Modelling and measuring soil organic carbon under different tillage practices in agricultural soils of the UK

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1) Introduction

Tillage modifies the physical properties of soils, such as promoting aeration and drainage of soil, changing thermal regimes and so on, and thereby alters the environment for microbial biomass, which usually further impacts the distribution of soil constituents including carbon and nutrients (Khan 1996; Sun et al. 2011; Sun et al. 2014).

Little research on the effects of tillage practice on SOC storage has been undertaken in regions with maritime climatic conditions and there are remarkably few corresponding data for eastern regions of the United Kingdom, particularly in calcareous soils. Approximately 12% of the world soil is calcareous soils (FAO 1995), which have a high stability of their organic matter (OM). Some studies have shown that the decomposition rates of SOM in calcareous soils was lower than those in other soils with similar organic carbon content because of lower microbial biomass and activity in calcareous soils (Garcia et al. 1997; Llorente and Turrión 2010).

It is well known that the content of SOC is determined by the balance between production and decomposition of SOM (Wang et al. 2013). Some studies showed that the suggested methods for improving carbon stocks are increasing the inputs of organic manure or sewage sludge amendments, incorporation of straw and extensification through arable–ley rotations (Smith et al. 1997), and lately also the cultivation of winter cover crops (Mazzoncini et al. 2011).

Cover crops are contributed on agricultural ecosystem in many ways (Dinesh 2004; Kuo et al. 1997). Besides an increased carbon input, cover crops have been shown to increase biodiversity (Lal 2004) , reduce soil erosion and drought stress for the following crop when used as mulch cover in water limited systems (Frye et al. 1988) as well as to impact yields due to the resource competition, such as photosynthetically active radiation, soil water and nitrogen (Picard et al. 2010). Cultivated in autumn and winter, cover crops are able to take up excess nitrogen, N from the soil and decrease N leaching (Blombäck et al. 2003). Thus, cover crops play a significant role in not only improving soil quality and thereby to increasing crop production, but also increasing SOC stocks and then mitigating climate change (Lal 2004). However, the impacts of cover crops on SOC stocks in subsoil (more than 30 cm soil depths) has been highlighted in very few studies.

The New Farming Systems (NFS) project and the Mid-Pilmore Tillage Experiment were set up in 2007 and 2003, respectively. These projects explore how disturbing soil with tillage influences plant productivity, soil sustainability, and agricultural ecosystems. Physical disturbance was manipulated using cultivation common in UK agricultural production, newer approaches aimed at minimising soil damage and potentially harmful practices chosen to manipulate the soil biophysical environment.

Therefore, my study focuses on the vertical and spatial distributions of soil organic carbon under different tillage practices over time, and will be delivered through a combination of analysis of data from the medium-term field station in UK (e.g., NFS project and Mid-Pilmore tillage experiment), and application/development of the DNDC and DayCent models.

2) Research Questions and Aims

The objectives of this study are (1) to assess the impacts of tillage practice and/or cover crop on soil organic carbon stocks in Calcareous soils; (2) to simulate soil carbon sequestration under different tillage practices in long-term field stations over time using DNDC and DayCent model.

3) Progress to date

3.1 Materials and Methods

3.1.1 Collecting historical field data (in the medium-term field stations of Mid-Plimore platform and NFS)

The historical field data on medium term experiments in the UK that were used are mainly from the "Platforms to test and demonstrate sustainable soil management: integration of major UK field experiments" Project. A total of 2 field stations (Mid-Pilmore platform and NFS) (Fig.1), were used, with Mid-Pilmore having 5 tillage (Conventional Plough (P), Compaction plough (CP), Deep plough (DP), Shallow non-inversion tillage (ST), Zero tillage (ZT)) practices. Data from Mid-Pilmore for 2008 and 2013 were included in the dataset for analysis. The data for 2008 in Mid-Pilmore was already published by Sun et al. (2011) and that for 2013 is still not publish (later we should get the permission from related researchers). NFS had ST and P, as well as a deep non-inversion (DT) tillage treatments, and data for 2013. The collected indices used were soil bulk density, soil pH, soil organic carbon and yield.

Climate data (e.g., mean annual air temperature and mean annual precipitation) will be obtained from literature descriptions or recording from nearby weather stations ((http://www.weatherbase.com). Soil properties (e.g. soil texture) will be obtained from the harmonized word soil database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012) (http://www.iiasa.ac.at/).

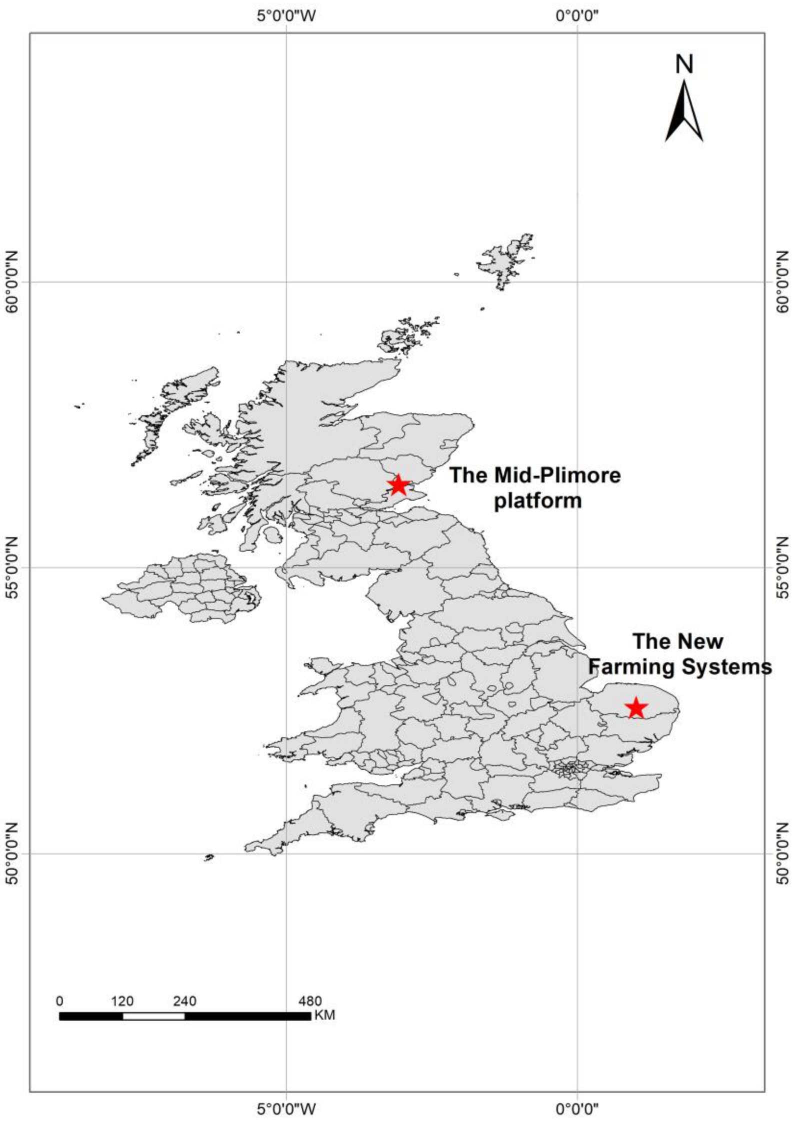

Fig. 1 Map of medium-term field stations of Mid-Plimore platform and New Farming Systems (NFS), UK. The figure was generated by using ArcMap 10.5 (http://www.esri.com/).

3.1.2 Experimental research (Experiments in the NFS)

3.1.2.1 Study area and soil sampling

The NFS experiment is located in Bullswood Field (Morley, Norfolk) on a medium sandy loam soil (N 52°33’14’’, E 1°01’44’’) (Fig.1). We selected 24 soil profiles (including 4 replications) across six treatments, namely three tillage practices (Conventional Plough (P), Deep non-inversion tillage (DT), Shallow non-inversion tillage (ST)) and two crop residue management methods (with or without cover crop), during March 2018. We collected 144 soil samples from 24 soil profiles over 0–5, 5–10, 10–20, 20–30, 30–40, and 40–60 cm soil depths.

3.1.2.2 Soil sampling analyses

3.1.2.2.1 Soil bulk densities and soil water contents

Each core's volume (V, cm^3) and weight (W_c, g) were recorded in advance. Soil samples were collected in soil cores inserted vertically into the profile, and weighed as wet soil (W_{ws}, g). Wet soil samples were placed in a drying oven for 48 h at 105 °C, and then the dried soil weights (W_{ds}, g) was recorded. For each soil depth, soil water content (W_{sw}, g) and bulk density (BD, g/cm^3) were calculated using the following equations:

$$W_{sw} = W_{ws} - W_{ds} \tag{1}$$

$$\text{BD} = \frac{W_{ds} - W_c}{V} \tag{2}$$

3.1.2.2.2 Soil pH and electric conductivity (EC)

Five grams (+/- 0.1g) of field moist soil samples were weighed into 50 mL centrifuge tubes and 25 mL of 0.01M $CaCl_2$ was added into centrifuge tubes. The suspension was swirled for 1 hour, and then left to equilibrate for 30 minutes. After this period, soil pH and EC were measured by a pH Meter and Conductivity Meter (HI5521 & HI5522), respectively.

3.1.2.2.3 Soil texture and organic matter

Moist soil samples (about 20 g) were dried (30ºC in the oven for 48 hours) and sieved to pass a 2 mm screen. About five grams of sieving to 2 mm natural dry soil were weighed into 50 mL centrifuge tubes, approximately 1m dH_2O and 5mL of 30% v/v H_2O_2 (hydrogen peroxide) (VWR, AnalaR) were added into centrifuge tubes (W_1) in order to remove organic matter, and left to react in the cold overnight. Then 30%

v/v H_2O_2 was added and the solution heated to 90 ^oC to decompose H_2O_2 – this was repeated until frothing had subsided. Once cool, centrifuge tubes and dry soil were weighed again (W_2).

Then 5ml of 50g/L sodium hexametaphosphate solution (Acros Organics, Fisher Scientific) was added, and shaken about 2-3 hours at 150 rpm on an orbital shaker. This solution was passed through a 63µm sieve in order to allow subsequent separation of the clay and silt fractions by partial size analyzer (LS 13 320). All material, separated into >63 µm and <63 µm, were put into oven dried for 48 hours at 105 ^oC and then weighed as separate soil samples ($W_{>63}$ and $W_{<63}$).

1ml dH_2O and 1ml of 50g/L sodium hexametaphosphate solution (Acros Organics, Fisher Scientific) were added to 0.6g of sieving to 63 µm dried soil samples. This was shaken about 2-3 hours at 150rpm on an orbital shaker and then measure soil sample solution using Laser Particle Analyzer (LS 13 320). For each soil depths, soil organic matter (W_M, g) was calculated by the following equations:

$$W_M = W_1 - W_2 \quad (3)$$

3.1.2.2.4 Exchange Ca^{2+} and Mg^{2+}

Moist soil samples (about 20 g) were dried (30^{o}C in the oven for 48 hours) and sieved to pass a 2 mm screen. About ten grams (accurate 2 decimal point) of sieving to 2 mm natural dry soil were weighed into 50 mL centrifuge tubes, and shaken for 30 minutes with 20ml of the extracting solution (1 M ammonium acetate salt-glacial acetic acid buffered at pH 7), then left to stand overnight. The extract solution was filtered through Whatman No.42 filter before being kept at 4^{o}C for analysis. The filtered extract solution was measured by using flame-atomic absorption spectroscopy (AAS).

3.1.2.2.5 Total carbon and nitrogen, soil organic and inorganic carbon

Representative sub-samples were crushed to 0.25 mm by using ball milling equipment for total carbon (TC) and nitrogen (TN), soil organic carbon (SOC) and soil inorganic carbon (SIC) measurements. The contents of total soil carbon and SOC were measured using a CNS analyzer (CE NA2500 Elemental Analyser). For SOC measurement, 10 mg soil was pretreated with 40 ul of 10% Hydrochloric acid for 12 h to remove carbonate and dried soil at 40-50 ^{o}C. The pretreated sample was combusted at 1020°C with a constant helium flow carrying pure oxygen to ensure completed oxidation of organic materials. Production of CO_2 was determined by a thermal conductivity detector. Soil inorganic carbon was calculated as the difference between total soil carbon and SOC.

For each soil profile, densities of TC, TN, SOC and SIC (X_{DENSITY}, kg C m^{-2}) were calculated from carbon content ($\mathrm{X_i}$, g kg^{-1}), BD (E_i, g cm^{-3}) and thickness (D_i, cm):

$$X_{\mathrm{DENSITY}} = \sum_{i=1}^{n} \mathrm{X_i} \times \mathrm{D}_i \times \mathrm{E}_i / 100, \qquad (4)$$

3.1.2.2.5 Soil Microbial Biomass Carbon

Chloroform Fumigation Extraction was used to measure soil microbial biomass carbon. This method works on the principle that fumigation by chloroform kills any microbes in the soil causing them to release the C bound up within them. By subtracting the background C of non-fumigated samples from that of the fumigated we can work out the microbial C content (Dawson et al. 2007; Vance et al. 1987).

Twenty grams (+/-2g) of field moist soil (ideally WHC: 60-80%, but it can be less) was weighed into two glass containers – one in a small beaker for fumigating and one in a conical flask for extracting straight away.

A large, valved, desiccator was prepared in a fume hood. Moist blue roll was placed at the base of the desiccator to help keep the atmosphere humid. Soil samples in beakers, which were to be fumigated, were placed in the desiccator, along with a 50ml beaker containing 25ml of acid-washed chloroform and anti-bumping granules (ensuring these beads are clean and dry).

The lid was placed on the desiccator and then evacuated for 10 minutes using a vacuum pump (connected to the tap in the fume hood) until the chloroform had boiled. Once vacuum was reached the valve was shut and left for 24 hours.

Meanwhile, for non-fumigated samples, soil samples in the flasks were shaken with 50 ml 0.5M K_2SO_4 for 30 minutes and then left to equilibrate for another 30 minutes. The non-fumigated sample solution was filtered through Whatman No.42 filter and stored at 5^oC in 50 centrifuge tubes.

The next day, a vacuum pump was used to remove most of the chloroform from the desiccator in the fume hood. After releasing the valve, the lid was removed, then evacuated for a further 3 times for 5 minutes each. Finally, the lid was removed carefully and left open for a further 2 hours to let any remaining chloroform evaporate. The soil samples in the beakers were moved to flasks and shaken with 50 ml 0.5M K_2SO_4 for 30 minutes and then left to equilibrate for another 30 minutes. The fumigated sample solution was filtered through Whatman No.42 filter and stored at 5^oC in 50 centrifuge tubes. All filtered solutions were measured by using LabTOC.

3.2 Preliminary results

3.2.1 Soil physical and chemical properties in NFS

Table 1 and 2 contain the basic soil properties under different tillage practices in each soil layer. In general, there was clearly more sand in all soil samples, with a large proportion of the total, ranging from 55% to 78%, which all soil had loamy sand texture (Table1).

Bulk density is used as an indicator of soil strength and/or mechanical resistance to plant growth, and can thus affect distribution of soil carbon content (Drewry et al. 2008). Moreover, carbon content is measured by weight but needs to be converted by volume to determine the total amount stored in a soil profile with variable bulk density (Burns et al. 2006). In general, the values of bulk density decreased significantly from 0-5 cm to 5-10cm under all tillage practices, followed by insignificant change with soil depths (Table 2). Similarly, there was a clear difference in bulk density in the 0-5 cm layer across different treatments, with larger values in the conventional plough (1.54 and 1.64 g/cm^3 in with and without radish, respectively), smaller values in the shallow tillage (1.44 and 1.45 g/cm^3 in with and without radish, respectively). At the 20-30 cm depth, the significantly larger values of bulk density were under deep tillage (1.66 and 1.73 g/cm^3 in land with and without radish, respectively), and were smaller under conventional plough (1.59 and 1.64 g/cm^3 in with and without radish, respectively). There were no obvious differences among six treatments for soil pH and EC.

Table 1. Values of soil texture for three tillage practices with cover crop over each soil layer in the NFS.

Depth (cm)	Plough (Radish)			Shallow tillage (Radish)			Deep tillage (Radish)		
	Sand (%)	Silt (%)	Clay (%)	Sand (%)	Silt (%)	Clay (%)	Sand (%)	Silt (%)	Clay (%)
0-5	72.58	16.72	10.71	76.08	18.32	5.60	70.20	17.85	11.95
5-10	72.63	20.13	7.24	74.00	18.50	7.50	72.74	17.87	9.40
10-20	74.29	19.11	6.60	73.36	18.73	7.91	73.25	19.13	7.62
20-30	71.89	19.07	9.03	73.40	17.00	9.60	73.03	16.02	10.95
30-40	73.54	17.14	9.32	73.71	16.16	10.13	70.44	18.34	11.22
40-60	78.09	13.17	8.74	73.04	15.59	11.37	54.54	26.22	19.25

Table 2. Mean values (four replicates) of bulk density (BD), soil pH and electric conductivity (EC) for different tillage practice and with or without cover crop over each layers in the NFS.

Depth (cm)	Deep tillage (Radish)	deep tillage	Plough (Radish)	Plough	Shallow tillage (Radish)	Shallow tillage
BD (g/cm³)						
0-5	1.52 (0.10) Bb	1.49 (0.07) Bb	1.54 (0.07) Abb	1.64 (0.03) Aa	1.44 (0.05) Bb	1.45 (0.08) Bb
5-10	1.65 (0.08) Aab	1.64 (0.05) Aa	1.66 (0.07) Aa	1.67 (0.08) Aa	1.62 (0.08) Aa	1.64 (0.04) Aa
10-20	1.72 (0.12) Aa	1.71 (0.05) Aa	1.64 (0.08) Aab	1.66 (0.04) Aa	1.65 (0.12) Aa	1.65 (0.05) Aa
20-30	1.66 (0.11) ABab	1.73 (0.07) Aa	1.59 (0.06) Bab	1.59 (0.06) Ba	1.64 (0.05) ABa	1.63 (0.05) ABa
30-40	1.66 (0.09) Aab	1.73 (0.06) Aa	1.68 (0.09) Aa	1.62 (0.14) Aa	1.65 (0.09) Aa	1.57 (0.13) Aa
40-60	1.60 (0.13) Aab	1.65 (0.05) Aa	1.66 (0.04) Aa	1.64 (0.06) Aa	1.66 (0.06) Aa	1.66 (0.07) Aa
pH						
0-5	5.62 (0.30) Aa	5.47 (0.49) Aa	5.89 (0.18) Aa	5.83 (0.18) Aa	5.47 (0.29) Aa	5.53 (0.18) Aa
5-10	5.61 (0.26) Aa	5.42 (0.48) Aa	5.88 (0.22) Aa	5.75 (0.14) Aa	5.43 (0.31) Aa	5.50 (0.20) Aa

10-20	5.65 (0.27) Aa	5.56 (0.51) Aa	5.87 (0.19) Aa	5.80 (0.11) Aa	5.56 (0.32) Aa	5.55 (0.24) Aa
20-30	5.76 (0.22) Aa	5.60 (0.46) Aa	5.84 (0.20) Aa	5.72 (0.08) Aa	5.74 (0.43) Aa	5.64 (0.22) Aa
30-40	5.77 (0.17) Aa	5.84 (0.41) Aa	5.88 (0.15) Aa	5.80 (0.09) Aa	5.83 (0.47) Aa	5.71 (0.31) Aa
40-60	5.84 (0.17) Aa	5.88 (0.40) Aa	5.93 (0.16) Aa	5.88 (0.13) Aa	5.89 (0.41) Aa	5.78 (0.26) Aa
EC (µs/cm)						
0-5	2153 (21) Aa	2159 (46) Aa	2136 (48) Aa	2131 (49) Aa	2142 (22) Aa	2140 (32) Aa
5-10	2117 (48) Ab	2098 (52) Aa	2098 (32) Aa	2104 (46) Aa	2096 (31) Aa	2109 (25) Aa
10-20	2107 (44) Ab	2094 (41) Aa	2093(28) Aa	2105 (31) Aa	2104 (31) Aa	2101 (27) Aa
20-30	2099 (47) Ab	2094 (39) Aa	2095 (22) Aa	2097 (33) Aa	2104 (28) Aa	2109 (30) Aa
30-40	2108 (38) Ab	2108 (28) Aa	2101 (30) Aa	2104 (31) Aa	2116 (39) Aa	2107 (27) Aa
40-60	2100 (49) Ab	2102 (33) Aa	2095 (39) Aa	2104 (42) Aa	2117 (35) Aa	2101 (21) Aa

*Values followed by the same letter (lower case letter within a column or upper case letter within a row) are not significantly different at P < 0.05 based on Duncan test. Values in brackets are the standard deviations; n = 4.

Table 3. Mean values (four replicates) of total N, total C, soil organic C (SOC), $CaCO_3$ (g/kg) and SOC:N ratio for different tillage practice and with or without cover crop over each layers in the NFS.

Treatment	**Deep tillage (Raddish)**	**Deep tillage**	**Plough (Raddish)**	**Plough**	**Shallow tillage (Raddish)**	**Shallow tillage**
Total N (g/kg)						
0-5	1.36 (0.25) Aa	1.45 (0.18) Aa	1.25 (0.24) Aab	1.30 (0.19) Aa	1.58 (0.12) Aa	1.48 (0.27) Aa
5-10	1.29 (0.18) Aab	1.33 (0.21) Aab	1.30 (0.23) Aa	1.23 (0.06) Aa	1.29 (0.08) Ab	1.23 (0.32) Aab
10-20	1.21 (0.29) Aab	1.02 (0.08) ABc	1.15 (0.09) ABab	1.20 (0.14) Aa	1.09 (0.15) ABc	0.93 (0.14) Bbcd
20-30	0.95 (0.30) Abc	1.08 (0.22) Abc	1.07 (0.27) Aab	1.17 (0.10) Aa	1.09 (0.14) Ac	1.02 (0.12) Abc
30-40	0.77 (0.11) Ac	0.59 (0.11) Ad	0.91 (0.23) Abc	0.85 (0.37) Ab	0.76 (0.10) Ad	0.71 (0.17) Acd
40-60	0.75 (0.22) Ac	0.59 (0.07) Ad	0.68 (0.15) Ac	0.60 (0.11) Ab	0.68 (0.13) Ad	0.62 (0.08) Ad

Total C (g/kg)						
0-5	12.65 (2.88) ABa	13.30 (2.74) ABa	10.94 (2.70) Ba	11.57 (1.39) Ba	15.58 (1.41) Aa	13.80 (2.48) ABa
5-10	11.97 (1.05) Aa	12.19 (1.81) Aa	10.95 (2.12) Aa	10.96 (1.40) Aa	11.97 (1.90) Ab	11.66 (2.40) Aab
10-20	10.28 (2.52) Aab	8.60 (1.40) Ab	10.28 (1.75) Aab	10.55 (0.84) Aa	9.40 (0.94) Ac	9.29 (2.73) Abc
20-30	8.49 (2.33) Abc	8.56 (2.21) Ab	8.63 (2.04) Aab	9.02 (1.27) Aab	9.05 (1.39) Ac	7.89 (1.71) Acd
30-40	5.50 (1.74) Ad	4.09 (0.95) Ac	7.51 (2.60) Abc	6.90 (3.45) Abc	5.41 (1.14) Ad	5.19 (1.73) Ade
40-60	5.80 (0.71)Acd	3.92 (0.46) Ac	4.63 (0.72) Ac	4.29 (0.54) Ac	4.24 (0.31) Ad	3.92 (0.55) Ae
Soil organic C (g/kg)						
0-5	8.95 (1.43) ABab	7.81 (2.10) Bab	8.00 (0.72) Ba	8.15 (0.56) Ba	11.09 (2.14) Aa	10.16 (2.28) ABa
5-10	9.24 (0.71) Aa	9.22 (1.20) Aa	7.21 (0.74) Aab	6.89 (1.09) Aab	9.38 (1.56) Aab	9.12 (2.42) Aa
10-20	7.83 (2.09) Aab	6.47 (1.23) Ab	7.90 (1.55) Aa	7.65 (1.17) Aa	7.49 (0.92) Abc	6.77 (0.87) Ab
20-30	6.88 (1.56) Ab	6.13 (1.96) Ab	6.27 (1.91) Aab	6.62 (1.71) Aab	6.51 (1.24) Ac	6.41 (0.84) Abc
30-40	4.44 (1.06) Ac	3.18 (0.90) Ac	5.40 (1.93) Abc	4.78 (2.13) Abc	4.15 (0.67) Ad	4.18 (1.19) Acd
40-60	3.02 (0.45) Ac	3.04 (0.78) Ac	3.85 (0.72) Ac	3.37 (0.62) Ac	3.31 (0.33) Ad	2.75 (0.50) Ad
$CaCO_3$ (g/kg)						
0-5	3.70 (2.02) Aa	5.50 (0.74) Aa	2.94 (2.35) Aab	3.42 (0.96) Aa	4.49 (1.49) Aa	3.64 (2.61) Aa
5-10	2.72 (0.37) Aab	2.97 (0.94) Ab	3.75 (1.71) Aa	4.07 (2.29) Aa	2.59 (1.30) Ab	2.54 (1.54) Aa
10-20	2.45 (0.75) Aab	2.13 (0.81) Abc	2.38 (0.63) Aab	2.90 (0.84) Aab	1.91 (0.50) Abc	2.52 (2.46) Aa
20-30	1.62 (0.81) Ab	2.43 (1.35) Ab	2.36 (0.67) Aab	2.40 (0.66) Aab	2.54 (0.28) Ab	1.48 (1.22) Aa
30-40	1.06 (0.73) Ab	0.91 (0.40) Ac	2.11 (0.83) Aab	2.12 (1.57) Aab	1.26 (0.48) Abc	1.01 (0.67) Aa
40-60	1.03 (0.38) Ab	0.88 (0.60) Ac	0.92 (0.40) Ab	0.93 (0.22) Ab	0.93 (0.02) Ac	1.17 (0.22) Aa
SOC:N						
0-5	6.71 (1.31) Aa	5.33 (0.91) Aa	6.59 (1.28) Aa	6.32 (0.69) Aa	6.97 (0.78) Aa	6.84 (0.57) Aa
5-10	7.22 (0.66) Aa	6.99 (0.49) Aa	5.61 (0.57) Aa	7.06 (1.15) Aa	7.24 (0.90) Aa	7.63 (2.48) Aa
10-20	6.44 (0.41) Aa	6.39 (1.38) Aa	6.92 (1.50) Aa	6.49 (1.54) Aa	6.99 (1.23) Aa	7.35 (1.27) Aa
20-30	7.40 (1.42) Aa	5.76 (1.69) ABa	5.78 (0.40) ABa	5.61 (1.09) Ba	5.97 (0.52) ABab	6.31 (0.58) ABab

30-40	5.81 (1.14) Aab	5.30 (0.52) Aa	5.86 (0.69) Aa	5.65 (0.58) Aa	5.44 (0.21) Ab	5.99 (1.41) Aab
40-60	4.56 (0.91) Ab	5.10 (0.95) Aa	5.51 (0.51) Aa	5.63 (0.69) Aa	5.02 (1.03) Ab	4.43 (0.72) Ab

*Values followed by the same letter (lower case letter within a column or upper case letter within a row) are not significantly different at $P < 0.05$ based on Duncan test. Values in brackets are the standard deviations; $n = 4$.

3.2.3 Vertical profiles of total N and C contents, and C:N ratio under different tillage practices

Overall, total N contents showed a significant decrease with soil depth independent tillage practice and cover crop (Table 3). But there were no clear difference between six treatments over different soil layers, except over 10-20 cm. Similarly, total C and SOC contents showed an obviously decrease with soil depth among different tillage practice and with or without cover crop. There were significant difference between tillage practice over 0-5 cm for both total C and SOC contents, with greater values in shallow non-inversion tillage (ST) (including with and without radish), smaller values in conventional plough (CP) (including with and without radish), followed by the deep inversion tillage (DP) (including with and without radish). There were no obvious differences below 5 cm soil depths for both total C and SOC contents.

The $CaCO_3$ contents showed a clear decrease with soil depths independent different tillage and cover crop, with a smaller range from 5.50 to 0.88 g/kg (Table 3). There were no clear difference between six treatments over different soil layers. In general, all values of soil C:N ratio were less than 8.00. Soil C:N ratio clearly decreased with soil depths in DT and ST. There were no clear difference between six treatments over different soil layers, except over 20-30 cm.

3.2.3 Variations of SOC stocks under different tillage practices over time

Table 4 showed the difference for integrated data of SOC densities over soil depths among different tillage practices. In the Mid-Pilmore site, SOC in the 0–5, the 0–10, 0-20 and 0-30 cm depth ranges were significantly different in 2008, with greater values of SOC densities in the zero tillage (ZT) and shallow tillage (ST), and smaller values of that in the conventional plough (CP) and deep tillage (DP) treatments. There was no clear differences in the 0-40, 0-50 and 0-60 cm soil depths. But for 2013 in the Mid-Pilmore, there was significant difference for SOC stocks, not only in the topsoil (e.g., 0-5, 0-10, 0-20 cm), but also in the subsoil (e.g., 0-50 and 0-60 cm). For example, SOC densities in the 0–50 and 0-60 cm depth ranges were significantly different in 2013, with higher values of SOC densities in the ZT and CP, and lower values of that in the ST and compaction plough (CP) treatments.

Unlike the values at the Mid-Pilmore site, SOC densities in NFS at 0–5, 0–10, 0-20 and 0-30 cm depth ranges were significantly different in 2013, with the highest values of SOC densities in the DT, and lowest values in the CP, followed by the ST treatments (Table 3). There was no clear difference in the 0-40, 0-50 and 0-60 cm soil depths. But for 2018 in NFS, there was significant difference only in the 0–5, the 0–10, 0-20 cm, with the highest values of SOC densities in the ST with radish, and lowest values in the CP with radish, followed by the DT with radish treatments. There was no clear difference under three tillage practices without radish across different depths.

Figure 2 shows that there was a clear difference for SOC density change over time in 0-20 and 0-60 cm soil depth. For instance, at the Mid-Pilmore site, there was no obvious change for SOC densities in 0-20 cm from 2008 to 2013 under CP and ZT treatments. However, SOC densities significantly increased in 0-60 cm from 2008 to 2013 under CP and ZT treatments. As for ST treatments, there was a clear decrease in the 0-20 cm layer from 2008 to 2013, but that was no obvious change in 0-60 cm. Unlike SOC dynamics at the Mid-Pilmore site, there was a significant decrease in SOC density from 2013 to 2018, independently of soil depths (e.g., 0-20 and 0-60 cm) and tillage practices (e.g., CP, ST and DT).

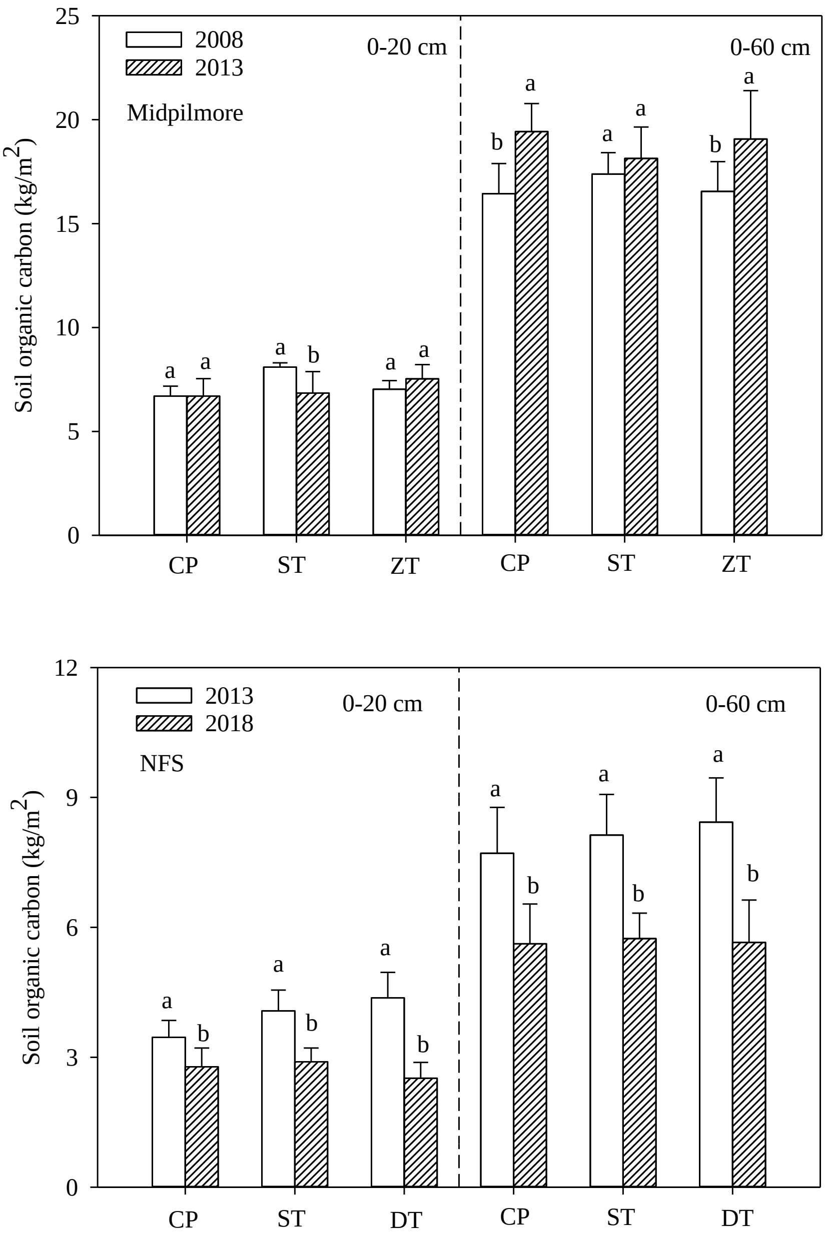

Fig. 2 Means of SOC densities for 0-20 and 0-60 cm in 2008 (open bar) and 2013 (hatched bars) under three tillage practices (conventional plough, CP; Shallow tillage, ST; Zero tillage, ZT) at the Mid-Pilmore site. Means of SOC densities for 0-20 and 0-60 cm in 2013 (open bar) and 2018 (hatched bars) under three tillage practices (Conventional plough, CP; Shallow tillage, ST; Deep tillage, DT) at the NFS. The error bars denote standard deviations.

Table 3. Mean values of soil organic carbon for different tillage practices over different depths in 2008 and 2013 for the NFS, and in 2013 and 2018 for Mid-Pilmore.

Year/Location	Treatment	Soil organic carbon (kg/m^2)						
		0-5 cm	0-10 cm	0-20 cm	0-30 cm	0-40 cm	0-50 cm	0-60 cm
2008/Mid-Pilmore	Conventional plough	1.52 (0.15) c	3.05 (0.27) b	6.70 (0.48) bc	10.21 (0.60) b	12.99 (0.90) a	15.88 (1.65) a	16.44 (1.45) a
	Deep plough	1.56 (0.12) c	3.18 (0.32) b	6.48 (0.46) c	10.02 (0.78) b	13.12 (0.91) a	15.10 (1.23) a	16.47 (1.59) a
	Shallow tillage	1.81 (0.08) b	3.62 (0.14) a	8.10 (0.20) a	10.88 (0.26) a	13.33 (0.63) a	15.30 (0.88) a	17.38 (1.03) a
	Zero tillage	2.00 (0.16) a	3.80 (0.27) a	7.03 (0.42) b	10.47 (0.65) ab	12.80 (0.74) a	14.79 (0.98) a	16.55 (1.43) a
2013/Mid-Pilmore	Conventional plough	1.60 (0.30) b	3.29 (0.45) bc	6.70 (0.84) b	10.89 (0.92) a	13.68 (0.99) a	17.10 (1.24) a	19.43 (1.35) a
	Compaction	1.44 (0.11) b	3.00 (0.20) c	6.17 (0.52) b	9.91 (0.87) a	12.12 (0.68) b	15.14 (0.85) b	16.62 (0.79) b
	Shallow tillage	1.64 (0.20) b	3.36 (0.44) b	6.85 (1.03) ab	10.12 (1.17) a	12.55 (1.35) ab	15.69 (1.68) ab	18.14 (1.51) ab
	Zero tillage	1.90 (0.15) a	3.78 (0.25) a	7.53 (0.69) a	10.90 (1.14) a	13.63 (1.41) a	17.03 (1.76) a	19.07 (2.33) a
2013/NFS	Conventional plough	0.90 (0.12) b	1.76 (0.21) b	3.46 (0.39) b	5.04 (0.60) b	5.92 (0.79) a	7.40 (0.99) a	7.71 (1.06) a
	Deep plough	1.22 (0.22) a	2.28 (0.35) a	4.37 (0.59) a	5.82 (0.78) a	6.50 (0.82) a	8.13 (1.02) a	8.43 (1.02) a
	Shallow tillage	1.04 (0.12) b	2.05 (0.23) a	4.07 (0.48) a	5.55 (0.54) ab	6.26 (0.68) a	7.82 (0.84) a	8.13 (0.94) a
2018/NFS	Conventional plough (Radish)	0.68 (0.08) ab	1.44 (0.10) ab	2.78 (0.43) a	3.92 (0.70) a	4.66 (0.81) a	5.14 (0.86) a	5.62 (0.92) a
	Deep plough (Radish)	0.62 (0.13) b	1.21 (0.20) b	2.51 (0.37) a	3.51 (0.67) a	4.42 (0.77) a	5.04 (0.87) a	5.65 (0.98) a
	Shallow tillage (Radish)	0.80 (0.15) a	1.66 (0.30) a	2.89 (0.32) a	3.96 (0.46) a	4.64 (0.49) a	5.19 (0.54) a	5.74 (0.59) a
	Conventional plough	0.60 (0.13) a	1.35 (0.20) a	2.46 (0.37) a	3.51 (0.67) a	4.09 (0.77) a	4.59 (0.87) a	5.09 (0.98) a
	Deep plough	0.67 (0.06) a	1.45 (0.46) a	2.73 (0.65) a	3.78 (0.78) a	4.55 (0.93) a	5.09 (1.02) a	5.64 (1.11) a
	Shallow tillage	0.74 (0.19) a	1.49 (0.39) a	2.60 (0.49) a	3.65 (0.54) a	4.31 (0.64) a	4.76 (0.62) a	5.22 (0.62) a

*Values followed by the same lower case letter within a column are not significantly different at $P < 0.05$ based on Duncan test. Values in brackets are the standard deviations.

4) Research plan for next 6 months

Expected goal: Finishing two manuscripts, one is about "A full profile analysis of soil organic carbon under different tillage practices over time using DNDC and DayCent models"; another one is about "impacts of forestation on SOC-A meta-analysis".

Process to date: On the one hand, I have collected data of SOC stocks from Mid-Pilmore in 2008 and 2013, and NFS in 2013. But the data from Mid-Pilmore in 2013 have yet to be published, so later I will not use those data in modelling. Besides, I also have collected some data about SOC stocks of forest in China. On the other hand, I have finished a part of measurement indices, such as total C and N, SOC, BD, soil pH, EC, soil texture. There are some indices that are not measured, such as stone density (in order to correct data of soil carbon contents), protected carbon, microbial biomass C, exchangeable Ca^{2+}&Mg^{2+}.

Detail timetable:

06/18-08/18 (more than two months)

- Continue to measure the rest of the indices, such as microbial biomass C, exchangeable Ca^{2+}&Mg^{2+}, protected carbon, soil texture
- Collect SOC and N data about "impacts of forestation on SOC" from published papers to learn meta-analysis.

09/18-10/18 (two months)

- Learn how to use the models (e.g., DNDC and DayCent) to analyze SOC dynamics under different tillage practice over time,
- Do a meta-analysis on the "impacts of forestry on soil organic carbon"

11/18-12/18 (two months)

- Finish the manuscript "A full profile analysis of soil organic carbon under different tillage practices over time using DNDC and DayCent models";
- Finish the manuscript "impacts of forestation on SOC-A meta-analysis".

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