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Soil C storage as affected by tillage and straw management: An assessment using field measurements and model predictions

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ABSTRACT

Soil tillage and straw management are both known to affect soil organic matter dynamics. However, it is still unclear whether, or how, these two practices interact to affect soil C storage, and data from long term studies are scarce. Soil C models may help to overcome some of these problems. Here we compare direct measurements of soil C contents from a 9 year old tillage experiment to predictions made by RothC and a cohort model. Soil samples were collected from plots in an Irish winter wheat field that were exposed to either conventional (CT) or shallow non-inversion tillage (RT). Crop residue was removed from half of the RT and CT plots after harvest, allowing us to test for interactive effects between tillage practices and straw management. Within the 0–30 cm layer, soil C contents were significantly increased both by straw retention and by RT. Tillage and straw management did not interact to determine the total amount of soil C in this layer. The highest average soil C contents (68.9 ± 2.8 Mg C ha^{-1}) were found for the combination of RT with straw incorporation, whereas the lowest average soil C contents (57.3 ± 2.3 Mg C ha^{-1}) were found for CT with straw removal. We found no significant treatment effects on soil C contents at lower depths. Both models suggest that at our site, RT stimulates soil C storage largely by decreasing the decomposition of old soil C. Extrapolating our findings to the rest of Ireland, we estimate that RT will lead to C mitigation ranging from 0.18 to 1.0 Mg C ha^{-1} y^{-1} relative to CT, with the mitigation rate depending on the initial SOC level. However, on-farm assessments are still needed to determine whether RT management practices can be adopted under Irish conditions without detrimental effects on crop yield.

1. Introduction

During the last two centuries, arable farming has led to a worldwide decline in soil organic C (SOC) stocks (Lal, 2004). Several mechanisms have been shown to contribute to this trend. Firstly, soil disturbance during cultivation decreases the physical protection of soil C against microbial decomposition (e.g. Six et al., 2000). Moreover, arable land is managed to maintain close to neutral pH levels and drained to avoid water logging, thereby further stimulating microbial oxidation of SOC. Finally, arable soils with annual crops are typically covered with vegetation for a relatively short time compared to natural ecosystems, causing lower soil C input rates (Baker et al., 2007). Besides its negative effect on soil quality, a loss of soil C also adds to anthropogenic CO_2 emissions (Lal, 2007; Sauerbeck, 2001). These issues spurred research interest in management practices that may arrest or partly reverse C losses from arable lands (Post and Kwon, 2000; Smith et al., 1998, 2000).

Most notably, reduced tillage (RT) and straw management have been suggested as instruments for soil C storage (Jarecki and Lal, 2003); whereas RT minimizes soil disturbance, the retention of crop residue increases soil C input. Although straw retention and RT practices have both been reported to improve soil quality (e.g. Salinas-Garcia et al., 1997; Mann et al., 2002; van Groenigen et al., 2010), claims of soil C storage are still widely debated. On the one hand, several studies have found that no-till (NT) and RT practices increase soil C contents in the top soil (West and Post, 2002; Smith et al., 1998; Ogle et al., 2005). However, other studies have suggested that C accumulation near the soil surface due to NT and RT practices might be negated by a loss of C at lower depths (e.g. Baker et al., 2007; Blanco-Canqui and Lal, 2008).

It may take several decades before a new SOC equilibrium is reached following a change in management practices (Odell

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et al., 1984). As such, many tillage experiments are too short to provide definitive answers on questions regarding soil C storage potential. Soil scientists often try to overcome the problem of limited experimental duration through the use of SOM turnover models. Two common types of models used for this purpose are (a) cohort models describing decomposition as a continuum, and (b) process based multi-compartment models such as RothC (Coleman and Jenkinson, 1999) and CENTURY (Parton et al., 1987).

Cohort models are based on a generic theory for soil C and N dynamics proposed by Bosatta and Ågren (1991). They proposed a mathematical model that considers the input of litter or organic material at various time intervals as separate cohorts of SOM with a quality distribution, each of which degrades in a similar manner. The model assumes a decay time-constant for each cohort that increases with age. This can be mathematically expressed by dividing each input cohort into different components, e.g. very labile, labile, protected and resistant, each of which decay exponentially with their own time-constants.

RothC on the other hand divides SOM into a number of conceptual pools of C, with each pool defined by its lability. The model splits soil C input into decomposable (DPM) and resistant (RPM) plant materials, with the ratio depending on the origin of the plant materials. DPM and RPM decompose at different rates into microbial biomass (BIO) and humus (HUM), thereby releasing CO_2 (Coleman and Jenkinson, 1999). BIO and HUM then decompose at different rates producing more CO_2, BIO and HUM. The partitioning of the products of the decomposition depends on the soil clay content, whereas decomposition rates are modified by temperature, soil moisture and cover vegetation. The model also includes a pool of inert soil organic matter (IOM). The RothC model has been applied to numerous sites worldwide under various types of agricultural management (Smith et al., 1997). Since the model requires only a small number of parameters to be initialized, it is also relatively easy to use.

Here, we report on soil C sequestration beneath a 9 year old tillage and straw management experiment. Measurements of soil C contents are compared to predictions made by both RothC and by a cohort model, to estimate the decomposition rate of crop residue under different tillage management practices. This decay rate is then used to predict changes in soil C stocks under the different treatment combinations. We hypothesized that straw incorporation would increase soil C storage, regardless of tillage practice.

2. Materials and methods

2.1. Site description and management history

In the autumn of 2000, sixteen 27 m × 30 m plots were established in a winter wheat (*Triticum aestivum* L.) field at Teagasc Crops Research Centre (Knockbeg Site; 52°86′N, 6°94′W) near Carlow, Ireland. Prior to the start of the field experiment, the land management of the site is known from 1981, when it was leased by the Teagasc Oak Park Centre. More than a century before that, historical maps from Ordnance Survey Ireland (OSE, 2009), that were drawn between 1829 and 1842, show the site as a field used for pasture. In 1847 the Knock Beg Estate, including the field used for the experiment, was acquired by the Diocese of Kildare and Leighlin for use as a Catholic Secondary School for boys. The field remained as pasture and was also used for playing fields until the land was leased to Teagasc for agricultural experiments. So the cultivation history is as follows:

Prior to 1847	Pasture
1847–1977	Pasture and/or playing fields
1977–1992	Experimental area. Mainly improved grassland for grazing and silage with 3 years arable
1993–2000	Cultivated (ploughed previous autumn for either winter cereals, spring cereals, or occasionally sugar beet or hemp)
2000–present	Field experiment begun. Basic plots with cultivation treatments continue for cropping years 2001–2009

The soil at this site is a haplic luvisol with a pH (KCl) of 5.8. The soil has a sandy loam texture in the top 30 cm and a clay loam texture at lower depths. Mean annual precipitation and temperature are 824 mm and 9.4 °C. Fertilizer N was supplied in the form of calcium ammonium nitrate at the rate of 200 kg N ha^{-1} y^{-1}, divided over three applications during the growing season.

Half of the sixteen plots were conventionally tilled (CT). The CT plots were ploughed to a depth of 20–25 cm, usually in late September. The other half of the plots was subjected to a reduced tillage (RT) treatment, consisting of shallow non-inversion tillage using a single pass of a tined stubble cultivator (Horsch Terrano FX) at a depth of 7–10 cm, carried out in August. After harvest, straw (crop residue) was chopped and incorporated in half of the CT and RT plots by the ploughing and stubble cultivation operations, while it was baled and removed from the other half. The incorporated straw amounted to an estimated additional soil C input of approximately 2.8 Mg C ha^{-1} y^{-1} (Table 1). In the first year of the experiment, straw was removed from all plots. In 2007, each plot was divided into 20 subplots (2.5 m × 15 m), to allow for different N fertilizer treatments to be applied. In each plot, the original N fertilizer treatment was continued in one subplot. Further details on site management can be found in van Groenigen et al. (2010).

2.2. Sample collection and processing

In March 2009, five soil cores (diameter 2 cm) were collected at 0–15 cm, 15–30 cm, 30–45 cm and 45–60 cm from each subplot that received 200 kg N ha^{-1} y^{-1}. The soil samples were bulked per depth increment and sieved to pass through a 2 mm mesh, after which visible roots and plant remains were carefully removed with tweezers. In March 2010, additional samples were taken to determine soil bulk density. For the 0–15 cm layer, bulk density was determined from 3 soil cores (inner diameter 4.8 cm) per plot. Bulk density samples for all other soil layers were taken from the face of a soil pit in each plot. All samples were oven dried and ball milled, after which carbonates were removed using HCl fumigation as described by Harris et al. (2001). Soil C concentrations were determined using an Elementar Vario EL CHNS analyzer (Elementar GmbH, Hanau, Germany). Bulk soil C contents were calculated on an area basis, thereby correcting for differences in bulk density and gravel content. Per plot, C contents of the 0–30 cm and the 30–60 cm soil layers were calculated as the sum of the C content derived from the two sampling depths encompassed by each layer.

2.3. Statistical analysis

The field experiment had a complete randomized block design. An ANOVA was conducted for all soil depths using SPSS, with tillage and straw management as fixed factors, and blocks as a random factor. Data that did not conform to normality assumptions of ANOVA were rank-transformed prior to analysis. Treatment effects were considered significant at $P < 0.05$.

2.4. Estimating soil C input

The annual inputs of straw, root and stubble at our site were not recorded throughout the experimental period. However, grain yields were measured (Forristal and Murphy, 2009) and these values were used to estimate the annual yield of root and stem

Table 1
Grain yield, estimated C content of plant components and soil C input in an Irish winter wheat field, as affected by soil tillage and straw retention.

Straw	Tillage	Grain dry matter	Aboveground biomass	Straw (including stubble)	Stubble	Root	Total soil input
		$Mg\,ha^{-1}\,y^{-1}$	$Mg\,C\,ha^{-1}\,y^{-1}$				
Incorporated	RT	8.08[a]	6.10	2.86	0.43	1.26	4.12
	CT	7.83	5.91	2.78	0.42	1.22	4.00
Removed	RT	8.17	6.17	2.90	0.43	1.27	1.71
	CT	8.08	6.09	2.86	0.43	1.26	1.69

[a] Mean across four replicates and 9 years (Forristal and Murphy, 2009).

materials, using default conversion factors in the DNDC model for European winter wheat (Li et al., 1994) (Table 1). Straw yields and root biomass were estimated using a ratio of grain C to above ground biomass C of 0.53 and a root C to above ground biomass C ratio of 0.2. Stubble was estimated as 15% of straw yields. The C content of all crop residues was assumed to be 40%.

2.5. Modelling soil C

As no soil samples were available from the start of the experiment, RothC (Coleman and Jenkinson, 1999) was used to estimate the initial amount of SOC. Firstly, RothC was run to equilibrium considering the land use to be managed pasture with a RPM/DPM ratio of 1.44 and an annual C input of 3.45 $Mg\,ha^{-1}$ (Coleman et al., 1997). The latter number was based on an estimated soil C input rate of 3 $Mg\,C\,ha^{-1}\,y^{-1}$ in the Rothamsted Park Grass experiment (Coleman et al., 1997), but was increased by 15% to account for the larger sampling depth at our site (0–30 cm vs. 0–23 cm in Coleman et al., 1997). The proportion of C added as plant material each month was adapted from Smith et al. (2005). We assumed an IOM of 12 $Mg\,C\,ha^{-1}$, based on measurements in a nearby arable field (Dondini et al., 2009). Using these values as the initial conditions, RothC was then run to model the 8 years of arable farming preceding the field experiment. For this period, we assumed the annual C input to be that of CT with straw removal (Table 1), and a RPM/DPM ratio of 1.44. The meteorological data used to drive the RothC model were the mean of the period 1900–2002. This model run established the soil C status of the soil at the start of the tillage experiment. RothC was then run using the initial SOC pools calculated from the spin-up run and the estimated C additions for all treatment combinations.

A multi cohort model based on Bosatta and Ågren (1991) was used to estimate the decay of the plant organic matter input. The model was parameterized with data from Thomsen and Christensen (2004). This Danish experiment on a winter wheat system under comparable conditions as the Carlow site consisted of CT with 4 straw amendment rates (0, 4, 8 and 12 $Mg\,straw\,ha^{-1}\,y^{-1}$). After 18 years, straw incorporation was stopped and the SOC was measured. Conventional tillage was continued with just stubble incorporation for another 4 years, after which the SOC was measured again. Since the initial soil C content was known, these data could be used to estimate straw decomposition rates during straw amendment. The initial SOC at the Danish site was modelled as being entirely old C with a decay time-constant of 500 years, as the site had been used for arable farming for a century prior to the experiment. The partitioning of the input cohorts of straw or stubble into 4 pools with decay time-constants of 0.1, 3.3, 30 and 500 years, respectively (Dondini et al., 2009) was varied until the observed values and modelled values agreed within one standard error of the experimental observations at completion of straw amendment. The partitioning was then verified by comparison to the measurements made after the 4 years without straw amendments (Fig. 1).

The cohort model was then used to model decomposition rates at the Carlow site. The initial SOC level used in the model was that obtained from the spin-up runs of RothC. The decomposition rate of the initial SOC was adapted from Dondini et al. (2009), who had used the cohort model to match the decay rate history of SOC on a nearby site in Carlow. Each annual input cohort of soil C input (Table 1) was then divided into 4 pools with the same decay time-constants used to analyze the data by Thomsen and Christensen (2004). The partitioning of the soil C input in each pool was initially adapted from the Danish experiment as well. These values were then adjusted to match the observed total SOC in the straw amendment treatments and were verified with the observed total SOC in the straw removed treatments. This approach was done separately for RT and CT treatments.

The stepwise adjustment starts with the solution of two sets of two simultaneous equations describing soil C changes throughout the experiment (1 set for RT plots and 1 set for CT plots). One equation in each set describes soil C changes in plots with straw incorporation, the other equation describes the same process in plots without straw incorporation. Both equations have the following format:

$$\text{Initial SOC} \times \text{proportion not degraded} + \text{soil C input}$$
$$\times \text{proportion not degraded} = \text{final SOC}$$

where initial SOC is the initial soil C content at the start of the experiment, as estimated by RothC. Soil C input for plots with and without straw incorporation is determined from Table 1. Final SOC refers to the soil C contents for each treatment combination. This approach assumes that the percentage of C in each pool, and the degradation rates of each pool are constant each year for both straw and stubble amendments.

The solution of these equations for CT gives 23% of input and 90% of initial SOC is preserved. For RT, the solution gives 21% of input and 103% of initial SOC is preserved. This suggests that the decay rates of straw and stubble inputs for CT and RT are the same, and that the initial SOC decays at different rates for CT and RT.

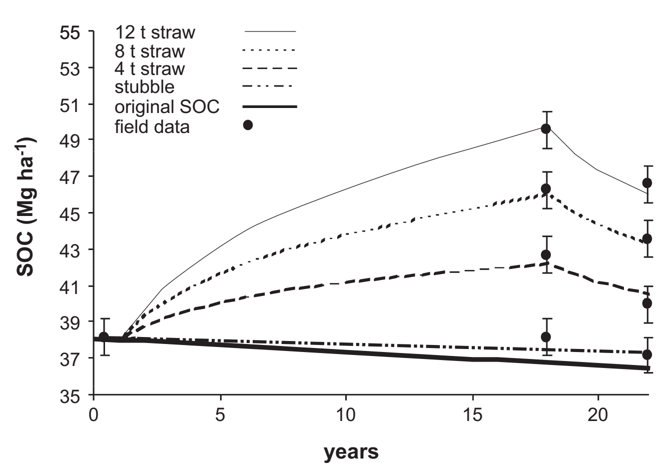

Fig. 1. Parameterization of the cohort model, using soil organic carbon (SOC) data by Thomsen and Christensen (2004).

Table 2
Soil C content in an Irish winter wheat field at four sampling depths, as affected by 9 years of soil tillage and 8 years of straw retention treatments.

Straw	Tillage	Total soil C (Mg ha^{-1})					
		0–15 cm	15–30 cm	0–30 cm	30–45 cm	45–60 cm	30–60 cm
Incorporated	RT	34.6 ± 1.2[a]	34.3 ± 1.9	**68.9** ± **2.8**	20.3 ± 1.7	14.5 ± 3.2	**34.8** ± **4.6**
	CT	27.7 ± 1.0	33.7 ± 0.7	**61.5** ± **1.5**	21.7 ± 1.7	11.6 ± 1.0	**33.3** ± **2.5**
Removed	RT	32.4 ± 0.7	32.4 ± 1.0	**64.8** ± **1.6**	25.1 ± 2.4	13.0 ± 1.8	**38.2** ± **4.2**
	CT	27.5 ± 0.8	29.9 ± 2.5	**57.3** ± **2.3**	18.7 ± 3.6	11.4 ± 1.0	**30.1** ± **3.3**
ANOVA							
Tillage		$P < 0.01$	NS	$\boldsymbol{P < 0.01}$	NS	NS	**NS**
Straw		NS	NS	$\boldsymbol{P < 0.05}$	NS	NS	**NS**
Tillage × straw		NS	NS	**NS**	NS	NS	**NS**

Total soil C stocks for the 0–30 cm and 30–60 cm soil layers are reported in bold characters.
[a] Mean ± SE; $n = 4$.

In the cohort model, the percentages of the soil C input pool sizes were then adjusted to match the proportion of remaining C over the experimental period. This was done first by dividing the proportion between 500 year pool and 30 year pool, then the 3.3 year pool and finally the 0.1 year pool. The initial step change is 10% then this is reduced to 1% to fine tune the result. This process is repeated for the initial SOC decay proportion.

The resulting cohort model was then used to predict the average annual soil C change for Ireland on a 0.0083333 degree grid block in Mg C ha^{-1} y^{-1} for the first 9 years of using RT on available arable land. Initial soil C contents were obtained from the World Harmonized Soil Data Base (FAO/IIASA/ISRIC/ISSCAS/JRC, 2009). Available arable land was identified from the CORINE 250 land use map from the European Environmental Agency. The meteorological data used in the model were from the CRU climate data (Mitchell et al., 2004). The results were mapped using ArcGIS^{TM} software.

3. Results

3.1. Bulk soil C contents, bulk density and C conversion efficiency

Integrated across the 0–30 cm soil layer, soil C contents ranged from 57.3 to 68.9 Mg C ha^{-1}. Reduced tillage and straw retention both significantly increased soil C contents, with the highest soil C contents occurring in RT plots with straw incorporation (Table 2). Reduced tillage increased soil C contents mostly in the 0–15 cm layer. Within CT plots, straw retention increased average soil C contents mostly in the 15–30 cm layer. Within RT plots on the other hand, straw incorporation increased average soil C contents in both soil layers to a similar extent. Tillage and straw incorporation did not significantly affect soil C contents below the 0–30 cm layer.

Reduced tillage significantly increased soil bulk density in the 0–15 cm and 15–30 cm soil layers. Straw retention on the other hand decreased soil bulk density, but only in the 0–15 cm layer (Table 3). As for soil C contents, soil C concentrations were increased by RT and straw incorporation, with significant treatment effects that are confined to the top 0–30 cm layer (Table 4).

The increase in soil C input caused by straw retention was approximately 2.3 and 2.4 Mg C ha^{-1} y^{-1} for RT and CT treatments, respectively (Table 1). Based on these estimates, and the difference in soil C contents between the treatment combinations (Table 2), the conversion efficiency of added straw C is approximately 21% under RT and 23% under CT.

3.2. Model fit to soil C analyses

Equilibrium SOC contents at the site (i.e. soil C contents in 1992) as calculated by RothC were 67.8 Mg C ha^{-1} in the top 30 cm. The subsequent 8 years of cropping resulted in an estimated SOC content of 60.0 Mg C ha^{-1} at the start of the experiment (Fig. 2). Using a default value of DPM/RPM and the estimated soil C input rates from Table 1 resulted in a match to measured soil C contents under CT, with and without straw incorporation, within half of the standard error (Fig. 3). The cohort model predictions also showed a good fit to the experimental data (Fig. 3) for CT with and without straw incorporation.

There is no standard way in either model to differentiate between CT and RT treatments. However, we achieved a fit in the cohort model to the experimental data under RT by reducing the decay rate of the initial SOC. Specifically, 100% of the original SOC in the RT plots had to be put in the protected pool with a decay $\tau = 500$ years, compared to 56% of the original SOC for the CT plots. The annual cohorts had the same decay rate for the RT and CT cases (Table 5). This knowledge gained from using the cohort model to understand the decay mechanism of both the input cohorts and the initial SOC enabled the RT case to be modelled using RothC by considering all of the initial SOC to be inert (IOM). Using the cohort model spatially indicated that for the current SOC levels of agricultural soils in Ireland, the first 9 years of management change from CT to RT would result in mitigation rates ranging between

Table 3
Bulk density of soil <2 mm in an Irish winter wheat field at four sampling depths, as affected by 9 years of soil tillage and 8 years of straw retention treatments.

Straw	Tillage	Bulk density (g cm^{-3})			
		0–15 cm	15–30 cm	30–45 cm	45–60 cm
Incorporated	RT	1.28 ± 0.01[a]	1.46 ± 0.04	1.37 ± 0.03	1.42 ± 0.09
	CT	1.21 ± 0.02	1.42 ± 0.02	1.40 ± 0.04	1.49 ± 0.07
Removed	RT	1.31 ± 0.02	1.50 ± 0.04	1.43 ± 0.03	1.48 ± 0.11
	CT	1.26 ± 0.02	1.35 ± 0.07	1.47 ± 0.07	1.42 ± 0.03
ANOVA					
Tillage		$P < 0.01$	$P < 0.05$	NS	NS
Straw		$P < 0.05$	NS	NS	NS
Tillage × straw		NS	NS	NS	NS

[a] Mean ± SE; $n = 4$.

Table 4
Soil C concentrations in an Irish winter wheat field at four sampling depths, as affected by 9 years of soil tillage and 8 years of straw retention treatments.

Straw	Tillage	Total soil C (%)			
		0–15 cm	15–30 cm	30–45 cm	45–60 cm
Incorporated	RT	1.91 ± 0.07[a]	1.65 ± 0.06	1.04 ± 0.09	0.70 ± 0.14
	CT	1.60 ± 0.07	1.69 ± 0.03	1.09 ± 0.08	0.56 ± 0.07
Removed	RT	1.74 ± 0.06	1.53 ± 0.05	1.23 ± 0.11	0.62 ± 0.06
	CT	1.52 ± 0.05	1.55 ± 0.07	0.87 ± 0.13	0.58 ± 0.05
ANOVA					
Tillage		$P < 0.01$	NS	NS	NS
Straw		$P < 0.05$	$P < 0.05$	NS	NS
Tillage × straw		NS	NS	NS	NS

[a] Mean ± SE; $n = 4$.

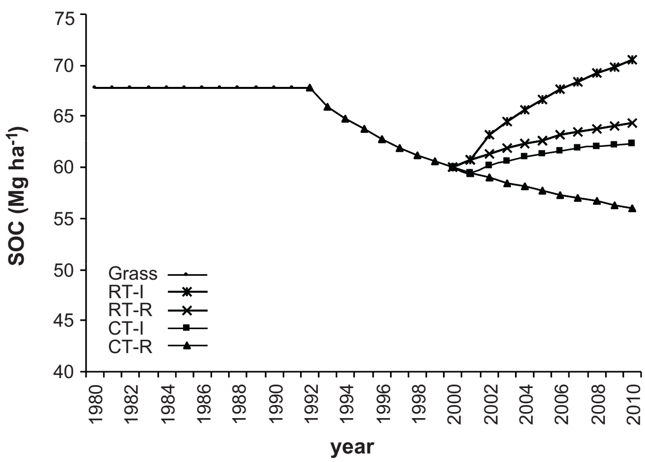

Fig. 2. RothC spin up of SOC contents for the 0–30 cm soil layer at the start of the experiment using the "Park Grass" land use for 300 years (only 1980–1992 shown in graph), followed by 8 years of arable farming. The tillage treatments commenced in 2000, the straw management treatments started 1 year later. The model is run out to 2009 for all treatment combinations: (1) CT with straw incorporated (CT-I), (2) RT with straw incorporated (RT-I), (3) CT with straw removed (CT-R), (4) RT with straw removed (RT-R).

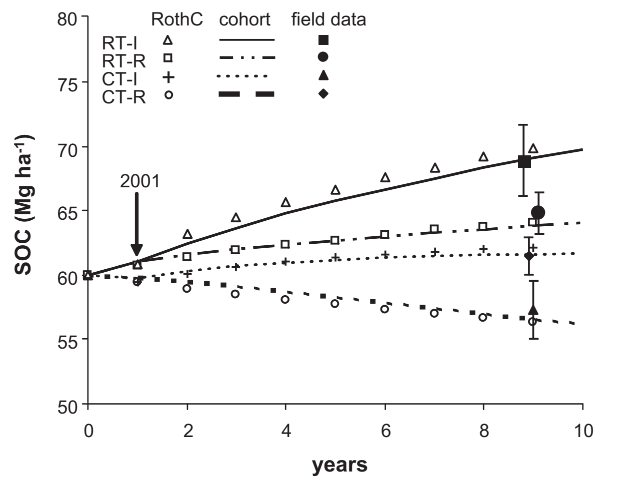

Fig. 3. Comparison of cohort model and the RothC model for the experimental period 2000–2009 of SOC predictions compared to the experimental measurements for the 4 treatments for the 0–30 cm soil layer. See Fig. 2 for definition of abbreviations. The CT and RT treatments require different C partition pools to obtain a match, see Table 5 for details.

0.18 and 1.0 Mg C ha^{-1} y^{-1} (Fig. 4). Grain yields at our site correspond closely to average values for Ireland of 8 tonnes per hectare (Eurostat, 2010). Assuming that soil C input rates and conversion efficiency at our site are also representative for the rest of Ireland, the combination of RT with straw incorporation would increase soil C contents by 0.5 Mg C ha^{-1} y^{-1}, as well as protecting existing SOC.

4. Discussion

Soil C levels are ultimately determined by the balance between the input of plant material and losses due to decomposition, erosion and leaching. As such, higher soil C input rates are generally expected to augment soil C stocks. Indeed, straw retention significantly increased soil C contents in the 0–30 cm soil layer at our site. Crop residue incorporation does not always translate to a significantly greater SOC. A review of the literature by Lemke et al. (2010) indicates that out of 35 published experimental comparisons, residue incorporation increased average soil C contents in 27 cases. However, the increase in soil C was significant in only 7 of these cases. Unfortunately, the effects of straw retention are difficult to discern in individual experiments because of spatial variability and the large amount of C in the soil relative to input rates (e.g. Hungate et al., 1996).

Soil C contents were significantly higher under RT than under CT at our site. This result corroborates a recent meta-analysis suggesting that RT practices significantly increase C contents in the top 30 cm of soils in wet temperate climates such as in Ireland (Ogle et al., 2005). Nonetheless, claims of soil C storage under RT and NT practices remain hotly debated. An on-farm assessment by Blanco-Canqui and Lal (2008) suggests that whereas NT practices increase soil C contents in the top soil layers, they do not affect integrated soil C stocks across the 0–60 cm soil profile. However, Franzluebbers (2009) points out that in this assessment, the tillage effect on SOC

Table 5
Estimated cohort model pool size partitions in an Irish winter wheat field as affected by tillage.

Pool	τ (year)	RT		CT	
		Original SOC	Cohort	Original SOC	Cohort
Very labile	0.1	0	0.57	0	0.57
Labile	3.3	0	0.2	0	0.2
Resistant	30	0	0.15	0.44	0.15
Protected	500	1	0.08	0.56	0.08

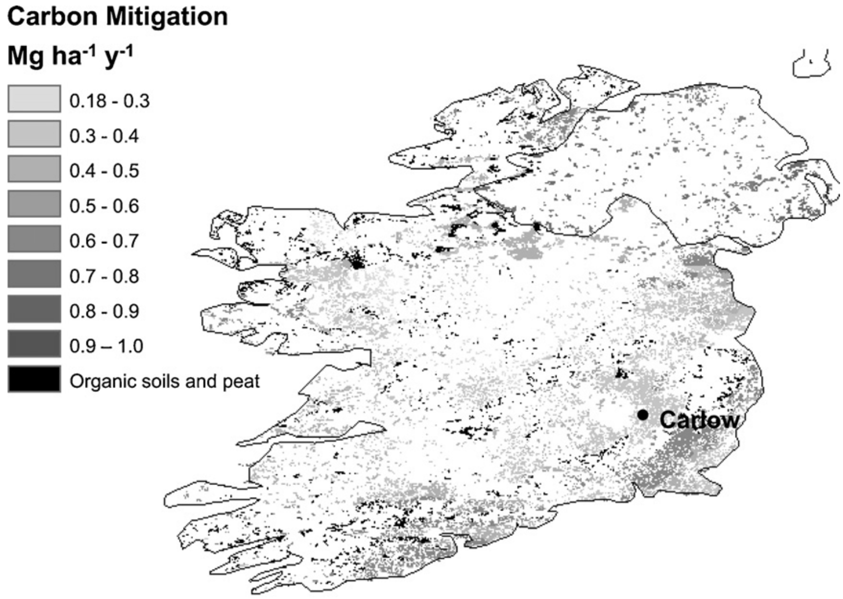

Fig. 4. Map of the estimation of the potential annual C emissions mitigation in Mg C ha^{-1} y^{-1} over a 9 year period, by changing arable land management from CT to RT for soils in Ireland.

disappeared because of greater random variation at lower depths, rather than because of greater SOC under CT.

Baker et al. (2007) suggested that by impeding root growth, RT may decrease plant C input at lower depths relative to CT. This would be because RT soils typically have a high soil strength and bulk density, thereby increasing resistance to root penetration (Cannell, 1985; Larney and Kladivko, 1989). Moreover, leaching and/or biological activity may transport residue C below the plough layer in CT treatments (Machado et al., 2003). All these mechanisms would increase soil C contents under CT relative to RT treatments at lower soil depths, and could in part or whole cancel out soil C increases near the surface under RT. However, we are not aware of any reports showing RT practices significantly decreasing soil C contents below the plough layer. Soil C contents below 30 cm were not significantly affected by tillage or straw management at our site either. As such, it is still unclear why most field studies find increases in the top soil C contents under RT, whereas soil profile studies often find no significant tillage effects (Baker et al., 2007). These results could simply be the consequence of higher random variation with depth, but it could also be that RT diminishes soil C contents deeper down the profile, which is in turn masked by the aforementioned variation. Definitive answers on these questions will require long term field studies on homogeneous soils, combined with spatially intensive soil sampling that extends well below the plough layer. Ideally, these studies would also assess changes in soil bulk density within individual plots over time, since this is an important source of uncertainty in soil C assessments (Lee et al., 2009). When bulk density is significantly altered by management practices, as in our study, a comparison of SOC amounts for an equivalent soil mass rather than for fixed depth intervals may provide more accurate estimates of treatment effects (e.g. Ellert and Bettany, 1995; Lee et al., 2009). Unfortunately, a lack of initial soil bulk density data prohibited such an approach in our experiment.

Our field data suggest that in short- to medium-term field experiments, the effects of tillage and straw retention do not interact to determine soil C contents, i.e. these effects are additive. Moreover, the cohort model suggests that the decay rate of the input cohorts is similar for both tillage treatments. As a consequence, the conversion efficiency of residue C input was largely similar between tillage treatments. These findings are in contrast with Duiker and Lal (1999), who reported that the conversion efficiency of added residue C into SOC was higher under RT than under CT practices. However, the sampling depth in that study (0–10 cm) did not cover the entire plough layer. If ploughing operations transport new residue below the 0–10 cm layer, such a sampling strategy would underestimate the increase in soil C due to straw incorporation under CT. Indeed, our own data suggest that within CT treatments, straw retention increased soil C contents mostly in the 15–30 cm soil layer.

The RothC and cohort model predictions closely matched the observed SOC contents for all treatment combinations. It should be noted, however, that SOC degradation rates in both models are estimated from a single measurement made after 9 years of treatments. Since any rate assumption needs at least two time intervals for measurements to be confirmed, the model projection should be treated as a leap of faith. Logically, the SOC of the original grassland would not be expected to be exceeded by any of the treatment combinations. Indeed, Gottschalk et al. (2010) suggested that RothC may underestimate the effect of soil disturbance on soil C losses in the short term. Their findings suggest that the conversion from grassland to arable land at our site may have caused larger soil C losses than currently assumed. In that case, soil C contents under the original grassland would be higher than those shown in Fig. 2. However, since a difference in initial soil C contents would affect all plots similarly, it would not affect our conclusions regarding treatment effects on old and new soil C.

Our field measurements suggest tillage effects that are relatively high compared to the 9% increase in total soil C stocks under RT over 20 years, as calculated in a recent meta-analysis (Ogle et al., 2005). Unlike the studies considered by Ogle et al. (2005), soil C contents at our site were not in equilibrium at the start of the experiment. Soil C stocks are expected to decrease further under CT at our site, thereby increasing the difference between RT and CT treatments. Indeed, both RothC and the cohort model suggest that RT stimulates soil C storage largely by protecting native SOC against decomposition. This result corroborates Balesdent et al. (1990), who used soil ^{13}C signatures to show that NT and RT practices reduced the mineralization of native soil C. Moreover, it implies that RT may have a larger C mitigation effect in soils with high initial SOC contents (Balesdent et al., 1988). This effect is also illustrated in the simulation with our cohort model applied to Ireland. Compared to the range of predicted C mitigation rates in Fig. 4, the difference in soil

C contents between RT and CT plots observed at our site is relatively large. Part of this difference is due to the downward trajectory on the field site, arising from the legacy of the recent plough-out from grassland. Soil C mitigation potential also depended on climate and soil mineralogy, both of which are known to affect soil C dynamics (Parton et al., 1987).

Whether arable land forms a source or sink of atmospheric CO_2 is not determined by changes in soil C stocks alone. For instance, plots in our study received relatively high doses of N fertilization, the production and distribution of which is associated with emissions of CO_2 (Schlesinger, 2000). These and other indirect sources of CO_2 should be included when assessing the net C balance of agricultural practises. In this context, it is important to remember that there are several other uses for straw besides incorporating it into the soil. In addition to its use as animal fodder and bedding, it can also be integrated into various building materials, and it forms a large potential source of bio-energy. Some of these options may have a larger C mitigation potential than straw incorporation (Powlson et al., 2008). However, the benefit of straw retention is not limited to C mitigation alone; several studies suggest that it can also help to improve soil structure, reduce the loss of fertilizer N, and decrease soil erosion (Blanco-Canqui and Lal, 2009). Clearly, decisions regarding straw management should not be based solely on its C mitigation potential.

Reduced tillage practices are still relatively uncommon in Ireland, and their effect on soil workability and crop yields under Irish conditions is still unclear. However, several studies suggest that RT practices may reduce crop yields under temperate humid climates, especially when combined with straw retention (e.g. Ball and Robertson, 1990). These effects have been attributed to waterlogging and the phytotoxic effects of surface straw. Under humid conditions, RT practices may also cause problems including weed infestation, fungal diseases or pests like slugs and mice (Cannell, 1985). Since our site is well drained, it is probably less prone to most of these problems. Indeed, straw retention and tillage have limited effects on crop yields at our site (Forristal and Murphy, 2009). However, on-farm assessments, including sites under sub-optimal conditions are still missing. Without these data, the potential for wide scale adaptation of RT practices in Ireland remains uncertain.

5. Conclusions

The field site used in this study provided a unique opportunity to assess the effects of tillage practices and straw management on soil C dynamics under Irish climatic conditions. We found that C contents in the 0–30 cm soil layer were significantly increased both by straw retention and by RT. Two independent soil C modelling efforts suggest that at our site, RT stimulates soil C storage largely by decreasing the decomposition of old soil C. When scaled up to the rest of Ireland, our findings imply that RT can lead to substantial C mitigation. We still need on-farm assessments to determine where in Ireland these management practices can be adopted without detrimental effects on crop yield. That said, our results show that under certain conditions both straw retention and RT are effective means to increase the C sink strength of Irish agricultural soils.

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