17 Responses of Soil Carbon Storage, Compaction, and Biological Properties Under No-Till and Conventional-Till Systems

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Abstract

Conventional-till (CT) practices can reduce soil organic matter (SOM) and microbial activity and increase soil erosion and compaction. In contrast, no-till (NT) has emerged as a viable option for protecting the soil surface against erosion and degradation. The NT has a lot of advantages such as reduced equipment costs, runoff, and erosion, increased drought resistance of crops, and higher SOM and microbial activity compared to the CT systems. Under the NT system, maintenance of high surface soil cover has resulted in a significant change in soil properties such as bulk density, soil water retention, pore size distribution, infiltration, soil organic C, enzyme activity, and microbial communities. Soil microbial communities are the drivers of SOM decomposition and nutrient cycling including the most limited nutrients for crop growth, N and phosphorus. This chapter mainly focuses on the impact of NT on soil C storage, compaction, and biochemical and microbial activity as compared to the CT systems.

Keywords

Soil carbon · No-till · Conventional till · Soil organic matter · Nutrient cycling

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17.1 Introduction

Tillage is defined as the mechanical manipulation of the soil for the purpose of better crop establishment and production. The impacts of tillage are conspicuous on soil physical, chemical, and biological properties and have a major influence on soil productivity and sustainability (Busari et al. 2015). Intensive tillage operations with either residue removal or burning, popularly known as conventional tillage (CT) practices, may adversely affect the long-term productivity of the soil due to higher loss of soil organic matter (SOM) and erosion (Feng and Balkcom 2017). Tillage activities can cause changes in soil physical properties such as bulk density (BD), aggregation, and water holding capacity. Such changes in physical properties can alter the habitats for microorganisms and eventually influence soil microbial community structure and its composition (Helgason et al. 2009). The no-till (NT) practices, for instance, can improve soil properties such as aggregate stability, nutrient availability, and the diversity of microbial populations while reducing soil disturbance (Heidari et al. 2016; Helgason et al. 2009). NT has emerged as a viable option compared to CT to ensure sustainable soil productivity and food production and maintain environmental integrity and ecosystem services (Corsi et al. 2012; Mathew et al. 2012). Conservation tillage, including NT, is an ecological approach with the principle of covering soil surface through the retention of crop residues (>30%) available from the previous crop (Corsi et al. 2012).

The major components of conservation tillage are reducing or minimizing tillage events to reduce soil degradation, conserve soil moisture, save crop production costs, and reduce the propensity for problems such as soil erosion, temperature fluctuations, weed control, and buildup of SOM (Busari et al. 2015; Hillel and Hatfield 2005; Mathew et al. 2012). Under the NT system, maintenance of high surface soil cover has resulted in a significant change in soil properties, especially in the topsoils (Anikwe and Ubochi 2007). Soil management such as NT is aimed at the maintenance of optimal soil conditions (physical properties) for crop production. Soil properties such as bulk density (BD), pore size distribution (PSD), penetration resistance (PR), soil water retention (SWR), and infiltration characteristics play a significant role in determining soil suitability for crop production (Bauer and Black 1994). For example, crop growth is profoundly impacted by SWR, which is directly influenced by other physical properties such as BD and PSD (Hubbard et al. 2013). Physical properties also influence the soil chemical composition and biological properties such as microbial activities and compositions. Conservation tillage systems increase the SWR and water infiltration and decrease soil erosion. Soil physical and chemical properties are generally more favorable with NT than with the CT-based systems (Busari and Salako 2012; Lal 1997). Studies conducted under a wide range of soil types, climate conditions, and crop rotation systems showed that soils under NT and reduced till have significantly higher SOM, labile carbon (C) and nitrogen (N) pools, and available nutrients compared with those under CT (Alvarez 2005; Awale et al. 2017; Kabiri et al. 2016; Schmidt et al. 2018). Thus, altered soil physical and chemical properties under NT create a more suitable soil environment for microbial community structure and biochemical activities (García-Orenes et al. 2013).

Soil microbial communities and enzyme activities are directly related to soil biogeochemical processes and play a prominent role in soil nutrient cycling and turnover (Sekaran et al. 2018) and other soil ecosystem services such as plant productivity and greenhouse gas (GHG) emissions (Finn et al. 2017). All these microbial functions drive sustainable soil health and, ultimately, impact crop productivity. The CT activities favor aerobic microorganisms to dominate in the soil microbial communities, while conservation tillage practices such as NT increase microbial population diversity and activity as well as microbial biomass (Balota et al. 2003). Therefore, microbial and enzyme activities have often shown to be important components and indicators of soil health (Nogueira et al. 2006). Soil microbes play a key role in the decomposition of organic matter via a variety of soil enzymes. The latter impact soil functions by catalyzing the cycling of fundamental plant nutrients such as C, N, phosphorus (P), and sulfur (S) and the ability to regulate SOM dynamics. Their activities have been suggested as potential indicators of soil quality (Saviozzi et al. 2001) because of their rapid response to changes in soil management practices (Kandeler et al. 1999). Soil enzyme data can be used as an early alert to the change in soil metabolic capacity after disturbances that occur following specific agriculture practices (Acosta-Martinez et al. 2007; Calderon et al. 2016). The long-term use of NT systems can provide higher SOM and enhance soil health by improving the biological status of the soil, which usually implies an increase in microbial and enzyme activities (García-Orenes et al. 2010, 2016; Mathew et al. 2012). Microbial diversity and biochemical activities are widely recognized as key factors in driving ecological functions in soil (Kabiri et al. 2016; Mohammadi et al. 2013; Sekaran et al. 2018). Thus, it is essential to understand the causes of tillage activities on soil microbial activity and biochemical properties (Tian et al. 2017).

17.2 Impact of NT on Soil C Storage

Soil C is important for sustaining soil health, protecting the global environment, and promoting sustainable crop production due to its impact on nutrient and water retention, nutrient cycling, soil aeration, and root growth and development (Ontl and Schulte 2012). The C in soils is presented in two distinct components: (1) soil organic C (SOC), composed of plant and animals' residues at various stages of breakdown (decomposition) of SOM and (2) the microbial biomass and their derivatives (cells and tissues of organisms). SOM acts as a major source and sink of soil C (Ontl and Schulte 2012). SOC is a heterogeneous mixture of organic materials such as carbohydrates, sugars, fresh residue, complex organic compounds, and pyrogenic compounds. Loss of C to the atmosphere as a gas (carbon dioxide, CO_2) due to agricultural management activities can contribute to global warming (Lal 2004). However, soil can act as a sink for sequestering C in the soil by retaining the crop residues on the soil surface and thus reducing the atmospheric CO_2 levels.

The C storage in soil is a natural process (Lal 2008). Plowing the soil brings organic materials such as plant roots and microorganisms to the soil surface. Tillage activity removes any plant residues covering the soil and loosens the soil by disintegrating the soil aggregates and leaving the soil bare (Günal et al. 2015). Soils with no residue on the surface are usually low in organic matter and more prone to erosion by water and wind. When these organic materials are exposed to oxygen in the atmosphere, it transforms into CO_2, contributing to the greenhouse gas (GHG) emissions that warm the earth. The CT systems accelerate the disruption of soil aggregates and SOC losses (Six et al. 2000).

Due to decreased soil disturbance under the NT system, C and other soil organic materials are retained better in the soil. NT systems protect soil, conserve energy, and improve soil health by improving SOM (0.17–0.23 ton C acre^{-1} year^{-1} increase with NT) (Al-Kaisi 2018). The C storage enriches soil biodiversity, reducing the need for inorganic fertilizers that emit GHGs and also additional costs for crop production. The major potential benefits of NT include an increase in SOM content, C sequestration, soil aggregation, and an increase in the intensification of crop sequence (Brouder and Gomez-Macpherson 2014; Rusinamhodzi 2015). To mitigate the C emissions that induce global warming, conservation agricultural (CA) practices such as NT are recommended to potentially sequester the C in agricultural soils. Compared to other tillage systems, the NT system has shown to increase the soil C stocks, thereby reducing the emission of CO_2. Through the adoption of conservation practices, globally, agricultural soils are estimated to sequester 0.4–0.8 Pg C per year. Among conservation practices, NT was one potential strategy for sequestering C in the soil with the rate of 100–1000 kg ha^{-1} (Lal 2004). It has been well documented that long-term implementation of conservation soil and crop management practices can increase soil C storage (Al-Kaisi and Yin 2005). Sithole et al. (2019) observed higher particulate organic C (POC) under the long-term NT system as compared to the CT system. Choudhury et al. (2014) stated that CA systems such as NT proved to be a good alternative to conventional agricultural systems in the maintenance of SOC and sustainable agricultural production. The NT system reduces the process of oxidation and loss of soil C and nutrients. The addition of crop residues under NT acts as a barrier between soil and the environment, which may have greater potential in reducing soil erosion and improving soil quality (Sithole et al. 2019). Soil physical, chemical, and biological properties, especially those related to sequestering C in the soil, are highly influenced by tillage practices (Indoria et al. 2017; Jat et al. 2018). Jat et al. (2019) observed considerable increase in oxidizable organic C, total organic C (TOC), and macroaggregates associated C at the soil surface layer under CA compared to the CT system. This may be due to the addition of huge quantities of crop residues coupled with NT, further easing the stabilization of organic C as SOM (Choudhury et al. 2014; Lorenz and Lal 2005) (Table 17.1). Increased TOC content over the years under CA practices might be due to the decomposition of added crop residues with time (Nachimuthu and Hulugalle 2016). Six et al. (2000) reported that under the CT system, a considerable amount of SOC was lost due to the disruptive effect and increased respiration of soil microbes. Higher C input in the soil through huge

Table 17.1 Impact of the no-tillage system on soil carbon (C)

Duration (years)	Cropping sequence/ system	Soil type	C type	NT vs. CT	Location	References
13	Continuous maize	Haplic Ferralsols (clay loam)	POC	25.3 and 20.7 t ha^{-1}	KwaZulu-Natal Province, South Africa	Sithole et al. (2019)
6	Rice-wheat-mungbean	Fine-loamy mixed hyperthermic family of Typic Natrustalf	Oxidizable organic C	8.1 and 4.9 g kg^{-1}	Haryana, India	Jat et al. (2019)
			TOC	11.4 and 8.7 g kg^{-1}		
	Maize-wheat-mungbean		Oxidizable organic C	8.2 and 4.9 g kg^{-1}		
			TOC	11.0 and 8.7 g kg^{-1}		
6	Rice-wheat/ maize	Fluvisol (silty clay)	TOC	7.25 and 6.38 g kg^{-1}	Bihar, India	Nandan et al. (2019)
5	Maize-soybean-wheat-cowpea	Silt loam	TC	16.9 and 11.8 g kg^{-1}	South-Central Ohio, USA	Aziz et al. (2013)
			AC	730.1 and 656.1 mg kg^{-1}		
7	Rice-wheat/ chickpea-mungbean	Typic Ustochrept (sandy loam)	AC	2.35 and 1.72 g kg^{-1}	Uttar Pradesh, India	Kumar and Nath (2019)
			SOC	3.40 and 2.56 g kg^{-1}		
3	Maize-soybean	Canisteo and clarion soil series	TOC	17.0 and 11.4 Mg ha^{-1}	Iowa, USA	Al-Kaisi and Yin (2005)
10	Cotton/rye-cotton-maize/ rye	Decatur silt loam (clayey, kaolinitic, thermic, Typic Paleudults)	SOC	40.1 and 37.4 Mg ha^{-1}	Alabama, USA	Sainju et al. (2008)

(continued)

Table 17.1 (continued)

Duration (years)	Cropping sequence/ system	Soil type	C type	NT vs. CT	Location	References
3	Sorghum/rye	Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludults)	SOC	41.6 and 40.6 Mg ha^{-1}	Georgia, USA	Franzluebbers and Stuedemann (2008)
25	Cotton-wheat/ soybean-cotton	Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults)	SOC	20.3 and 10.1 Mg ha^{-1}	South Carolina, USA	Bauer et al. (2006)
24	Cotton-wheat/ soybean-cotton	Norfolk loamy sand	SOC	31.4 and 20.6 Mg ha^{-1}	South Carolina, USA	Novak et al. (2007)
20	Sorghum-wheat/soybean	Westwood silty clay loam (fine-silty, mixed, superactive, thermic Udifluventic Haplustept)	SOC	49.2 and 35.4 Mg ha^{-1}	Central Texas, USA	Dou and Hons (2006)
11	Cotton-wheat/ soybean	Bojac (coarse-loamy, mixed, semiactive, thermic Typic Hapludults)	SOC	29.9 and 20.2 Mg ha^{-1}	Virginia, USA	Spargo et al. (2008)
13	Cotton/wheat-soybean	Ultisols	SOC	31.4 and 20.4 Mg ha^{-1}	USA	Causarano et al. (2008)

POC particulate organic carbon, *TOC* total organic C, *TC* total C, *AC* active C, *SOC* soil organic C quantities of crop residues under the NT system resulted in the formation of higher POC (Six et al. 2000). In soil, the particulate organic matter (POM) decomposition process led to soil aggregation (Torres-Sallan et al. 2017). Soil microbes, especially bacteria, produce mucilage during the mineralization of POM, which serves as an adhesive between the POM and soil mineral particles. Through the binding of POM with soil mineral matter, SOC is enclosed into large and small macroaggregates (Torres-Sallan et al. 2017). Soils managed with NT systems can be benefited in increasing SOC content and improving soil aggregation. Protecting the SOC within soil aggregates can protect the SOC from the microbial attack and increases the C sequestration or storage for a long period. The impact of NT has significant effects on soil health by sequestering more C and improving soil aggregation when systematically followed for longer durations.

17.3 Impact of NT on Soil Compaction

In mechanized agriculture, soil compaction has been recognized as a severe problem and has an impact on many soil physical, chemical, and biological properties and also on crop yield (Etana et al. 2013). Soil compaction in agricultural soil is caused by the compression of soil particles from heavy machinery traffic or livestock trampling (Chamen et al. 2015). Compacted soil has low porosity and air permeability, reduced water infiltration and drainage, and increased traction power in seedbed preparation. Soil compaction also leads to increased emission of GHGs (CO_2, CH_4, and N_2O) and contributes to global warming (Horn et al. 1995). At the soil surface or subsurface, soil compaction can occur in the form of soil crusting. Soil compaction can be caused by various farming practices and occur at different times of the year: (1) Soil tillage activity removes the protective crop residues from the surface soil, leaves the soil surface prone to excessive tillage or natural environmental forces (rain and wind), which causes soil aggregate breakdown, and can lead to soil crusting (Aikins and Afuakwa 2012); (2) when soils are wet, soil tillage equipment can induce compaction just below the depth of tillage (So et al. 2009); and (3) the heavy machinery used in agriculture systems (tractors, seed carts, combines, trucks, manure spreaders) to provide an optimum condition for all processes relevant to crop production (Aikins and Afuakwa 2012) can cause compaction through wheel traffic to a considerable depth within the root zone (Defossez and Richard 2002). As the moisture content of the soil increases, the depth of soil compaction also increases (Fig. 17.1). Soil compaction will restrict root growth and penetration into the subsoil (Badalíková 2010). This can lead to restricted water and nutrient uptake and stunted and drought-stressed plants, which results in reduced crop yields. In high-moisture conditions, soil compaction can reduce soil aeration and lead to anaerobic conditions (soil pores are mostly filled with water) (Badalíková 2010). Under anaerobic conditions, loss of nitrate-N (NO_3-N) increased through the denitrification process, which is the conversion of available NO_3-N into gaseous N forms, which are then lost to the atmosphere (Skiba 2008). Reduced soil aeration can also lead to restricted

Fig. 17.1 Visible wheel traffic compaction on soil surface under conventional till system compared to no-till. (Photo: Peter Sexton)

root growth and function and increase the risk of crop disease. All these factors can result in reduced crop yield and increased crop stress.

Living roots under the NT system increase soil pore space for increased soil permeability, infiltration, and water holding capacity. In a natural system, the land is not tilled extensively, and the presence of living cover protects the soil from the impact of a raindrop (Hoorman et al. 2009; Schnepf and Cox 2006). Growing cover crops in the winter season adds C inputs into the soil and keeps nutrients within the system. Organic matter retention under the NT system retains more soil moisture, thus helping the soil to rebound against soil compaction. The long-term NT system with continuous living crop cover (cover crops) is a system that closely imitates a natural system. Long-term NT with a continuous living crop cover protects the soil from compaction in various ways: (1) The soil surface with high organic matter acts like a sponge that absorbs the weight of heavy traffic (Håkansson and Reeder 1994); (2) Living plants with active root systems create voids and macropores in the soil so that water and air move into the soil. Oxygen is required for root respiration and supports an aerobic microbial community in the soil; (3) Soil microorganisms (especially fungi) and burrowing soil fauna get their food from plant roots and keep the soil from compaction (Jastrow and Miller 1997); (4) Organic matter added by the decaying plants, animals, and microorganisms is lighter and less dense than soil fractions. The average bulk density (BD) of SOM is 0.3–0.6 Mg m^{-3} compared to soil BD of 1.4–1.6 Mg m^{-3}. So, adding SOM to the soil reduces the average soil BD; and (5) Soil compaction can be reduced by combining microaggregates to form macroaggregates in the soil. Glomalin and polysaccharides weakly combine with microaggregates and form macroaggregates, but this bond is broken down once the soil is tilled or disturbed (Wright and Upadhyaya 1996).

Plant roots and microorganisms combine microaggregates together in the soil to form macroaggregates. Macroaggregates are mainly linked by fungal hyphae, polysaccharides, and root fibers. Macroaggregates with a size of more than 250 μm give soil its structure and improve air and water infiltration (Hoorman et al. 2009). Generally, compacted soils tend to have lesser macroaggregates and more microaggregates. Plant and soil microbes together produce glomalin, which acts like a glue that binds soil particles together and improves soil aggregate and soil structure. Glomalin, a glycoprotein in soil, cements microaggregates together, forms strong macroaggregates, and improves soil structure. Glomalin is in soil created by mycorrhizal fungus with sugars from plant root exudates (Allison 1968; Hoorman et al. 2009). To produce glomalin in soil, plants and mycorrhizal fungus must exist together. Glomalin must be continually produced because it is easily consumed by microorganisms in the soil, especially bacteria. Bacteria survive well under tilled soils because they are hardier and smaller than fungus, so the population of soil bacteria increases in tilled soil (Hoorman et al. 2009; Wright and Upadhyaya 1996). With a constant source of C and continuous living crop cover, fungi grow better under NT soils. Since fungi grow well under NT soils, more glomalin is produced, and higher macroaggregates are formed. On the other hand, under CT soils, fungi do not grow well and produce less glomalin and fewer macroaggregates (Wright and Upadhyaya 1996). Higher macroaggregates are associated with better soil structure, and fewer macroaggregates are associated with poor soil structure and lead to soil compaction. Soil compaction increases due to the lack of the production of polysaccharides, root exudates, and glomalin by active roots and mycorrhizal fungus. Heavy machinery under conventional systems pushes the microaggregates together so they can bind chemically and compact the soil (Hoorman et al. 2009).

The presence of higher organic matter content and enhanced microbial activity in NT soils makes the soil more resilient to compaction. Under the NT system, the presence of a thick layer of plant residues as the protective surface cover can reduce the negative effects of environmental forces such as raindrop impact or irrigation water causing soil crusting. Soil physical properties such as BD, porosity, PR, and soil structure are the most commonly measured properties under tillage conditions (Strudley et al. 2008) (Table 17.2). Soil BD is often used to evaluate the impact of traffic on soil quality. BD is an indicator of soil compaction and soil health (Badalíková 2010). Generally, lower BD values were obtained in CT treatments compared to NT systems (Aikins and Afuakwa 2012; Lampurlanés and Cantero-Martinez 2003; Romaneckas et al. 2009). Soil BD gives an indication of soil's strength and thus resistance to tillage activities. However, Sekwakwa and Dikinya (2012) reported that BD was the lowest under the NT system. Higher BD indicates lower total porosity because total porosity is inversely related to BD. While soil compaction increases BD, it decreases volume and pore size (Logsdon and Karlen 2004). Low porosity increases PR and decreases soil aeration (Kuht et al. 2012; Lampurlanés and Cantero-Martinez 2003). PR changes with soil moisture conditions, and it is one of the common methods used to measure soil strength. Therefore, PR is considered to be a good indicator of soil compaction due to different tillage practices (Celik 2011). Soil tillage and compaction have a close relationship, and generally the highest PRs were determined under NT than CT soils (Aikins and Afuakwa 2012; Lampurlanés and Cantero-Martinez 2003). In contrast, Olaoye (2002) found that NT soils provided the lowest PR. Nkakini and Fubara-Manuel (2012) reported no significant differences in PR and the total porosity under different

Table 17.2 Impact of tillage on soil physical and hydrological properties

Location	Soil type	Parameter	Salient findings	Reference
KwaZulu-Natal Province, South Africa	Haplic Ferralsols (clay loam)	Infiltration	NT soils took 5 min to reach 160 mm and CT soils took more than 50 min to reach a similar depth	Sithole et al. (2019)
South-Central Ohio, USA	Silt loam	Aggregate stability (AS)	AS increased 7% under NT, while it decreased by 2% under CT over time. (NT: 42.6% and CT: 33.8%)	Aziz et al. (2013)
Jokioinen, Finland	Vertic Cambisol	Mean weight diameter (MWD)	0.84 (NT) and 0.55 (CT) mm	Sheehy et al. (2015)
Central semiarid region of Argentina	Entic haplustolls	Bulk density (BD)	Significantly higher BD found at 0.10–0.20 cm under CT than NT (1.26 and 1.21 Mg m^{-3}, respectively)	Quiroga et al. (2009)
Grafton NSW, Australia	Ultisols	Soil strength	1874 kPa under CT and 1236 kPa under NT	So et al. (2009)
		Hydraulic conductivity	The NT surface soil had a greater hydraulic conductivity at field saturation (K_{sat}) and a smaller unsaturated hydraulic conductivity (K_{unsat}) than the CT surface soil	
Southern Queensland, Australia	Alfisol (Typic Natrustalf)	BD	BD under NT (1.44 Mg m^{-3}) was greater than CT (1.38 Mg m^{-3}) at 0–10 cm depth	Thomas et al. (2007)
Pasinler of East Anatolia Agricultural Research Institute, Turkey	Inceptisol	BD	BD under NT (1.38 Mg m^{-3}) was greater than CT (1.17 Mg m^{-3}) at 0–10 cm depth	Gozubuyuk et al. (2014)
		Penetration resistance (PR)	PR under NT (2.60 MPa) was greater than CT (0.51 MPa)	
Kumasi, Ghana	Ferric Acrisol	BD	1.45 Mg m^{-3} under NT and 1.25 Mg m^{-3} under CT	Aikins and Afuakwa (2012)
		PR	Soil PR was significantly higher under NT (661 kPa) as compared	

(continued)

Table 17.2 (continued)

Location	Soil type	Parameter	Salient findings	Reference
			with that in the tilled soil (117 kPa)	
Northeast Ebro Valley, Spain	Fine-loamy, mixed, Mesic Fluventic Xerochrept	BD	BD was greater for NT (1.34 Mg m^{-3}) and lower for CT (1.22 Mg m^{-3})	Lampurlanés and Cantero-Martinez (2003)
		PR	PR in NT was 1 MPa greater than CT in the first 10-cm depth	
Niger State, Nigeria	Ferruginous Ferrisols	PR	PR under NT was 0.18 MPa and 0.76 MPa under CT	Olaoye (2002)

tillage treatments. Lower PR values under the CT system could be associated with the increase in the intensity of soil loosening due to tillage activities. Therefore, following NT and retaining crop residues on the soil surface could improve soil properties and reduce soil compaction and soil erosion.

17.4 Impact of NT on Soil Biological Properties

Tillage systems influence the physical and chemical properties of soil and bring about changes in soil biochemical activities, microbial community structure, and function. CT practices may adversely affect the long-term productivity of soil due to the loss of organic matter and soil erosion. Tillage activities can directly affect microbial communities due to habitat modifications, loss of connectivity between species, disruption of nutrient passage, and increased runoff (Young and Ritz 2000). The frequent soil disturbances under tillage systems may induce changes in soil biodiversity by favoring disturbance tolerating species (Buckling et al. 2000), thus affecting not only the composition of the microbial communities but also their diversity. Human-induced changes in soil microbial community structure, composition, and function are well documented (Andrade et al. 2003; Ceja-Navarro et al. 2010b; Souza et al. 2015). Intensive tillage practices may negatively affect soil biochemical activities and microbial community structure through (1) a reduction of substrate availability (SOM) for the growth of microorganisms, (2) a decline in favorable microhabitat for soil microbes (water-stable macroaggregates), and (3) changes in soil temperature, moisture, and other environmental conditions (Balota et al. 2004; Dilly et al. 2003).

The negative effects of CT on soil erosion, loss of nutrients, SOM, and soil macro- and microorganisms have led to increased usage of the NT system. Currently, NT activities are practiced on nearly 155 M ha worldwide, which comprises 11% of the total arable land in the world (Kassam et al. 2014). South and North America are the largest adopters of the NT system with the adaptation rates of nearly 45% and 32%, respectively (Friedrich et al. 2012). Sustainable conservational practices can be followed through NT, high residue return, and diversified crop rotation (Hobbs et al. 2007). Soil tillage systems, fertilizer management, climatic conditions, and soil types influence the soil microbial and macrofaunal population and diversity (Blankinship et al. 2011; Chan 2001). CT management system and the removal of crop residues have, for many years, resulted in the decline of SOM content, deterioration of soil physical, chemical, and biological properties, and high rates of increase in the risk of soil erosion (Ouédraogo et al. 2006). Conservation tillage practices leave more than 15% of crop residues on the surface as a soil cover, while CT leaves less than 15% residue at the time of planting to the succeeding cash crop. SOM dynamics are highly dependent on the microbial community and diversity (Álvaro-Fuentes et al. 2013). Conservational tillage is comparatively advantageous to CT (moldboard or disk plow) with respect to SOM, microbial activity, enzyme production, soil physical properties, and prevention of wind and water erosion (Bossuyt et al. 2002; Hevia et al. 2007). The response of biochemical activities and soil microbes to tillage activities have been measured by estimating the soil enzymatic activities and the size and activity of the microbial community (Carter et al. 1999).

Mathew et al. (2012) investigated the effects of CT and NT practices on soil microbial communities and enzyme activities in a continuous maize production system. Phospholipid fatty acid (PLFA) analysis revealed that total PLFA increased higher under NT than under a CT system (Table 17.3). Total PLFA is an indicator of viable soil microbial biomass and ranged from 30 nmol g^{-1} of soil under CT at 5–15 cm depth to 104 nmol g^{-1} of soil under the NT system at 0–5 cm depth. They reported that as soil depth increased, total PLFA biomass decreased in both tillage treatments. The results also revealed that soil under the long-term NT system had higher soil microbial community structure and enzyme activities than that under the CT system. These observations are in agreement with previous findings reported by Ceja-Navarro et al. (2010a), Ekenler and Tabatabai (2003), and Helgason et al. (2009). Carpenter-Boggs et al. (2003) evaluated the response of soil microbial activities between CT and NT management in South Dakota. They reported that mineralized C was increased under NT (96 μg C kg^{-1} soil) compared to the CT (62 μg C kg^{-1} soil) system. Collins et al. (2000) also reported that higher soil microbial biomass C accumulated at 0–20 cm under the NT system than CT. The adoption of NT also has a positive impact on soil bacterial assemblages. White and Rice (2009) reported greater microbial abundance under NT compared to CT soils in Kansas, USA. This same study also found that total gram-positive and negative bacterial and fungal PLFA were greater under NT owing to greater crop residue decomposition. Similarly, Mbuthia et al. (2015) observed an increase in the mean abundance of actinomycetes, gram-positive bacteria, and mycorrhizae PLFA biomarkers under the NT system compared to CT in continuous cotton in West Tennessee, USA. Feng et al. (2002) also demonstrated an increase in microbial biomass C under the NT system compared to tilled soils. Mathew et al. (2012) reported a greater total PLFA under the NT system compared to CT soils in Alabama, USA. Dorr de Quadros et al. (2012) found that when NT was implemented, anaerobic communities were dominant in the microbial community

Table 17.3 Impact of tillage on soil biological properties

Duration (years)	Soil type	Depth (cm)	Parameter	NT vs. CT	Location	References
14	Decatur silt loam (fine, kaolinitic, thermic Rhodic Paleudults)	0–5	Total phospholipid fatty acid (PLFA)	104 and 39 nmol g^{-1}	Alabama, USA	Mathew et al. (2012)
		5–15		38 and 30 nmol g^{-1}		
		0–5	Acid phosphatase	367 and 200 μg of *p*-nitrophenol g^{-1} h^{-1}		
		5–15		307 and 202 μg of *p*-nitrophenol g^{-1} h^{-1}		
6	Highmore silt loam	0–15	Mineralized carbon (C)	96 and 62 μg C kg^{-1} soil	South Dakota	Carpenter-Boggs et al. (2003)
			Alkaline phosphatase	325 and 190 μg NP g^{-1} soil h^{-1}		
12	Decatur silt loam (fine, kaolinitic, thermic Rhodic Paleudults)	0–3	Microbial biomass C (MBC)	633 and 266 μg g^{-1}	Alabama, USA	Feng et al. (2002)
32	Lexington silt loam (fine-silty, mixed, thermic, Ultic Hapludalf)	0–7.5	Gram-positive bacteria	12.71 and 12.15 nmol g^{-1} soil	West Tennessee, USA	Mbuthia et al. (2015)
			Actinomycetes	5.78 and 5.46 nmol g^{-1} soil		
			Mycorrhiza	3.94 and 3.36 nmol g^{-1} soil		
22	Oxisol (Typic Haplorthox)	0–5	MBC	372 and 145 μg g^{-1}	State of Parana, Brazil	Balota et al. (2003)
			Microbial biomass nitrogen (MBN)	28.3 and 17.2 μg g^{-1}		
			Microbial biomass phosphorus (MBP)	18.3 and 10.7 μg g^{-1}		
20	Muir silt loam	0–5	Total PLFA	NT was 1.5 times higher than the CT	Kansas, USA	White and Rice (2009)

structure. According to Doran (1980), Balota et al. (2004), and DeBruyn et al. (2011), such variation in microbial composition and structure is mainly associated with changes in soil moisture, C, N, and pH.

Soil microbes improve soil health by cycling nutrients and breaking crop residues down into SOM. The reduction in SOM also affects soil macrofauna, which has a key role in soil structural formation, recycling of soil nutrients, and decomposition of SOM. The effect of macrofauna, especially earthworms and termites, on soil structural formation has been well documented and they are considered ecosystem engineers because of their key role in soil structural formation (Blanchart et al. 2004). Earthworms, through their burrowing and casting activities and biological and physicochemical changes, modify soil structure and significantly impact soil physical properties such as water infiltration and aeration (Blanchart et al. 2004). Termites, through their activities of transporting and cementing soil particles, alter the soil structure and its properties (Mando and Miedema 1997). On the other hand, other groups of soil macrofauna such as epigeic earthworms and Mollusca (litter transformers) have little effect on soil structure (Lavelle et al. 1997). These macrofaunae concentrate their activities mostly on surface soil where they physically break crop residues and deposit organic matter. Therefore, maintaining a suitable environment for soil macrofauna and microorganisms in cropland is important to maintain long-term soil health and sustainability of crop production.

17.5 Summary

Conservation tillage systems such as NT have a positive impact on SOC storage, nutrient availability, soil compaction, aggregate stability, soil productivity, and profitability under different climatic and soil conditions. The no-till system is a powerful tool to combat soil degradation because of reduced soil erosion and soil compaction. These systems increase crop residue cover and living roots and create better soil structure. Soils managed with NT systems can be beneficial in increasing SOC content and improving soil aggregation. Living roots and crop residue cover under the NT system increase soil porosity, permeability, infiltration, and water holding capacity. The presence of a thick layer of plant residues as a protective surface cover under the NT system can reduce the negative effects of environmental forces such as raindrops or irrigation water causing soil crusting. These conservation systems protect the soil surface, conserve energy, and improve soil health by enhancing SOM and microbial activity. Practicing NT systems for a longer duration can enhance soil health by improving SOM content, soil structure, infiltration, and microbial diversity.

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References

Acosta-Martinez V, Mikha MM, Vigil MF (2007) Microbial communities and enzyme activities in soils under alternative crop rotations compared to wheat–fallow for the central Great Plains. Appl Soil Ecol 37:41–52

Aikins S, Afuakwa J (2012) Effect of four different tillage practices on soil physical properties under cowpea. Agric Biol J North Am 3:17–24

Al-Kaisi M (2018) Let's talk no-till. https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=3518&context=cropnews

Al-Kaisi MM, Yin X (2005) Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn–soybean rotations. J Environ Qual 34:437–445

Allison FE (1968) Soil aggregation—some facts and fallacies as seen by a microbiologist. Soil Sci 106:136–143

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

Álvaro-Fuentes J, Morell F, Madejón E, Lampurlanés J, Arrúe J, Cantero-Martínez C (2013) Soil biochemical properties in a semiarid Mediterranean agroecosystem as affected by long-term tillage and N fertilization. Soil Tillage Res 129:69–74

Andrade DS, Colozzi-Filho A, Giller KE (2003) The soil microbial community and soil tillage. Soil Tillage Agroecosyst:51–81

Anikwe M, Ubochi J (2007) Short-term changes in soil properties under tillage systems and their effect on sweet potato (*Ipomea batatas* L.) growth and yield in an Ultisol in South-Eastern Nigeria. Soil Res 45:351–358

Awale R, Emeson MA, Machado S (2017) Soil organic carbon pools as early indicators for soil organic matter stock changes under different tillage practices in Inland Pacific Northwest. Front Ecol Evol 5:96

Aziz I, Mahmood T, Islam KR (2013) Effect of long term no-till and conventional tillage practices on soil quality. Soil Tillage Res 131:28–35

Badalíková B (2010) Influence of soil tillage on soil compaction. In: Soil Engineering. Springer, New York, pp 19–30

Balota EL, Colozzi-Filho A, Andrade DS, Dick RP (2003) Microbial biomass in soils under different tillage and crop rotation systems. Biol Fert Soils 38:15–20

Balota EL, Colozzi Filho A, Andrade DS, Dick RP (2004) Long-term tillage and crop rotation effects on microbial biomass and C and N mineralization in a Brazilian Oxisol. Soil Tillage Res 77:137–145

Bauer A, Black AL (1994) Quantification of the effect of soil organic matter content on soil productivity. Soil Sci Soc Am J 58(1):185–193

Bauer PJ, Frederick JR, Novak JM, Hunt PG (2006) Soil CO_2 flux from a Norfolk loamy sand after 25 years of conventional and conservation tillage. Soil Tillage Res 90:205–211

Blanchart E, Albrecht A, Brown G, Decaens T, Duboisset A, Lavelle P, Mariani L, Roose E (2004) Effects of tropical endogeic earthworms on soil erosion. Agric Ecosyst Environ 104:303–315

Blankinship JC, Niklaus PA, Hungate BA (2011) A meta-analysis of responses of soil biota to global change. Oecologia 165:553–565

Bossuyt H, Six J, Hendrix PF (2002) Aggregate-protected carbon in no-tillage and conventional tillage agroecosystems using carbon-14 labeled plant residue. Soil Sci Soc Am J 66:1965–1973

Brouder SM, Gomez-Macpherson H (2014) The impact of conservation agriculture on smallholder agricultural yields: a scoping review of the evidence. Agric Ecosyst Environ 187:11–32

Buckling A, Kassen R, Bell G, Rainey PB (2000) Disturbance and diversity in experimental microcosms. Nature 408:961

Busari MA, Salako FK (2012) Effect of tillage and poultry manure application on soil infiltration rate and maize root growth in a sandy Alfisol. Agro-Science 11:24–31

Busari MA, Kukal SS, Kaur A, Bhatt R, Dulazi AA (2015) Conservation tillage impacts on soil, crop and the environment. Int Soil Water Conserv Res 3:119–129

Calderon FJ, Nielsen D, Acosta-Martinez V, Vigil MF, Drew L (2016) Cover crop and irrigation effects on soil microbial communities and enzymes in semiarid agroecosystems of the Central Great Plains of North America. Pedosphere 26:192–205

Carpenter-Boggs L, Stahl PD, Lindstrom MJ, Schumacher TE (2003) Soil microbial properties under permanent grass, conventional tillage, and no-till management in South Dakota. Soil Tillage Res 71:15–23

Carter M, Gregorich E, Angers D, Beare M, Sparling G, Wardle D, Voroney R (1999) Interpretation of microbial biomass measurements for soil quality assessment in humid temperate regions. Can J Soil Sci 79:507–520

Causarano HJ, Franzluebbers AJ, Shaw JN, Reeves DW, Raper RL, Wood C (2008) Soil organic carbon fractions and aggregation in the southern Piedmont and coastal plain. Soil Sci Soc Am J 72:221–230

Ceja-Navarro JA, Rivera-Orduna FN, Patino-Zúniga L, Vila-Sanjurjo A, Crossa J, Govaerts B, Dendooven L (2010a) Phylogenetic and multivariate analyses to determine the effects of different tillage and residue management practices on soil bacterial communities. Appl Environ Microbiol 76:3685–3691

Ceja-Navarro JA, Rivera FN, Patiño-Zúñiga L, Govaerts B, Marsch R, Vila-Sanjurjo A, Dendooven L (2010b) Molecular characterization of soil bacterial communities in contrasting zero tillage systems. Plant Soil 329:127–137

Celik I (2011) Effects of tillage methods on penetration resistance, bulk density and saturated hydraulic conductivity in a clayey soil conditions. Tarim Bilimleri Dergisi 17:143–156

Chamen WT, Moxey AP, Towers W, Balana B, Hallett PD (2015) Mitigating arable soil compaction: a review and analysis of available cost and benefit data. Soil Tillage Res 146:10–25

Chan K (2001) An overview of some tillage impacts on earthworm population abundance and diversity—implications for functioning in soils. Soil Tillage Res 146(57):179–191

Choudhury SG, Srivastava S, Singh R, Chaudhari S, Sharma D, Singh S, Sarkar D (2014) Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice–wheat cropping system under reclaimed sodic soil. Soil Tillage Res 146 (136):76–83

Collins H, Elliott E, Paustian K, Bundy L, Dick W, Huggins D, Smucker A, Paul E (2000) Soil carbon pools and fluxes in long-term corn belt agroecosystems. Soil Biol Biochem 32:157–168

Corsi S, Friedrich T, Kassam A, Pisante M, Sà JDM (2012) Soil organic carbon accumulation and greenhouse gas emission reductions from conservation agriculture: a literature review Food and Agriculture Organization of the United Nations (FAO). FAO, Rome

DeBruyn JM, Nixon LT, Fawaz MN, Johnson AM, Radosevich M (2011) Global biogeography and quantitative seasonal dynamics of Gemmatimonadetes in soil. Appl Environ Microbiol 77:6295–6300

Defossez P, Richard G (2002) Models of soil compaction due to traffic and their evaluation. Soil Tillage Res 67:41–64

Dilly O, Blume HP, Sehy U, Jimenez M, Munch JC (2003) Variation of stabilised, microbial and biologically active carbon and nitrogen in soil under contrasting land use and agricultural management practices. Chemosphere 52:557–569

Doran JW (1980) Soil microbial and biochemical changes associated with reduced tillage 1. Soil Sci Soc Am J 44:765–771

Dorr de Quadros P, Zhalnina K, Davis-Richardson A, Fagen JR, Drew J, Bayer C, Camargo FA, Triplett EW (2012) The effect of tillage system and crop rotation on soil microbial diversity and composition in a subtropical acrisol. Diversity 4:375–395

Dou F, Hons FM (2006) Tillage and nitrogen effects on soil organic matter fractions in wheat-based systems. Soil Sci Soc Am J 70:1896–1905

Ekenler M, Tabatabai M (2003) Responses of phosphatases and arylsulfatase in soils to liming and tillage systems. J Plant Nutr Soil Sci 166:281–290

Etana A, Larsbo M, Keller T, Arvidsson J, Schjønning P, Forkman J, Jarvis N (2013) Persistent subsoil compaction and its effects on preferential flow patterns in a loamy till soil. Geoderma 192:430–436
Feng Y, Balkcom KS (2017) Nutrient cycling and soil biology in row crop systems under intensive tillage. In: Soil health and intensification of agroecosytems. Elsevier, Amsterdam, pp 231–255
Feng Y, Motta A, Burmester C, Reeves D, Van Santen E, Osborne J (2002) Effects of tillage systems on soil microbial community structure under a continuous cotton cropping system. In: Making conservation tillage conventional: building a future on 25 years of research. Alabama Agricultural Experiment Station, Auburn University, Auburn, pp 222–226
Finn D, Kopittke PM, Dennis PG, Dalal RC (2017) Microbial energy and matter transformation in agricultural soils. Soil Biol Biochem 111:176–192
Franzluebbers AJ, Stuedemann JA (2008) Early response of soil organic fractions to tillage and integrated crop–livestock production. Soil Sci Soc Am J 72:613–625
Friedrich T, Derpsch R, Kassam A (2012a) Overview of the global spread of conservation agriculture. Field Actions Science Reports. J Field Actions 6
García-Orenes F, Guerrero C, Roldán A, Mataix-Solera J, Cerdà A, Campoy M, Zornoza R, Bárcenas G, Caravaca F (2010) Soil microbial biomass and activity under different agricultural management systems in a semiarid Mediterranean agroecosystem. Soil Tillage Res 109:110–115
García-Orenes F, Morugán-Coronado A, Zornoza R, Scow K (2013) Changes in soil microbial community structure influenced by agricultural management practices in a Mediterranean agro-ecosystem. PLoS One 8:e80522
García-Orenes F, Morugán-Coronado A, Zornoza R, Cerdà A, Scow K (2016) Correction: Changes in soil microbial community structure influenced by agricultural management practices in a Mediterranean agro-ecosystem. PLoS One 11:e0152958
Gozubuyuk Z, Sahin U, Ozturk I, Celik A, Adiguzel MC (2014) Tillage effects on certain physical and hydraulic properties of a loamy soil under a crop rotation in a semi-arid region with a cool climate. Catena 118:195–205
Günal H, Korucu T, Birkas M, Özgöz E, Halbac-Cotoara-Zamfir R (2015) Threats to sustainability of soil functions in central and southeast Europe. Sustainability 7:2161–2188
Håkansson I, Reeder RC (1994) Subsoil compaction by vehicles with high axle load—extent, persistence and crop response. Soil Tillage Res 29:277–304
Heidari G, Mohammadi K, Sohrabi Y (2016) Responses of soil microbial biomass and enzyme activities to tillage and fertilization systems in soybean (*Glycine max* L.) production. Front Plant Sci 7:1730
Helgason BL, Walley FL, Germida JJ (2009) Fungal and bacterial abundance in long-term no-till and intensive-till soils of the Northern Great Plains. Soil Sci Soc Am J 73:120–127
Hevia GG, Mendez M, Buschiazzo DE (2007) Tillage affects soil aggregation parameters linked with wind erosion. Geoderma 140:90–96
Hillel D, Hatfield JL (2005) Encyclopedia of soils in the environment. Elsevier, Amsterdam
Hobbs PR, Sayre K, Gupta R (2007) The role of conservation agriculture in sustainable agriculture. Philos Trans R Soc B Biol Sci 363:543–555
Hoorman JJ, de Moraes Sá JC, Reeder R (2009) The biology of soil compaction. Columbus, OH, Agriculture and Natural Resources, The Ohio State University
Horn R, Domżżał H, Słowińska-Jurkiewicz A, Van Ouwerkerk C (1995) Soil compaction processes and their effects on the structure of arable soils and the environment. Soil Tillage Res 35:23–36
Hubbard RK, Strickland TC, Phatak S (2013) Effects of cover crop systems on soil physical properties and carbon/nitrogen relationships in the coastal plain of southeastern USA. Soil Tillage Res 126:276–283
Indoria AK, Srinivasa Rao C, Sharma KL, Sammi Reddy K (2017) Conservation agriculture – a panacea to improve soil physical health. Curr Sci 112:52–61
Jastrow J, Miller R (1997) Soil aggregate stabilization and carbon sequestration: feedbacks through organomineral associations. Soil Process Carbon Cycle 11:207

Jat H, Datta A, Sharma P, Kumar V, Yadav A, Choudhary M, Choudhary V, Gathala M, Sharma D, Jat M (2018) Assessing soil properties and nutrient availability under conservation agriculture practices in a reclaimed sodic soil in cereal-based systems of North-West India. Arch Agron Soil Sci 64:531–545

Jat H, Datta A, Choudhary M, Yadav A, Choudhary V, Sharma P, Gathala M, Jat M, McDonald A (2019) Effects of tillage, crop establishment and diversification on soil organic carbon, aggregation, aggregate associated carbon and productivity in cereal systems of semi-arid Northwest India. Soil Tillage Res 190:128–138

Kabiri V, Raiesi F, Ghazavi MA (2016) Tillage effects on soil microbial biomass, SOM mineralization and enzyme activity in a semi-arid Calcixerepts. Agric Ecosyst Environ 232:73–84

Kandeler E, Tscherko D, Spiegel H (1999) Long-term monitoring of microbial biomass, N mineralisation and enzyme activities of a Chernozem under different tillage management. Biol Fertil Soils 28:343–351

Kassam A, Friedrich T, Shaxson F, Bartz H, Mello I, Kienzle J, Pretty J (2014) The spread of conservation agriculture: policy and institutional support for adoption and uptake. Field Actions Sci Rep 7

Kuht J, Reintam E, Edesi L, Nugis E (2012) Influence of subsoil compaction on soil physical properties and on growing conditions of barley. Agron Res 10:329–334

Kumar N, Nath CP (2019) Impact of zero-till residue management and crop diversification with legumes on soil aggregation and carbon sequestration. Soil Tillage Res 189:158–167

Lal R (1997) Long-term tillage and maize monoculture effects on a tropical Alfisol in western Nigeria. I. Crop yield and soil physical properties. Soil Tillage Res 42:145–160

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627

Lal R (2008) Carbon sequestration. Philos Trans R Soc B 363:815–830

Lampurlanés J, Cantero-Martinez C (2003) Soil bulk density and penetration resistance under different tillage and crop management systems and their relationship with barley root growth. Agron J 95:526–536

Lavelle P, Bignell D, Lepage M, Wolters V, Roger PA, Ineson P, Heal OW, Dhillion S (1997) Soil function in a changing world: the role of invertebrate ecosystem engineers. Eur J Soil Biol 33 (4):159–193

Logsdon SD, Karlen DL (2004) Bulk density as a soil quality indicator during conversion to no-tillage. Soil Tillage Res 78:143–149

Lorenz K, Lal R (2005) The depth distribution of soil organic carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons. Adv Agron 88:35–66

Mando A, Miedema R (1997) Termite-induced change in soil structure after mulching degraded (crusted) soil in the Sahel. Appl Soil Ecol 6:241–249

Mathew RP, Feng Y, Githinji L, Ankumah R, Balkcom KS (2012) Impact of no-tillage and conventional tillage systems on soil microbial communities. Appl Environ Soil Sci 2012:548620

Mbuthia LW, Acosta-Martínez V, DeBruyn J, Schaeffer S, Tyler D, Odoi E, Mpheshea M, Walker F, Eash N (2015) Long term tillage, cover crop, and fertilization effects on microbial community structure, activity: implications for soil quality. Soil Biol Biochem 89:24–34

Mohammadi K, Heidari G, Javaheri M, Karimi Nezhad MT (2013) Soil microbial response to tillage systems and fertilization in a sunflower rhizosphere. Arch Agron Soil Sci 59:899–910

Nachimuthu G, Hulugalle N (2016) On-farm gains and losses of soil organic carbon in terrestrial hydrological pathways: a review of empirical research. Int Soil Water Conserv Res 4:245–259

Nandan R, Singh V, Singh SS, Kumar V, Hazra KK, Nath CP, Poonia SP, Malik RK, Bhattacharyya R, McDonald A (2019) Impact of conservation tillage in rice–based cropping systems on soil aggregation, carbon pools and nutrients. Geoderma 340:104–114

Nkakini S, Fubara-Manuel I (2012) The effects of tillage methods on soil penetration resistance, porosity and okra yield. Res J Appl Sci Eng Technol 4:387–392

Nogueira M, Albino U, Brandão-Junior O, Braun G, Cruz M, Dias B, Duarte R, Gioppo N, Menna P, Orlandi J (2006) Promising indicators for assessment of agroecosystems alteration among natural, reforested and agricultural land use in southern Brazil. Agric Ecosyst Environ 115:237–247

Novak J, Bauer P, Hunt P (2007) Carbon dynamics under long-term conservation and disk tillage management in a Norfolk loamy sand. Soil Sci Soc Am J 71:453–456

Olaoye J (2002) Influence of tillage on crop residue cover, soil properties and yield components of cowpea in derived savannah ectones of Nigeria. Soil Tillage Res 64:179–187

Ontl TA, Schulte LA (2012) Soil carbon storage. Nat Educ Knowl 3(10):35

Ouédraogo E, Mando A, Stroosnijder L (2006) Effects of tillage, organic resources and nitrogen fertiliser on soil carbon dynamics and crop nitrogen uptake in semi-arid West Africa. Soil Tillage Res 91:57–67

Quiroga A, Fernández R, Noellemeyer E (2009) Grazing effect on soil properties in conventional and no-till systems. Soil Tillage Res 105:164–170

Romaneckas K, Romaneckien R, Šarauskis E, Pilipaviius V, Sakalauskas A (2009) The effect of conservation primary and zero tillage on soil bulk density, water content, sugar beet growth and weed infestation. Agron Res 7:73–86

Rusinamhodzi L (2015) Crop rotations and residue management in conservation agriculture. In: Conservation agriculture. Springer, New York, pp 21–37

Sainju UM, Senwo ZN, Nyakatawa EZ, Tazisong IA, Reddy KC (2008) Tillage, cropping systems, and nitrogen fertilizer source effects on soil carbon sequestration and fractions. J Environ Qual 37:880–888

Saviozzi A, Levi-Minzi R, Cardelli R, Riffaldi R (2001) A comparison of soil quality in adjacent cultivated, forest and native grassland soils. Plant Soil 233:251–259

Schmidt R, Gravuer K, Bossange AV, Mitchell J, Scow K (2018) Long-term use of cover crops and no-till shift soil microbial community life strategies in agricultural soil. PLoS One 13:e0192953

Schnepf M, Cox C (2006) Environmental benefits of conservation on cropland: the status of our knowledge. Soil and Water Conservation Society, Ankeny, IA

Sekaran U, McCoy C, Kumar S, Subramanian S (2018) Soil microbial community structure and enzymatic activity responses to nitrogen management and landscape positions in switchgrass (Panicum virgatum L.). GCB Bioenergy 11:836–851. https://doi.org/10.1111/gcbb.12591

Sekwakwa O, Dikinya O (2012) Tillage-induced compaction: effects on physical properties of agricultural loamy soils. Sci Res Essays 7:1584–1591

Sheehy J, Regina K, Alakukku L, Six J (2015) Impact of no-till and reduced tillage on aggregation and aggregate-associated carbon in northern European agroecosystems. Soil Tillage Res 150:107–113

Sithole NJ, Magwaza LS, Thibaud GR (2019) Long-term impact of no-till conservation agriculture and N-fertilizer on soil aggregate stability, infiltration and distribution of C in different size fractions. Soil Tillage Res 190:147–156

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

Skiba U (2008) Denitrification. In: Jorgensen SE, Fath BD (eds) Encyclopedia of ecology. Elsevier, Oxford

So H, Grabski A, Desborough P (2009) The impact of 14 years of conventional and no-till cultivation on the physical properties and crop yields of a loam soil at Grafton NSW, Australia. Soil Tillage Res 104:180–184

Souza RC, Hungria M, Cantão ME, Vasconcelos ATR, Nogueira MA, Vicente VA (2015) Metagenomic analysis reveals microbial functional redundancies and specificities in a soil under different tillage and crop-management regimes. Appl Soil Ecol 86:106–112

Spargo JT, Alley MM, Follett RF, Wallace JV (2008) Soil carbon sequestration with continuous no-till management of grain cropping systems in the Virginia coastal plain. Soil Tillage Res 100:133–140

Strudley MW, Green TR, Ascough JC II (2008) Tillage effects on soil hydraulic properties in space and time: state of the science. Soil Tillage Res 99:4–48

Thomas G, Dalal RC, Standley J (2007) No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics. Soil Tillage Res 94:295–304

Tian Q, Taniguchi T, Shi WY, Li G, Yamanaka N, Du S (2017) Land-use types and soil chemical properties influence soil microbial communities in the semiarid Loess Plateau region in China. Sci Rep 7:45289

Torres-Sallan G, Schulte RP, Lanigan GJ, Byrne KA, Reidy B, Simó I, Six J, Creamer RE (2017) Clay illuviation provides a long-term sink for C sequestration in subsoils. Sci Rep 7:45635

White PM, Rice CW (2009) Tillage effects on microbial and carbon dynamics during plant residue decomposition. Soil Sci Soc Am J 73:138–145

Wright SF, Upadhyaya A (1996) Extraction of an abundant and unusual protein from soil and comparison with hyphal protein of arbuscular mycorrhizal fungi. Soil Sci 161:575–586

Young IM, Ritz K (2000) Tillage, habitat space and function of soil microbes. Soil Tillage Res 53 (3–4):201–213