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Soil carbon varies between different organic and conventional management schemes in arable agriculture

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ABSTRACT

The effects of organic versus conventional farming systems on changes in soil organic carbon (SOC) has long been debated. The effects of such comparisons may depend considerably on the design of the respective systems and climate and soil conditions under which they are performed. Here, we compare a range of arable organic and conventional crop systems at three sites (Jyndevad, Foulum and Flakkebjerg) in Denmark through long-term experiments initiated in 1997. The experimental treatments in the organic farming systems included use of whole-year green manure crops, catch crops and animal manure (as cattle, pig or digested slurry). Data on plant residues and animal manure were used to estimate C inputs to the soil. This was compared with measured changes in topsoil (0–25 cm) SOC content over 4–8 years.

During 1997–2004, green manure, catch crops and animal manure enhanced estimated C input by 0.9, 1.0 and 0.7 Mg C ha^{-1} yr^{-1} respectively, across all locations. Based on measured SOC changes, green manure enhanced SOC by 0.4 Mg C ha^{-1} yr^{-1} and catch crops by 0.2 Mg C ha^{-1} yr^{-1}, while animal manure by insignificantly 0.1 Mg C ha^{-1} yr^{-1}. After 2005, advantages of using green manure (grass-clover) on SOC change disappeared, because cuttings of the grass-clover was removed whereas before 2005 they were mulched in the field, albeit there was still a small extra estimated C input of 0.2 Mg C ha^{-1} yr^{-1}. An estimated higher C input of 0.7 Mg C ha^{-1} yr^{-1} with catch crops did not result in significant increase in measured topsoil SOC.

From 2005–2008, the first 4 years of comparison between organic and conventional farming at all three sites, organic farming with animal manure had 0.3 Mg C ha^{-1} yr^{-1} higher estimated C input, but SOC measurements showed that conventional farming accumulated 0.4 Mg C ha^{-1} yr^{-1} more SOC than organic farming. At Foulum from 2005 to 2012, organic farming with animal manure had 0.7 Mg C ha^{-1} yr^{-1} more input, and topsoil SOC measurements showed a higher accumulation of 0.4 Mg C ha^{-1} yr^{-1} in organic compared with conventional farming.

Regressions of changes in topsoil SOC against estimated C inputs showed that 10–20% of C inputs were retained in topsoil SOC over the experimental period. There was no clear indication that belowground C input contributed more to SOC than aboveground C inputs. Despite consistently higher estimated C inputs in organic versus conventional systems, we were not able to detect consistent differences in measured SOC between the systems.

1. Introduction

Globally, soil is one of the most important terrestrial stores of carbon (C) (Davidson et al., 2000; Lal, 2008; Lehmann and Kleber, 2015); however, agricultural soil C is undergoing substantial change due to both environmental conditions and management effects (Janzen et al., 1997; West and Post, 2002; Crowther et al., 2016). Soil organic C (SOC) is an essential indicator of soil fertility and soil quality (Susanne and Michelle, 1998; Al-Kaisi et al., 2005; Huang et al., 2007; Merante et al., 2017). Properly managing SOC may not only bring benefit to productivity and environment, but also mitigate negative effects of extreme events, like droughts, by improving soil hydraulic properties (Gomiero et al., 2011). Enhancing SOC can contribute to reducing net agricultural greenhouse gas emissions, not only by storing C in soils, but also facilitating changes in soil structure that in some cases may reduce N_2O emissions (Mutegi et al., 2010; Powlson et al., 2011). SOC is also associated with higher contents of nutrients such as nitrogen, phosphorus and sulphur (Kirkby et al., 2011), and managing SOC is therefore also closely linked to soil nutrient management, in particular in organic farming (Watson et al., 2002; Gomiero et al., 2011; Reganold

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Table 1
Structure of the organic (O) and conventional (C) crop rotations at three locations: JY = Jyndevad, FO = Foulum, FL = Flakkebjerg.

Crop rotations	O1			O2			O4			C4		
Cycles	Crop	M[1]	CC[2]	Crop	M[1]	CC[2]	Crop	M[1]	CC[2]	Crop	M[1]	CC[2]
1st cycle 1997–2000	S. barley:ley	50		S. barley:ley	50		S. oat	40	+[5]			
	Grass-clover	0		Grass-clover	0		W. wheat	70	+[5]			
	S. wheat	50	+[3]	W. wheat	50	+[3]	W. cereal	70	+[5]			
	Lupin	0	+[4]	Pea/barley	0	+[4]	Pea/barley	0	+[4]			
2nd cycle 2001–2004	S. barley:ley	50		S. barley:ley	50		W. wheat	50	+[4]			
	Grass-clover	0		Grass-clover	0		S. oat	50	+[4]			
	S. oat	30	+[3]	W. cereal	50	+[3]	S. barley	50	+[3]			
	Pea/barley	0	+[4]	Lupin	0	+[4]	Lupin	0				
Locations	JY			JY, FO, FL			FO, FL					
3rd cycle 2005–2009	Discontinued			S. barley:ley	60		S. barley	60	+[4]	S. barley	130	+[3]
				Grass-clover	0		F. bean	0	+[4]	F. bean	0	+[3]
				Potato	100		Potato	110		Potato	140	
				W. wheat	100	+[4]	W. wheat	110	+[4]	W. wheat	165	+[3]
Locations				JY, FO, FL			JY, FO, FL			JY, FO, FL		
4th cycle 2010–2012				S. barley:ley	60		S. barley	60	+[4]	S. barley	120	+[3]
				Lucerne, 1st	0		Hemp	90		Hemp	125	
				Lucerne, 2nd	0		Peas/barley	0	+[4]	Pea/barley	0	+[3]
				S. wheat	100	+[4]	S. wheat	100	+[4]	S. wheat	110	+[3]
				Potato	100	+[4]	Potato	100	+[4]	Potato	140	+[3]
Locations				FO			FO			FO		

[1]M: Manure application target rates in +M treatments. Unit: kg NH_4-N ha^{-1} in 1st and 2nd cycles and kg total-N ha^{-1} in 3rd cycle. Inorganic fertilizer rates are shown as target mineral N in kg N ha^{-1}. [2]CC: Crops succeeded by catch crops in +CC treatments. [3]Monocultures or mixtures of non-N_2-fixing catch crop. [4]Mixtures of N_2-fixing and non-N_2-fixing catch crop. [5]White clover.

and Wachter, 2016).

SOC is primarily managed through soil C inputs, since tillage intensity has shown to have little effect on total SOC storage, although the vertical profile of C concentration is affected by tillage (Powlson et al., 2014). Enhancing SOC thus requires that additional C is added to the soil, which may be achieved by enhancing crop productivity to achieve a higher amount of crop residues or by retaining a larger proportion of the residues in the cropping systems (Powlson et al., 2011). Organic farming, as an approach to environmentally friendly agriculture practice (Reganold and Wachter, 2016), emphasizes increasing SOC and enhancing nutrient cycling through measures such as growing green manure and catch crops, and applying manure (Olesen et al., 2007), which provides additional sources of C inputs besides residues from arable crops. Organic farming has been demonstrated to have higher total C input (Gattinger et al., 2013) and topsoil SOC stocks (Gomiero et al., 2011; Gattinger et al., 2012; Tuomisto et al., 2012) than conventional farming. This is partly a consequence of higher external C input in organic farming, e.g. through animal manure and compost. Compared to conventional farming, organic farming has been criticised for lower crop yields that may lead to lower C inputs (Connor, 2008; Leifeld, 2012; Seufert et al., 2012) and less net transfer of C to the soil from photosynthesis of the crops being grown (Leifeld et al., 2013). However, crops vary greatly in their C inputs from above- and belowground crop residues, and in particular, belowground C inputs are difficult to quantify. Recent research strongly suggests that belowground C input is independent of aboveground biomass for many crop species (Chirinda et al., 2012; Taghizadeh-Toosi et al., 2016; Hu et al., 2018). Additionally, higher root biomass C input of cereals in organic farming compared to conventional systems indicates that belowground C input in organic farming systems may be underestimated (Chirinda et al., 2012). The inputs of C from roots and rhizodeposition may be of particular importance for SOC, since studies have shown that these sources of C may be better retained in soils than C from aboveground crop residues (Rasse et al., 2005; Kätterer et al., 2011; Berti et al., 2016).

There is thus a need to improve the understanding of how the management measures in organic farming contribute to C inputs and retention in soils. Data from long-term experiments with variation in cropping system design and crop management may provide valuable insights by providing information on C inputs and on changes in SOC storage. Such long-term experiments were initiated at three sites in Denmark in 1997 (Olesen et al., 2000), and they thus provide an opportunity to reveal how different components of organic farming systems contribute to soil C inputs and to changes in SOC. The aim of this study was to assess how different components from conventional and organic cropping systems in long-term experiments in Denmark contribute to changes in SOC. For this, we hypothesize: 1) Green manure crops, catch crops and manure add significant amounts of C to the soil that also contribute to measureable changes in SOC; 2) Organic farming can provide higher C input than conventional farming, and this will result in higher SOC of organic compared with conventional farming; 3) Belowground plant inputs contribute to SOC through higher retention of the added organic C than for aboveground parts.

2. Materials and methods

2.1. Field sites

Changes in soil C monitored in long-term experiments on organic and conventional cropping systems at three sites in Denmark, varying in soil type and climate, i.e. Jyndevad (54°54′N, 09°08′E), Foulum (56°30′N, 09°35′E) and Flakkebjerg (55°20′N, 11°23′E) were used for this study. Jyndevad is located in Southern Jutland on a coarse sandy soil (Gleyic Podzol), Foulum is situated in Central Jutland on loamy sand soil (Mollic Luvisol), and Flakkebjerg is placed in Western Zealand on sandy loam soil (Glossic Phaeozem) (classification according to WRB and FAO). In the topsoil (0–25 cm), the clay content at Jyndevad, Foulum and Flakkebjerg were 45, 88 and 155 g kg^{-1}, respectively. The soil pH of the respective locations was 6.1, 6.5 and 7.4. SOC content was 1.17, 2.29 and 1.01%, and soil C/N ratio was 13.8, 13.1 and 9.4 at start of the experiments. The soil bulk density at Jyndevad, Foulum and Flakkebjerg were 1.572, 1.422 and 1.702 g cm^{-3}. Average annual temperature and precipitation during 1961–1990 were 7.9 °C and 964 mm, 7.3 °C and 704 mm and 7.8 °C and 626 mm for the three sites, respectively. Additional information on soil properties of these three locations are provided by Olesen et al. (2000) and Berntsen et al. (2004).

2.2. Experimental treatments

The experiments were conducted according to an experimental design with three factors. At all three sites, four or five-year crop rotation cycles were used, where four crops in the rotations were present every year (Table 1). From 1997–2004, three factors were included in a fully factorial design: (i) N_2-fixing whole-year green manure crops in organically managed rotations (with: O1 and O2, without: O4), (ii) catch crops (with: +CC, without: −CC), and (iii) manure (with: +M, without: −M), which composed 8 treatment combinations. During this period, O1 was conducted at Jyndevad, whereas O4 was conducted at Foulum and Flakkebjerg. From 2005, rotation O4 replaced O1 at Jyndevad (Askegaard et al., 2011). Since 2005, treatments of O2-CC-M and O4-CC-M were converted to conventional rotation (without N_2-fixing green manures, but using inorganic fertilisers: +IF), as C4-CC+IF and C4+CC+IF, in which mineral fertilisers and pesticides were used (Shah et al., 2017). The experiments were conducted at all three locations until 2009, when it was stopped at Jyndevad and Flakkebjerg, but continued at Foulum. To obtain better control of perennial weeds (*Cirsium arvense* L. and *Elytrigia repens* L.) the crop rotations were converted in 2010 from 4 to 5 years. In particular, an additional year of green manure was added in O2, while hemp was introduced in O4 and C4. During the original experiment design all four crops in the rotation was represented every year in each treatment, but from 2010 only 4 of the 5 crops were present in any given year. The experiments were conducted with 2 replicates in a total of 64 plots at each site every year. Since the analyses were done on 4-year rotational basis, there were in total 8 replications for each of the 8 aforementioned treatment combinations. Plots sizes were 378, 216 and 169 m^2 at Jyndevad, Foulum and Flakkebjerg, respectively.

2.3. Crop management

The main crops included in the experiment were: spring barley (*Hordeum vulgare* L.), spring and winter wheat (*Triticum aestivum* L.), winter rye (*Secale cereale* L.), winter triticale (*Triticosecale*), lupin (*Lupinus angustifolius* L.), faba bean (*Vicia faba* L.), a mixture of pea (*Pisum sativum* L.) and spring barley, potato (*Solanum tuberosum* L.), grass-clover, mainly including perennial ryegrass (*Lolium perenne* L.), white clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.) and lucerne (*Medicago sativa* L.) (Table 1).

In the first two 4-year cycles (1997–2004), the non-legume catch crops varied between monocultures of ryegrass or mixtures of ryegrass and chicory (*Cichorium intybus* L.) undersown in spring. The legume catch crop varied between pure stands of white clover, mixtures of ryegrass + white clover or mixtures of ryegrass + white clover + red clover or mixtures of ryegrass + black medic (*Medicago lupulina* L.) + serradella (*Ornithopus sativus Brot*.) + birdsfoot-trefoil (*Lotus corniculatus* L.) + subterranean clover (*Trifolium subterraneum* L.) or a mixture of ryegrass + chicory + black medic + kidney vetch (*Anthyllis vulneraria* L.). All catch crop mixtures were undersown in spring. From the 3rd cycle (2005–2009), a mixture of winter rye + hairy vetch (*Vicia villosa* L.) + fodder radish (*Raphanus sativus oleiformis* L.) sown after harvest of the crop was used at Flakkebjerg. From the 4th cycle (2010–2012), mixtures of radish + rye, radish + rye + vetch or chicory + grass + clover were used at Foulum. Various catch crop species were chosen over time reflecting experience of which species provided the most reliable establishment and growth.

From 1997–2004, in treatments with manure (+M), cattle slurry, pig slurry and anaerobically digested slurry was used at Jyndevad, Foulum and Flakkebjerg, respectively, at ammonium-N rates corresponding to 40% of the recommended N rates for conventional farming in Denmark (Plantedirektoratet, 1997). From 2005, pig slurry was used at all three locations, and rates applied were updated according to a revised Danish national standard allowing import of animal manure of conventional origin corresponding to 70 kg total-N ha^{-1} yr^{-1} (Plantedirektoratet, 2005). From 2011 anaerobically digested slurry was used at Foulum. Analyses of manure N contents confirmed that the actual rates of N applied were close to the target levels.

From 1997–2008, all straw was incorporated into the soil or left on the ground. From 2010 onwards at Foulum, straw of spring barley, spring wheat and peas/barley were removed in C4 treatments. From 2011 onwards, removing straw of spring barley was extended to O2 treatments.

Before 2005, grass-clover was cut 3–4 times and left on the ground in all treatments of rotation O1 and O2 in the growing season, except in 1999 at Jyndevad for controlling couch grass (*Agropyrum repens* L.). Since the 3rd cycle in 2005, the grass-clover cuttings were removed in the +M treatments.

Mechanical weed harrowing (tine harrowing in cereals and pulses and ridging in potatoes) were conducted to control weeds. In −CC treatments harrowing (stubble cultivation) was conducted in autumn when there was a need to control perennial weeds. In some years, +CC treatments identified to have high level of weeds were harrowed immediately after harvest before establishing the catch crops.

In the 1st and 2nd cycles, Jyndevad was the only location irrigated. After introduction of potato in the 3rd cycle, irrigation was conducted in the plots with potato at Flakkebjerg and in all plots at Foulum according to the need for irrigating potato. Irrigation was not applied in the 4th cycle, where the experiment was only conducted at Foulum (Table 1).

2.4. Soil sampling

Soil samples to 25 cm depth in each plot were taken for SOC content measurement in 1996, 2004, and 2008 at all locations and in 2012 at Foulum. In each plot, eight soil samples were taken and pooled to a composite sample. Soil C percentage contents were then measured using a LECO CNS-1000 analyser with IR detector (LECO Corporation, St. Joseph, MI). SOC percentage content was calculated by subtracting the percentage content of carbonates from soil C, if present (Nelson and Sommers, 1996). SOC percentage contents were converted to topsoil SOC amounts by multiplying by 0–25 cm soil bulk densities of each location and the associated soil volume. Soil density was assumed independent of treatments.

2.5. C input estimation

Soil C input originated from green manure, catch crops, crops and animal manure. The aboveground biomass returned to the soil was estimated by measured aboveground biomass minus harvested biomass of each crop and catch crop. Each plot was subdivided into four or five subplots. Two of the subplots were harvested for crop yield. The other subplots were used for plant and soil sampling. The size of the net harvest plots was 22.5, 24 and 16 m^2 at Jyndevad, Foulum and Flakkebjerg, respectively. Cereal and grain legume crops were harvested in August using a combine harvester, whereas potato was harvested with a potato harvester and grass with a plot grass harvester. Aboveground biomass at all plants (potatoes excluded) was sampled from two 0.5 m^2 sampling plots. Crops (potatoes excluded) were sampled shortly before maturity. Potatoes were sampled as 10 plants per plot in organic rotations at the early stage of potato late blight and in conventional rotations before spraying to wilt the crop. Green manures were sampled shortly before each cut. Samples of catch crops were taken during late autumn (about November). The aboveground dry matter (DM) contents of plant samples were weighed after oven drying at 80 °C for 24 h.

Belowground C inputs from roots were based on estimates of root biomass, which was assumed as fixed amounts depending on farming systems (organic or conventional) and species, and thus independent of aboveground biomass (Chirinda et al., 2012; Taghizadeh-Toosi et al., 2016). This assumption was validated based on measurements from a range of studies conducted in Denmark (Hu et al., 2018). Because of similar species and cutting times, first production year data of red clover from Bolinder et al. (2002) was used to estimate the fixed root amount of grass-clover crops. For the green manure crop of lucerne grown after 2010, lucerne data of the first and second production year from Bolinder et al. (2002) were used separately for the first and second production years of lucerne, respectively, in the experiment. Estimates of root biomass of cereals (wheat, barley and their average for other cereals), catch crops and weeds for organic and conventional farming systems were taken from Hu et al. (2018). Legume:barley mixtures were regarded as barley for calculating belowground C input. Fixed root dry biomass of potatoes from 25 to 30 cm depth was collected from Bolinder et al. (2015). Root biomass data for faba bean (Munoz-Romero et al., 2011), lupin (Russell and Fillery, 1996) and hemp (Amaducci et al., 2008) were used to estimate fixed root amounts for these crops.

C content of applied animal manure was measured using a LECO CNS-1000 analyzer. C content in plant material was taken as 0.45 of the dry biomass for residues and roots (Chirinda et al., 2012). Root biomass (except for potato) was corrected to 0–25 cm depth using the Michaelis-Menten-type root depth distribution function of Kätterer et al. (2011). Soil C inputs from roots also include root exudates, which were taken as 0.65 times root biomass C according to Bolinder et al. (2007). Estimation of belowground C inputs for individual crops and farming systems are shown in Table 2.

Table 2
Estimated root + exudates C for different type of plants.

Farming systems	Species	Estimated root + exudates C input $Mg\,C\,ha^{-1}\,yr^{-1}$	Reference
Organic systems	Grass-clover	4.43	Bolinder et al. (2002)
	Lucerne	3.03	Bolinder et al. (2002)
	Lucerne 2nd	5.36	Bolinder et al. (2002)
	Wheat	1.80	Hu et al. (2018)
	Barley	1.43	Hu et al. (2018)
	Other cereals	1.62	Hu et al. (2018)
	Catch crops	0.94	Hu et al. (2018)
	Weeds[1]	0.26	Hu et al. (2018)
Conventional systems	Wheat	1.05	Hu et al. (2018)
	Barley	0.96	Hu et al. (2018)
	Other cereals	1.03	Hu et al. (2018)
	Catch crops	0.56	Hu et al. (2018)
	Weeds[1]	0.21	Hu et al. (2018)
Both systems	Lupin	1.59	Russell and Fillery (1996)
	Potato	0.22	Bolinder et al. (2015)
	Faba bean	1.11	Munoz-Romero et al. (2011)
	Hemp	1.12	Amaducci et al. (2008)

[1] Treatments/years without catch crops and soil tillage in autumn.

2.6. Statistical analysis

Data on total C input and changes in SOC content (0–25 cm) of O2, O4 and C4 at all locations were analysed separately for different periods, i.e. from 1996 to 2004 and from 2005 to 2008. Data from rotation O1 were not included, since this rotation was only conducted at Jyndevad. Data from Foulum were also analysed from 2005 to 2012. This reflected the different design of the systems in the different periods, with conventional systems only being present from 2005 onwards. Effects of treatments (crop rotation, catch crops and manure) on total C input and changes in SOC were analysed using an analysis of variance with the procedure GLM of SAS (SAS Institute, 2008), and the Least Significant Difference (LSD) ($P < 0.05$) was used for the significance of mean observation differences.

The following regression models were used to estimate the contribution of C input in plant materials (aboveground plus belowground), animal manure and original SOC content to the SOC content during 1996–2008 at all locations and 1996–2012 at Foulum:

$$C_t = K_P \times C_{plant} + K_{AM} \times C_{AM} + K_O \times C_o \quad (1)$$

where C_t is the SOC content ($Mg\,C\,ha^{-1}$) at sampling time t (2008 or 2012), C_{plant} is the C input from plant material ($Mg\,C\,ha^{-1}$), C_{AM} is C input in animal manure ($Mg\,C\,ha^{-1}$), and C_o is the SOC content ($Mg\,C\,ha^{-1}$) of soil sampled in topsoil (0–25 cm) at the starting time (in 1996). K_P and K_{AM} are coefficients describing the effects of C inputs from plant materials and animal manure, respectively. K_O defines the effect of original SOC content on C_t at sampling time t.

Effects of aboveground parts and belowground parts on the SOC content were examined with the following model:

$$C_t = K_A \times C_{aboveground} + K_B \times C_{belowground} + K_{AM} \times C_{AM} + K_O \times C_o \quad (2)$$

where $C_{aboveground}$ is the C input in aboveground residues ($Mg\,C\,ha^{-1}$), $C_{belowgorund}$ is C input in roots and rhizodeposition ($Mg\,C\,ha^{-1}$). K_A, K_B and K_{AM} are coefficients describing the effects of the above- and belowground plant C and animal manure inputs, respectively.

The parameters in Eqs. (1) and (2) were estimated using the MIXED procedure of SAS (SAS Institute, 2008), where intercept was set as 0, and block effects nested within locations were set as random. Data in rotation O1 were also used in modelling for these equations. In Eqs. (1)–(2), K_O refers to the proportion of original SOC left in soil. Thus, the proportion of C lost every year is calculated as:

$$D_C = 1 - K_O^{\ 1/n} \quad (3)$$

Where D_C means proportion of SOC decomposed in one year (decomposition rate of original SOC), and n is the span of years.

3. Results

3.1. C input

3.1.1. All sites, 1997–2004

Across all three sites from 1997 to 2004, mean C inputs were around 3.62–6.62 $Mg\,C\,ha^{-1}\,yr^{-1}$ (Table 3). The highest C inputs were observed in O2 + CC + M (Jyndevad and Flakkebjerg) and O4 + CC + M (Foulum). The lowest C inputs consistently occurred in O4-CC-M (Table 3). As shown in Fig. 1a for average C inputs, the one-year green manure provided approximately 2.22 $Mg\,C\,ha^{-1}\,yr^{-1}$ of the 5.71 $Mg\,C\,ha^{-1}\,yr^{-1}$ for the entire 4-year rotation as average of the O2 treatments. Crops provided around 2.89 $Mg\,C\,ha^{-1}\,yr^{-1}$ in O2 and 3.85 $Mg\,C\,ha^{-1}\,yr^{-1}$ in O4. C inputs from catch crops, if applied, provided about 0.77 $Mg\,C\,ha^{-1}\,yr^{-1}$ in O2 and 1.67 $Mg\,C\,ha^{-1}\,yr^{-1}$ in O4, while weeds supplied around 0.28 $Mg\,C\,ha^{-1}\,yr^{-1}$. Animal manure added another 0.23 $Mg\,C\,ha^{-1}\,yr^{-1}$ of C input. Significant treatment effects (green manure, catch crops and animal manure) on C inputs

Table 3
Mean carbon input (Mg C ha^{-1} yr^{-1}) estimated in different treatments at Jyndevad, Foulum, Flakkebjerg during 1997–2004 (Jyndevad, Foulum and Flakkebjerg), 2005–2008 (Jyndevad, Foulum, Flakkebjerg) and 2005–2012 (Foulum). Analysis was also conducted with data of all three locations combined during 1997–2004 and 2005–2008. Part I of the table shows carbon inputs for individual treatment components and part II shows main effects of individual treatments. In part II treatments with –M were not used in analysis after 2004.

Treatment	Jyndevad		Foulum			Flakkebjerg		All locations	
	1997–2004	2005–2008	1997–2004	2005–2008	2005–2012	1997–2004	2005–2008	1997–2004	2005–2008
Part I									
O2-CC-M	4.43 ^{c}	–	5.48 ^{e}	–	–	5.57 ^{c}	–	5.16 ^{c}	–
O2-CC + M	5.33 ^{b}	3.62 ^{bc}	6.02 ^{cd}	4.46 ^{c}	4.19 ^{c}	6.01 ^{b}	3.64 ^{cd}	5.79 ^{b}	3.91 ^{c}
O2 + CC-M	4.96 ^{b}	4.44 ^{a}	6.18 ^{bc}	5.41 ^{a}	5.48 ^{a}	6.13 ^{b}	4.45 ^{a}	5.76 ^{b}	4.77 ^{a}
O2 + CC + M	5.75 ^{a}	4.32 ^{a}	6.32 ^{b}	4.72 ^{b}	4.58 ^{b}	6.36 ^{a}	4.15 ^{ab}	6.14 ^{a}	4.39 ^{b}
O4-CC-M	–	–	3.93 ^{g}	–	–	3.62 ^{e}	–	3.48 ^{e}	–
O4-CC + M	–	3.30 ^{d}	4.77 ^{f}	3.63 ^{e}	3.50 ^{d}	4.60 ^{d}	3.11 ^{ef}	4.39 ^{d}	3.35 ^{e}
O4 + CC-M	–	3.61 ^{bc}	5.80 ^{d}	4.20 ^{d}	4.17 ^{c}	5.34 ^{c}	3.38 ^{de}	5.27 ^{c}	3.73 ^{d}
O4 + CC + M	–	4.48 ^{a}	6.62 ^{a}	4.89 ^{b}	4.74 ^{b}	6.20 ^{ab}	4.12 ^{b}	6.11 ^{a}	4.50 ^{b}
C4-CC + IF	–	3.33 ^{cd}	–	3.61 ^{e}	3.15 ^{e}	–	3.01 ^{f}	–	3.32 ^{e}
C4 + CC + IF	–	3.71 ^{b}	–	4.06 ^{d}	3.66 ^{d}	–	3.72 ^{c}	–	3.83 ^{cd}
Part II									
O2	–	3.97 ^{a}	6.00 ^{a}	4.59 ^{a}	4.39 ^{a}	6.02 ^{a}	3.90 ^{a}	5.71 ^{a}	4.15 ^{a}
O4	–	3.89 ^{a}	5.28 ^{b}	4.26 ^{b}	4.12 ^{b}	4.94 ^{b}	3.62 ^{b}	4.81 ^{b}	3.92 ^{b}
C4	–	3.52 ^{b}	–	3.84 ^{c}	3.41 ^{c}	–	3.36 ^{c}	–	3.57 ^{c}
-CC	4.88 ^{b}	3.42 ^{b}	5.05 ^{b}	3.90 ^{b}	3.62 ^{b}	4.95 ^{b}	3.25 ^{b}	4.77 ^{b}	3.52 ^{b}
+CC	5.36 ^{a}	4.17 ^{a}	6.23 ^{a}	4.55 ^{a}	4.33 ^{a}	6.01 ^{a}	4.00 ^{a}	5.76 ^{a}	4.24 ^{a}
-M	4.70 ^{b}	–	5.35 ^{b}	–	–	5.17 ^{b}	–	4.94 ^{b}	–
+M	5.54 ^{a}	–	5.93 ^{a}	–	–	5.79 ^{a}	–	5.59 ^{a}	–

For each group (treatments in Part I; rotations, catch crops and manure respectively in Part II) mean values having different letters within a column are significantly different at the 0.05 significance level.

were observed at all sites (Table 3). Overall, applying green manure increased C input in O2 by 0.90 Mg C ha^{-1} yr^{-1} above that in O4. Using catch crops brought in about 0.99 Mg C ha^{-1} yr^{-1} more C input than weeds (Table 3), where this amount of C input was mainly from catch crops themselves, and partly contributed by higher crop biomass (Fig. 1a). Using animal manure, resulted in additional 0.65 Mg C ha^{-1} yr^{-1} of C input (Table 3). Besides the 0.23 Mg C ha^{-1} yr^{-1} in animal manure itself, the input of 0.41 Mg C ha^{-1} yr^{-1} (0.24 Mg C ha^{-1} yr^{-1} in O2 and 0.59 Mg C ha^{-1} yr^{-1} in O4) was from increased crop biomass due to manure application (Fig. 1a).

3.1.2. All sites, 2005–2008

During 2005–2008, treatments of −CC-M were converted to conventional farming systems where mineral fertilisers were applied. C inputs across all sites ranged from 3.01–5.41 Mg C ha^{-1} yr^{-1} (Table 3). Since the aboveground part of green manure was removed in +M treatments, highest C inputs appeared in O2+CC-M (Foulum and Flakkebjerg) and O4+CC+M (Jyndevad), while the lowest were in C4-CC+IF (Foulum and Flakkebjerg) and O4-CC-M (Jyndevad) (Table 3). As shown in Fig. 1b, green manure brought in 2.42 Mg C ha^{-1} yr^{-1}, but this value dropped to only 1.38 Mg C ha^{-1} yr^{-1} if the aboveground parts were removed. Crops provided around 2.14, 2.89 and 3.16 Mg C ha^{-1} yr^{-1} in O2, O4 and C4, respectively. Accordingly, catch crops contributed about 0.43, 1.11 and 0.69 Mg C ha^{-1} yr^{-1} in each rotation system. In treatments without catch crops, weeds added on average 0.12 Mg C ha^{-1} yr^{-1}. Animal manure itself brought in 0.29 Mg C ha^{-1} yr^{-1}. Generally at all sites, there were significant treatment effects (rotation systems and catch crops) when considering the six fertilised treatments (Table 3). When comparing O2 with O4, using green manure only increased average inputs by 0.23 Mg C ha^{-1} yr^{-1} (Table 3), because the aboveground part of green manure was removed in O2 + M treatments. The aboveground in O2 contributed negatively 0.33 Mg C ha^{-1} yr^{-1} and belowground positively more than 0.56 Mg C ha^{-1} yr^{-1}, compared with O4 (Fig. 1b). Compared to C4, O4 had 0.35 Mg C ha^{-1} yr^{-1} more C input (Table 3), where the belowground part added 0.47 Mg C ha^{-1} yr^{-1} (Fig. 1b), and the aboveground part reduced this value. Applying catch crops increased C inputs with 0.71 Mg C ha^{-1} yr^{-1} (Table 3), where 0.61 Mg C ha^{-1} yr^{-1} of C input was from catch crops, and the rest was from higher biomass yield from the main crops in organic systems, especially in O4.

3.1.3. Foulum, 2005–2012

Even though cereal straw in C4 and barley straw in O2 were removed since 2010 and 2011, the treatment differences of C inputs at Foulum during 2005–2012 did not change much compared to 2005–2008 (Table 3). O2 + CC-M and C4-CC + IF were still the ones that contributed most and least C input, respectively (Table 3). Fig. 1c shows that during the 8 years from 2005 to 2012 at Foulum, green manure provided C inputs of respectively 2.97 and 1.58 Mg C ha^{-1} yr^{-1} without and with removal of grass-clover and lucerne cuts. On average, crops in O2, O4 and C4 brought in 2.15, 3.07 and 2.88 Mg C ha^{-1} yr^{-1}, respectively. Catch crops increase C inputs of 0.53, 1.23 and 0.78 Mg C ha^{-1} yr^{-1} for the respective rotation systems. Weeds and animal manure contributed C inputs of 0.19 and 0.28 Mg C ha^{-1} yr^{-1}, respectively. Green manure with removal of cuttings in O2 helped C input to increase by 0.27 Mg C ha^{-1} yr^{-1} compared to O4 (Table 3), which originated mostly from a higher belowground C input in O2. The C input was 0.71 Mg C ha^{-1} yr^{-1} higher in O4 than in C4, which resulted from differences in C inputs in belowground plant materials and animal manure (Fig. 1c). Catch crops added extra C input of 0.71 Mg C ha^{-1} yr^{-1} (Table 3), which was mostly direct input from the catch crops and less from higher main crop biomass returns.

3.2. Change in SOC

3.2.1. All sites, 1997–2004

From 1997–2004, O2+CC+M at all sites had the highest SOC increase or the least loss, even though the amount of SOC change in the treatment at each site was very different, with 0.40 Mg C ha^{-1} yr^{-1} at Jyndevad, −0.44 Mg C ha^{-1} yr^{-1} at Foulum and 0.27 Mg C ha^{-1} yr^{-1} at Flakkebjerg (Table 4). Generally, the largest decreases in C concentration were obtained with O4-CC-M, except at Jyndevad where O4 was not represented (Table 4). Overall, including the green manure in O2 significantly enhanced SOC by 0.40 Mg C ha^{-1} yr^{-1} when

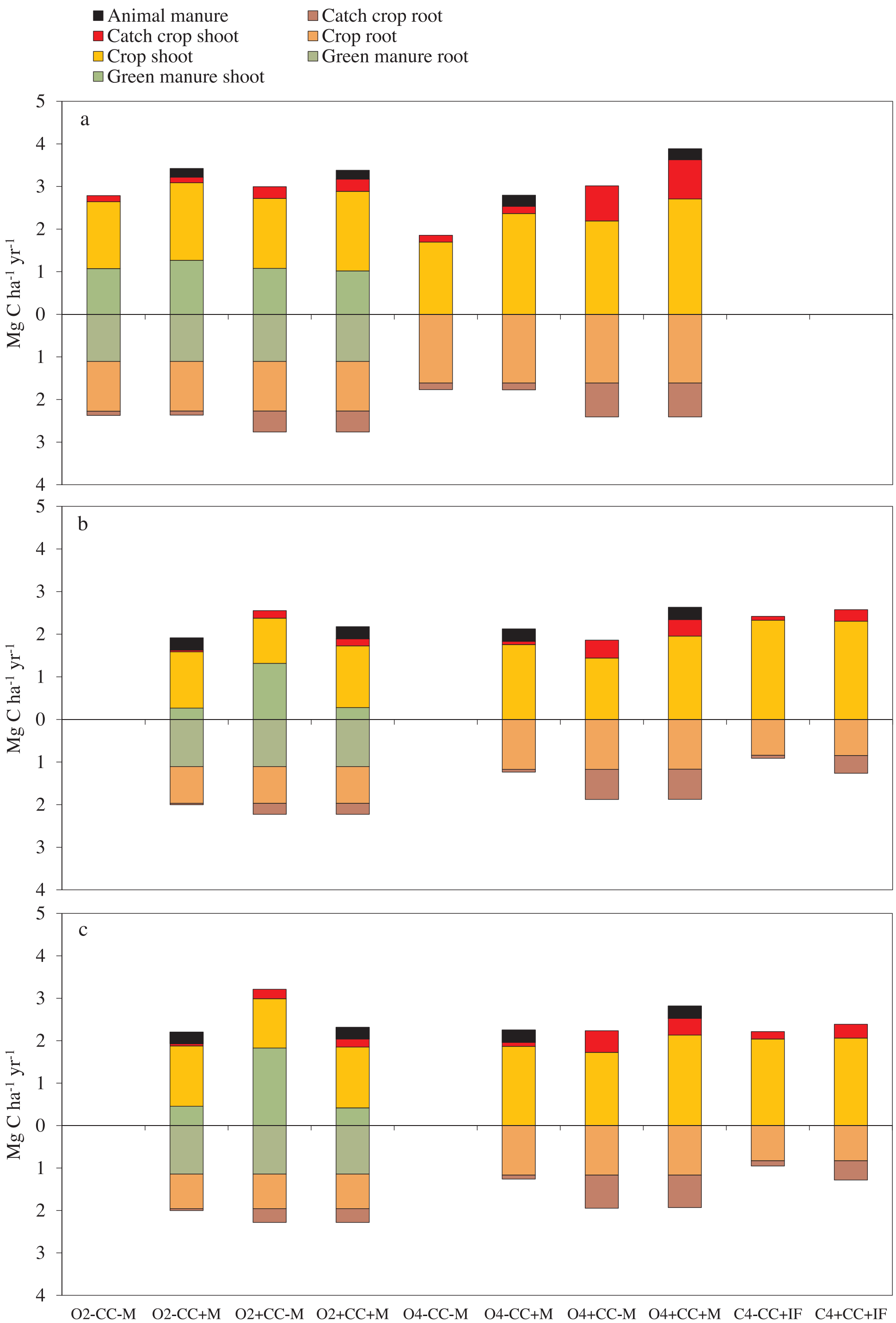

Fig. 1. Measured above-ground and estimated below-ground C input of plant residues and animal manure in different treatments at all locations during 1997–2004 (a) and 2005–2008 (b), and at Foulum alone during 2005–2012 (c). In (a), (b) and (c), C inputs from above-ground plant residues and animal manure are shown above the reference line, and C inputs from below-ground plant residues are shown below the reference line.

comparing O2 and O4 at Foulum and Flakkebjerg (Table 4). Using catch crops enhanced SOC by 0.21 Mg C ha^{-1} yr^{-1}. The use of animal manure was not significant in enhancing SOC in the overall data analysis across all locations, but showed significant effects at both Jyndevad and Flakkebjerg (Table 4), where cattle slurry and anaerobically digested slurry was applied, respectively.

3.2.2. All sites, 2005–2008

During 2005–2008, there were little difference between treatments in SOC changes (Table 4). The cuttings of green manure was removed in +M treatments, and O2+CC-M became the treatment that best retained SOC in O2 at all sites (Table 4). In the analysis involving all locations, O2+CC-M was the treatment with the highest increase in SOC (Table 4). Generally, O4+CC+M was the treatment that lost most SOC. When the six fertilised treatments were compared, results showed that use of green manure in O2 did not significantly enhance SOC when compared to the rotation without green manure in O4 (Table 4). The organic rotation (O4) had significantly less SOC accumulation of 0.35 Mg C ha^{-1} yr^{-1} than the similar conventional (C4) rotation during the first four years of conventional farming (Table 4). Applying catch crops showed no significant effects at any site during this period.

3.2.3. Foulum, 2005–2012

From 2005–2012 at Foulum, O2+CC-M retained more SOC than other O2 treatments, likely because cuttings were retained in the −M treatment and removed in the +M treatments (Table 4). Overall,

Table 4
Mean change of soil organic carbon content (Mg C ha^{-1} yr^{-1}) in 0–25 cm depth in different treatments at Jyndevad, Foulum, Flakkebjerg during 1997–2004 (Jyndevad, Foulum and Flakkebjerg), 2005–2008 (Jyndevad, Foulum, Flakkebjerg) and 2005–2012 (Foulum). Analysis was also conducted with data of all three locations combined during 1997–2004 and 2005–2008. Part I of the table shows carbon inputs for individual treatment components and part II shows main effects of individual treatments. In part II treatments with –M were not used in analysis after 2004.

Treatment	Jyndevad		Foulum			Flakkebjerg		All locations	
	1997–2004	2005–2008	1997–2004	2005–2008	2005–2012	1997–2004	2005–2008	1997–2004	2005–2008
Part I									
O2-CC-M	0.10 ^{ab}	–	−0.84 ^{abc}	–	–	−0.18 ^{cd}	–	−0.30 ^{bc}	–
O2-CC + M	0.18 ^{ab}	−0.33 ^{ab}	−1.13 ^{bc}	−0.13 ^{a}	−0.17 ^{ab}	0.00 ^{abc}	−0.25 ^{abc}	−0.32 ^{bc}	−0.25 ^{ab}
O2 + CC-M	−0.31 ^{b}	0.05 ^{a}	−0.66 ^{ab}	0.08 ^{a}	−0.15 ^{ab}	0.15 ^{ab}	0.07 ^{a}	−0.27 ^{b}	0.06 ^{a}
O2 + CC + M	0.40 ^{a}	−0.95 ^{bc}	−0.44 ^{a}	−0.02 ^{a}	−0.56 ^{b}	0.27 ^{a}	−0.01 ^{ab}	0.07 ^{a}	−0.34 ^{ab}
O4-CC-M	–	–	−1.26 ^{bc}	–	–	−0.65 ^{e}	–	−0.80 ^{d}	–
O4-CC + M	–	−1.02 ^{bc}	−1.16 ^{bc}	0.39 ^{a}	−0.20 ^{ab}	−0.37 ^{de}	−0.36 ^{abc}	−0.61 ^{cd}	−0.33 ^{ab}
O4 + CC-M	–	−0.53 ^{abc}	−1.23 ^{bc}	0.24 ^{a}	−0.46 ^{b}	−0.09 ^{bcd}	−0.61 ^{c}	−0.51 ^{bcd}	−0.30 ^{ab}
O4 + CC + M	–	−1.40 ^{c}	−1.26 ^{c}	0.58 ^{a}	0.13 ^{a}	−0.03 ^{abc}	−0.50 ^{bc}	−0.49 ^{bcd}	−0.44 ^{b}
C4-CC + IF	–	−0.17 ^{ab}	–	0.11 ^{a}	−0.30 ^{ab}	–	0.19 ^{a}	–	0.04 ^{a}
C4 + CC + IF	–	−0.81 ^{abc}	–	0.64 ^{a}	−0.53 ^{b}	–	−0.16 ^{abc}	–	−0.11 ^{ab}
Part II									
O2	–	−0.64 ^{ab}	−0.77 ^{a}	-0.08 ^{b}	−0.37 ^{b}	0.06 ^{a}	−0.14 ^{ab}	−0.21 ^{a}	−0.30 ^{ab}
O4	–	−1.21 ^{b}	−1.23 ^{b}	0.48 ^{a}	−0.04 ^{a}	-0.28 ^{b}	−0.43 ^{b}	−0.61 ^{b}	−0.38 ^{b}
C4	–	−0.49 ^{a}	–	0.38 ^{ab}	−0.41 ^{b}	–	0.01 ^{a}	–	−0.03 ^{a}
-CC	0.14 ^{a}	−0.51 ^{a}	−1.10 ^{a}	0.12 ^{a}	−0.22 ^{a}	−0.30 ^{b}	−0.14 ^{a}	−0.51 ^{b}	−0.18 ^{a}
+CC	0.04 ^{a}	−1.05 ^{a}	−0.90 ^{a}	0.40 ^{a}	−0.32 ^{a}	0.07 ^{a}	−0.23 ^{a}	−0.30 ^{a}	−0.30 ^{a}
-M	−0.10 ^{b}	–	−1.00 ^{a}	–	–	−0.19 ^{b}	–	−0.48 ^{a}	–
+M	0.29 ^{a}	–	−1.00 ^{a}	–	–	−0.03 ^{a}	–	−0.34 ^{a}	–

For each group (treatments in Part I; rotations, catch crops and manure respectively in Part II) mean values having different letters within a column are significantly different at the 0.05 significance level.

O4 + CC + M had the highest SOC increase, while O2 + CC + M and C4 + CC + IF had the greatest decreases (Table 4). Considering only fertilised treatments in different rotations, O4 had significantly less SOC decrease than O2 and C4. During this eight-year period, using catch crops did not significantly affect SOC at Foulum (Table 4).

3.3. Effects of C input on SOC

When combining data from all sites in model I, around 82% ($p < 0.01$) of SOC in topsoil in 1997 was estimated to remain in 2008, with an estimated annual soil decomposition rate of 1.6% (Table 5). The estimated humification rate of C input from plant materials was about 12% ($p < 0.01$). For animal manure about 14% ($p > 0.05$) was estimated to be retained, but this value was associated with considerable uncertainty. Aboveground and belowground plant materials were estimated to contribute 4% ($p > 0.05$) and 19% ($p < 0.01$), respectively, of their C to SOC as shown in model II (Table 5). However, the standard error of the humification coefficients of above- and below-ground plant material was about 6% in model II compared to 2% for total plant biomass in model I. Lower AIC and RMSE values of model I compared to model II also indicated that the use of separate humification coefficients for above- and below-ground plant material cannot be justified (Table 5). For individual sites, model I showed negative contribution from animal manure in some cases, while model II showed

Table 5
Estimated contribution of C input (Mg C ha^{-1}) from plant materials, animal manure (AM) and from original SOC content in top soil (0–25 cm in 1997) to the SOC content in 2008 at Jyndevad, Foulum and Flakkebjerg, and in 2012 at Foulum using two different models. Estimations were also performed with data of all three locations combined during 1997–2008. Values in brackets show the standard error.

		Jyndevad	Foulum	Foulum	Flakkebjerg	All locations
		1997–2008	1997–2008	1997–2012	1997–2008	1997–2008
	N	63	64	64	62	189
Model I	K_P (%)	17 (5.2) **	9 (5.7)	11 (4.2) **	17 (3.5) **	12 (2.3) **
	K_{AM} (%)	27 (22.8)	−10 (52.2)	40 (33.8)	−5 (24.6)	14 (18.7)
	K_O (%)	76 (5.8) **	85 (4.3) **	76 (4.1) **	73 (4.7) **	82 (2.2) **
	D_C (% yr^{-1})	2.2	1.4	1.7	2.6	1.6
	AIC	344.3	409.2	403.9	308.9	1076.9
	RMSE (Mg C ha^{-1})	3.29	5.34	5.03	2.64	3.93
	R^2	0.54	0.62	0.63	0.63	0.61
Model II	K_A (%)	35 (9.6) **	−12 (17.7)	13 (12.4)	−8 (8.3)	4 (6.3)
	K_B (%)	−1 (10.1)	35 (22.3)	8 (14.1)	43 (8.9) **	19 (6.5) **
	K_{AM} (%)	23 (22.2)	−1 (52.7)	41 (34.2)	9 (23.3)	16 (18.7)
	K_O (%)	77 (5.7) **	86 (4.2) **	76 (4.2) **	76 (4.5) **	83 (2.1) **
	D_C (% yr^{-1})	2.1	1.3	1.7	2.3	1.5
	AIC	341.4	407.8	404.8	301.1	1078.0
	RMSE (Mg C ha^{-1})	3.19	5.34	5.07	2.45	3.94
	R^2	0.57	0.62	0.62	0.68	0.61

Model I: $C_t = K_P \times C_{plant} + K_{AM} \times C_{AM} + K_O \times C_o$; Model II: $C_t = K_A \times C_{aboveground} + K_B \times C_{belowground} + K_{AM} \times C_{AM} + K_O \times C_o$; **: $0.0001 < P < 0.01$; AIC: Akaike information criterion; D_C: Decomposition rate of original SOC.

negative contributions of plant materials in some cases (Table 5). The large standard error for the humification coefficient for animal manure was probably an effect of the low input of C in manure compared with C input in plant material (Fig. 1).

During 16 years at Foulum (1997–2012), the estimated annual decomposition rate of original SOC was estimated as 1.7% (Table 5). The humification coefficient of plant materials was about 11% ($p < 0.01$) of C input. The humification coefficient for animal manure was considerably higher than for other analyses, about 40%, but with a standard error of 34% (Table 5). Splitting C input from plant materials as aboveground and belowground parts in model II showed similar contribution in both parts of around 10%, but none of these were statistically significant (Table 5). Model I had a lower AIC compared to model II, again indicating that a common humification coefficient for above- and belowground plant residues could be used.

4. Discussion

4.1. Effects of green manure, catch crops and animal manure on SOC change

4.1.1. Green manure

Including grassland in crop rotations is known to increase soil C (Leifeld, 2012), and generally the increase of SOC ranged from 0.3–1.9 Mg C ha^{-1} yr^{-1} (Christensen et al., 2009; Müller-Stöver et al., 2012; Rosenzweig et al., 2016). A previous monitoring study in Denmark also found significant increase of SOC by 0.9 Mg C ha^{-1} yr^{-1} in 0–25 cm soil layer for each year of grass in a crop rotation (Taghizadeh-Toosi et al., 2014). Our study showed that the inclusion of green manure significantly helped adding 0.4 Mg C ha^{-1} yr^{-1} more SOC in 0–25 cm soil depth (Table 4) during 1997–2004. Since the green manure only occupied 25% of the crop rotation, this corresponds to an additional 1.6 Mg C ha^{-1} yr^{-1} for each year of grass, which is slightly above the estimate of Taghizadeh-Toosi et al. (2014). Accordingly, using green manure increased total C input, even if it caused less C input from crops and catch crops (Fig. 1). The benefit of using green manure could be attributed to the large increment of C input, especially in C from root materials. The advantage in soil C retention by inclusion of green manure crops was also observed in O2 + CC-M compared to O4 + CC-M at all locations, even after 2004 (Table 4).

However, during 2005–2008 the advantage in SOC retention disappeared in O2 compared with O4, because grass-clover in the green manure was harvested and removed in +M treatments (Fig. 1), and the gap in C input between O2 and O4 was narrowed to less than 0.2 Mg C ha^{-1} yr^{-1} (Table 3). This also reduced the ability of O2 compared to O4 to retain SOC (Table 4). This indicates that an organic system with a harvested green manure crop does not necessarily retain more SOC than a system without green manure crops.

4.1.2. Catch crops

From 1997–2004, catch crops enhanced SOC on average by 0.2 Mg C ha^{-1} yr^{-1}, even though only significantly at Flakkebjerg (Table 4). However, using catch crops significantly increased estimated C input at all sites and most of this originated from C in catch crops (Fig. 1). After 2005, C input from catch crops decreased (Table 3), because of changes in catch crop management to enhance yield (Shah et al., 2017). However, an enhancing effect of catch crops on SOC was no longer observed at any of the sites (Table 4), even if there were still more C input in treatments with catch crops (Fig. 1). Considering the stability of more C input in treatments with catch crops (Table 3), the inconsistent SOC change may not be simply related to the quantity of C input from catch crops. In addition to higher C inputs, using rapidly decomposable material like catch crops could enlarge microbial community and enhance energy supply, accelerating the decomposition of more stable soil organic matter (Chen et al., 2014; Poeplau and Don, 2015), which would compromise the effect of enhanced C inputs from catch crops. Moreover, change in crop management and climate conditions could also cause uncertainties to the decomposition of catch crops (Kaspar et al., 2006; Steele et al., 2012). Also, high spatial variability of SOC makes it difficult to detect the small SOC changes after application of catch crops (Poeplau and Don, 2015).

4.1.3. Animal manure

From 1997–2004, application of animal manure did not significantly enhance SOC when all locations were considered, while at both Jyndevad and Flakkebjerg a significant effect was observed (Table 4). The average C input with animal manures at all sites was only about 0.2 Mg C ha^{-1} yr^{-1}. However, animal manure increased overall C input to 0.6 Mg C ha^{-1} yr^{-1} due to the higher input from crops (on average over 0.4 Mg C ha^{-1} yr^{-1}), resulting from higher crop productivity due to enhanced nutrient supply (Maillard and Angers, 2014). However, the expected increases in SOC were difficult to detect, which may also be related to the type of animal manure used (Maillard and Angers, 2014). In our study, cattle slurry (0.3 Mg C ha^{-1} yr^{-1}), pig slurry (0.2 Mg C ha^{-1} yr^{-1}) and anaerobically digested slurry (0.2 Mg C ha^{-1} yr^{-1}) were respectively used at Jyndevad, Foulum and Flakkebjerg during the first 8 years. Higher soil C content was observed in a large number of European long-term experiments with application of cattle manure (Zavattaro et al., 2017). In a review, Maillard and Angers (2014) found that animal manure from different animal species had different impacts, and that cattle manure led to significant positive SOC change, while pig and poultry manure did not. Domingo-Olivé et al. (2016) also observed that dairy cattle manure increased SOC significantly, while pig slurry did not. The different impacts between manures from cattle and pig were generally ascribed to the higher stability of organic matter in cattle manure (Velthof et al., 2000). Some reports also showed insignificant effects on SOC change after applying pig slurry (Rochette et al., 2000; Plaza et al., 2004).

4.2. SOC change under organic farming and conventional farming

The organic farming system O4 had higher C input compared with the similar conventional system (C4) during 2005–2008 at all three locations (Table 3), where C inputs from all plant residues were similar in both rotations, while a higher C input was estimated from root materials in O4 (Fig. 1b). In contrast to the estimated C inputs, SOC in O4 declined more than in C4 (Table 4). However, this was not the case at Foulum, where O4 accumulated more SOC than C4. This could indicate biases in the estimation of SOC inputs between the two treatments, and since aboveground C inputs were based on measurements, it is likely that the bias may have occurred with the estimation of belowground C inputs. Our estimates of root C inputs were based on measurements in the experiment in some of the years, but we did not have measurements in all years, and there were in general few measurements comparing catch crop roots between organic and conventional systems. This therefore points to the need for further studies to quantify root C inputs in the different cropping systems.

Treatments in conventional farming were converted from O2-CC-M and O4-CC-M, which received very limited nutrients during 1997–2004. Research have shown that unfertilised treatments have much lower microbial biomass and enzyme activities than treatments fertilised with pig slurry or cattle manure (Plaza et al., 2004; Francioli et al., 2016), while use of mineral fertilisers did not lead to significant increase in either microbial biomass or enzyme activities in a 4-year field experiment (Plaza et al., 2004). Moreover, Lori et al. (2017) reported that globally conventional farming had lower microbial abundance and activity than organic farming, based on meta-regression. Studies from the present long-term experiments showed significantly lower microbial biomass in the conventional treatments compared with the organic treatments at all sites during 2007 and 2008 (Petersen et al., 2013). These differences in microbial activity may have affected turnover of the added organic matter resulting in slower decomposition in conventional versus organic treatments, which may also have contributed to differences in SOC between O4 and C4.

Considering the C input from 2005 to 2012 at Foulum, straw of cereals in C4 was removed from 2010, thus enlarging the advantage of O4 in C input quantity over C4 (Table 3). In addition, there was a higher C input from plant materials in O4, especially from roots (Fig. 1c). In contrast to results for 2005–2008, SOC change during 2005–2012 at Foulum showed that O4 retained more SOC than C4 (Table 4). This agrees with the estimated higher C input in O4 compared with C4. A possible reason could be that over time the use of mineral fertilisers have increased microbial activity of the conventional farming systems thus giving similar turnover rates in O4 and C4, resulting in SOC changes reflecting C inputs. Also, removing straw of cereals reduced C input after 2010, which may have affected measured SOC in C4 in 2012.

4.3. Contribution of C input from aboveground and belowground biomass to SOC

Belowground C has been found to be better retained in soils than C from aboveground plant parts (Rasse et al., 2005; Kätterer et al., 2011; Berti et al., 2016). However, this was not indicated from our analyses of relations between C inputs and SOC changes. After 2005, the significant ability of O2 in enhancing SOC over O4 disappeared, and at the same time, a practice of removing the aboveground part of green manure in O2 started (Table 4). The estimation of root C input still indicated higher inputs in O2 compared with O4 (Fig. 1b). Moreover, removing cereal straw in C4 after 2010 seemed to enhance the difference in SOC change between C4 and O4 at Foulum (Table 4). These results indicate that aboveground C input also contributed considerably to topsoil SOC. Similarly, in the regression analyses between SOC change and C inputs (Table 5), models that used whole plant material as input performed better than models where C input were divided between above- and belowground parts. Austin et al. (2017) observed in their reciprocal litter transfer experiment that aboveground plant material was more decomposed than belowground materials after 5 months, while this difference disappeared after 17 months. This may be related to the chemical properties of above- versus belowground materials (Rasse et al., 2005), which in particular plays a role during the initial phase of organic matter decomposition, but may be less important over a longer time span (Gentile et al., 2011). Our statistical analyses covered periods of more than 10 years, which may have hidden the short-term effects and reduced the differences in degradability of root versus aboveground materials. Also, we studied arable systems with regular tillage, which may stimulate degradation of below- and aboveground residues to similar extents.

5. Perspectives

Using green manure, catch crops and animal manure each increased C input of 0.6–1.0 Mg C ha^{-1} yr^{-1} at crop rotation level. However, only the effect of green manure was consistently reflected in observed SOC change. This calls for more detailed studies on measurements of C inputs from various sources and how the C inputs are degraded and contributes to stabilized SOC. In particular, better estimation of C inputs from roots and root exudates is highly needed to assess the effect of cropping systems and crop management on SOC. We applied a fixed amount of C inputs in roots, whereas other approaches estimate root C input to be proportional to aboveground biomass. The latter approach would have given different estimated belowground C inputs between the systems. This illustrates the needs to develop and consolidate methods for improved estimation of belowground C input as also found in a recent model-based comparison (Keel et al., 2017).

Including grass crops in the crop rotation has been widely reported to increase soil C (Leifeld, 2012; Taghizadeh-Toosi and Olesen, 2016). However, grassland management also has considerable effects on SOC (Conant et al., 2017) and this should be considered when evaluating the effects of organic farming systems on total greenhouse gas emissions. This is illustrated by the effect in our study of removing grass-clover cuttings as compared to mulching these in the field. This removal of grass-clover in the experiment was meant to simulate a situation where the grass-clover was used for biogas and the digested slurry was used to fertilise the other crops in the rotation. This approach enhanced yields of the arable crops in the rotation by about 30% (Shah et al., 2017), which also enhanced C inputs from crop residues (Fig. 1b). However, this could not make up for the C not returned in mulched grass-clover. It is therefore challenging agronomically in organic arable systems to achieve both high yields and high soil C inputs.

Our study showed slightly higher estimated C inputs in conventional compared with similar organic cropping systems (Table 3), whereas measured SOC changes showed opposite trends although this was reversed over time at Foulum (Table 4). This contrasts with other studies that showed consistently higher SOC accumulation in organic compared with conventional systems (Gattinger et al., 2012). In reality, there may be considerable variation between different organic and conventional systems in their ability to enhance SOC, and factors such as use of green manure, catch crops and residue management play a large role.

6. Conclusions

Including a whole-year green manure with mulching of crop residues in organic cropping systems increased C input with about 0.9 Mg C ha^{-1} yr^{-1}, and enhanced SOC by 0.4 Mg C ha^{-1} yr^{-1} as average over a 4-year rotation. However, this effect largely disappeared when cuttings of the green manure crop was removed. Catch crops were estimated to contribute nearly 1.0 Mg C ha^{-1} yr^{-1} of additional C input, whereas the effect on SOC could not broadly and consistently be observed. Similarly, the advantage of applying animal manure on SOC was not observed at all locations, even though animal manure across all locations increased the C input with about 0.7 Mg C ha^{-1} yr^{-1}, where over 0.4 Mg C ha^{-1} yr^{-1} of the extra C input was due to increased crop production and more crop residues. Compared with conventional farming, organic farming systems had more total C inputs, in particular from estimated belowground plant materials and added animal manure. Analysis of the relation between changes in SOC and inputs of C in above- and belowground plant residues and animal manure could not differentiate effects of above- and belowground C input, and these inputs may therefore be considered as having similar effects on SOC.

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