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Linking Soil Organic Carbon and Environmental Quality through Conservation Tillage and Residue Management

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Soil tillage is an ancient practice that was originally used to loosen the soil for planting seeds and to eradicate weeds (Lal, 2001). In modern agriculture, tillage is still performed for (i) improving the soil's physical condition by loosening compacted layers and enhancing soil warming in spring; (ii) controlling weeds, insects, and diseases; (iii) incorporating fertilizer, herbicide, and plant residues; (iv) conserving soil and water; and (v) preparing a quality seedbed (Jones et al., 1990). During the past several decades, conservation tillage and particularly no-tillage (NT) have been increasingly utilized, as the need for inversion tillage has been reevaluated. The susceptibility of inverted soil to wind and water erosion has highlighted the environmental and production threats to sustainability. The term *conservation tillage* includes a variety of systems, all of which are designed to minimize residue incorporation with the intent of abating soil erosion. According to the USDA definition of the term, >30% residue cover must be on the soil surface immediately after planting.

Tillage practices range from the very simple to the very complex. Excellent descriptions of the types of tillage operations and their intended use have been presented by Buckingham (1976) and Swinford (1994). The moldboard plow was perhaps the most widely used primary tillage implement during the early part of the 20th century (Allmaras et al., 2000). The moldboard plow inverts soil to a depth of usually 15 to 30 cm, resulting in complete burial of aboveground crop residues. Secondary tillage operations of disking and/or harrowing are often needed to prepare a suitable seedbed following plowing.

Shallow tillage is accomplished using a wide diversity of implements to scarify the soil surface. One primary tillage tool that has replaced the moldboard plow in some regions is the chisel plow. Working depth of the chisel plow may be similar to the moldboard plow, but the degree of soil inversion with the chisel plow is much less. In semiarid regions with small grains as the main crop, primary tillage operations may be accomplished with an offset disk or field cultivator. Working depth of these implements is often less than with plow tools, for

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example, 10 to 15 cm. The extent of residue incorporation depends on the number of passes performed.

A conservation-tillage method with greater opportunities for controlling traffic is ridge tillage. The extent of soil disturbance varies greatly with the type of equipment and number of cultivations with this system. Ridges are typically formed, the tops scraped off to create a clean seedbed, and ridges reshaped during summer cultivation. The negative effects of machinery traffic can be limited to the same rows year after year so that the majority of the field is not compacted.

No-tillage relies completely on herbicides and management to control weeds. Planting operations are typically the only disturbance to the soil surface.

When crop residues are considered a by-product without much value and a hindrance to future production, they may be removed from the field by burning. Residues may also be harvested from the field as valuable fodder for animals, as materials for construction, or as a feedstock for biofuel production. Removal of residues either by burning or by harvest has important implications for soil organic matter (SOM) dynamics. Crop residues are rich in organic C and N, and therefore, their removal is a loss of input to the soil, resulting almost always in a decline in soil organic matter compared with retention of residues (Saffigna et al., 1989; Dalal et al., 1991; Kapkiyai et al., 1999).

Residues left in the field ultimately undergo decomposition, with a majority of the C respired back to the atmosphere as CO_2 and a smaller fraction retained as SOM. The rate and extent of residue transformation into SOM depends on the type, quantity, and quality of residues produced and how and when residues are manipulated. The quantity of residues depends on climatic, soil, and fertility variables. The quality of residues depends on the plant species (e.g., small grain straw low in N vs. legume cover crop forage rich in N) and developmental stage when killed. Residues of primary crops may be cut, shredded, or left standing in the field. Cover crops may be allowed to mature, mowed, rolled, or terminated with herbicides. No-tillage management with a dense mat of previous crop residues can be effective at controlling erosion and weeds and moderate temperature and moisture fluctuations.

My objective was to review the effects of soil disturbance, tillage, and residue management on the quantity and depth distribution of SOM fractions. How stratification of SOM fractions might affect environmental quality was to be generally addressed. In particular, the effect of high levels of surface-soil organic C on nutrient distribution, potential water runoff quality, and greenhouse gas emission was explored.

Depth Distribution of Soil Organic Carbon

Inversion tillage mixes organic residues with soil at deeper depths. The type of tillage tool greatly influences the eventual location of aboveground residues within the soil profile. Allmaras et al. (1996) showed that moldboard plowing to a depth of 25 cm buried 70% of the aboveground oat residue at a depth of 12 to 24 cm, whereas chisel plowing to a depth of 15 cm left nearly 60% of the residue at a depth of 0 to 6 cm (Fig. 16–1). No-tillage leaves nearly all aboveground residues at or above the soil surface. Since plant residues contribute greatly to subsequent SOM formation, the placement of plant residues with different tillage practices is of utmost importance for understanding the depth distribution of SOM.

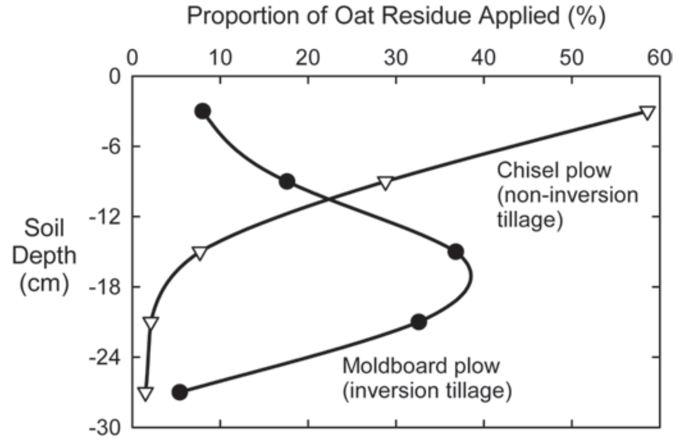

Fig. 16–1. Proportion of oat residue applied as a function of soil depth under inversion- and noninversion-tillage systems in Minnesota. (Data from Allmaras et al., 1996.)

Soil organic matter has a direct impact on the density of soil, and therefore, the content of organic matter within a given volume of soil. Since conservation tillage systems leave residues near the soil surface, most investigations report a substantial change in SOM in surface soil as compared with inversion-tillage systems. However if the net change in SOM content with a change in tillage management is to be determined, then sampling should be made to at least the deepest penetration of tillage tool in both systems. At the end of 4 yr of management in a Typic Kanhapludult in Georgia, soil organic C under NT was greater than under disk tillage (15-cm depth) at a depth of 0 to 2.5 cm, but not different at lower depths (Fig. 16–2). Carbon content was 81% greater (although C concentration was 95% greater) with NT than with disk tillage at a depth of 0 to 2.5 cm. Similarly, C content was only 2% lower with NT (C concentration was 14% lower) than with disk tillage at a depth of 2.5 to 7.5 cm. Summation of C content to a depth of 15 cm indicated no difference between tillage systems due to counteracting effects of residue placement at lower depths with disk tillage. However, including surface residue C along with soil organic C to a depth of 15 cm did result in significantly greater storage of C under NT compared with disk tillage.

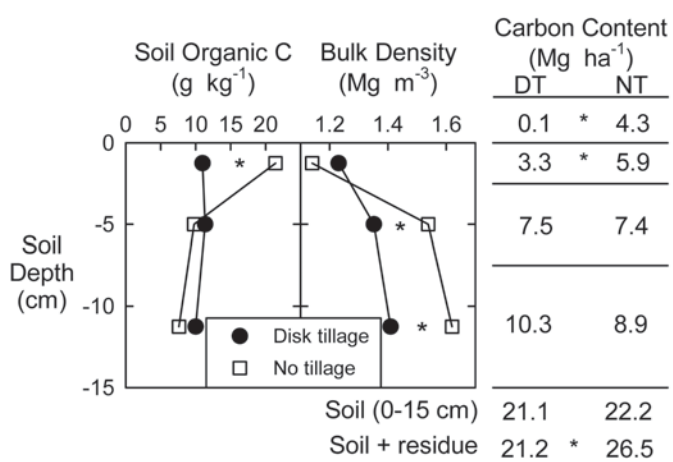

Fig. 16–2. Depth distribution of soil organic carbon concentration, soil bulk density, and soil organic C content at the end of 4 yr under conventional disk tillage (DT) and no-tillage (NT) in Georgia. *, significance between tillage systems at $p \leq 0.1$. (Data from Franzluebbers et al., 1999.)

With repeated inversion tillage, SOM becomes uniformly distributed within the plowed layer (Fig. 16–2). The fate of organic matter that is mixed into soil compared with that left on the soil surface depends on the prevailing climatic conditions. In general, however, the environment deeper in the soil profile is more buffered against extremes in moisture and temperature than at the soil surface. Greater moisture content in soil than on the soil surface is probably the biggest factor that leads to greater decomposition of organic matter in tilled soil (Franzluebbers et al., 1996).

Surface-placed crop residues under conservation tillage systems experience frequent drying and rewetting, depending on precipitation events. Decomposition of surface-placed residues is slower than that of buried residues (Brown and Dickey, 1970; Douglas et al., 1980; Wilson and Hargrove, 1986; Ghidey and Alberts, 1993). However, N concentration of remaining residues can increase with time relative to buried residues (Varco et al., 1993; Franzluebbers et al., 1994b). Typically, residues higher in N concentration decompose faster than residues low in N concentration (Vigil and Kissel, 1991). This contradiction suggests that frequent drying and rewetting of surface-placed residues increases the resistance of certain N compounds to microbial decomposition (Franzluebbers et al., 1994b), which leads to greater total N accumulation in the surface of NT soils. More work is needed to understand the transformations that occur during decomposition of various crop residues under different micro- and macroclimatic conditions.

At the end of 8 yr of different tillage management systems on a Fluventic Eutrudept in Italy, soil organic C in the surface 20 cm was greater under minimum tillage and ripper subsoiling than under conventional tillage (CT) (Piovanelli et al., 2006). Concomitant with changes in total organic C, extractable C and humified C were also greater in the surface 10 cm of soil than with less disturbance.

Since tillage and residue management systems alter the dynamics of SOM formation and decomposition, it has also been of keen scientific interest to characterize how management affects the quality of organic matter in various fractions.

Particulate Organic Carbon

Particulate organic C is a methodologically defined soil fraction that is often associated with the slow pool of organic C between active and passive pools (Parton et al., 1987; Cambardella and Elliott, 1992). It is determined as a sand-sized fraction (>53 μm) of organic matter derived from semidecomposed aboveground crop residues near the soil surface or roots below the soil surface. Particulate organic C is often greater near the soil surface than at lower depths because of the dominant input from aboveground crop residues (Fig. 16–3). Surface-residue retention with NT can lead to greater particulate organic C near the soil surface than with inversion-tillage systems.

At the end of 8 yr of NT management in the semiarid region of eastern Colorado, particulate organic C within the surface 10 cm of soil was predominantly (85%) located in the surface 2.5 cm of soil (Ortega et al., 2002). Soil residue (0–10 cm) and surface residue C in this NT experiment were 0.6 and 0.4 Mg ha^{-1}, respectively, under wheat–fallow, and 1.0 and 1.4 Mg ha^{-1}, respectively, under wheat–corn–millet–fallow. Greater soil- and surface residue C in the latter cropping system were related to greater crop biomass production as a result of greater cropping intensity (Peterson et al., 1993). In long-term studies, a positive relationship between the input of crop residue C and the stock of total soil organic C has

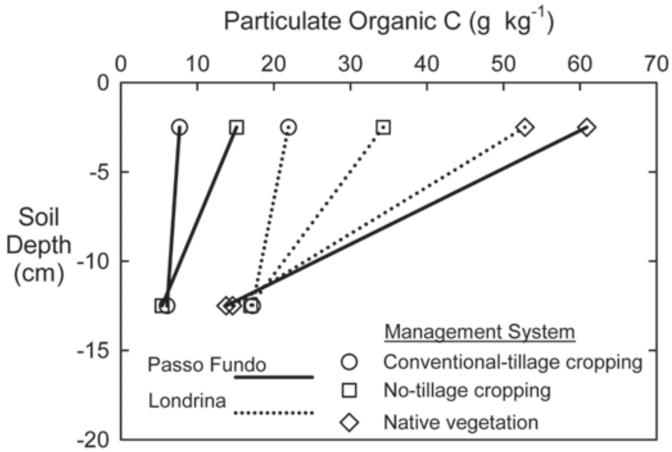

Fig. 16–3. Depth distribution of particulate organic carbon as affected by tillage management of crops and long-term, undisturbed native vegetation at two locations in Brazil. (Data from Zotarelli et al., 2007.)

been frequently found, including in Iowa (Larson et al., 1972), in Montana (Black, 1973), in Oregon (Rasmussen et al., 1980), in Colorado (Wood et al., 1991), in Texas (Franzluebbers et al., 1998), throughout the U.S. Corn Belt (Huggins et al., 1998), in Minnesota (Clapp et al., 2000), and in Ohio (Jacinthe et al., 2002).

Avoiding soil disturbance is a key factor for accumulation of particulate organic C in soil. Comparing different long-term land uses in Georgia, particulate organic C was greatest under grassland ecosystems in the surface 5 cm, but greatest under forestland at depths of 5 to 20 cm (Fig. 16–4). Surface residue C averaged 2.1, 3.1, 2.2, and 19.4 Mg C ha^{-1} under cropland, hayed grassland, grazed pasture, and forestland, respectively (Franzluebbers et al., 2000). The extent of soil biotic activity to incorporate surface residue was much greater under grassland than under forestland, probably because of low soil pH that limited microbial activity in the unmanaged forest. Particulate organic C accumulation was rapid near the soil surface in three of four different soils converted from cropping with inversion tillage to nondisturbed condition with alfalfa in China (Fig. 16–5). In this study, the proportion of total organic C as particulate organic C increased as sand concentration of soil increased (Su, 2007), suggesting that coarse-textured

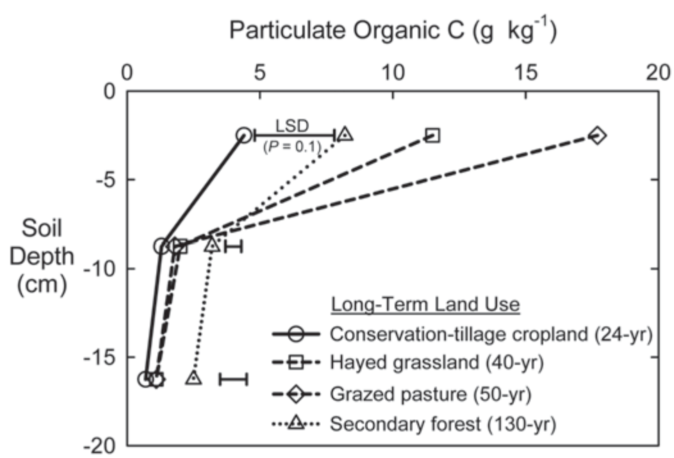

Fig. 16–4. Depth distribution of particulate organic carbon under four different long-term land uses in Georgia. (Data from Franzluebbers and Stuedemann, 2002.)

soils benefit as much or more than fine-textured soils from conservation management of the soil surface. Difference in surface-soil accumulation of particulate organic C also occurred in two Oxisols in Brazil (Fig. 16–3). Managing these soils with NT compared with CT resulted in 10 ± 4 g kg^{-1} greater particulate organic C in the surface 5 cm of soil, but values under NT were only 13 and 41% of particulate organic C under native vegetation at Passo Fundo and Londrina, respectively (Zotarelli et al., 2007).

When particulate organic matter of different sizes (0.075–0.25 and 0.25–2 mm) was added to soil, its relative decomposition was similar to whole-soil mineralization (Yakovchenko et al., 1998). The decomposability of particulate organic matter does not appear to be affected by tillage management, since specific mineralization of particulate organic C was similar between shallow tillage and NT in northwestern Canada (Franzluebbers and Arshad, 1997a). However, the ratio of specific particulate organic C mineralization to specific whole-soil organic C mineralization was greater under NT (1.3) than under shallow tillage (1.0) (Franzluebbers and Arshad, 1997a), suggesting that particulate organic C was of higher quality (i.e., more mineralizable) under NT relative to other pools of soil organic C.

Enrichment of particulate organic matter with persistent metals has been observed (Besnard et al., 2001; Balabane and van Oort, 2002). Balabane and van Oort (2002) demonstrated that metal enrichment was related to the extent of particulate organic matter decay and residence time in soil. The smaller the diameter of particulate organic matter, the denser the fraction and the more enriched in Zn, Pb, and Cd. However, crop residue mineralization was not thought to be affected by the presence of metals in particulate organic matter (Balabane and van Oort, 2002). Greater sorption rate of Zn and Cu to surface soil managed with NT than with CT was due to accumulation of soil organic C (Düring et al., 2002). However, transport of these metals vertically through the soil profile and horizontally across the landscape would be expected to be lower with NT than with CT, because of reduced availability.

Loss of particulate organic C following conversion of native vegetation to cropland can be dramatic, as a result of inversion tillage that mixes organic matter, breaks down aggregates, and stimulates microbial decomposition of particulate organic matter. Following 20 yr of cultivation in Nebraska, particulate organic C

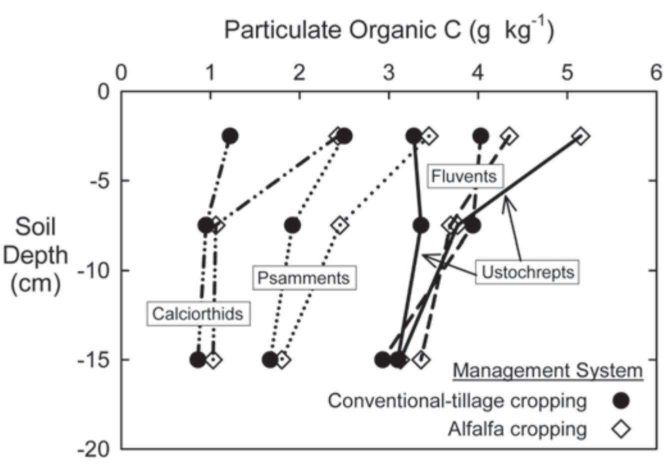

Fig. 16–5. Depth distribution of particulate organic carbon at the end of 4 yr of undisturbed soil management with alfalfa cropping compared with conventional-tillage cropping in four soils in China. (Data from Su, 2007.)

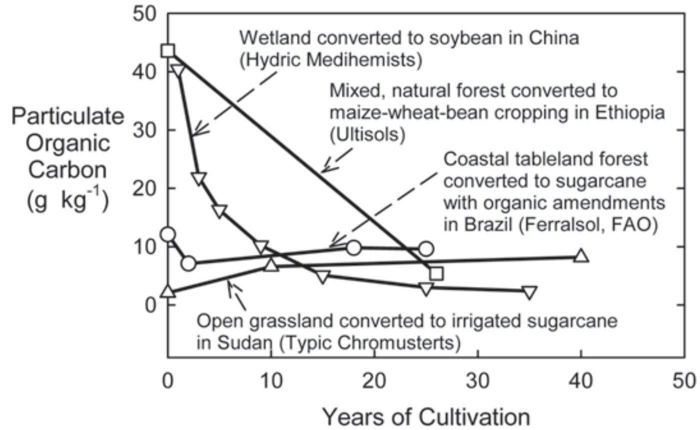

Fig. 16–6. Particulate organic carbon in four different cropping chronosequences following removal of native vegetation. (Data for China from Zhang et al., 2007; for Ethiopia from Ashagrie et al., 2007; for Brazil from Silva et al., 2007; and for Sudan from Mubarak et al., 2005.)

concentration in the 0- 20-cm depth was reduced to 43 ± 11% of that under native grassland (Cambardella and Elliott, 1992). Depending on the condition of native vegetation and extent of disturbance with subsequent cultivation, particulate organic C may decline dramatically during several decades or remain relatively stable (Fig. 16–6). Certainly it seems that soils relatively high in organic matter concentration have greater potential to lose particulate organic C on disruptive land conversion. How cultivated soils are subsequently managed can also lead to large effects on particulate organic C in surface soil (Table 16–1). Conservation tillage and organic amendments are two important management variables that help to increase particulate organic C concentration in soil.

Aggregate-Associated Organic Carbon

Not only is organic matter stratified with depth, but it can also be stratified three-dimensionally within aggregates of different size. Soil disturbance results in a more uniform distribution of organic substrates within soil. Lack of soil disturbance leads to concentration of organic matter within soil macroaggregates, which protect and isolate SOM from consumption by soil fauna and microorganisms (Beare et al., 1994a, 1994b; Franzluebbers and Arshad, 1997b; Six et al., 2000b). Soil disturbance with tillage breaks apart macroaggregates and allows organic matter, once protected from decomposition, to be exposed to new environments and communities of organisms. Mineralization of organic C following disruption of soil macroaggregates is rapid, suggesting that this organic matter is highly labile on exposure (Fig. 16–7).

A hierarchical approach to aggregate formation has been theorized, such that macroaggregates (>0.25 mm) form as a result of root entanglement and polysaccharides produced by heterotrophic microorganisms, which decompose particulate organic matter and glue microaggregates (0.05–0.25 mm) together (Tisdall and Oades, 1982). From a compilation of studies, aggregation characteristics of cultivated soils of surface soil have mostly been shown to be poorer than in soils left undisturbed with natural vegetation (Table 16–2). For example, mean-weight diameter averaged 67% greater and aggregate stability or macroaggregation averaged 45% greater under uncultivated than cultivated conditions (Table 16–2). In a

Table 16–1. Particulate organic carbon concentration of surface soil as affected by tillage system in various published studies.

Location	Soil type	Texture†	Years	Depth	Tillage system		Notes	Reference
					Inversion	Conservation		
				cm	—— $g\ kg^{-1}$ soil ——			
Alberta	Mollic Cryoboralf	CL	4	0–5	17.4	18.8		Franzluebbers and Arshad, 1997a
Alberta	Typic Natriboralf	C	6	0–5	9.1	12.6		Franzluebbers and Arshad, 1997a
British Columbia	Typic Cryoboralf	L	7	0–5	10.6	11.4		Franzluebbers and Arshad, 1997a
British Columbia	Typic Cryoboralf	SiL	16	0–5	16.1	20.9		Franzluebbers and Arshad, 1997a
Burkina Faso	Ferric Lixisol (FAO)	SL	10	0–15	0.9	1.1	Without manure	Mando et al., 2005
Burkina Faso	Ferric Lixisol (FAO)	SL	10	0–15	3.0	3.2	With manure	Mando et al., 2005
Colorado	Aridic Argiustoll	CL	11	0–5	2.1	2.7		Frey et al., 1999
Georgia	Rhodic Kanhapludult	SCL	13	0–5	1.9	5.5		Beare et al., 1994b
Georgia	Typic Kanhapludult	SL	4	0–2.5	2.9	10.8 ± 2.1		Franzluebbers et al., 1999
Illinois	Aquic Argiudoll	SiL	10	0–5	2.9	5.3		Wander et al., 1998
Illinois	Aquic Hapludoll	SiL	10	0–5	3.6	8.6		Wander et al., 1998
Illinois	Typic Haplaquoll	SiCL	10	0–5	10.3	10.3		Wander et al., 1998
Illinois	Oxyaquic Fragiudalf	SiL	8	0–5	4.1	7.1		Hussain et al., 1999
Illinois	Argiudoll-Argiaquoll	SiCL	>5	0–5	4.4	5.8	36-field survey	Needelman et al., 1999
Illinois	Argiudoll-Argiaquoll	SiCL	>5	0–15	3.5	3.7	36-field survey	Wander and Bollero, 1999
Iowa	Hapludolls-Udorthents	SiL	20	0–15	3.3 ± 0.4	4.4	Watershed scale	Cambardella et al., 2004
Kansas	Cumulic Haplustoll	SiL	22	0–5	2.3	4.0		Frey et al., 1999
Kentucky	Typic Paleudalf	SiCL	26	0–5	1.7	3.2		Frey et al., 1999

Location	Soil type	Texture†	Years	Depth	Tillage system		Notes	Reference
					Inversion	Conservation		
				cm	—— g kg^{-1} soil ——			
Kentucky	Typic Paleudalf	SiCL	25	0–20	1.7	2.3		Six et al., 1999
Michigan	Typic Hapludalf	SL	10	0–20	1.5	1.4		Six et al., 1999
Morocco	Vertic Calcixeroll	C	11	0–2.5	8.3	13.2		Mrabet et al., 2001
Nebraska	Pachic Haplustoll	L	26	0–5	1.4	4.4		Frey et al., 1999
Nebraska	Pachic Haplustoll	L	27	0–20	1.5	2.3		Six et al., 1999
New South Wales	Typic Pellustert	C	10	0–15	3.8	5.6 ± 0.4		Hulugalle and Entwistle, 1997
North Dakota	Pachic Haplustoll	SiL	16	0–7.5	2.9	9.0		Liebig et al., 2004
North Dakota	Typic Argiboroll	SiCL	12	0–5	2.6	2.6		Frey et al., 1999
Ohio	Typic Fragiudalf	SiL	34	0–20	2.0	3.1		Six et al., 1999
Texas	Torrertic Paleustoll	SiCL	15	0–5	1.3	1.3		Frey et al., 1999
Zimbabwe	Rhodic Paleustalf	C	9	0–30	1.9	2.4		Chivenge et al., 2007
Zimbabwe	Udic Kandiustalf	LS	9	0–30	0.8	1.8		Chivenge et al., 2007
Inversion vs. conservation tillage (paired *t* test, $n = 30$, $p < 0.001$)					4.3	6.3		

† C, clay; CL, clay loam; L, loam; LS, loamy sand; SCL, sandy clay loam; SiL, silt loam; SiCL, silty clay loam; SL, sandy loam.

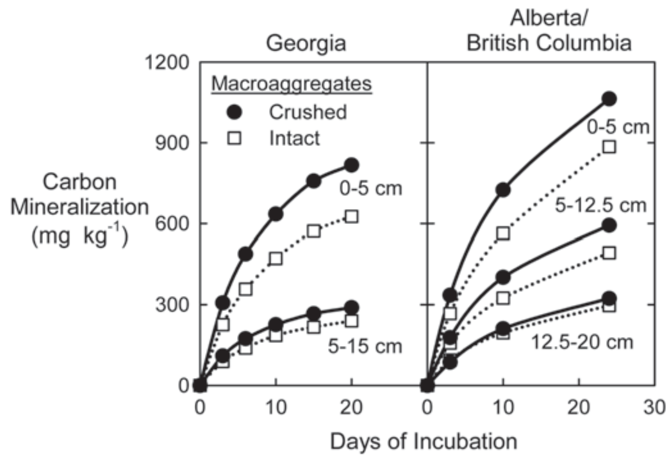

Fig. 16–7. Mineralization of carbon during incubation of intact and crushed macroaggregates (>0.25 mm) from different soil depths. (Data for Georgia from Beare et al., 1994a; and for Alberta and British Columbia, from Franzluebbers and Arshad, 1996c.)

similar manner, soils under conservation tillage would be expected to have better aggregation characteristics than soils with continuous inversion tillage. Available data suggest that macroaggregates under NT have a slower turnover time than under CT because of less physical perturbation, resulting in macroaggregates under NT that are enriched in fine particulate organic matter, which is more resistant to decomposition (Six et al., 2000a).

No-tillage often leads to an improvement in soil structure because of reduced mechanical disturbance and greater reliance on soil organisms that deposit enriched organic debris along permanent soil pores. However, the depth to which changes in soil aggregation occurs may be limited, at least in the first decade. From a set of four soils in northern Alberta and British Columbia, the fraction of soil as water-stable macroaggregates (>0.25 mm) was greater under NT than under CT in the surface 12.5 cm, but not below this depth (Franzluebbers and Arshad, 1996c). Enrichment of the soil surface with crop residues under NT led to significantly greater macroaggregation, especially in soils with coarse texture since the level of macroaggregation was lower than in soils with fine texture. Fine-textured soils have a higher inherent level of macroaggregation, even with soil disturbance, due to the cohesive nature of highly reactive clays. This higher inherent level of aggregation may limit improvement with adoption of conservation tillage.

A continuous supply of crop residues and organic amendments is needed to supply microorganisms with readily available substrates and, therefore, produce the biochemical products of decomposition that help create stable aggregates. With 8 yr of a gradient in wheat straw application to an Aeric Ochraqualf in Ohio, soil organic C and mean-weight diameter of water-stable aggregates increased with increasing residue application rate, irrespective of whether soil was tilled or not (Duiker and Lal, 1999).

Additional organic C input to soil via cover crops and animal manure is another management strategy that improves soil organic C and macroaggregate formation. With 13 yr of farmyard manure and green manure additions to a Typic Ustipsamment in India, soil organic C and mean-weight diameter of water-stable aggregates were greater than without additions (Singh et al., 2007). On

Table 16–2. Soil aggregation characteristics as affected by cultivated and uncultivated management in various published studies.

Location	Soil type	Texture‡	Depth	Response variable§	Management system†		Notes	Reference
					Cultivated	Uncultivated		
			cm					
Brazil	Typic Haplothorox	C	0–5	MWD (mm)	2.0 (CT) 3.0 (NT)	4.2	3 yr of cultivation following grass	Pinheiro et al., 2004
				Macroaggregates (%)	77 (CT) 87 (NT)	96		
				Organic C (g kg^{-1})	11 (CT) 18 (NT)	21.8		
Brazil	Rhodic Hapludox	NA	0–5	MWD (mm)	0.8 (CT) 0.9 (NT)	1.4	20 yr of cultivation compared with Cerrado	Green et al., 2007
				Organic C (g m^{-3})	25 (CT) 30 (NT)	43.3		
Brazil	Ferralsol (FAO)	SC	0–20	Aggregate stability (%)	72	88	18–25 yr of sugarcane cultivation compared with native forest	Silva et al., 2007
				Organic C (g kg^{-1})	24.8	26.2		
China	Aridisols	SL	0–15	Aggregate stability (%)	2.3 ± 1.1	2.2 ± 1.4	26 ± 36 yr of irrigated cultivation compared with desertic vegetation	Li et al., 2007
				Organic C (g kg^{-1})	5.2 ± 1.7	2.9 ± 0.6		
Ethiopia	Ultisols	C	0–20	MWD (mm)	0.4	0.9	26 yr of CT cultivation compared with natural forest	Ashagrie et al., 2007
				Macroaggregates (%)	50	73		
				Organic C (g kg^{-1})	34 ± 5	72 ± 7		
Georgia	Typic Kanhapludult	SCL	0–20	MWD (mm)	1.0	0.9	130 yr of cultivation with past 24 yr under NT compared with secondary forest	Franzluebbers et al., 2000
				Macroaggregates (%)	75	73		
				Organic C (g kg^{-1})	7.8	11.0		
Nebraska	Pachic Haplustoll	L	0–30	MWD (mm)	0.4	1.2	14 yr of cultivation compared with native grassland	Elliott, 1986
				Macroaggregates (%)	24	48		
				Organic C (g kg^{-1})	18.2	23.5		
Nigeria	Oxic Tropudalf	SCL	0–20	MWD (mm)	0.6	0.9	CT cultivation compared with rainforest	Adesodun et al., 2007
				Macroaggregates (%)	67	84		
				Organic C (g kg^{-1})	18.7	23.1		

Table continued.

Table 16–2. Continued.

Location	Soil type	Texture‡	Depth	Response variable§	Management system†		Notes	Reference
					Cultivated	Uncultivated		
			cm					
Nigeria	Oxic Paleustalf	SCL	0–20	MWD (mm) Macroaggregates (%) Organic C (g kg^{-1})	0.8 59 44.0	1.1 72 38.4	CT cultivation compared with savanna	Adesodun et al., 2007
North Dakota	Pachic Haplustoll	SiL	0–7.5	Aggregate stability (%) Organic C (g kg^{-1})	14 (CT) 47 (NT) 18 (CT) 28 (NT)	93 49.5	16 yr of cultivation compared with grazed pasture	Liebig et al., 2004
Queensland	Chromic Luvisol (FAO)	SL	0–10	MWD (mm) Macroaggregates (%) Organic C (g kg^{-1})	0.4 26 10.2	1.7 85 33.5	20 yr of sugarcane cultivation compared with pasture	Blair, 2000
MWD (paired *t* test, n = 8, p = 0.01)					0.9	1.5		
Aggregate stability/macroaggregation (paired *t* test, n = 10, p = 0.01)					49	71		
Soil organic C (paired *t* test, n = 11, p = 0.03)					20.8	31.4		

† CT, conventional tillage; NT, no-tillage.

‡ C, clay; L, loam; NA, not available; SC, sandy clay; SCL, sandy clay loam; SiL, silt loam; SL, sandy loam.

§ MWD, mean-weight diameter.

two Cryoboralfs in Saskatchewan, 5 yr of NT compared with CT led to greater soil organic C and mean-weight diameter of dry-stable aggregates (Malhi and Kutcher, 2007). Whether crop residues were burned or not had less impact on soil organic C and mean-weight diameter, suggesting that aboveground inputs may be secondary to belowground inputs in affecting soil organic C and aggregation.

Biologically Active Organic Carbon

Biologically active fractions of SOM are important in assessing nutrient cycling, decomposition potential, and biophysical manipulation of soil structure. Biologically active fractions of SOM include microbial biomass, readily mineralizable C and N, and some chemical indices of labile organic substrates. All of these fractions have a relatively short turnover time and would be part of the active pool of the active–slow–passive SOM continuum (Parton et al., 1987). From a compilation of studies, mineralizable C and N were generally greater under NT than under inversion-tillage systems (Table 16–3). As with other pools of organic matter, differences in mineralizable C between tillage systems tend to be greatest nearest the soil surface. Data in Table 16–3 were compiled from the uppermost sampling depth reported and, therefore, are not necessarily representative of results that might occur summed to the surface 20 to 30 cm of soil. Mineralizable C represents potential activity under optimum temperature and moisture conditions. As such it represents the lack of in situ mineralization that might occur in the field. Inversion tillage that stimulates microbial activity in the field leads to an exhaustion of substrates that would otherwise contribute to this mineralizable C pool.

Lack of C input to feed the heterotrophic community of soil organisms will lead to a reduction in biologically active SOM pools. When sorghum residues were removed for 6 yr from an Entic Pellustert in Australia, mineralizable C of the surface 10 cm of soil declined an average of 29% (Saffigna et al., 1989). Microbial biomass N in the surface 10 cm of soil was reduced 16 ± 8% in an Udic Pellustert in Australia following 20 yr of burning of wheat and barley residues compared with residue retention (Dalal et al., 1991). During the ninth and 10th years of a cropping system study on a Fluventic Ustochrept in Texas, mineralizable C increased linearly with additional C input from more intensive cropping systems under both CT and NT (Franzluebbers et al., 1998). In this study there was no evidence of an interaction between cropping intensity and tillage management on the response in mineralizable C, as slopes between tillage systems were essentially the same.

Accumulation of residues at the soil surface with conservation tillage systems also provides a habitat for a variety of soil fauna, which have important implications on the cycling of organic matter into biologically active pools (Kladivko, 2001). The most visible effect of conservation tillage is on earthworms. Earthworms require a moist environment with adequate organic debris, both of which are provided by conservation tillage. In a Typic Rhodudult in Georgia, earthworms, microarthropods, and various macroarthropods were two- to severalfold more numerous under NT than under CT as a result of the stratification of organic debris near the soil surface (House and Parmelee, 1985). Earthworms can determine whether soil macro- and microstructures are biogenically or physicogenically derived, thus mitigating topsoil compaction (Jongmans et al., 2003).

Table 16–3. Mineralizable C in surface soil as affected by tillage system in various published studies.

Location	Soil type	Texture†	Years	Depth	Tillage system		Reference
					Inversion	Conservation	
				cm	—— mg kg^{-1} d^{-1} ——		
Alabama	Typic Hapludult	fSL	10	0–5	7	14	Wood and Edwards, 1992
Alabama	Udults-Xeralfs	SL	13	0–5	11	13	Causarano-Medina et al., 2008
Alabama	Kanhapludults	SL	10	0–5	10	15	Causarano-Medina et al., 2008
Alberta	Typic Boroll	SiL	16	0–4	12	16	Carter and Rennie, 1984
Alberta	Mollic Cryoboralf	CL	4	0–5	63	42	Franzluebbers and Arshad, 1996b
Alberta	Typic Natriboralf	C	6	0–5	22	29	Franzluebbers and Arshad, 1996a
Argentina	Typic Argiudoll	SiL	15	0–5	14	51	Alvarez et al., 1998
British Columbia	Typic Cryoboralf	SiL	16	0–5	49	50	Franzluebbers and Arshad, 1996b
British Columbia	Typic Cryoboralf	L	7	0–5	50	34	Franzluebbers and Arshad, 1996b
Burkino Faso	Ferric Lixisol (FAO)	SL	10	0–15	2	3	Mando et al., 2005
Georgia	Rhodic Kanhapludult	SCL	13	0–5	22	37	Beare et al., 1994b
Georgia	Typic Kanhapludult	SL	4	0–2.5	19	70	Franzluebbers et al., 1999
Georgia	Kandiudults	SL	15	0–5	6	16	Causarano-Medina et al., 2008
Georgia	Kanhapludults	SL	8	0–5	16	21	Causarano-Medina et al., 2008
Michigan	Typic Hapludalf	L	8	0–20	2.9	3.1	Collins et al., 2000
Nebraska	Pachic Haplustoll	L	16	0–10	11	22	Follett and Schimel, 1989
New Zealand	Udic Dystrochrept	SiL	5	0–2.5	30	38	Haynes, 1999
North Carolina	Psamments-Udults	SL	8	0–5	5	12	Causarano-Medina et al., 2008
North Carolina	Kanhapludults	SL	13	0–5	11	26	Causarano-Medina et al., 2008
Ohio	Mollic Ochraqualf	SiCL	30	0–20	4.0	7.9	Collins et al., 2000

Location	Soil type	Texture†	Years	Depth	Tillage system		Reference
					Inversion	Conservation	
				cm	—— mg kg^{-1} d^{-1} ——		
Ohio	Typic Fragiudalf	SiL	30	0–20	3.6	5.6	Collins et al., 2000
Queensland	Entic Pellustert	SC	5	0–10	4.6	3.2	Saffigna et al., 1989
Saskatchewan	Typic Haploboroll	L	6	0–7.5	12	21	Campbell et al., 1989
Saskatchewan	Udic Boroll	CL	12	0–5	15	20	Carter and Rennie, 1984
Saskatchewan	Typic Boroll	CL	4	0–5	15	26	Carter and Rennie, 1984
Saskatchewan	Typic Boroll	L	2	0–5	14	14	Carter and Rennie, 1984
South Carolina	Udults	SL	16	0–5	7	14	Causarano-Medina et al., 2008
South Carolina	Kanhapludults	SL	15	0–5	18	26	Causarano-Medina et al., 2008
Texas	Fluventic Ustochrept	SiCL	9	0–5	11	21	Franzluebbers et al., 1994a
Texas	Typic Ochraqualf	SCL	15	0–20	13	19	Salinas-Garcia et al., 1997
Virginia	Udults–Udalfs	SL	13	0–5	12	25	Causarano-Medina et al., 2008
Virginia	Udults	SL	9	0–5	12	21	Causarano-Medina et al., 2008
Wisconsin	Typic Hapludalf	SiL	12	0–5	7	35	Karlen et al., 1994
Inversion versus conservation tillage (paired *t* test, $n = 33$, $p = 0.001$)					15	23	

† C, clay; CL, clay loam; fSL, fine sandy loam; L, loam; SC, sandy clay; SCL, sandy clay loam; SiL, silt loam; SiCL, silty clay loam; SL, sandy loam.

Surface accumulation of residues with NT also leads to changes in soil microbial community composition. The proportion of microbial biomass composed of fungi was greater under NT than under CT in several long-term experiments, including in Colorado, Kentucky, Nebraska, North Dakota, and Texas (Frey et al., 1999), as well as in Georgia (Beare et al., 1993). In an Oxisol in Brazil, soil enzyme activities and mineralizable C and N were enhanced in surface soil under NT relative to CT (Green et al., 2007), suggesting greater biological potential of NT surface soils.

Stratification of Organic Carbon and Environmental Quality

Stratification of SOM with soil depth is common in many natural ecosystems and managed grasslands and forests (Schnabel et al., 2001), as well as cropland under long-term conservation tillage (Stockfisch et al., 1999). Stratification of SOM fractions with depth under conservation-tillage systems has consequences on C storage, but also on other important soil functions. The soil surface is the vital interface that (i) receives much of the fertilizers and pesticides applied to cropland, (ii) receives the intense impact of rainfall, and (iii) partitions the fluxes of gases and water into and out of soil. It has been hypothesized that the degree of SOM stratification can be used as an indicator of soil quality or soil ecosystem functioning because surface organic matter is essential to erosion control, water infiltration, conservation of nutrients, and controlling greenhouse gas emissions (Franzluebbers, 2002a).

No-tillage management of a 2.7-ha cropped watershed for 24 yr on a Typic Kanhapludult in Georgia reduced water runoff to 22 mm yr^{-1} compared with 180 mm yr^{-1} under previous management with conventional inversion tillage (Endale et al., 2000). Soil loss was even more dramatically reduced with NT management (3 vs. 129 kg ha^{-1} mm^{-1} runoff). A greenhouse study to separate the short- and long-term effects of disturbance on soil hydraulic properties of this same soil revealed that previous doubling of soil organic C content in freshly tilled soil improved water infiltration by 27% (Franzluebbers, 2002b). However, water infiltration was 3.3 times greater in intact cores from long-term conservation tillage with a high degree of SOM stratification compared with intact cores from a long-term conventionally tilled soil (but untilled during the previous 14 mo) with a low degree of SOM stratification. Thus, surface accumulation of soil organic C was more effective for water infiltration than uniform distribution of organic C in soil.

Stratification of SOM with conservation tillage depends on (i) the inherent level of SOM dictated by climatic conditions, (ii) type and intensity of soil disturbance, (iii) type of cropping system, which determines the quantity and quality of organic C inputs, and (iv) years of management. In an analysis of stratification ratios (soil organic C in the surface 5 cm divided by that at 12.5–20 cm depth) under NT in three different ecoregions, greater differences in the stratification of soil organic C between tillage systems occurred in hot–wet–low SOM environments than in cold–dry–high SOM environments (Fig. 16–8). Those soils with low inherent levels of organic matter may be the most functionally improved with conservation tillage, despite modest or no change in total standing stock of soil organic C within the rooting zone. Alternatively, those soils with inherently high SOM even under CT management would likely obtain relatively little additional soil functional benefit with adoption of conservation tillage, since inherent soil properties would be at a high level.

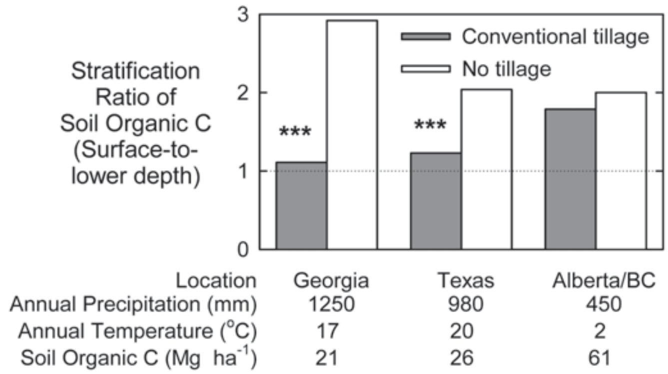

Fig. 16–8. Stratification ratio of soil organic carbon under conventional tillage and no-tillage at three locations differing in climatic characteristics and content of soil organic C. *, significance between tillage systems at $p \leq 0.001$. (Data from Franzluebbers, 2002a.)**

Stratification ratio of particulate organic C in a Typic Kanhapludult in Georgia was greatest in a cropping system with minimum soil disturbance and lowest in a cropping system with frequent disturbance (Franzluebbers, 2002a). Less-intensive mixing of soil preserves crop residues and SOM near the soil surface, where it has the most beneficial impact. Stratification of mineralizable C in a Fluventic Ustochrept in Texas increased with increasing cropping intensity under CT but was always greater under NT than under CT, independent of cropping intensity (Franzluebbers, 2002a). More-intensive cropping increases the quantity of residues produced, which can lead to higher levels of SOM.

Stratification ratio of soil organic C (0–2.5 cm and 12.5–20 cm depth) in an Aquic Hapludult in Maryland was 1.0 under plow tillage and increased with time under NT from 1.1 at 1 yr, to 1.4 at 2 yr, and to 1.5 at 3 yr (McCarty et al., 1998). From a survey of farms in the southeastern United States, stratification ratio of soil organic C (0–5 cm and 12.5–20 cm depth) increased from an average of 1.4 under CT to a plateau of 2.7 within 10 yr of conservation tillage (Causarano-Medina et al., 2008). Stratification ratios of particulate organic C, microbial biomass C, and mineralizable C were also greater under conservation tillage than under CT, but ratios were even greater under pastures than under NT (Causarano-Medina et al., 2008). On a Typic Paleudalf in Kentucky, stratification ratio of soil organic C and extractable P increased with time under NT, and values after 2 yr of NT were always greater than under CT (Diaz-Zorita and Grove, 2002).

Stratification of Soil Nutrients

Many SOM fractions can become stratified with depth, including total, particulate organic, microbial biomass, and mineralizable C and N (Franzluebbers, 2002a). The degree of stratification appears to depend on the SOM fraction, soil type, climatic conditions, management, and time (Fig. 16–3 through 16–5, Fig. 16–8). Stratification of total soil N at the end of 20 yr of conservation-tillage management on a silt loam in Kentucky increased with increasing N fertilization (Fig. 16–9). Accumulation of total N at the soil surface was likely a function of greater crop production that contributed to surface-residue accumulation and subsequent decomposition at the soil surface (Ismail et al., 1994). Total soil N was highly stratified with depth under 9 yr of NT and ridge tillage on a Typic Calciustoll in Texas (Zibilske et al., 2002), as well as with 6 yr of NT on an Alfisol, Andisol,

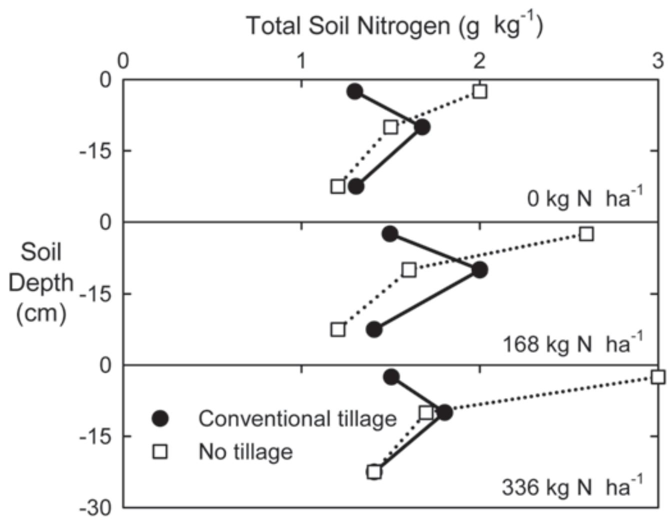

Fig. 16–9. Depth distribution of total soil N at the end of 20 yr of tillage and N-fertilization practices in Kentucky. (Data from Ismail et al., 1994.)

and two Vertisols in Mexico (Salinas-Garcia et al., 2002). Extractable P followed similar depth distribution patterns as total N and soil organic C in both of these studies, in which values were stratified with depth under NT and uniformly distributed with CT. At the end of 23 yr of NT management of a Pachic Argiustoll in Kansas, soil organic C was greater under NT than under CT within the surface 7.5 cm, but not below this depth (Guzman et al., 2006). Extractable P and K were greater under NT than under CT only at a depth of 0 to 2.5 cm, whereas extractable K, Ca, and Mg were lower under NT than under CT at a depth of 7.5 to 15 cm. On a Typic Hapludalf in Pennsylvania, SOM and pH were greater under NT than under CT at a depth of 0 to 5 cm due to surface-residue accumulation and 14.5 Mg ha^{-1} of lime application during 25 yr (Duiker and Beegle, 2006). Corresponding to changes in surface SOM, extractable P, K, Ca, and cation exchange capacity were also greater under NT than under CT at a depth of 0 to 5 cm. The low mobility of P in soil when surface applied appears to create an equally stratified distribution with depth as SOM fractions.

During the seventh to 10th years of NT on a Mollic Cryoboralf in Alberta, soil inorganic N was not different between tillage treatments, but soil microbial biomass N was greater at a depth of 0 to 10 cm under NT than under CT (Soon and Arshad, 2005). Level of soil microbial biomass N was positively correlated with barley and canola yield, indicating that turnover of labile N in surface SOM contributed significantly to crop yield. On a Typic Natrustalf in Queensland, soil organic C and total N at a depth of 0 to 10 cm were greater under NT than under CT at the end of 9 yr of management (Thomas et al., 2007). Exchangeable K and extractable P were also greater under NT than under CT, but exchangeable Mg and Na and cation exchange capacity were lower, suggesting greater solute movement through surface soil under NT than under CT. During the first 4 yr of NT management of a Calciortidic Haploxeralf in Spain, soil organic C and total N became greater with NT than with CT (Martin-Rueda et al., 2007). Extractable P, K, Fe, Mn, Cu, and Zn were also greater in the surface 30 cm of soil under NT than under CT, contributing to enhanced fertility and maintenance of yield. Similar enhancement of surface-soil nutrients was observed at the end of 8 yr of NT on a

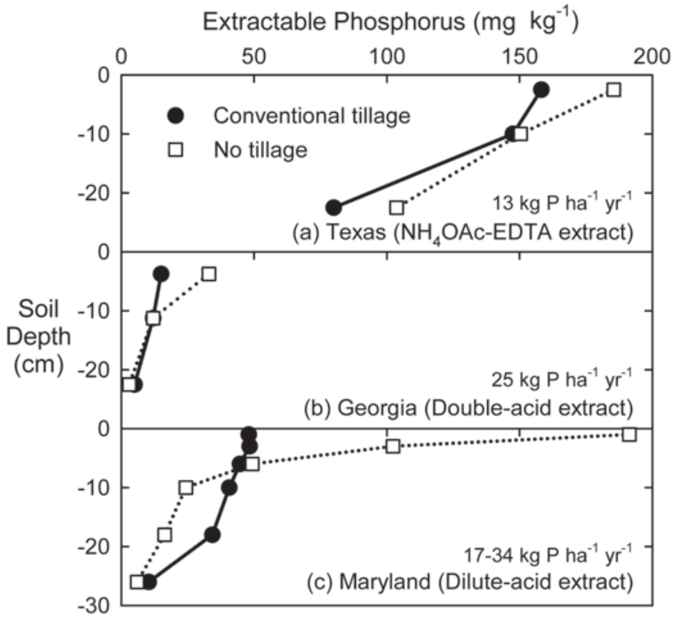

Fig. 16–10. Depth distribution of extractable soil P under conventional tillage and no-tillage at the end of 9 yr in Texas (a), at the end of 5 yr in Georgia (b), and at the end of 11 yr in Maryland (c). (Data for Texas from Franzluebbers and Hons, 1996; for Georgia from Hargrove et al., 1982; and for Maryland from Weil et al., 1988.)

Fluventic Ustochrept in Texas (Franzluebbers and Hons, 1996) and at the end of 5 yr of reduced tillage compared with CT in Texas (Wright et al., 2007). Greater stratification of soil nutrients under reduced tillage was associated with significantly greater cotton lint yield (Wright et al., 2007).

With the continuous application of P fertilizer (either inorganic or organic), stratification of soil P can occur in the soil profile, especially under conservation tillage. There is growing concern that continual manure application to pasture or conservation-tilled soils might lead to deterioration of surface-water quality from the accumulation of P at the soil surface (Sharpley, 2003). Different research organizations determine soil P with different extraction protocols, because of variations in management goals, soil mineralogy, and historical calibrations for various crops. Despite these differences, greater stratification of extractable soil P was observed under NT than under CT in a silty clay loam in Texas, a sandy loam in Georgia, and a silt loam in Maryland (Fig. 16–10). At the end of 4 yr of NT on a clay soil in Finland, organic C and water-extractable P were greater in the surface 5 cm of soil than under CT (Muukkonen et al., 2007). In this same report, but for a clay loam, no differences in C and P occurred between tillage systems.

The accumulation of surface SOM combined with high N-input cropping systems can lead to declining soil pH (Blevins et al., 1977) and concerns for micronutrient availability and loss of base cations (Limousin and Tessier, 2007). Incorporation of lime before implementation of NT alleviated soil acidity and increased barley grain and stover yield on a Mollic Cryoboralf in Alberta (Arshad et al., 1999). To alleviate soil acidity concerns after implementation of NT has begun, surface application of lime is recommended to be applied earlier and at a higher rate than under CT (Conyers et al., 2003). On a Rhodic Hapludox in Brazil, surface lime application to undisturbed soil successfully neutralized soil acidity and increased exchangeable Ca and Mg to a depth of 10 cm within 4 yr (Caires et al., 2006). Crop yield was not different between surface-applied and incorporated lime, but both of these treatments had greater crop yield than without liming. Economic return from liming was greater from surface-applied lime than from incorporated lime.

Mitigation of Greenhouse Gas Emission

Sequestration of soil organic C with conservation agricultural management practices has become increasingly recognized as a viable marketing strategy (e.g., trading of carbon credits through the Chicago Climate Exchange, which is a voluntary, greenhouse gas emission reduction and trading system) to take action against the rising CO_2 concentration in the atmosphere. Accumulation of soil organic C with conservation tillage can be slow (Franzluebbers and Arshad, 1996a) or not different from that under CT due to inherent soil variability and lack of differences in decomposition of organic C input despite differences in organic C placement (Angers et al., 1997; Deen and Kataki, 2003). However, the majority of research quantifying soil organic C change with conservation tillage compared with CT has resulted in positive soil organic C sequestration with conservation tillage, and especially NT (Franzluebbers and Steiner, 2002; West and Post, 2002). In reviews of quantitative data within a regional context, soil organic C sequestration rate with NT compared with CT averaged 0.27 Mg C ha^{-1} yr^{-1} in the northwestern United States and western Canada (Liebig et al., 2005), –0.07 Mg C ha^{-1} yr^{-1} in the northeastern United States and eastern Canada (Gregorich et al., 2005), 0.48 Mg C ha^{-1} yr^{-1} in the central United States (Johnson et al., 2005), 0.30 Mg C ha^{-1} yr^{-1} in the southwestern United States (Martens et al., 2005), and 0.42 Mg C ha^{-1} yr^{-1} in the southeastern United States (Franzluebbers, 2005). Coefficients of variation in these means were ≥70%, suggesting that a great deal more research is needed to understand the causes for this variation. Some possible reasons for high variation include length of time of comparisons, different responses due to soil type and cropping system, depth of sampling, inherent variability in soil organic C determinations, methods of calculations, and so forth.

Surface accumulation of soil organic C is a key characteristic of conservation-tillage systems, especially in soils with inherently low SOM content due to coarse soil texture or due to climatic conditions that promote rapid decomposition of organic matter. Although it may be possible to achieve significant soil organic C sequestration with depth in some soils (Fisher et al., 1994), available data from the southeastern United States indicates that soil organic C sequestration is primarily limited to the surface 12 cm of soil (Table 16–4). Soil organic C sequestration with conservation tillage compared with CT on working farms in the southeastern United States averaged 0.45 Mg C ha^{-1} yr^{-1}, with 90% of that occurring in the surface 5 cm of soil (Causarano-Medina et al., 2008). Soil organic C sequestration with pasture compared with CT averaged 0.74 Mg C ha^{-1} yr^{-1}, with 71% of that occurring in the surface 5 cm of soil. The longer time of pasture management combined with potentially deeper rooting of perennial vegetation probably contributed to significant sequestration of soil organic C to somewhat deeper depth.

Baker et al. (2007) argued that if the soil organic C content in the entire rooting profile were accounted (ca. 0–2 m), the only reasonable conclusion would be that conservation-tillage systems only change the depth distribution of soil organic C, not the total amount of C stored in soil. Their analysis of available

Table 16–4. Estimates of soil organic C sequestration by conservation tillage (12 ± 6 yr) and pasture management (24 ± 11 yr) relative to conventional tillage as a function of depth increment when averaged across sampling from 29 farms in the southeastern United States. (Data from Causarano-Medina et al., 2008.)

Soil depth	Soil organic C sequestration			
	Conservation tillage		Pasture management	
cm	Mg C ha^{-1} yr^{-1}			
0–5	0.41 ± 0.28	s†	0.53 ± 0.34	s
5–12.5	0.08 ± 0.31	ns‡	0.17 ± 0.26	s
12.5–20	−0.03 ± 0.25	ns	0.05 ± 0.18	ns
0–20	0.45 ± 0.69	s	0.74 ± 0.64	s

† s, significant from zero at $p \leq 0.05$.

‡ ns, not significant.

data did not fully appreciate the data-intensive studies (albeit few) that have been reported, in which soil has been collected at numerous depth increments and periodically with time. Certainly when considering soil depth, it becomes increasingly difficult to declare significance between treatments or with time due to lower concentrations with depth and greater coefficient of variation. In a 5-yr analysis of soil organic C and N with bermudagrass management in Georgia, coefficient of variation in soil organic C was approximately 30% in the surface 30 cm of soil but increased to 60% in the 30- to 60-cm depth, and even to 100% in the 60- to 90-cm depth (Franzluebbers and Stuedemann, 2005). Soil organic C and total N by depth increment throughout the soil profile in long-term tillage studies in Prince Edward Island (Carter, 2005) and in Minnesota (Dolan et al., 2006) also exhibited increasing coefficient of variation with depth, which led to conclusions of no difference in C and N stocks between tillage systems when summed across the soil profile. Data in Table 16–5 illustrate the implication of increasing variation with depth on our ability to declare significance of soil organic C sequestration. Assuming an estimate of soil organic C sequestration of 10 Mg C ha^{-1}, significance could be declared only within the surface 30 cm, but not below this depth, even if the estimate of soil organic C sequestration would not change with depth. More research is needed to quantify soil organic C content within the rooting profile of long-term cropping systems. Of particular importance is repeated sampling at regular intervals to obtain best estimates.

Table 16–5. Soil organic C content and its variation with depth in the soil profile at the end of 12 yr of pasture management. (Data from Franzluebbers and Stuedemann, 2008.)

Soil depth	Stock of soil organic C	LSD*
cm	Mg ha^{-1}	
0–15	38.4	6.0
0–30	50.0	8.9
0–60	59.9	11.2
0–90	63.8	11.7
0–120	66.2	12.3
0–150	68.1	12.7

* Significant at the 0.05 probability level.

Summary and Conclusions

Disturbance of soil has major impacts on soil physical properties, distribution of organic substrates within the soil profile, and accessibility of these substrates to soil biota. Conservation-tillage systems with surface-residue retention create a biologically intensive, yet ecologically protective interface between the soil profile and the atmosphere. Protection of the soil surface from natural physical forces that can cause severe degradation (i.e., wind, water, and traffic) is needed to allow soils to function to their highest potential. Storage of fixed C in soil, creating a nutrient-rich environment for the proliferation of plants, and allowing water to pass through and be filtered are some critical functions of soil that can be enhanced with conservation tillage and high residue retention systems. Although there is concern for high concentration of nutrients at the soil surface under conservation-tillage management, more watershed-level data are needed to fairly evaluate the consequences of nutrient enrichment of the soil surface on water quality. Stratification ratios of SOM fractions may be viable indicators of environmental quality, especially when land is managed with conservation tillage and surface residues are retained.

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