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ScienceDirect
Soil & Tillage Research 95 (2007) 1–10
Soil & Tillage Research
www.elsevier.com/locate/still

Review

Impacts of periodic tillage on soil C stocks: A synthesis

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Received 17 July 2006; received in revised form 2 December 2006; accepted 25 December 2006

Abstract

Long-term loss of soil C stocks under conventional tillage and accrual of soil C following adoption of no-tillage have been well documented. No-tillage use is spreading, but it is common to occasionally till within a no-till regime or to regularly alternate between till and no-till practices within a rotation of different crops. Short-term studies indicate that substantial amounts of C can be lost from the soil immediately following a tillage event, but there are few field studies that have investigated the impact of infrequent tillage on soil C stocks. How much of the C sequestered under no-tillage is likely to be lost if the soil is tilled? What are the longer-term impacts of continued infrequent no-tillage? If producers are to be compensated for sequestering C in soil following adoption of conservation tillage practices, the impacts of infrequent tillage need to be quantified. A few studies have examined the short-term impacts of tillage on soil C and several have investigated the impacts of adoption of continuous no-tillage. We present: (1) results from a modeling study carried out to address these questions more broadly than the published literature allows, (2) a review of the literature examining the short-term impacts of tillage on soil C, (3) a review of published studies on the physical impacts of tillage and (4) a synthesis of these components to assess how infrequent tillage impacts soil C stocks and how changes in tillage frequency could impact soil C stocks and C sequestration. Results indicate that soil C declines significantly following even one tillage event (1–11% of soil C lost). Longer-term losses increase as frequency of tillage increases. Model analyses indicate that cultivating and ripping are less disruptive than moldboard plowing, and soil C for those treatments average just 6% less than continuous NT compared to 27% less for CT. Most (80%) of the soil C gains of NT can be realized with NT coupled with biannual cultivating or ripping.

Keywords: Agriculture; Soil carbon; Tillage; Tillage intensity; Tillage frequency

Contents

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0167-1987/$ – see front matter
doi:10.1016/j.still.2006.12.006

1. Introduction

Tillage has been used ubiquitously in agriculture to prepare the seed bed, to incorporate fertilizer, manure and residues into the soil, to relieve compaction and to control weeds (Phillips et al., 1980; Leij et al., 2002). However, tilling the soil is disruptive and can promote soil erosion, high moisture loss rates, degradation of soil structure and depletion of soil nutrients and C stocks. Following long-term tillage soil C stocks can be reduced by as much as 20–50% (Haas et al., 1957; Davidson and Ackerman, 1993; Murty et al., 2002; Ogle et al., 2003). Conservation tillage reduces the negative impacts of tillage, preserves soil resources and can lead to accrual of much of the soil C lost during tillage (Paul et al., 1997; Paustian et al., 1997a,b; Lal et al., 1998; Ogle et al., 2003). Conservation tillage is one of the largest potential sources of greenhouse gas mitigation within the agricultural sector and, coupled with associated declines in fuel use, could make an immediate, substantial contribution to offsetting and reducing greenhouse gas emissions (Caldeira et al., 2004; Paustian et al., 2004).

Conservation tillage is common in the US (CTIC, 1998) and has been spreading globally (Meese, 2004). The conservation tillage method that involves the least amount of soil disturbance is no-till (NT). Most cropland in the US is not under continuous no-till, but undergoes periodic tillage events (CTIC, 1998). Producer experimentation with NT is widespread among corn–soybean producers in Minnesota, Indiana and Illinois (77% of producers in IN), but the average duration of NT was only 1.4 (MN) to 2.4 (IL) years (Hill, 2001). Reasons for tilling are varied, but include enabling earlier planting (in cooler climates) and controlling pests (Hill, 2001), which may improve yields. We wonder what the short-term impacts of tillage are, how soil C is impacted, and what fractions of soil C are most susceptible to loss after tillage. We recognize that sequestration of C in soils is a promising way to offset CO_2 emissions (Fig. 1a), but how does potential sequestration differ between continuous NT and infrequently tilled systems (Fig. 1b)? How much does tillage every 1.5 or 2.5 years reduce soil C stocks? Does tillage 1 year out of four or eight substantially reduce soil C stocks compared with long-term continuous NT?

The objective of this work was to address these questions as comprehensively as possible using existing information. We used three complimentary approaches to investigate the impacts of infrequent tillage on soil C stocks. First, we carried out a modeling exercise with a soil C model that illustrates expectations of infrequent tillage impacts on soil C stocks. Long-term agricultural experiment stations have not systematically investigated the impacts of infrequent tillage, likely due to the value of maintaining long-term treatments. Our modeling exercise thus enabled us to examine responses in a much more comprehensive manner than is possible based solely on experimental data. The expectations generated from this modeling exercise were then

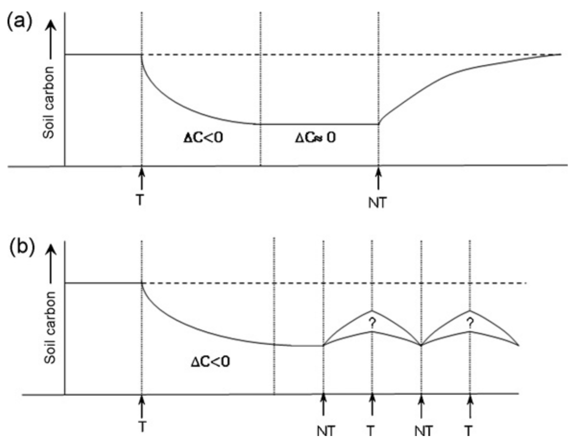

Fig. 1. Conceptual diagram illustrating potential responses to short-term impacts of tillage on soil C dynamics.

evaluated against data from studies examining short-term soil C losses and short-term soil C gains. Finally, we briefly review studies examining the physical mechanisms that control decomposition and stabilization of C in the soil and short-term responses to and recovery from disturbance. From this information we produce a synthesis of the current state of knowledge regarding the impacts of infrequent tillage-induced disturbances on soil C stocks.

2. Model analyses

2.1. Methods

Soil organic matter models embody our current understanding of how multiple interacting factors influence soil C dynamics. For our purposes, a model-based investigation is most useful because it enables us to investigate a much wider variety of tillage management practices than have been investigated in the field. On the other hand, our model results are not definitive and we use conclusions based upon them primarily to guide our reviews of studies investigating short-term tillage impacts on soil C stocks and mechanisms that stabilize C in soil.

We used the Century model (Parton et al., 1987; Metherell et al., 1993) to forecast soil C stock changes in response to introduction of infrequent management practices at three long-term agroecosystem experimental sites. Site characteristics are described in Table 1. Actual land use/management history information prior to 1999 was used to drive the model to current conditions (Paul et al., 1997). NT was then simulated until equilibrium was reached and experimental model runs were initiated for 220 years thereafter (for illustrative purposes, data are displayed from 2005 to 2230). Tillage experimental treatments included continuous NT, continuous conventional tillage (CT) and discontinuous NT with tillage every 2 (NT2), 4 (NT4), 6 (NT6), 8 (NT8) or 10 (NT10) years. Within the Century model, each tillage event leads to incorporation of surface residues and a temporary increase in decomposition rates. The width, depth and degree of soil turnover are a function of the type of tillage implement(s) used, and are modeled using an integrated tillage intensity term that dictates the magnitude and duration of the response. Simulated tillage events consisted of moldboard plow or tandem disk passes as practiced on-farm (simulated in Century with turnover intensities of 90 and 60% and mixing depth of 20 and 7.5 cm, respectively). Multiple passes with a tandem disc were simulated at the time of planting and moldboard plow operations were simulated in the fall after annual grain crops were harvested and at the end of the hay/meadow sequence in the rotations. We also included ripping and cultivator treatments. Ripping treatments were designed to mimic the disturbance likely caused by a subsoil ripper, like that used to relieve soil compaction and improve drainage. Cultivator treatments, like those used to control weeds, were evaluated as well.

2.2. Results

Model results demonstrated that CT reduced soil C content (compared to NT) by an average of nearly 27% across the three sites (Table 2 and Fig. 2). Extending the time between tillage events tended to increase the amount of C in soil, but the magnitude of soil C increases following cessation of tillage declined substantially as duration between tillage events increased. At the East Lansing site, for example, the difference in soil C content between a site tilled every other year and one tilled every fourth year was 6.2 Mg C ha^{-1} while the difference between every eighth year and every 10th year was only 1.4 Mg C ha^{-1}. NT-2 treatments resulted in soil C stocks that were an average of 13% greater than that under CT. Across the three sites, 2 successive years of NT returned soil C stocks to an average of 83% of that under continuous NT while 10 successive years returned soil C stocks to an average of 94% of that under continuous NT. The model results suggested that use of a cultivator or ripper every 4 years results in only minor reductions to soil C stocks, which average 6% less than those under continuous NT.

Table 1
Characteristics of agroecosystem research sites at which we carried out model experiments

Site	Latitude	Longitude	MAT[a] (°C)	MAP[b] (mm)	Soil texture (silt plus clay, %)	Crop rotation
East Lansing, MI	42.5N	85.5W	8.6	782	46	Continuous corn
Hoytville, OH	41N	84W	9.5	845	79	Corn–soybean/corn–oats–meadow
Manhattan, KS	36.5N	96W	11.9	588	92	Continuous wheat

[a] Mean annual temperature.
[b] Mean annual precipitation.

Table 2
Modeled steady state soil C content for duration of conventional tillage (CT), infrequent tillage (NT, with number that indicate number of years between tillage events) and no-tillage (NT) at three experimental sites

Site	Soil C (Mg C ha^{-1})								
	CT	NT-2	NT-4	NT-6	NT-8	NT-10	NT-cult	NT-rip	NT
East Lansing, MI	47.6	53.7	59.9	63.2	65.1	66.5	66.4	67.6	74.2
Hoytville, OH	41.9	48.4	50.7	51.7	52.3	52.8	52.3	52.7	54.8
Manhattan, KS	31.6	34.6	36.9	37.8	38.3	38.6	38.2	38.5	40.2

NT-cult and NT-rip indicate semi-annual cultivation with a cultivator and ripper, respectively.

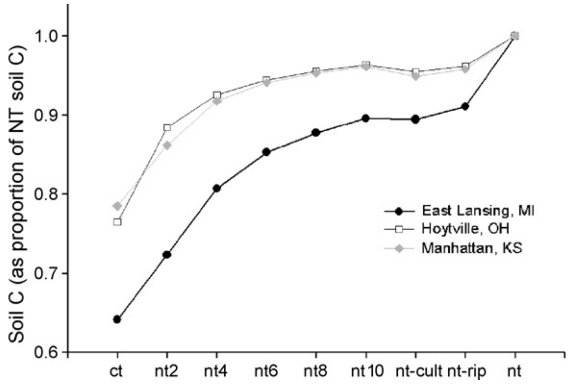

Fig. 2. Proportional reductions in soil C stocks (relative to long-term NT) for three sites: East Lansing, MI; Hoytville, OH and Manhattan, KS. Data are from Century model output.

From these model results, we have identified seven general observations that are common to the three sites. These general observations are all illustrated in Fig. 3. (1) Tillage-induced losses of soil C after long-term NT are small relative to losses due to long-term CT, averaging less than 2% for the NT-2 during first 2 years and 8% over the first 10 years (versus 18% for CT after 10 years). (2) Most of the C gain between CT and NT is realized with infrequent tillage. (2a) Correspondingly, losses with 1 year of tillage within long-duration NT are relatively small—less than 1% of soil C. (3) The amount of soil C lost due to a tillage event is proportional to the amount that is gained during NT. Thus, (4) as the duration between tillage events increases, the amount of C lost with a single tillage event increases. This suggests that (4a) during infrequent tillage the soil C gained during NT is lost during the next tillage. (5) Decreased frequency of tillage, and increased NT duration, result in greater soil C stocks. (6) Soil C stocks are more responsive to a decrease in tillage frequency as the frequency of tillage in the reference case increases (i.e., change in C stocks for NT4 versus NT2 is greater than that for NT10 versus NT8). (7) Over time under a given tillage frequency, the amount of C lost following a tillage event decreases. These model results suggest that doubling the average duration of NT adoption in IN, IL and MN, and other places where duration of NT is short, will have very significant implications for soil C storage.

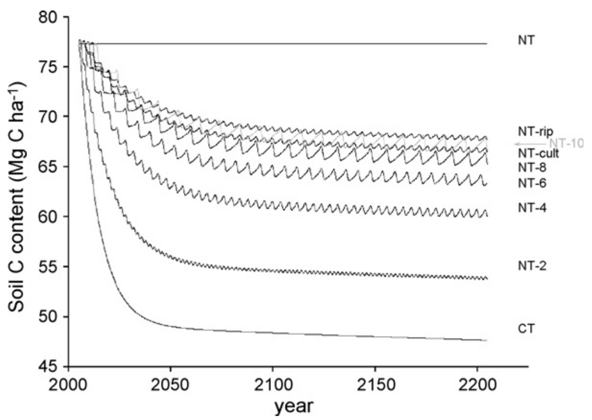

Fig. 3. Century model output illustrating changes in soil C stocks over time and steady-state soil C stocks for different tillage operations and frequencies at East Lansing, MI.

Now we review the literature on tillage impacts on soil C stocks and on the mechanisms that stabilize soil C stocks. Only observations 2a and 3 can be evaluated using those data—and these only in part. We use these observations to guide our synthesis of those data.

3. Impacts of tillage on NT soil C stocks

3.1. Immediate-term

Immediately following a tillage event, large amounts of CO_2 are lost from the soil (Reicosky et al., 1997, 2005). CO_2 emission rates as high as 29 g CO_2 m^{-2} h^{-1} have been observed (Reicosky and Lindstrom, 1993). Some of this initial flush has been attributed to emission of CO_2 from the soil atmosphere, particularly the initial flux (Reicosky et al., 1995), but CO_2 flux rates for tilled soils can be substantially higher than for untilled soils even 19 days after a tillage event (Reicosky and Lindstrom, 1995). The relative contributions of increased microbial activity and physical changes to the soil structure enabling rapid exchange of the soil atmosphere have not been firmly quantified (Otten et al., 2000; Jackson et al., 2003; Reicosky et al., 2005), but immediate-term changes in CO_2 flux rates may serve as an indicator for longer-term changes in soil C stocks (Reicosky et al., 1997).

3.2. Long-term responses

We have compiled a database of published studies that investigate how agricultural practices impact soil C stocks (see Ogle et al., 2005). From that database we identified published articles containing data on the short-term impacts of tillage on soil C stocks. To identify new articles and to ensure that we had gathered as many articles as possible, we used the Institute for Scientific Information Web of Science database (Thompson Corporation, Stamford, CT, USA) to carry out searches for articles containing keywords tillage, and soil carbon or soil organic matter. We required that articles clearly document the duration of NT treatments and measure soil C preceding tillage or from a control plot. We reviewed all of the articles that we thought might be relevant and we report data from those articles that contained information that met our criteria. The same methods were used to identify studies examining short-term impacts of cessation of tillage on soil C stocks, which is discussed in the next section. All studies were restricted to the top 30 cm.

Our literature review identified experimental studies from five locations: East Lansing, MI (Pierce et al., 1992, 1994), southern Ontario (VandenBygaart and Kay, 2004), southern Saxony, Germany (Stockfisch et al., 1999), western Nebraska (Kettler et al., 2000) and eastern Colorado (Bowman et al., 1990) (Table 3). VandenBygaart and Kay (2004) investigated the impacts of infrequent tillage event for three soil textures (silty clay loam, sandy clay loam and sandy loam) and two drainage classes, reflected by different soil C contents (sandy loam with high soil C and sandy loam with low soil C). All treatments were located on one private farm in southern Ontario and had been under continuous NT for 22 years. Soil samples were collected before, 3 days, 7 months and 18 months after tillage with a single pass of a moldboard plow. Samples were corrected to a cumulative mass sampling of 6000 Mg ha^{-1}. Impacts of tillage were assessed by comparing soil C stocks seven and 18 months after tillage with those immediately (3 days) after tillage. Soil C stocks declined significantly for only one of the four soils (the sandy loam low C soil). By comparing with data from long-term CT in the same area (Yang and Kay, 2001), VandenBygaart and Kay (2004) concluded that NT soil C stocks at the sandy loam, low soil C site were 15% greater than under conventional tillage and that the amount of soil C lost within the 18 months after tillage amounted to approximately two thirds of the C sequestered during 22 years of NT, or loss of 8% of total NT soil C stocks before tillage.

Following 21 years of minimum tillage (rotary harrow for stubble cultivation and seedbed preparation), Stockfisch et al. (1999) moldboard plowed (to 30 cm depth) a silt loam soil to assess the impacts on soil C stocks. Following this tillage event, soil C concentrations in the top 20 cm declined significantly, going from

Table 3
Summary of studies examining the short-term impacts of tillage on soil C (Mg C ha^{-1}) stocks under conventional tillage (CT), no-tillage (NT) and following tillage of long-term NT systems (NT-plow)

Location	Soil/treatment	CT soil C	NT soil C	NT-plow soil C	Duration between measurements	Sampling depth (cm)	Author
S. Ontario	Sandy loam high soil C		92.8	96.6	7 months	~30 cm[a]	VandenBygaart and Kay (2004)
S. Ontario	Sandy loam low soil C	35.7	42.0	41.9	7 months	~30 cm[a]	VandenBygaart and Kay (2004), Yang and Kay (2001)
S. Ontario	Sandy clay loam		89.0	85.4	7 months	~30 cm[a]	VandenBygaart and Kay (2004)
S. Ontario	Silty clay loam		126.3	128.4	7 months	~30 cm[a]	VandenBygaart and Kay (2004)
Lower Saxony			105	93	12 months		Stockfisch et al. (1999)
E. Lansing, MI	NP86	22.7	25.7	20.4	4 years	10	Pierce et al. (1992, 1994)
E. Lansing, MI	NP87	22.7	28.9	21.9	4 years	10	Pierce et al. (1992, 1994)
W. Nebraska	+0 kg N	35.2	36.2	35.9	5 years	30	Kettler et al. (2000)
W. Nebraska	+45 kg N	35.0	41.0	39.6	5 years	30	Kettler et al. (2000)

[a] Sampled to soil mass of approximately 4400 Mg ha^{-1}.

significantly greater than those under conventional tillage to equivalent to those under conventional tillage. Changes in bulk density were not measured. However, compaction is one reason that NT systems are periodically tilled (Hill, 1998) and bulk density changes considerable following tillage (VandenBygaart and Kay, 2004). The ability to draw conclusions about changes in soil C stocks is limited without good data on bulk density.

Pierce et al. (1992, 1994) measured soil C stocks for a zone tillage treatment at a site that had been under NT for 6 (NTP86 treatment) or 7 (NTP87 treatment) years prior to tillage. Soil C stocks in both NPT treatments decreased at the surface (0–5 cm) immediately after tillage (i.e., for the 1987 sampling), while soil C stocks at depth increased slightly. Soil C stocks (top 20 cm) for all treatments declined significantly between 1987 and 1991 (by an average of nearly 20%), making interpretation of sequential sampling challenging. But, the soil C contents of the NT and NTP treatments were similar initially (in 1986) and subsequently (in 1991), suggesting that one tillage event did not substantially impact soil C content at this site.

In 1991/1992 (for experimental blocks A and B) following 22 years under continuous NT, experimental plots at Sidney, NE were split, with half remaining under NT and the other half undergoing a one-time cultivation treatment consisting of spring moldboard plowing (top 15 cm depth) and disking, chisel plow (twice) and rod weeding (three times) in the fall (Kettler et al., 2000). The cultivation treatment was designed to limit downy brome weed establishment. Soil C stocks were measured to 30 cm depth 5 years after plowing. Significant soil C declines following tillage in the surface (7.5 cm) were offset by increases at depth (7.5–15 cm). Over the deeper soil column (to 30 cm) there were no significant changes in soil C stocks following plowing.

In a related study, Bowman and Anderson (2002) investigated how using tillage to control weedy species within Conservation Reserve Program grasslands impacts soil C stocks (Table 4). Following 4 years of conventional tillage (five annual sweep plow tillage events), soil C stocks declined by nearly 20%. Of the two reduced tillage treatments (one with one annual sweep plow tillage event, the second with two), soil C stocks declined 11–18%. Loss of soil C that had been sequestered with implementation of NT was less, but was still approximately 10%.

The final three studies investigated impacts of conventional tillage of native grass/rangeland on soil C stocks. Bowman et al. (1990) examined soil properties after 3, 20 and 60 years of cultivation at a series of sites in northeastern Colorado. Soil C content, soil carbohydrate content, and mineralizable soil C were determined for soils from native rangeland and three adjacent sites that had been cultivated for different periods of time. Most (64%) of the soil C that was lost after 60 years was lost within the initial 3 years. Further, almost all (an average of 90% for carbohydrate and mineralizable C) of the labile C that was lost over 60 years was lost within the first 3 years. The two labile C pools that Bowman et al. measured accounted for an average of only 13% of soil C (Woods, 1989).

Chan et al. (1995) examined soil C losses following cultivation across a chronosequence near Walgett, north-western New South Wales. Time since initial tillage ranged from 2 to 50 years. Short-term (2 year) soil C losses were on the order of 15% of total soil C

Table 4
Summary of studies examining the short-term impacts of tillage on soil C (Mg C ha^{-1}) stocks in native or CRP[a] systems

Location	Soil/treatment	Initial soil C stocks	Final soil C stocks	Duration between measurements	Sampling depth (cm)	Author
E. Colorado	NT	6.6	6.2	4 years	5	Bowman and Anderson (2002)
E. Colorado	[b]RT	6.6	6.1	4 years	5	Bowman and Anderson (2002)
E. Colorado	RT	6.6	5.6	4 years	5	Bowman and Anderson (2002)
E. Colorado	CT	6.6	5.6	4 years	5	Bowman and Anderson (2002)
E. Colorado		15.7	9.4	3 years	15	Bowman et al. (1990)
E. New South Wales		[c]10.8	9.2	2 years	7.5	Chan et al. (1995)
Planaltina, Brazil	75 kg N ha^{-1}, 109 kg P ha^{-1}	28.5	28.5	5 years	10	Westerhof et al. (1998)
Planaltina, Brazil	150 kg N ha^{-1}, 218 kg P ha^{-1}	28.5	26.33	5 years	10	Westerhof et al. (1998)

[a] Conservation reserve program sties were studied by Bowman and Anderson (2002).
[b] Reduced tillage.
[c] Values in g C kg $soil^{-1}$.

(Table 4). Soil C loss rates were greatest during the first 2 years and subsequently declined over time. Nearly 60% of soil C was lost over 50 years.

Westerhof et al. (1998) collected soil samples from native Cerrado vegetation and from cultivated fields in the Federal District, Brazil. Both plots were located at the EMPRAPA-CIAT Research Institute in Planaltina. The fields had been cultivated for 5 years at the time of collection. Soil C content in the cultivated fields was either unchanged or decreased by 7.6% compared to the native Cerrado (Table 4; Westerhof et al., 1998).

3.3. Were losses with 1 year of tillage within long-duration NT relatively small?

Two studies (VandenBygaart and Kay, 2004; Stockfisch et al., 1999) with a combined total of five observations investigated the impacts of tillage on soil C stocks over a period of 7 months to 1 year. Across those treatments an average decline of 1.8% of soil C stocks was observed. Soil C stocks increased for two of those five observations. Average soil C loss across the three observations that lost soil C was 6.3% with the largest loss (11%) observed at the Lower Saxony site (Stockfisch et al., 1999). Changes in bulk density were not measured at that site, possibly confounding results. More soil C was lost over longer periods of cultivation. Tillage of NT fields led to average annual losses of 2.3% year^{-1} of soil C stocks for studies of up to 5 years in duration. Tillage of native grass/rangeland ranged from slight gains of soil C (7.0% year^{-1}) to substantial losses (13% year^{-1}). Tillage of native soils led to an average of loss rate of 4% year^{-1}.

3.4. Was the amount of soil C lost due to a tillage event proportional to the amount that was gained during NT?

We were only able to identify five observations for which CT, NT and NT-plow data have been published. Soil C loss rates (lost per year%) following tillage were weakly ($r = 0.57$) correlated with the amount of soil C that had been stored in the soil following the adoption of NT. Our confidence in these results is limited due to the very small number of observations.

4. Physical impacts of tillage and mechanisms of C loss

4.1. Physical disturbance and recovery

Soil organic matter is physically protected from decomposition when it is located within aggregates or in pores small enough to limit microbial accessibility and preclude microbial attack (Sollins et al., 1996). The compressive and shearing forces, and soil inversion and mixing, associated with tillage promote the breakdown of aggregate structure, decrease soil bulk density – thus increasing pore space – and alter pore size distribution (Schjonning and Rasmussen, 2000). Tillage frequency, depth and intensity all act to influence how much tillage disturbs soil structure and physical protection of soil C from decomposition.

Textural soil pores – inter-spaces between primary particles – are a function of soil particle size distribution and tend to be relatively stable (Leij et al., 2002). In contrast, structural soil pores – inter-spaces between soil aggregates – are very susceptible to disturbance due to tillage. Structural soil pores tend to be longer and thinner than textural soil pores (Nimmo, 1997). Soil C located with structural pores is thus well-protected from decomposition, but that soil C is vulnerable to loss following tillage (Reicosky et al., 2005). Changes to soil pore structure and out-gassing of CO_2 are observed immediately after tillage (Otten et al., 2000; Jackson et al., 2003) and can be maintained for several days (Otten et al., 2000).

Macroaggregates can be broken up by shearing forces during tillage (Tisdall and Oades, 1982). Tillage also exposes a greater portion of the soil to the freeze–thaw and wet–dry cycles which promote breakdown of macroaggregates (aggregates 53–250 μm) (Rovira and Greacen, 1957; Six et al., 2004). A large portion of physically protected soil C resides in microaggregates located within macroaggregates (aggregates larger than 250 μm) (Blanco-Canqui and Lal, 2004; Denef et al., 2004). By promoting more rapid turnover of macroaggregates, tillage precludes formation of microaggregates within macroaggregates and associated physical protection of soil C (Six et al., 2000). Untilled soils seem to resist soil structural disturbance (Wiermann et al., 2000; Horn, 2004), but disruption of soil structure by repeated tillage seems to produce a soil that is more susceptible to degradation (Blanco-Canqui and Lal, 2004; Taboada et al., 2004).

Laboratory studies have documented that macroaggregate formation and turnover can be rapid (e.g., Angers et al., 1993), with observed turnover times of 40–60 days (Denef et al., 2002; De Gryze et al., 2005). Conventionally tilled soils have a high affinity for added C residues, but conventionally tilled soils have a lower capacity for stabilizing that C over the longer-term (Bossuyt et al., 2002). Addition of labile C to soils promotes rapid recovery of soil structure, while addition of more resistant material sustains soil structural recovery over longer periods of time (Tisdall and Oades, 1982). Soil C within aggregates recovers over time with reduction of tillage intensity, but is still significantly less than for native vegetation (Six et al., 1999). Recovery of soil C lags behind recovery of physical structure, which takes on the order of a decade for macroaggregates and centuries for microaggregates (Jastrow, 1996).

The current aggregate soil C stabilization paradigm suggests that physical protection of soil C occurs across a hierarchy of structures with differential resistance to and recovery from tillage (Six et al., 2004). As is the case for more intensive tillage, it may be that more frequent tillage disrupts successively smaller, more stable structures, and those structures recover more slowly. If tillage-induced losses of soil structure are confined to the largest, least stable physical structures (i.e., macroaggregates), associated soil C losses will be small and recovery will be rapid. The fact that soil slowly recovers the ability to: (1) stabilize added C, (2) to re-form the primary physical structures (microaggregates) that protect C from microbial attack and (3) to resist subsequent disturbances suggest that frequent tillage will significantly reduce the capacity of a soil to physically protect soil C. The aggregate hierarchy model and associated soil C responses to disturbance are supported by the above observations, and are aligned with soil C stock expectations derived from our model exercise.

5. Synthesis

5.1. Model observations and field data

Published studies examining the impacts of infrequent tillage on soil C stocks are limited in number and difficult to interpret. Soil C content seems to decline in the surface soil, but may not decline as much or at all deeper in the profile. Since tillage tends to alter bulk density, bulk density must be measured after tillage to accurately assess changes in soil C stocks. Modeling allowed us to address our main question – how does infrequent tillage impact soil C stocks – with several experiments at four diverse sites. Since the Century model, like other soil organic matter models, embodies the basic, widely accepted soil C cycling paradigms, we feel drawing qualitative conclusions from the results of these model runs is well-justified.

Just two of the nine observations derived from our modeling exercise were amenable to testing with published field data. One of those – that losses within 1 year of tillage are relatively small compared to long-term losses – was largely supported by the data. Of the studies reviewed, none with a duration shorter than 1 year reported significant changes in soil C stocks. Of those with longer duration, two studies found declines in soil C stocks greater than 10% of soil C stocks and eight others found little or no change. These limited data offer some support of our model-based observation that soil C stock declines are small following a tillage event in a long-term NT system.

Our second observation amenable to testing with published data – that soil C losses following tillage are proportional to gains following adoption of NT – was ultimately restricted to evaluation with just five data points. We feel that these data are not fully adequate to address this question. Most of the data on physical responses to tillage are not useful for evaluating whether the impacts of tillage are symmetrical—that is, changes due to tillage are reflective of changes due to cessation of tillage.

Current ideas about physical protection of soil C are aligned with expectations based on model output (Paustian et al., 1997a,b). Other data (Wiermann et al., 2000; Horn, 2004) suggest a non-linear relationship in which the capacity to resist physical disturbance is a function of disturbance; greater disturbance equates with lower capacity to resist disturbance and less disturbance increases the capacity to resist disturbance. These observations are not reflected in model output.

We should make it clear that all of our model runs were carried out at long-term agroecosystem experiment stations that collected data on soil C stocks within the last 15 years (Paul et al., 1997) and many of the experiments are ongoing. So at the starting point for our experimental runs, soil C stocks had accrued soil C following adoption of NT, but two of the three sites were still accruing soil C (Paul et al., 1997). At two of the sites (Hoytville, OH and Manhattan, KS) soil stocks for the model experiment with tillage every other year (NT-2) were equivalent to soil C stocks at the initiation of the model runs.

5.2. Implications for C sequestration

Soil C stocks under infrequent NT can be substantially different than those under continuous NT. If infrequent tillage is not accounted for, inventories could be inaccurate. However, the impacts of ripping to break up compacted soils and cultivating to control weeds reduced soil C stocks by an average of only 4–6%. If those tillage activities are the most common in an otherwise long-term NT system, impacts on soil C stocks will be minimal.

All of the model runs indicate a loss of soil C following even one tillage event. Losses increased as the frequency of tillage increased. Losses were also greater following more intensive tillage. Cultivating and ripping are less disruptive than moldboard plowing, and soil C losses were substantially less for cultivating and ripping. Our results suggest that most of the soil C gains of NT can be realized with NT coupled with biannual cultivating or ripping. Thus, if weed control and compaction are the main impediments to adoption of continuous NT, and they can be controlled with a cultivator or ripper, infrequent NT may sequester nearly as much C as continuous NT systems. Alternatively, if producers continue to experiment with NT, but adoption rates are low and the duration of NT before moldboard plowing is short, infrequent NT soil C sequestration would be substantially less than that for continuous NT. Thus, adoption of NT, duration of NT and type of infrequent tillage will all have a significant impact on C sequestration projections and potentials.

5.3. Research directions

Our model results produced nine responses to infrequent NT that were common to three long-term study sites. Before fully investigating the literature data, we determined that published studies could only be used to assess two of these observations, and those two observations were very data limited as well. Our review of the impacts of tillage on soil physical characteristics shed some light on possible mechanisms of disturbance and recovery, but those observations are qualitative. Open questions thus remain about whether the nine observations we generated with model output are robust and how physical and biological mechanisms control short-term responses to tillage.

Acknowledgement

Support for this work was provided by the Consortium for Agricultural Soil Mitigation of Greenhouse Gases (CASMGS) funded by Cooperative State Research, Education, and Extension Service, U.S. Department of Agriculture, under Agreement No. 2001-38700-11092.

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