Muller A, Haeni M, Skinner C, Fliessbach A, Buchmann N, Mäder P, Stolze M, Smith P, El-Hage Scialabba N, Niggli U. 2012. Enhanced top soil carbon stocks under organic farming. *Proc. National Academy of Sciences USA.* 109(44):18226–18231.
- Goidts E, van Wesemael B. 2007. Regional assessment of soil organic carbon changes under agriculture in Southern Belgium (1955–2005). *Geoderma.* 141:341–354.
- Gubler A, Wächter D, Schwab P, Müller M, Keller A. 2019. Twenty-five years of observations of soil organic carbon in Swiss croplands showing stability overall but with some divergent trends. *Environ. Monit. and Assess.* 191:1–17.
- Hanegraaf C, Hoffland E, Kuikman PJ, Brussard L. 2009. Trends in soil organic matter contents in Dutch grasslands and maize fields on sandy soils. *Europ. J. Soil Sci.* 60:213–222.
- Hermle S, Anken T, Leifeld J, Weisskopf P. 2008. The effect of the tillage system on soil organic carbon content under moist, cold-temperate conditions. *Soil Till. Res.* 98:94–105.
- Hu T, Sørensen P, Olesen JE. 2018. Soil carbon varies between different organic and conventional management schemes in arable agriculture. *Europ. J. Agron.* 94:79–88.
- Jenkinson DS. 1991. The Rothamsted long-term experiments: are they still of use? *Agron. J.* 83:2–10.
- Jensen JL, Christensen BT, Schjøning P, Watts CW, Munkholm LJ. 2018. Converting loss-on-ignition to organic carbon content in arable topsoil: pitfalls and proposed procedure. *Europ. J. Soil Sci.* 69:604–612.
- Johnston AE, Poulton PR, Coleman K. 2009. Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. In: Sparks D. L., editor. *Advances in agronomy series* vol. 101. Burlington: Elsevier Academic Press Inc; p. 1–57.
- Jones A, Stolbovoy V, Rusco E, Gentile A-R, Gardi C. 2009. Climate change in Europe impact on soil. A review. *Agron. Sustain. Dev.* 29(3):423–432.
- Keel SG, Leifeld J, Mayer J, Taghizadeh-Toosi A, Olesen JE. 2017. Large uncertainty in soil carbon modelling related to method of calculation of plant carbon input in agricultural systems. *Europ. J. Soil Sci.* 68:953–963.
- Keel SG, Anken T, Büchi L, Chervet A, Fliessbach A, Flisch R, Huguenin-Elie O, Mäder P, Mayer J, Sinaj S, et al. 2019. Loss of soil organic carbon in Swiss long-term agricultural experiments over a wide range of management practices. *Agric. Ecosyst. Environ.* 286:106654.
- Korsaaeth A, Eltun R. 2000. Nitrogen mass balances in conventional, integrated and ecological cropping systems and the relationship between balance calculations and nitrogen

- runoff in an 8-year field experiment in Norway. *Agric. Ecosyst. Environ.* 79:199–214.
- Korsaeth, A. 2008. Relations between nitrogen leaching and food productivity in organic and conventional cropping systems in a long-term field study. *Agric. Ecosyst. Environ.* 127:177–188.
- Korsaeth A, Eltun R. 2008. Synthesis of the Apelsvoll cropping experiment in Norway – nutrient balances, use efficiencies and leaching. In: H. Kirchmann, L. Bergström, editor. *Organic crop production – ambitions and limitations*. Dordrecht, Netherlands: Springer. p. 117–142.
- Kuzyakov Y, Domanski G. 2000. Carbon input by plants into the soil. review. *J Plant Nutr Soil Sci.* 163:421–431.
- Lal R. 2004. Soil carbon sequestration to mitigate climate change. *Geoderma.* 123:1–22.
- Lilly A, Baggaley NJ, Edwards AC, Goss M. 2020. Changes in the carbon concentrations and other soil properties of some Scottish agricultural soils: evidence from a resampling campaign. *Soil Use Manage.* 36:299–307.
- Luo Z, Wang E, Sun OJ. 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. *Agric. Ecosyst. Environ.* 139:224–231.
- Maillard E, Angers DA. 2014. Animal manure application and soil organic carbon stocks: a meta-analysis. *Global Change Biol.* 20:666–679.
- Nilsson J, Tidåker P, Sundberg C, Henryson K, Grant B, Smith W, Hansson PA. 2020. Assessing the climate and eutrophication impacts of grass cultivation at five sites in Sweden. *Acta Agric. Scand. Section B - Plant Soil Science.* 70:605–619.
- Norwegian Government. 2018. National strategy for organic farming 2018-2030. [https://www.regjeringen.no/contentassets/0036969bc3a547deb46aa7f5653155da/lmd\\_0020\\_nasjonal-strategi-for-okologisk-jordbruk\\_med-ekstrasider.pdf](https://www.regjeringen.no/contentassets/0036969bc3a547deb46aa7f5653155da/lmd_0020_nasjonal-strategi-for-okologisk-jordbruk_med-ekstrasider.pdf)
- Pausch J, Kuzyakov Y. 2018. Carbon input by roots into the soil: quantification of rhizodeposition from root to ecosystem scale. *Global Change Biol.* 24:1–12.
- Poeplau C, Don A. 2015. Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agri. Ecosyst. Environ.* 200:33–41.
- Poeplau C, Aronsson H, Myrbeck Å, Kätterer T. 2015. Effect of perennial ryegrass cover crop on soil organic carbon stocks in southern Sweden. *Geoderma Regional.* 4:126–133.
- Riley H. 2014. Grain yields and soil properties on loam soil after three decades with conservation tillage in southeast Norway. *Acta Agric. Scand. Section B - Plant Soil Science.* 64:185–202.
- Riley H. 2016. Residual value of inorganic fertilizer and farmyard manure for crop yields and soil fertility after long-term use on a loam soil in Norway. *Nutr. Cycling Agroecosyst.* 104:25–37.
- Riley H, Bakkegard M. 2007. Declines of soil organic matter content under arable cropping in southeast Norway. *Acta Agric. Scand. Section B - Plant Soil Science.* 56:217–223.
- Riley H, Eltun R. 1994. The Apelsvoll cropping system experiment II soil characteristics. *Norw. J. Agric. Sci.* 8:317–333.
- Riley H, Pommeresche R, Eltun R, Hansen S, Korsaeth A. 2008. Soil structure, organic matter and earthworm activity in a comparison of cropping systems with contrasting tillage, rotations, fertilizer levels and manure use. *Agric. Ecosyst. Environ.* 124:275–284.
- Saby NPA, Arrouays D, Antoni V, Lemerrier B, Follain S, Walter C, Schvartz C. 2008. Changes in soil organic carbon in a mountainous French region, 1990–2004. *Soil Use Manage.* 24:254–262.
- Skinner RJ, Todd AD. 2006. Twenty-five years of monitoring pH and nutrient status of soils in England and Wales. *Soil Use Manage.* 14:162–169.
- Smith P. 2008. Soil organic carbon dynamics and land-use change. In: Braimoh A. K., Vlek P. L. G., editor. *Land use and soil resources*. Dordrecht: Springer. p. 9–22.
- Smith J, Smith P, Wattenbach M, Zaehle S, Hiederer R, Jones RJA, Montanarella L, Rounsevell MDA, Reginster I, Ewert F. 2005. Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080. *Global Change Biol.* 11:2141–2152.
- Soil Survey Staff. 1998. *Keys to soil taxonomy*, Eighth ed. Washington: USDA. 326 p.
- Uhlen G. 1991. Long-term effects of fertilizers, manure, straw and crop rotation on total N and total C in soil. *Acta Agric. Scand.* 41(119):127.
- Wiesmeier M, Poeplau C, Sierra CA, Maier H, Frühauf C, Hübner R, Kühnel A, Spölein P, Geuß U, Hangen E, et al. 2016. Projected loss of soil organic carbon in temperate agricultural soils in the 21st century: effects of climate change and carbon input trends. *Sci Rep.* 6:32525.