Chapter 18
No-Till Systems to Sequester Soil Carbon: Potential and Reality

Kathryn L. Page, Yash P. Dang, Neal W. Menzies, and Ram C. Dalal

Abstract The conversion of soils from conventional till (CT) to no-till (NT) management has been identified as a soil management practice with the potential to increase soil organic carbon (SOC) sequestration and help mitigate global climate change. However, the changes in SOC observed in NT systems have often been variable and dependent on a combination of factors, including climate, cropping system, soil type and crop/soil management. This had led to large variation in the rates of sequestration observed worldwide. In addition, there is concern some studies may have overestimated SOC sequestration rates due to methodological issues, with some authors concluding that once these methodological factors are considered, the potential for NT to sequester C on a worldwide scale may be limited. When the effect of NT on N_2O and CH_4 emissions are also considered, the benefits of NT management to mitigate climate change can be further eroded and NT may even increase net greenhouse gas (GHG) emissions - for example from fine textured and poorly drained soils where NT management increases N_2O emissions. However, the potential for net C sequestration in NT systems is site specific and where site conditions/management favor SOC accumulation and lead to neutral or decreases in N_2O production, significant decreases in global warming potential (GWP) can be observed. This highlights the need to consider the net GWP of NT on a soil type, site or regional basis.

Keywords Soil organic carbon · Carbon sequestration · No-tillage · Global warming potential

---

K. L. Page (✉) · Y. P. Dang · N. W. Menzies · R. C. Dalal
School of Agriculture and Food Sciences, The University of Queensland, St Lucia, QLD, Australia
e-mail: kathryn.page@uq.edu.au; y.dang@uq.edu.au; n.menzies@uq.edu.au; r.dalal@uq.edu.au

Y. P. Dang et al. (eds.), *No-till Farming Systems for Sustainable Agriculture*,
https://doi.org/10.1007/978-3-030-46409-7_18

18.1 Introduction

It has been well documented that the conversion of native vegetation to cultivation and cropping results in significant declines in SOC (Kopittke et al. 2017). This loss occurs due to both the decreases in C input under cropping, and increases in soil mineralization rates due to the disruption of soil aggregates and exposure of previously protected organic matter to microbial decay (Six et al. 2000). However, it has been noted that if this lost C could be replaced and stored (a potential soil C sink) than it would represent a significant opportunity to sequester C from the atmosphere and contribute to the mitigation of global climate change. Changes to a range of agricultural management practices have been identified as having the potential to achieve this, including the conversion of soils from conventional tillage (CT) to no-till (NT) management (Lal 1997; West and Post 2002; Abdalla et al. 2013).

While some studies have reported increases in SOC stocks following conversion from CT to NT (Franzluebbers 2010; Aguilera et al. 2013; Conceição et al. 2013; Francaviglia et al. 2017), others have also reported no change (Angers et al. 1997; Luo et al. 2010) or even decreases (Christopher et al. 2009; Du et al. 2017). These varied results are due to the different climates, soil types and soil/crop management techniques present in different locations, indicating that rates of sequestration are likely to be site specific. Consequently, it is the aim of this chapter to review information on the factors governing SOC sequestration under NT and the estimates of realistic SOC sequestration rates worldwide. The overall impact of NT on greenhouse gas (GHG) reduction given its impact on the emission of CH_4 and N_2O, will also be discussed.

18.2 Measurement of Soil Carbon Sequestration

When assessing SOC sequestration, it is essential to be aware of methodological aspects that can affect the rates observed. For example, significant differences in estimates can occur when stocks are measured over shallow (<0.2–0.3 m) compared to deeper (>0.4 m) soil depths (Angers et al. 1997; Angers and Eriksen-Hamel 2008; Blanco-Canqui and Lal 2008; Christopher et al. 2009). This occurs because NT promotes higher concentrations of C at the soil surface (C stratification due to the accumulation of crop residues in this location), but lower concentrations at depth due to the absence of soil mixing. Differences in root distribution and rhizodeposition between NT and CT systems can also influence SOC distribution (Sisti et al. 2004; Boddey et al. 2010; Piccoli et al. 2016). Where these differences exit, it is important to consider the entire profile so that the different distributions of SOC are adequately sampled (Angers and Eriksen-Hamel 2008; Blanco-Canqui and Lal 2008; Du et al. 2017). Some authors have proposed that soil sampling needs to exceed at least 0.4–0.5 m, and preferably encompass the entire root zone to fully capture differences (Boddey et al. 2010; Gentile et al. 2011; Olson 2013). Although where it is confirmed that differences at greater depths do not exit, sampling within the plough layer alone (e.g. top 0.3 m) may be sufficient (Govaerts et al. 2009).

Due to differences in bulk density between NT and CT systems, it is also desirable to use an equivalent soil mass, rather than a fixed depth, to compare between management types. Sequestration of SOC can be overestimated when using fixed depths due to the higher bulk density often observed in the surface of NT soils (Gentile et al. 2011; Olson 2013; Du et al. 2017). Ideally, rates of sequestration should also be determined by measuring SOC at the beginning and end of an experiment, rather than simply measuring the difference between NT and CT plots with the assumption that the CT treatment did not change over time. This is not always a valid assumption e.g. if all treatments lose C over time, or if erosion occurs from the CT plots (Olson 2013). For those studies that fail to use 'best practice' methodologies it is important to interpret results with care.

18.3 Factors Governing SOC and C Sequestration in No-Till Cropping Systems

A soil's SOC stock is determined by the difference between C inputs (biomass) and losses (erosion, decomposition, leaching), and the effect of NT management on the balance between these processes governs whether it increases or decreases SOC stocks. Various factors can influence the impact of NT systems on this balance, including climate, crop rotation, soil type and crop/soil management, as discussed below.

18.3.1 Climate

Climate can affect SOC sequestration due to its impact on both plant biomass production and decomposition rates (Ogle et al. 2005; Govaerts et al. 2009; Ogle et al. 2012). The potential for SOC sequestration is greater in areas where biomass production is highest, and decomposition rates lowest. For this reason, SOC increases in NT systems are generally observed to be lower in arid and semi-arid v humid locations, due to the reduced biomass production possible in these areas (Six et al. 2004; Ogle et al. 2005; Francaviglia et al. 2017). Higher soil decomposition rates can also decrease the likelihood of C sequestration, with higher C turnover typically observed in tropical v temperate locations due to warm moist conditions (Six et al. 2002). In addition, processes such as freeze/thaw cycles in colder environments and wetting and drying cycles in drier environments can also increase mineralization (Butterly et al. 2010; Edwards 2013), and may reduce the potential for SOC storage in drier and cooler climates (Ogle et al. 2019).

Overall, the effect of climate on C stock change following the introduction of NT will be dependent on the balance achieved between biomass production v decomposition in NT v CT systems. In one meta-analysis, the relative increases in SOC upon conversion to NT (estimated after a 20 year period) for different environments were tropical moist[1] (23% increase) > tropical dry (17% increase) > temperate moist (>16% increase) > temperate dry (>10% increase) (Ogle et al. 2005), and a later study based on data from 178 experimental sites also confirmed that greater SOC storage would occur in tropical moist compared to cool dry climates (Ogle et al. 2019). However, a different meta-analysis concluded that rates of C sequestration were similar between temperate and tropical locations once the whole plough layer was considered (Six et al. 2002). In an analysis conducted across the USA and Canada, it was observed that maximum sequestration occurred under NT when the ratio of mean annual precipitation:mean annual potential evapotranspiration was 1.27 mm mm^{-1} (Franzluebbers and Steiner 2002). At ratios <0.75 no sequestration under NT occurred, probably because low precipitation limited the ability of plants in both systems to fix C, or limited decomposition even when residues were mixed with the soil. At ratios >1.74 there was also little SOC storage potential within NT systems, possibly because abundant moisture at the soil surface and decreased aeration at depth increased decomposition of surface retained *v* buried residues, and/or lower soil temperatures limited yield and thus biomass input (Franzluebbers and Steiner 2002; Gregorich et al. 2005; Ogle et al. 2012).

18.3.2 Crop Types and Crop Rotation

Greater SOC sequestration is more likely to be observed in situations of greater C input (under both CT and NT management). This can be achieved by greater residue return, more intense cropping rotations, and/or the growth of higher biomass crops (Christopher and Lal 2007; Govaerts et al. 2009; Luo et al. 2010; González-Sánchez et al. 2012; Virto et al. 2012; Du et al. 2017). Indeed, where NT is implemented without concurrent increases in biomass input, it is not generally observed to lead to SOC sequestration relative to CT, with long fallow periods in particular associated with an absence of sequestration (Halvorson et al. 2002; Diekow et al. 2005).

In addition, greater SOC sequestration can be observed following increases in biomass input in NT v CT systems (Franzluebbers and Steiner 2002; Govaerts et al. 2009; Conceição et al. 2013). For example, in studies across the USA and Canada it was found that the annualized change in SOC with increasing cropping intensity was greater in NT v CT (Franzluebbers and Steiner 2002). In some instances, especially in drier locations, the introduction of NT can also increase the ability to intensify cropping (and potentially increase biomass input), due to increased soil moisture

---

[1] Tropical = mean annual temperature of >20 °C; dry = mean annual rainfall of <1000 mm

and the faster turnaround time between harvest and planting in the absence of cultivation (Govaerts et al. 2009).

18.3.2.1 Crop Type

The type of crop grown can influence SOC sequestration under NT. Different crops may have different effects on the quantity, quality, and periodicity of C inputs and can modify the soil in different ways (e.g. rates of water extraction, nutrient use), which can influence mineralization rates and the growth of subsequent crops (Huggins et al. 2007). For example, crop rotations that return greater amounts of residue to the soil, and in particular have greater root C additions, are often associated with greater SOC stock in NT systems (Huggins et al. 2007; dos Santos et al. 2011; Conceição et al. 2013). Greater biomass production is also often associated with greater water use, which can decrease soil water contents and lead to reductions in mineralization rates (Havlin et al. 1990). However, different crops may also respond differently to the changed growing conditions under NT v CT and where NT has a negative impact on yield (and hence biomass input), this may reduce sequestration capacity. For example, the ability of NT to sequester C in western but not eastern regions of Canada has partly been attributed to the fact that NT had limited or negative effects on yields in the east (maize dominated), but yield advantages in the west (wheat dominated) (Gregorich et al. 2005).

Crop residue quality may also influence C sequestration. For example, a recent analysis of the literature suggested that the increase in microbial biomass and the production of microbial residues associated with addition of high-quality litter (low C:N, lignin) can increase micro- and macro-aggregate formation and increase the protection of particulate organic material (Castellano et al. 2015). Thus, in two identical soils, the soil where high quality residues are added should reach its equilibrium C content more quickly (Castellano et al. 2015). Indeed, in some situations the addition of low quality residue to the soil can lead to overall decreases in SOC as soil microorganisms increase the mineralization of existing SOM to obtain the nutrients they require for growth (Fontaine et al. 2004; Richardson et al. 2014).

18.3.3 Soil Type

While climate can affect the balance between production and decomposition, soil properties determine the level of C sequestration possible within a given climate (Palm et al. 2014). A number of aspects of soil type can influence SOC sequestration, including texture, SOC content and topography.

18.3.3.1 Texture

Adsorption onto the surfaces of clay minerals and metal oxides is one of the primary ways SOC can resist decomposition in soil (Barré et al. 2014). The clay fraction is also involved in the formation of soil aggregates, which protect SOC from biodegradation (Barré et al. 2014). Consequently, soils with higher clay contents have a greater ability to retain SOC (Lal 1997; Liang et al. 2002; Six et al. 2002). In sandy soils, any increases in SOC tend to accumulate in the particulate organic C (POC) fraction, which has a higher turnover time and is more susceptible to loss following disturbance (Feller and Beare 1997; Castellano et al. 2015).

In accordance with this, studies in the Canadian prairies have observed a linear relationship between the amount of SOC sequestered following conversion to NT and soil clay content (between ~27–63% clay content) (Liang et al. 2002). Similarly, other authors have observed that reduced intensity of tillage has little (Chivenge et al. 2007) or reduced (Nyamangara et al. 2014) impact on SOC storage in sandy soils, but does lead to higher SOC concentrations in soils with higher clay content (Chivenge et al. 2007; Nyamangara et al. 2014). Although it should be noted that some meta-analyses have also observed greater SOC sequestration following adoption of NT in coarse compared to fine textured soils (Du et al. 2017), while others observe little impact of texture (Puget and Lal 2005). Analysis of the SOC sequestration rates possible in different climatic regions on either heavy (loamy, silty, clayey) or light (sandy) textured soils based on data from 178 experimental sites suggests that the amount of SOC likely to be sequestered in heavy and light textured soils may vary depending on climate (Ogle et al. 2019). For example, this analysis found that there would be a net SOC increase in the sandy soils of tropical moist, tropical dry, warm temperate moist and cool temperate moist climates following the introduction of NT, but that in heavier textured soils, increases were only likely in soils in tropical moist and warm and cool temperate moist climates. The reason for these differences could not be determined from this study, but were likely related to differences in C input, decomposition rates and physical protection of C in the soil in different regions (Ogle et al. 2019).

Soil mineralogy is also likely to impact SOC sequestration, although the effect of different minerals are often contradictory, and it is not currently clear how mineralogy affects the magnitude of soil sequestration (Barré et al. 2014). However, some analyses have suggested that soils dominated by 1:1 clay minerals are likely to have reduced capacity to stabilize C due to their reduced CEC compared to 2:1 minerals (Six et al. 2002). Moreover, protection within soil aggregates is not as important a mechanism for SOC protection in soils dominated by 1:1 minerals (Six et al. 2002; Zotarelli et al. 2005).

18.3.3.2 Baseline SOC Content

The amount of SOC present in a soil at the time NT is introduced will have a large impact on the amount of C that can subsequently be sequestered. A soil that is highly depleted in SOC following years of cultivation will have greater potential to sequester C compared to a site where C concentrations are already high and near the equilibrium content that can be achieved under NT in that environment (Steinbach and Alvarez 2006). Sites that already have high background concentrations of SOC tend not to show any increase in SOC stocks, or even lose SOC, following the introduction of NT management (VandenBygaart et al. 2002; Govaerts et al. 2009).

18.3.3.3 Topography

Topography can affect SOC sequestration, largely due to its influence on soil erosion. Areas that have previously experienced erosion typically have lower SOC stocks due to the preferential removal of SOC (Lal 2003), and thus have greater potential to sequester SOC following the introduction of NT. This effect is likely to be greatest in topographical positions most susceptible to erosion i.e. sloping areas (Govaerts et al. 2009). For example, one study that examined changes in SOC stocks following conversion to NT observed that areas with low SOC stocks due to past erosion (convex positions) had a greater capacity to sequester SOC compared to depositional areas (concave and toeslope positions). On the other hand, depositional areas often lose SOC following conversion to NT, partly due to reductions in C addition from upslope via erosion (VandenBygaart et al. 2002).

18.3.4 Soil and Crop Management

18.3.4.1 Tillage Type

In some instances, the type of tillage conducted is believed to have an impact on the change in SOC stocks following conversion to NT. For example, in areas where full inversion tillage is carried out, residues may be buried in a region where poor soil aeration can limit decomposition (relative to the soil surface), particularly under cool, moist climatic conditions (Gregorich et al. 2005; Christopher et al. 2009). Where this is the case, SOC stocks can be similar or even decline following conversion to NT (Gregorich et al. 2005; Blanco-Canqui and Lal 2008; Christopher et al. 2009). Conversely, where shallower, non-inversion tillage is conducted, and such burial does not occur, overall positive gains following the introduction of NT are more commonly observed (Gregorich et al. 2005). However, it should be noted that when tillage type is considered on a broader scale and over a range of climate types, tillage intensity can also be found to have limited impact on SOC sequestration (Steinbach and Alvarez 2006; Haddaway et al. 2017; Ogle et al. 2019) and further studies are required that include all tillage types in the same experiment to fully evaluate the differences between inversion and non-inversion tillage (Ogle et al. 2019).

18.3.4.2 Residue Management

Crop residues can be defined as plant root or top material remaining in or on the soil after harvest. Increasing residue input by either reducing removal (ceasing burning or grazing), or by increasing crop production, can potentially lead to increases in SOC storage (Duiker and Lal 1999, 2002; Liu et al. 2014; Abdalla et al. 2016). Indeed, linear increases in SOC stocks are often observed with increasing rates of residue addition (Duiker and Lal 2002; Virto et al. 2012; Liu et al. 2014), with the proportion of C retained greater in NT v CT systems (Duiker and Lal 1999, 2002).

In situations where there is limited residue return, either due to removal or due to poor crop biomass production, SOC sequestration is generally not observed (Dendooven et al. 2012; Virto et al. 2012; Palm et al. 2014). This can be a particular problem in more arid regions, where competition for residue can be high (e.g. from grazing animals) (Chivenge et al. 2007; Govaerts et al. 2009; Palm et al. 2014). Increasing residue input by increasing crop production can be a challenge in these areas, especially in small holder operations where the capacity of farmers to increase soil fertility is limited (Chivenge et al. 2007). Thus, in such circumstances, the conversion to NT may have little impact on SOC storage. Situations where the characteristics of the NT system lead to reduced yields (e.g. lower soil temperatures, increases in disease) can also lead to decreases in residue inputs and lower or no SOC sequestration (Yang et al. 2013).

18.3.4.3 Soil Nutrient Management

The addition of nutrients via fertilizers can influence soil SOC sequestration due to their impact on both decomposition rates and the production of biomass. Nutrient addition, particularly N, will often increase plant biomass production, leading to greater C inputs into the soil and greater SOC storage (Alvarez 2005; Christopher and Lal 2007; Macdonald et al. 2018). No increases in SOC storage following N addition have also been observed, although this tends to occur in areas where SOC stocks are already high and there is limited capacity for further increases (Christopher and Lal 2007). Nitrogen addition can also affect SOC decomposition, with both increases, and decreases in SOC storage observed following N addition - with the direction of change largely dependent on the makeup of organic materials, the microbial community, and pre-existing N availability (Neff et al. 2002; Macdonald et al. 2018).

While it is well known that nutrient addition can affect SOC sequestration, less information is available on the different effects in NT v CT soils. In a study of sites in Canada and the USA, for example, it was observed that while the amount of SOC stored under NT and CT was greater with increasing rate of N fertiliser application, there was no significant difference in the rate of change in SOC with NT v CT (Franzluebbers and Steiner 2002). However, other studies have observed that SOC sequestration is unlikely in NT unless there are sufficient nutrients present to facilitate the processing of organic material into stable forms of C (Lal et al. 2007; Kirkby et al. 2014), indicating that SOC sequestration following conversion to NT is likely to be low in nutrient limited environments.

18.3.4.4 Time

The time NT management has been in place can also influence the rate of SOC sequestration. Following the introduction of NT, sequestration will initially be high and then gradually approach a new steady state as the soil reaches the maximum C content possible under the new management. For example, a meta-analysis conducted in Spain observed that those studies conducted for <10 years had a sequestration rate of 0.85 Mg ha^{-1} year^{-1}, while those that had been conducted for >10 years averaged 0.16–0.4 Mg ha^{-1} year^{-1} (González-Sánchez et al. 2012). Estimates of the time taken to reach steady state include 15–20 years (West and Post 2002) and 25–30 years (Alvarez 2005). Some studies have also noted an initial decrease in SOC under NT v CT, particularly in drier temperate climates, although after 5–10 years accumulations are generally observed (Six et al. 2002; Six et al. 2004; Steinbach and Alvarez 2006). This initial decrease has been attributed to the slower decomposition and reduced soil mixing with residues on the soil surface (Six et al. 2002).

18.4 Estimates of Realistic SOC Sequestration

Numerous meta-analyses have been conducted to estimate the likely magnitude of SOC sequestration worldwide (Table 18.1). These studies report average sequestration rates ranging from −0.15 Mg ha^{-1} year^{-1} in areas such as the midwestern USA (Christopher et al. 2009) to +0.93 Mg ha^{-1} year^{-1} in tropical Brazil (Bernoux et al. 2006) (Table 18.1). However, it should be noted that the studies included in these analyses have often not sampled the whole soil profile (<0.4 m depth), have not compared SOC stocks on an equivalent mass basis, and include studies that have only been conducted for relatively short periods of time (<5 years). Most studies are also based on comparisons between treatments at the end of an experimental period, rather than comparison of SOC stocks under NT at the beginning and end of an experiment. Consequently, the uncertainty surrounding these estimates is high and some authors have even concluded that worldwide, the potential of NT to sequester SOC is limited once this uncertainty is taken into account (Powlson et al. 2014; Powlson et al. 2016).

Table 18.1 Worldwide estimates of carbon sequestration rates following conversion to NT

Study location	Sequestration rate (Mg ha^{-1} $year^{-1}$)	Reference
Midwestern USA	−0.15	Christopher et al. (2009)
Central USA	+0.4	Johnson et al. (2005)
Southeastern USA	+0.45	Franzluebbers (2010)
Canada	nsd	Angers et al. (1997)
Canada	West:+0.32	VandenBygaart et al. (2003)
	East: −7	
Mediterranean climatic zones.	+0.44	Aguilera et al. (2013)
Mediterranean regions	+0.3	Francaviglia et al. (2017)
Spain	+0.51	González-Sánchez et al. (2012)
Tropical Brazil	+0.35	Bayer et al. (2006)
Subtropical Brazil	+0.48	
Tropical Brazil	+0.93	Bernoux et al. (2006)
Subtropical Brazil	+0.54	
Argentine Pampas	0.4 years: 0	Steinbach and Alvarez (2006)
	4–9 years: +0.46	
	>10 years: 0	
China	+0.25	Du et al. (2017)
Sub-Saharan Africa	+0.37	Powlson et al. (2016)
Indo-Gangetic Plains	+0.54	
African continent	+0.14	Gonzalez-Sanchez et al. (2019)
Worldwide	+0.33	Kirkby et al. (2016), Six et al. (2002), and Puget and Lal (2005)
Worldwide	nsd	Luo et al. (2010)
Worldwide	+0.26	Alvarez (2005)
Worldwide	Tropical +0.86	Mangalassery et al. (2015)
	Temperate +0.17	
	World: +0.52	
Worldwide	+0.48	West and Post (2002)

However, several broad trends can be identified. In environments where rates of crop production are inherently low due to climate or soil fertility factors, and where farmers have insufficient economic resources to ensure optimum crop production, the conversion to NT is unlikely to lead to significant SOC sequestration (Cheesman et al. 2016; Powlson et al. 2016). Similarly, in environments where CT increases SOC storage relative to NT due to the burial of residues in zones with lower rates of decomposition, NT is also unlikely to sequester C, and may even lead to SOC loss relative to CT (Christopher et al. 2009). However, in regions where soil and climatic conditions are favorable for biomass production and where NT does not negatively impact yield, then moderate rates of sequestration may occur. However, the large range in the sequestration rates observed indicates that the ability of NT to sequester SOC is likely to be highly site specific.

In addition, current estimates of SOC sequestration are generally based on data from experimental research plots where growing conditions are carefully and consistently controlled. These experimental conditions may differ substantially from conditions in actual farmer's fields, where decisions surrounding management are taken according to multiple economic and practical considerations, and there thus may be considerable differences between the SOC sequestration observed by scientists compared to that achieved by farmers. To achieve SOC sequestration in the long-term, it will also be necessary for farmers to maintain NT management over an extended period. Any decision to convert back to CT may lead to the re-emission of sequestered C, leading to further uncertainty regarding the level of SOC sequestration that can be realistically achieved.

It is also important to consider that while the potential for SOC sequestration may exist in certain regions, whether it is likely to be adopted by farmers will depend on a range of socio-economic factors. For example, the adoption of NT in some developing regions can be limited by lack of access to specialized planting equipment and the increased time and labor requirements where herbicides are unavailable (Giller et al. 2009). Where NT management leads to yield reductions, the prospect of its adoption is also unrealistic.

18.5 Perspectives

When considering the benefits of SOC sequestration with NT management from a climate change perspective, it is also essential to conduct a full lifecycle assessment. This includes assessment of changes in CH_4 and N_2O emissions, and an account of CO_2 emissions from agricultural operations (e.g. fuel usage).

It is well accepted that NT uses less fuel than CT management. For example, fossil fuel emissions from tillage and herbicide production/application were estimated to be 53 kg C ha^{-1} $year^{-1}$ for intensive tillage (moldboard plough) 45.1 kg C ha^{-1} $year^{-1}$ for minimum tillage (chisel and disc plough) and only 29 kg C ha^{-1} $year^{-1}$ for NT (Kern and Johnson 1993). However, the impact on CH_4 and N_2O emissions can be more variable.

18.5.1 CH_4 and N_2O Emissions

The impact of NT on N_2O emissions is governed by the interaction between soil and climate factors that affect soil aeration and there is potential for NT to both increase or decrease N_2O emissions. Where NT leads to increased bulk density and higher soil water contents, greater microbial biomass, and higher concentrations of labile SOC, there is potential for greater rates of nitrification/denitrification and N_2O emissions (Palm et al. 2014). Conversely, where NT leads to lower soil temperatures and/or improvements in soil structure and better drainage, denitrification may be lower and N_2O emissions may decrease (Govaerts et al. 2009; Palm et al. 2014).

In line with this, reviews of studies worldwide have reported increases, decreases, and no change in N_2O emissions from NT v CT systems (Six et al. 2002; Steinbach and Alvarez 2006; Rochette 2008; van Kessel et al. 2013; Palm et al. 2014). However, one review concluded that greater N_2O emission were most likely where NT was practiced on fine textured and poorly drained soils, whereas in well drained soils differences between tillage systems were relatively small (Rochette 2008). It has also been noted that N_2O emissions from NT soils decrease over time (Six et al. 2002; Six et al. 2004; van Kessel et al. 2013; Palm et al. 2014; Mangalassery et al. 2015). For example, the results of a meta-analysis indicated that in both humid and dry temperate environments, N_2O emissions were higher in NT v CT systems during the first 10 year period, however, after 20 years N_2O emissions were lower under NT in humid temperate climates and similar regardless of tillage in dry temperate climates (Six et al. 2004). Similarly, in a second meta-analysis, NT significantly reduced N_2O emissions in experiments >10 years, especially in dry climates (van Kessel et al. 2013). It has been hypothesized that the decrease in N_2O emissions is likely due to increases in SOC and associated improvements in soil structure over time, which decreases the tendency for the formation of anaerobic conditions conducive to N_2O production (Six et al. 2004; van Kessel et al. 2013). However, overall, due to the large spatial and temporal variability in N_2O emissions, and a paucity of measurements from some climatic regions (e.g. tropical locations) worldwide estimates of emissions under NT v CT systems are currently uncertain (Six et al. 2002; Palm et al. 2014; Mangalassery et al. 2015).

Fewer studies have been conducted into the effect of NT on CH_4, however, while results are variable, most studies in aerated systems observe either no difference or greater CH_4 uptake in NT systems (Six et al. 2002; Six et al. 2004; Abdalla et al. 2013; Mangalassery et al. 2015). This has been attributed to the greater aggregate stability and porosity in NT soils that facilitates the diffusion of CH_4 into oxidizing zones, and a greater abundance of methanotrophic bacteria (Six et al. 2002; Abdalla et al. 2013; Mangalassery et al. 2015). In rice paddy systems, increases in residue retention are known to increase CH_4 emissions due to the increases in available C (Palm et al. 2014), although where residue inputs are kept constant between tillage systems, large reductions in CH_4 emissions have been observed with NT, and attributed to slower decomposition rates (Abdalla et al. 2013).

18.5.2 Net Effects

Fewer studies have examined the net impact of NT on GHG emissions, and large uncertainty still exists around emissions estimates. For example, one global meta-analysis concluded that NT would have positive impact on net GWP in a range of soils and climatic regions (Sainju 2016). Conversely, other authors have concluded that, in some environments, NT may have only a small or even negative impact on net GHG emissions due to increases in N_2O emissions (Gregorich et al. 2005; Steinbach and Alvarez 2006). Other analyses still have concluded that greater GHG emissions are likely under NT in the first 5–10 years of adoption, but after 20 years net GWP is negative in humid temperate areas, and weakly negative in dry temperate areas as N_2O emissions decline (Six et al. 2004).

Despite the variability in results, it is clear that in some individual instances NT can have significant benefits for net GHG production. For example, one long-term (19 years) Mexican study found that NT with residue retention led to a net GWP of −6.27 Mg CO_2 ha^{-1} $year^{-1}$, while CT with residue retention led to net emissions of 1.89 Mg CO_2 ha^{-1} $year^{-1}$ (Dendooven et al. 2012). Similarly, work conducted in India by Parihar et al. (2018) observed that net GWP was ~18% lower under NT compared to CT due to higher SOC sequestration and lower N_2O emissions. In a long-term Australian trial (>40 years) net GHG emission were over 50% lower in fertilized (urea) NT systems compared to fertilized CT systems where cultivation and stubble burning were conducted, largely due to the greater preservation of SOC, removal of emissions associated with stubble burning and decreased fuel usage (Wang and Dalal 2015).

However, even in those instances where NT results in reduced GHG emission, as the sites approach their equilibrium C content, their ability to further sequester C, or slow C loss, will decline and net GHG emissions will be a function of reductions in CO_2 emissions due to fuel savings, combined with the net impact on N_2O emissions and CH_4 emissions/consumption. Given the likely large impact of N_2O emissions on long-term net GWP, the efficient management of N fertilizers is clearly important to maximize any potential decreases in GHG in NT systems. In addition, the large variation in SOC sequestration and emission of other GHGs depending on climate, soil type and management suggest that it is necessary to consider the net effect of NT on total GWP on a site by site or region by region basis.

References

Abdalla M, Osborne B, Lanigan G, Forristal D, Williams M, Pea S (2013) Conservation tillage systems: a review of its consequences for greenhouse gas emissions. Soil Use Manag 29:199–209

Abdalla K, Chivenge P, Ciais P, Chaplot V (2016) No-tillage lessens soil CO_2 emissions the most under arid and sandy soil conditions: results from a meta-analysis. Biogeosciences 13(12):3619–3633

Aguilera E, Lassaletta L, Gattinger A, Gimeno BS (2013) Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. Agric Ecosyst Environ 168:25–36

Alvarez R (2005) A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. Soil Use Manag 21:38–52

Angers DA, Eriksen-Hamel NS (2008) Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. Soil Sci Soc Am J 72(5):1370–1374

Angers DA, Bolinder MA, Carter MR, Gregorich EG, Drury CF, Liang BC, Voroney RP, Simard RR, Donald RG, Beyaert RP, Martel J (1997) Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. Soil Till Res 41(3):191–201

Barré P, Fernandez-Ugalde O, Virto I, Velde B, Chenu C (2014) Impact of phyllosilicate mineralogy on organic carbon stabilization in soils: incomplete knowledge and exciting prospects. Geoderma 235–236:382–395

Bayer C, Martin-Neto L, Mielniczuk J, Pavinato A, Dieckow J (2006) Carbon sequestration in two Brazilian Cerrado soils under no-till. Soil Till Res 86(2):237–245

Bernoux M, Cerri CC, Cerri CEP, Siqueira-Neto M, Metay A, Perrin AS, Scopel E, Razafimbelo T, Blavet D, Piccolo MD, Pavei M, Milne E (2006) Cropping systems, carbon sequestration and erosion in Brazil, a review. Agron Sustain Dev 26:1–8

Blanco-Canqui H, Lal R (2008) No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Sci Soc Am J 72(3):693–701

Boddey RM, Jantalia CP, Conceicao PC, Zanatta JA, Bayer C, Mielniczuk J, Dieckow J, Dos Santos HP, Denardin JE, Aita C, Giacomini SJ, Alves BJR, Urquiaga S (2010) Carbon accumulation at depth in ferralsols under zero-till subtropical agriculture. Glob Chang Bio 16:784–795

Butterly CR, Marschner P, McNeill AM, Baldock JA (2010) Rewetting CO2 pulses in Australian agricultural soils and the influence of soil properties. Bio Fert Soils 46(7):739–753. https://doi.org/10.1007/s00374-010-0481-9

Castellano MJ, Muller KE, Olk DC, Sawyer JE, Six J (2015) Integrating plant litter quality, soil organic matter stabilization, and the carbon saturation concept. Glob Chang Bio 21:3200–3209

Cheesman S, Thierfelder C, Eash NS, Kassie GT, Frossard E (2016) Soil carbon stocks in conservation agriculture systems of Southern Africa. Soil Till Res 156:99–109

Chivenge PP, Murwira HK, Giller KE, Mapfumo P, Six J (2007) Long-term impact of reduced tillage and residue management on soil carbon stabilization: implications for conservation agriculture on contrasting soils. Soil Till Res 94(2):328–337

Christopher SF, Lal R (2007) Nitrogen management affects carbon sequestration in North American cropland soils. Crit Rev Plant Sci 26(1):45–64

Christopher SF, Lal R, Mishra U (2009) Regional study of no-till effects on carbon sequestration in the Midwestern United States. Soil Sci Soc Am J 73(1):207–216

Conceição PC, Dieckow J, Bayer C (2013) Combined role of no-tillage and cropping systems in soil carbon stocks and stabilization. Soil Till Res 129:40–47

Dendooven L, Patiño-Zúñiga L, Verhulst N, Luna-Guido M, Marsch R, Govaerts B (2012) Global warming potential of agricultural systems with contrasting tillage and residue management in the central highlands of Mexico. Agric Ecosyst Environ 152:50–58

Diekow J, Mielniczuk J, Knicker H, Bayer C, Dick DP, Kögel-Knabner I (2005) Soil C and N stocks as affected by cropping systems and nitrogen fertilisation in a southern Brazil Acrisol managed under no-tillage for 17 years. Soil Till Res 81(1):87–95

dos Santos NZ, Dieckow J, Bayer C, Molin R, Favaretto N, Pauletti V, Piva JT (2011) Forages, cover crops and related shoot and root additions in no-till rotations to C sequestration in a subtropical Ferralsol. Soil Till Res 111(2):208–218

Du Z, Angers DA, Ren T, Zhang Q, Li G (2017) The effect of no-till on organic C storage in Chinese soils should not be overemphasized: a meta-analysis. Agric Ecosyst Environ 236:1–11

Duiker SW, Lal R (1999) Crop residue and tillage effects on carbon sequestration in a Luvisol in Central Ohio. Soil Till Res 52:73–81

Duiker SW, Lal R (2002) Mulch rate and tillage effects on carbon sequestration and CO_2 flux in an Alfisol in Central Ohio. In: Kimble JM, Lal R, Follet RF (eds) Agricultural practices and policies for carbon sequestration in soil. Lewis Publishers, Boca Raton, pp 53–61

Edwards LM (2013) The effects of soil freeze–thaw on soil aggregate breakdown and concomitant sediment flow in Prince Edward Island: a review. Can J Soil Sci 93(4):459–472. https://doi.org/10.4141/cjss2012-059

Feller C, Beare MH (1997) Physical control of soil organic matter dynamics in the tropics. Geoderma 79(1):69–116

Fontaine S, Bardoux G, Abbadie L, Mariotti A (2004) Carbon input may decrease soil carbon content. Ecol Lett 7:314–320

Francaviglia R, Di Bene C, Farina R, Salvati L (2017) Soil organic carbon sequestration and tillage systems in the Mediterranean Basin: a data mining approach. Nut Cycling Agroecos 107(1):125–137

Franzluebbers AJ (2010) Achieving soil organic carbon sequestration with conservation agricultural Systems in the Southeastern United States. Soil Sci Soc Am J 74(2):347–357

Franzluebbers AJ, Steiner JL (2002) Climatic influences on soil organic carbon storage with no tillage. In: Kimble JM, Lal R, Follett RF (eds) Agricultural practices and policies for carbon sequestration in soil. Lewis Publishers, Boca Raton, pp 71–86

Gentile R, Vanlauwe B, Six J (2011) Litter quality impacts short- but not long-term soil carbon dynamics in soil aggregate fractions. Ecol Appl 21:965–703

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crop Res 114(1):23–34

González-Sánchez EJ, Ordóñez-Fernández R, Carbonell-Bojollo R, Veroz-González O, Gil-Ribes JA (2012) Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture. Soil Till Res 122:52–60

Gonzalez-Sanchez EJ, Veroz-Gonzalez O, Conway G, Moreno-Garcia M, Kassam A, Mkomwa S, Ordoñez-Fernandez R, Triviño-Tarradas P, Carbonell-Bojollo R (2019) Meta-analysis on carbon sequestration through conservation agriculture in Africa. Soil Till Res 190:22–30. https://doi.org/10.1016/j.still.2019.02.020

Govaerts B, Verhulst N, Castellanos-Navarrete A, Sayre KD, Dixon J, Dendooven L (2009) Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Crit Rev Plant Sci 28(3):97–122

Gregorich EG, Rochette P, VandenBygaart AJ, Angers DA (2005) Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. Soil Till Res 83(1):53–72

Haddaway NR, Hedlund K, Jackson LE, Kätterer T, Lugato E, Thomsen IK, Jørgensen HB, Isberg P-E (2017) How does tillage intensity affect soil organic carbon? A systematic review. Environ Evid 6(1):30. https://doi.org/10.1186/s13750-017-0108-9

Halvorson AD, Wienhold BJ, Black AL (2002) Tillage, nitrogen, and cropping system effects on soil carbon sequestration Contribution from USDA-ARS. Soil Sci Soc Am J 66(3):906–912

Havlin JL, Kissel DE, Maddux LD, Claassen MM, Long JH (1990) Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci Soc Am J 54(2):448–452

Huggins DR, Allmaras RR, Clapp CE, Lamb JA, Randall GW (2007) Corn-soybean sequence and tillage effects on soil carbon dynamics and storage. Soil Sci Soc Am J 71(1):145–154

Johnson JMF, Reicosky DC, Allmaras RR, Sauer TJ, Venterea RT, Dell CJ (2005) Greenhouse gas contributions and mitigation potential of agriculture in the Central USA. Soil Till Res 83(1):73–94

Kern JS, Johnson MG (1993) Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Sci Soc Am J 57(1):200–210

Kirkby CA, Richardson AE, Wade LJ, Passioura JB, Batten GD, Blanchard C, Kirkegaard JA (2014) Nutrient availability limits carbon sequestration in arable soils. Soil Bio Biochem 68:402–409

Kirkby CA, Richardson AE, Wade LJ, Conyers M, Kirkegaard JA (2016) Inorganic nutrients increase humification efficiency and C-sequestration in an annually cropped soil. PLoS One 11(5):e0153698

Kopittke PM, Dalal RC, Finn D, Menzies NW (2017) Global changes in soil stocks of carbon, nitrogen, phosphorus, and sulphur as influenced by long-term agricultural production. Glob Chang Bio 23(6):2509–2519

Lal R (1997) Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO2-enrichment. Soil Till Res 43(1):81–107

Lal R (2003) Soil erosion and the global carbon budget. Environ Int 29(4):437–450

Lal R, Follett F, Stewart BA, Kimble JM (2007) Soil carbon sequestration to mitigate climate change and advance food security. Soil Sci 172:943–956

Liang BC, McConkey BG, Campbell CA, Johnston AM, Moulin AP (2002) Short-term crop rotation and tillage effects on soil organic carbon on the Canadian prarires. In: Kimble JM, Lal R, Follet RF (eds) Agricultural practices and policies for carbon sequestration in soil. Lewis Publishers, Boca Raton, pp 287–293

Liu C, Lu M, Cui J, Li B, Fang C (2014) Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. Glob Chang Bio 20:1366–1381

Luo Z, Wang E, Sun OJ (2010) Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric Ecosyst Environ 139:244–231

Macdonald CA, Delgado-Baquerizo M, Reay DS, Hicks LC, Singh BK (2018) Chapter 6 – soil nutrients and soil carbon storage: modulators and mechanisms. In: Singh BK (ed) Soil carbon storage. Academic, London, pp 167–205

Mangalassery S, SjÖGersten S, Sparkes DL, Mooney SJ (2015) Examining the potential for climate change mitigation from zero tillage. J Agric Sci 153(7):1151–1173

Neff JC, Townsend AR, Gleixner G, Lehman SJ, Turnbull J, Bowman WD (2002) Variable effects of nitrogen additions on the stability and turnover of soil carbon. Nature 419:915–917

Nyamangara J, Marondedze A, Masvaya EN, Mawodza T, Nyawasha R, Nyengerai K, Tirivavi R, Nyamugafata P (2014) Influence of basinbased conservation agriculture on selected soil quality parameters under smallholder farming in Zimbabwe. Soil Use Manag 30:550–559

Ogle SM, Breidt FJ, Paustian K (2005) Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochem 72(1):87–121

Ogle SM, Swan A, Paustian K (2012) No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agric Ecosyst Environ 149:37–49

Ogle S, Alsaker C, Baldock J, Bernoux M, Breidt F, McConkey BG, Regina K, Vazquez Amabile G (2019) Climate and soil characteristics determine where no-till Management can store carbon in soils and mitigate greenhouse gas emissions. Sci Rep 9. https://doi.org/10.1038/s41598-019-47861-7

Olson KR (2013) Soil organic carbon sequestration, storage, retention and loss in U.S. croplands: issues paper for protocol development. Geoderma 195–196:201–206

Palm C, Blanco-Canqui H, DeClerck F, Gatere L, Grace P (2014) Conservation agriculture and ecosystem services: an overview. Agric Ecosyst Environ 187:87–105

Parihar CM, Parihar MD, Sapkota TB, Nanwal RK, Singh AK, Jat SL, Nayak HS, Mahla DM, Singh LK, Kakraliya SK, Stirling CM, Jat ML (2018) Long-term impact of conservation agriculture and diversified maize rotations on carbon pools and stocks, mineral nitrogen fractions and nitrous oxide fluxes in inceptisol of India. Sci Tot Environ 640–641:1382–1392

Piccoli I, Chiarini F, Carletti P, Furlan L, Lazzaro B, Nardi S, Berti A, Sartori L, Dalconi MC, Morari F (2016) Disentangling the effects of conservation agriculture practices on the vertical distribution of soil organic carbon. Evidence of poor carbon sequestration in North- Eastern Italy. Agric Ecosyst Environ 230:68–78

Powlson DS, Stirling CM, Jat ML, Gerard BG, Palm CA, Sanchez PA, Cassman KG (2014) Limited potential of no-till agriculture for climate change mitigation. Nat Clim Chang 4:678. https://doi.org/10.1038/nclimate2292

Powlson DS, Stirling CM, Thierfelder C, White RP, Jat ML (2016) Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric Ecosyst Environ 220:164–174

Puget P, Lal R (2005) Soil organic carbon and nitrogen in a Mollisol in Central Ohio as affected by tillage and land use. Soil Till Res 80(1):201–213

Richardson AE, Kirkby CA, Banerjee S, Kirkegaard JA (2014) The inorganic nutrient cost of building soil carbon. Carbon Manage 5(3):265–268. https://doi.org/10.1080/17583004.2014.923226

Rochette P (2008) No-till only increases N2O emissions in poorly-aerated soils. Soil Till Res 101(1):97–100

Sainju UM (2016) A global meta-analysis on the impact of management practices on net global warming potential and greenhouse gas intensity from cropland soils. PLoS One 11(2):e0148527

Sisti CPJ, dos Santos HP, Kohhann R, Alves BJR, Urquiaga S, Boddey RM (2004) Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. Soil Till Res 76(1):39–58

Six J, Elliott ET, Paustian K (2000) Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Bio Biochem 32(14):2099–2103

Six J, Feller C, Denef K, Ogle S, De Moraes Sa JC, Albrecht A (2002) Soil organic matter, biota and aggregation in temperate and tropical soils – effects of no-tillage. Agronomie 22(7–8):755–775

Six J, Ogle SM, Breidt FJ, Conant RT, Mosier AR, Paustian K (2004) The potential to mitigate global warming with no tillage management is only realized when practiced in the long term. Glob Chang Bio 10:155–160

Steinbach HS, Alvarez R (2006) Changes in soil organic carbon contents and nitrous oxide emissions after introduction of no-till in Pampean Agroecosystems. J Environ Qual 35:3–13

van Kessel C, Venterea R, Six J, Adviento-Borbe MA, van Groenigen KJ (2013) Climate, duraction, and N placement determine N2O emissions in reduced tillage systems: a meta-analysis. Glob Chang Bio 19:33–44

VandenBygaart AJ, Yang XM, Kay BD, Aspinall JD (2002) Variability in carbon sequestration potential in no-till soil landscapes of southern Ontario. Soil Till Res 65(2):231–241

VandenBygaart AJ, Gregorich EG, Angers DA (2003) Influence of agricultural management on soil organic carbon: a compendium and assessment of Canadian studies. Can J Soil Sci 83(4):363–380

Virto I, Barré P, Burlot A, Chenu C (2012) Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems. Biogeochem 108(1):17–26

Wang W, Dalal RC (2015) Nitrogen management is the key for low-emission wheat production in Australia: a life cycle perspective. Eur J Agron 66:74–82. https://doi.org/10.1016/j.eja.2015.02.007

West TO, Post WM (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci Soc Am J 66(6):1930–1946

Yang X, Drury CF, Wander MM (2013) A wide view of no-tillage practices and soil organic carbon sequestration. Acta Agriculturae Scandinavica Sect B Soil Plant Sci 63(6):523–530

Zotarelli L, Alves BJR, Urquiaga S, Torres E, dos Santos HP, Paustian K, Boddey RM, Six J (2005) Impact of tillage and crop rotation on aggregate-associated carbon in two Oxisols. Soil Sci Soc Am J 69(2):482–491