Chapter 2

Impacts of Soil Organic Carbon on Soil Physical Behavior

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Abstract

Management-induced changes in soil organic carbon (SOC) concentration can affect soil physical behavior. Specifically, removal of crop residues as biofuel may thus adversely affect soil attributes by reducing SOC concentration as crop residues are the main source of SOC. Implications of crop residue management for soil erosion control, water conservation, nutrient cycling, and global C cycle have been discussed, but the potential impacts of residue removal-induced depletion of SOC on soil physical properties have not been widely studied. We reviewed published information on the relationships of SOC concentration with soil structural stability, consistency, compaction, soil water repellency, and hydraulic properties with emphasis on crop residue management. Our review indicates that studies specifically assessing relationships between crop residue management-induced changes in SOC concentration and soil physical properties are few. These studies indicate, however, that crop removal or addition can alter SOC concentration and concomitantly affect soil physical attributes with a magnitude depending on the amount of residue removed or returned, constituents of residue-derived SOC, tillage and cropping system, soil type, and climate. Our review also indicates that, in general, management practices that effect SOC concentration can directly influence soil physical properties. Decrease in SOC concentration reduces subcritical water repellency and aggregate stability and strength, increases soil's susceptibility to excessive compaction, and reduces macroporosity, hydraulic conductivity, and water retention. Soil organic matter improves soil physical properties by providing organic binding agents, inducing slight water repellency, lowering soil bulk density, and improving the elasticity and resilience of the whole soil. The numerous benefits of SOC on soil physical attributes suggest that crop residues should be returned to soil to maintain or increase SOC concentration. Indiscriminate residue removal for off-farm uses reduces SOC pools and can adversely affect soil and environment. Crop residues not only protect the soil surface from erosive forces but also maintain SOC concentration, which is essential to improve soil physical behavior and sustain soil productivity. Management practices including no-till with residue return, continuous cropping systems, cover crops, and grass-based rotations should be promoted to further increase SOC concentration and thus improve soil physical behavior.

Abbreviations: SOC, soil organic carbon.

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Management practices including tillage, cropping systems, and crop residue removal or addition alter the concentration of organic C in the soil. The changes in SOC concentration may concomitantly impact soil physical attributes and soil productivity. Soil organic particles interact with inorganic particles to promote soil aggregation, increase porosity, and stabilize soil structure (Kay, 1997). Influence of soil organic matter on soil structure, nutrient cycling, C cycling, soil biological processes, and other ecosystem services has been studied (Weil and Magdoff, 2004), yet the mechanisms involved and the magnitude at which management-induced changes in SOC influence soil physical properties deserve further discussion.

Specifically, crop residue removal or addition dictates C input and SOC dynamics. At present, crop residues are confronted by a number of competing on- and off-farm uses. On one hand, crop residues are needed to conserve soil and water, reduce water and wind erosion, and maintain SOC concentration (Wilhelm et al., 2004). On the other hand, residues have potential off-farm uses including cellulosic ethanol production (Perlack et al., 2005), fiber production (Reddy and Yang, 2005), and livestock feed (Tanaka et al., 2005).

Influence of residue-management-induced SOC gains or losses on soil physical behavior such as structural stability, compactibility, and soil-water relationships has not been widely documented. Changes in soil physical properties and SOC concentration in residue management studies have often been discussed as static or separate parameters with little emphasis on the mutual interrelationships between soil structure and SOC. A synthesis of information on SOC vs. soil physical behavior relationships is needed to better understand the implications that crop residue management may have on soil physical properties. Correlations between soil structural properties and SOC concentration have been reported, but information is fragmented and has not been presented in a common framework applied to crop residue management.

Therefore, the specific objective of this chapter is to discuss the relationships of SOC with soil structural stability, consistency, compaction, soil water repellency, and hydraulic properties based on published studies with emphasis on crop residue management. We reviewed (i) published studies, which assessed the independent effects of crop residue management on soil physical properties and SOC concentration and (ii) relevant studies reporting information on SOC vs. soil properties deserve discussion to better understand interactions and soil-specific response to crop residue management.

Factors that Affect Relatiohships between Organic Carbon and Soil Physical Properties

The extent at which changes in SOC concentration affect soil physical properties depends on various interacting factors including climatic conditions, amount and constituents of SOC, textural class, tillage management, and others (Fig. 2–1). For example, climate in interaction with tillage and cropping systems directly influences crop residue production and rates of soil organic matter decomposition (Benjamin et al., 2008). The numerous interacting factors make the characterization of SOC influence on soil physical and hydraulic properties somewhat difficult.

Amount and Constituents of Soil Organic Carbon

Both amount and form of SOC influence soil physical behavior. A narrow range of SOC concentrations among residue management systems may have reduced or no effects on soil physical properties. In the central Great Plains, correlation

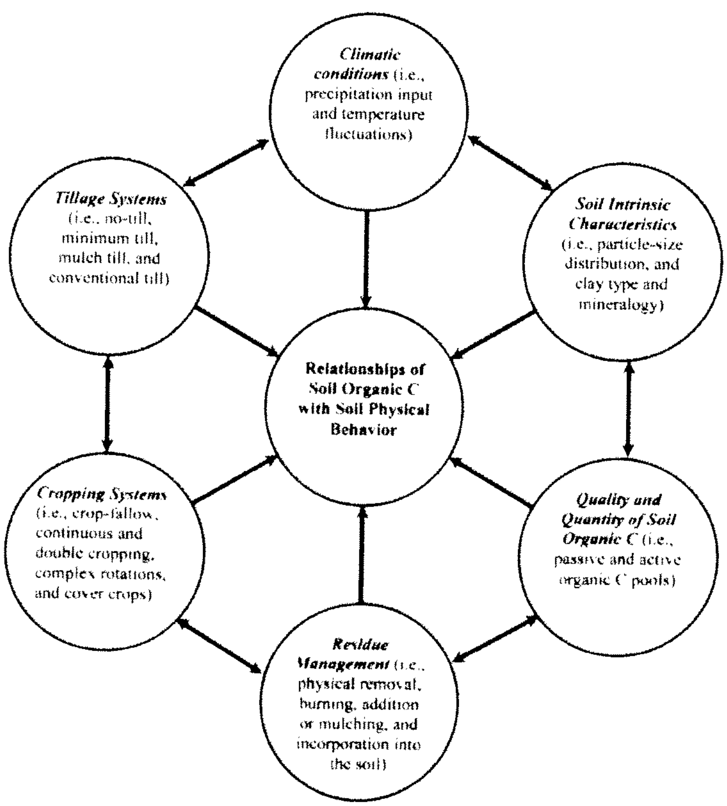

Fig. 2–1. Factors and interactions that influence relationships of soil organic C concentration with soil structural, compaction, consistency, mechanical, and hydraulic properties.

Table 2–1. Some examples of relationships of SOC with soil physical properties (≤20 cm depth).

Aggregate stability					
Soane (1990) and Chaney and Swift (1984)	26 soils	Great Britain	Agricultural use	MWD (mm×100) = 26.8 + 23.2*SOM (%)	0.79***
Blanco-Canqui and Lal (2007)	Silt loam	United States	Straw management in no-till	MWD (mm) = - 3.29 + 1.24*SOC (g kg^{-1})	0.96***
Pikul et al. (2009)	Silty clay loam	United States	No-till and plow till	WSA (%) = −8.70 + 2.47*FPOM/SOM	0.64***
Jordán et al. (2010)	Loam	Spain	Straw management in no-till	AG (number of raindrops) = 13215 + 37729*SOM (%) + 08566(SOM)²	0.91***
Bulk density and proctor maximum bulk density					
Soane (1990) and Ball et al. (1989)	Two loams	Great Britain	No-till and plow till	Proctor ρ_{bmax} (Mg m^{-3}) = 2.07–0.102*SOC (%)	0.93***
Quiroga et al. (1999)	24 sites (sand, loamy sand, sandy loam, and loam)	Argentina	Conventional till	Proctor ρ_{bmax} (Mg m^{-3}) = 1.75–0.01*SOM (g kg^{-1})	0.52***
Diaz-Zorita and Grosso (2000)	26 sites (loamy sand, loamy, and loamy silt)	Argentina	Conservation tillage and grasslands	Proctor ρ_{bmax} (Mg m^{-3}) = 1.74–0.01*TOC (%)	0.75***
Blanco-Canqui and Lal (2007)	Silt loam	United States	Straw management in no-till	ρ_b (Mg m^{-3}) = 4.39*(SOC, g kg^{-1}) $^{-0.49}$	0.87***
Particle density					
Blanco-Canqui et al. (2006b)	Silt loam	United States	No-till and plow till	ρ_s (Mg m^{-3}) = 2.57- 0.004*SOC (g kg^{-1})	0.62***
Blanco-Canqui and Lal (2007)	Silt loam	United States	Straw management in no-till	ρ_s (Mg m^{-3}) = 2.87- 0.01*SOC (g kg^{-1})	0.89***
Water repellency					
Blanco-Canqui and Lal (2007)	Silt loam	United States	Straw management in no-till	WDPT (s) = −2.15 + 0.09*SOC (g kg^{-1})	0.52**
Blanco-Canqui (2011)	11 soils	United States	No-till and plow till	LogWDPT (s) = 0.31 + 0.01*SOC (g kg^{-1})	0.18***
Soil consistency					
Eynard et al. (2006)	Loam and silt loam	United States	Plow till and grasslands	PL (g kg^{-1}) = 189 + 2.5*SOC (g kg^{-1})	0.89***
Blanco-Canqui et al. (2006b)	Silt loam	United States	No-till and plow till	LL (kg kg^{-1}) = 20.67 + 0.83*SOC (g kg^{-1})	0.92***
				PL (kg kg^{-1}) = 14.06 + 0.58*SOC (g kg^{-1})	0.88***

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† MWD, mean weight diameter of aggregates; WSA, water-stable aggregates; AG, aggregate stability; FPOM, fine particulate organic matter; SOM, soil organic matter; SOC, soil organic C; TOC, total organic C; rs, particle density; rb, bulk density; Proctor rbmax, Proctor maximum bulk density; WDPT, water drop penetration time; PL, plastic limit; LL, liquid limit.

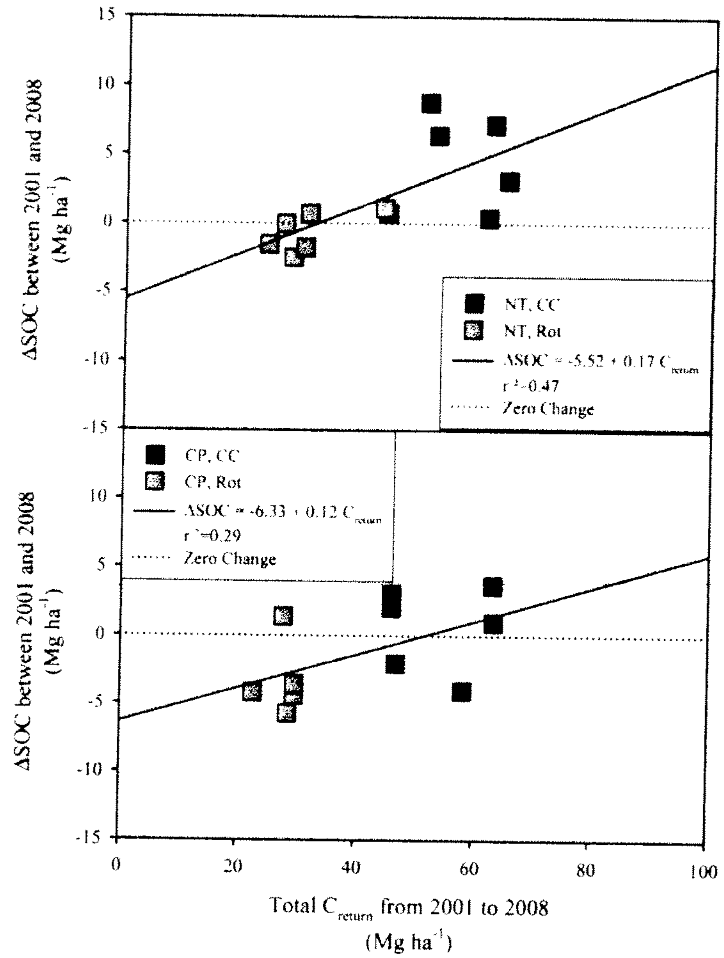

Fig. 2–2. Relationship of added crop residue C plus estimated added root and rhizodeposition C (C_{return}) on changes in soil organic C (ΔSOC) in the 0- to 30-cm depth increment between 2001 and 2008. NT denotes the no-till cropping system. The CP denotes the chisel plow cropping system. CC denotes the continuous corn rotation. Rot denotes the mixed grass and broadleaf crop rotation. (From Benjamin et al., 2010).

loam in the central Great Plains, there was no significant correlation between SOC concentration and macroaggregates in the 0- to 18-cm depth, but, in the 20- to 37-cm depth, macroaggregates were positively correlated, although weakly, with differences in SOC concentration across cropping systems with different amounts of annual biomass C input (Benjamin et al., 2008). Differences in root growth patterns and interactions between SOC and clay fractions may affect soil aggregation at deeper depths. Further assessment of SOC vs. soil structure relationships for the whole soil profile is needed to understand how different scenarios of crop residue management influence soil properties.

Tillage also affects the nature and partitioning of organic binding agents that affect soil aggregation and stability of aggregates. Plowing reduces the proportion of temporary and transient organic binding agents through a rapid oxidization of tration promotes aggregation, reduces soil compactibility, and improves soil hydraulic properties. On the other hand, improved soil structural properties promote SOC protection and storage, which is essential to long-term C sequestration and overall soil productivity. The specific relationships of SOC with soil physical properties are discussed in the following sections.

EFFECT OF ORGANIC CARBON ON SOIL WATER REPELLENCY

Crop-residue derived SOC may induce some hydrophobic properties to soil (Table 2–1). While excessive soil water repellency can adversely affect soil structure and hydrology (Doerr et al., 2000; MacDonald and Huffman, 2004), slight water repellency observed in cultivated soils can have positive impacts on aggregate stabilization and long-term C sequestration (Hallett et al., 2001; Eynard et al., 2006; Lamparter et al., 2009). Residues are a food source for decomposers including earth-

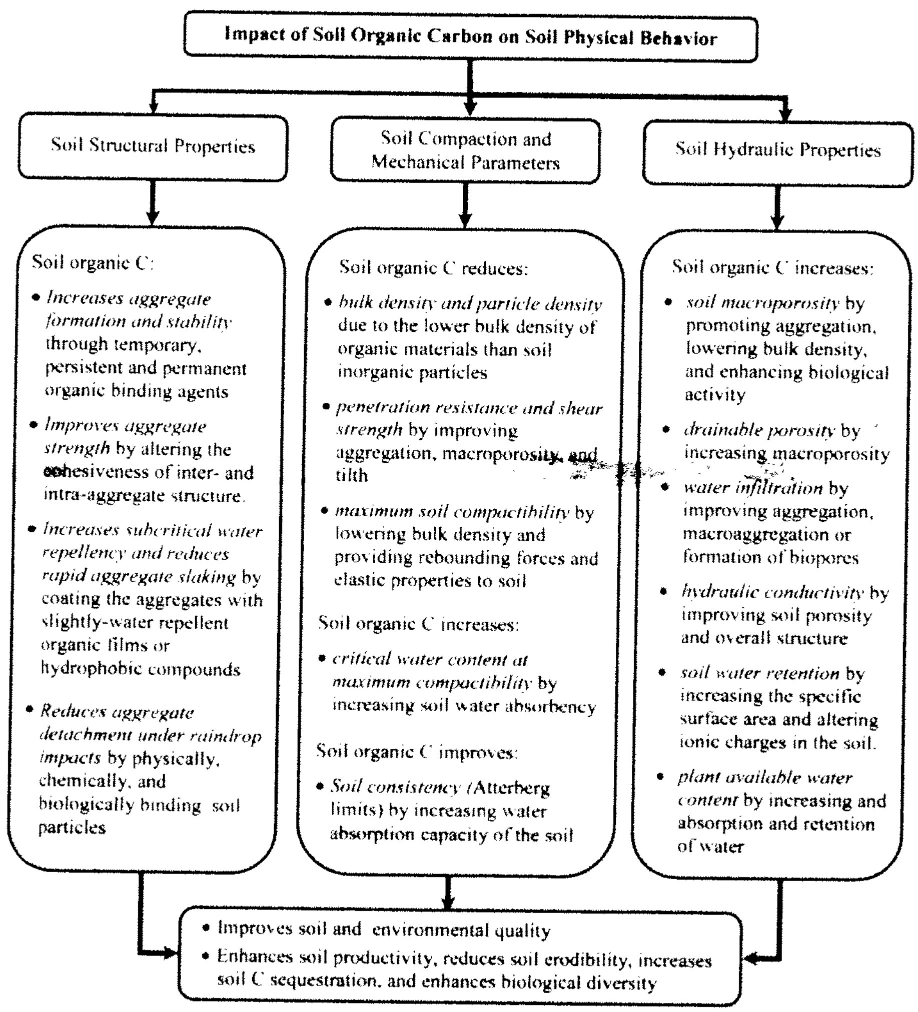

Fig. 2–4. Role of organic C concentration in improving soil physical and hydraulic properties.

Interaction between clay content and SOC concentration most probably increases soil hydrophobicity in clayey soils over clay or SOC concentration alone. Association of SOC or humic compounds with clay minerals has been found to increase soil hydrophobicity in clayey soils (Chenu et al., 2000; Rodriguez-Alleres et al., 2007). Particularly, recalcitrant SOC fractions associate with the finest clay fractions and induce high hydrophobicity (Spaccini et al., 2002). Predominant factors that influence the manifestation of soil water repellency include SOC, clay concentration, and soil matric potential (De Jonge et al., 2007; Blanco-Canqui and Lal, 2008b).

Increase in SOC concentration with intensive cropping systems with high residue input also increases water repellency. Continuous cropping systems with conservation tillage, which leave residues on the soil surface, can accumulate SOC near the soil surface and induce water repellency to soils. In a 33-yr cropping system experiment in the central Great Plains, continuous wheat had 5 times greater aggregate water repellency than the average across sorghum-fallow, wheat-sorghum [*Sorghum bicolor* (L.) Moench]-fallow, continuous sorghum, and wheat-fallow under no-till for the 0- to 2.5-cm soil depth (Blanco-Canqui et al., 2010a). The hydrophobicity of residue-derived SOC varies with the quality of crop residues. De Jonge et al. (2007) observed that soils under barley and potatoes (*Solanum tuberosum* L.) had slightly greater soil water repellency than those under rye (*Secale cereal* L.), wheat, and corn. They also observed that grass plots had consistently greater soil water repellency than cropped systems at all soil water contents. Overall, changes in SOC concentration with residue removal or addition may change the hydrophobicity of soil, depending on the quantity and quality of residues. More experimental data on the impacts of crop residue management on soil water repellency are needed.

Effect of Organic Carbon on Soil Structural Stability and Strength

Influence of organic matter on soil aggregation has been widely discussed (Tisdall and Oades, 1982; Chaney and Swift, 1984; Weil and Magdoff, 2004; Fig. 2–4), but discussion on the specific impacts of crop residue removal or addition on SOC vs. soil structure relationships is somewhat limited (Table 2–1). Crop residues may differ on their impacts on soil structure from other amendments (e.g., animal manure, sawdust, and compost) as SOC influences on soil structure depend on the type and quality of amendments (Bhogal et al., 2009). Loss of SOC with residue removal may have a greater impact on soil structural parameters such as aggregate stability and strength than on other soil physical properties (Sparrow et al., 2006).

residue management, wheat and sorghum residue removal from irrigated and dryland soils reduced both the proportion of macroaggregates from 29.7 to 25.3 g kg^{-1} and SOC concentration from 85 to 64.5 g kg^{-1} (Bordovsky et al., 1999).

Application of crop residues has the opposite effect to residue removal because it increases SOC concentration and it thus improves aggregate stability. On a silt loam in Ohio, increase in SOC concentration was linearly related (r = 0.50) to the increase in percentage of water-stable aggregates in the 0- to 10-cm depth after a 7-yr wheat straw application at five different rates to no-till, plow-till, and ridge-till soils (Duiker and Lal, 1999). On a loam in Spain, an increase in SOC concentration with the application of wheat straw at five different levels increased wet aggregate stability, explaining 91% of its variability in a no-till soil in the 0- to 10-cm depth in a 3-yr study (Jordán et al., 2010). Addition of by-products of corn stover fermentation can also increase soil aggregate stability by increasing SOC concentration. Johnson et al. (2004) reported that addition of stover fermentation by-product with 486 g kg^{-1} of SOC concentration linearly increased the aggregate stability, explaining 98% of its variability.

The main mechanisms by which crop residue removal reduces the stability of wet aggregates is by reducing the amount of organic binding agents and hydrophobicity of aggregates (Tisdall and Oades, 1982; Fig. 2–4). As discussed earlier, slight or subcritical water repellency can contribute to aggregate stabilization (Goebel et al., 2005; Bottinelli et al., 2010). Crop residues are a source of transient, temporary, and persistent organic binding agents that are essential to soil aggregation. Transient or labile soil organic matter fractions first bind soil particles into aggregates while the persistent or recalcitrant soil organic matter fraction, often occluded inside aggregates, contributes to permanent stabilization of soil structure (Kay, 1997; Weil and Magdoff, 2004). Constituents of soil organic matter, particularly persistent fractions, react with polyvalent cations, oxides, and aluminosilicates to form complex compounds and stabilize aggregates (Tisdall and Oades, 1982).

The SOC concentration and soil aggregates are mutually interrelated (Bossuyt et al., 2005). The SOC-enriched organic materials form and stabilize aggregates by providing organic binding agents, while aggregates in turn occlude and prevent SOC from rapid decomposition. Weaker aggregates store less SOC than more stable aggregates. Macroaggregate-protected SOC is mostly labile and young with faster turnover rates than micro-aggregate-protected SOC (Puget et al., 2005). Labile SOC fractions decrease more rapidly than stable or recalcitrant SOC fractions following residue removal (Karlen et al., 1994).

The degree at which the residue-derived SOC associates with soil mineral particles and stabilizes aggregates depends on the degree of residue decomposition (Kay, 1997). The association of residue-derived organic materials affect soil consistency. Soils with high SOC concentration are more friable, have better tilth, and are less compactable than soils with low SOC concentration. The SOC increases water content at liquid and plastic limits due to the high surface area of organic particles. Soil organic matter particles in association with the mineral fraction increases the water adsorption capacity of the soil. In some soils, correlations between SOC concentration and soil consistency may be weak due to differences in soil parent material, clay content and mineralogy, and type and nature of organic matter (De Jong et al., 1990; Saxton and Rawls, 2006).

EFFECT OF ORGANIC CARBON ON SOIL COMPACTION

Changes in SOC concentration due to management may influence risks of soil compaction. The SOC is a sensitive parameter for predicting bulk density changes as the result of soil compaction (Rawls, 1983; Kay et al., 1997; Benites et al., 2007; Ruehlmann and Körschens, 2009; Table 2–1). Kaur et al. (2002) cited a number of pedotransfer functions for predicting bulk density from changes in SOC concentration. Bulk density may decrease linearly or exponentially with increasing SOC concentration (Rawls, 1983; Kay et al., 1997; Ruehlmann and Körschens, 2009). Across 176 sites in Europe, bulk density, determined by the uniaxial compression test, decreased with an increase in organic matter content in soils with <15% of organic matter concentration (Keller and Håkansson, 2010). Soil organic C often interacts with soil particle-size distribution to influence bulk density (Arvidsson, 1998; Kaur et al., 2002; Benites et al., 2007).

Changes in bulk density and SOC concentration can occur rapidly after removal or addition of crop residues. On a sandy loam in Nigeria, application of rice (*Oryza sativa* L.) straw to a no-till soil at 0, 2, 4, 6, and 12 Mg ha^{-1} increased SOC concentration and reduced bulk density in the 0- to 5-cm depth after one and half years of straw application (Lal et al., 1980; Fig. 2–7A). The increase in SOC concentration with residue addition may not only reduce bulk density but also

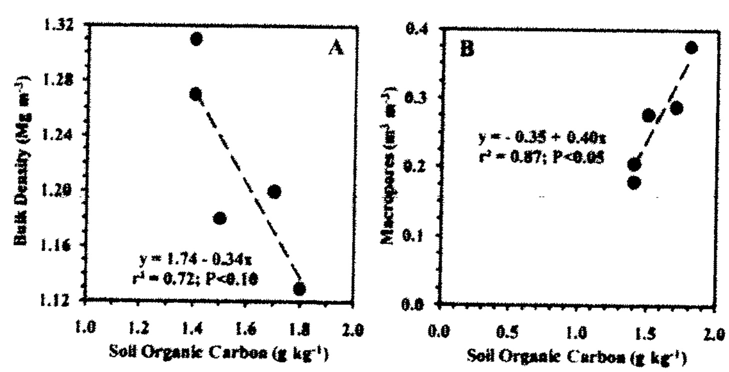

Fig. 2–7. Effect of soil organic C concentration on (A) bulk density and (B) macroporosity after 18 mo of rice straw management (data from Lal et al., 1980).

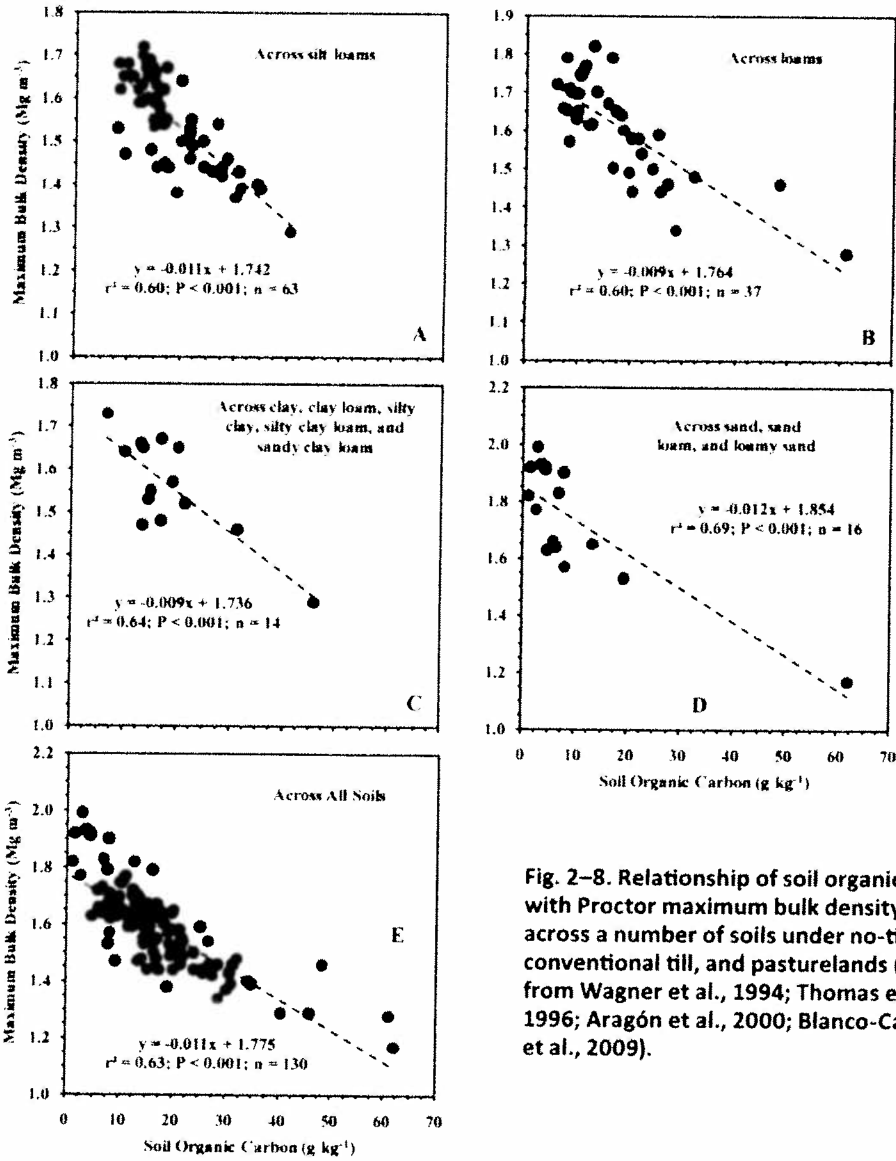

Fig. 2–8. Relationship of soil organic C with Proctor maximum bulk density across a number of soils under no-till, conventional till, and pasturelands (Data from Wagner et al., 1994; Thomas et al., 1996; Aragón et al., 2000; Blanco-Canqui et al., 2009).

SOC concentration. The Proctor maximum bulk density decreased significantly as SOC concentration increased, whereas Proctor critical water content increased as SOC concentration increased. Proctor maximum bulk density and its critical water content were strongly correlated with changes in SOC concentration regardless of differences in soil textural class (Fig. 2–8A to 2–8E and 2–9A to 2–9E) and climatic zones (Fig. 2–10C and 2–10D). These results indicate that a decrease in SOC concentration can increase risks of soil compaction. Soil compactibility is sensitive to management and may be more significantly affected by changes in SOC concentration than other soil physical properties. The decrease in soil water content at which the soil is most compacted due to the decrease in SOC concentration is important to manage soil compaction. The implication is that

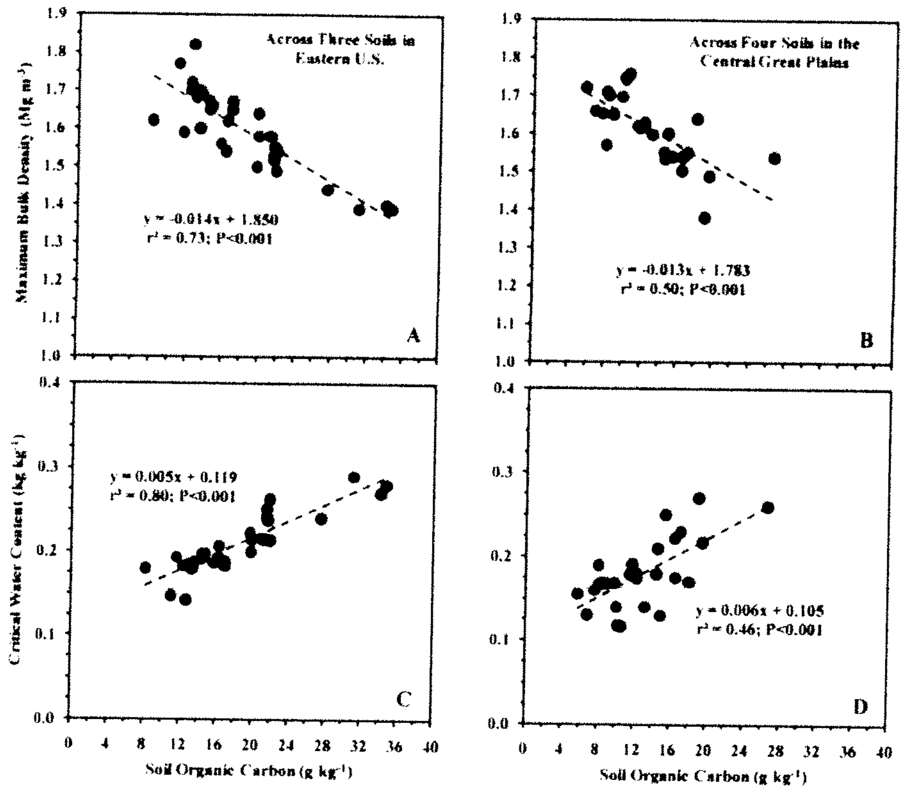

Fig. 2–10. Effect of soil organic C on (A and B) Proctor maximum bulk density and (C and D) critical water content at maximum compaction in the 0- to 5-cm soil depth in two different climatic regions in the United States (data from Thomas et al., 1996; Blanco-Canqui et al., 2009).

also changes the strength of bonds and electrical charges at the intra-aggregate contact points between organic and inorganic particles, which can change the behavior of the soil matrix (Soane, 1990; Ball et al., 2000).

The increase in maximum compactibility with decreased SOC concentration can have important implications for managing crop residues and soil compaction. It suggests that residues should be returned to soil to maintain or increase SOC and to reduce, at least in part, some of the risks of excessive compaction. The focus to alleviate soil compaction has been on reducing axle loads, controlling timing and frequency of traffic, and implementing remediation measures such as subsoiling, vertical tillage, and others. The ability of SOC to influence the soils' susceptibility to compaction has been somewhat ignored when managing excessive soil compaction. While crop residue mulch alone may not be highly effective in reducing soil bulk density from an increase in applied stress (Gupta et al., 1987), SOC accumulation with continued residue addition may improve soil resilience and rebounding capacity in the long term. The role of SOC in alleviating excessive soil compaction can be particularly relevant at low than at high axle loads of field equipment. Overall, because SOC management is critical to reduce pore volume, water retention, and soil structural parameters, and changes in SOC concentration had much stronger effects than changes in clay concentration.

Differences in SOC concentration may also affect porosity by altering soil particle density (Table 2–1). The few studies have available on this topic have shown that particle density decreases with an increase in SOC concentration. Across various cultivated soils in the UK, Ball et al. (2000) reported that particle density was negatively and significantly correlated ($r = -0.38$; $P < 0.001$) with SOC concentration. Similarly, across no-till, chisel plow, and moldboard plow systems in Ohio, Blanco-Canqui et al. (2006b) found that particle density was as sensitive to changes in SOC concentration as bulk density. They reported that a decrease in SOC concentration due to differences in residue management between no-till and plowed systems explained 38% ($P < 0.001$) of the variability in particle density in the 0- to 10-cm soil depth. Similar to the effects on bulk density, the decrease in particle density with increase in SOC concentration is attributed to the dilution effect of soil organic particles. Changes in particle density can affect soil hydraulic properties by altering soil porosity.

Many studies have shown that residue management-induced changes in SOC concentration alter water retention. On two silt loams in Iowa, increased SOC concentration by doubling the amount of corn stover for 10 yr in no-till increased plant available water at −0.5, −1.4, and −9.8 kPa (Karlen et al., 1994). On a silt loam in Ohio, wheat straw addition to no-till plots for 7 yr increased both water retention at >30 kPa suctions and SOC concentration in the 0- to 10-cm depth (Duiker and Lal, 1999). Correlations in Table 2–2 for three contrasting no-till soils show that water retention and plant available water decreased linearly with a loss in SOC concentration due to corn stover removal (Blanco-Canqui et al., 2006a; Blanco-Canqui et al., 2007). Decrease in SOC concentration reduces the soil's ability to absorb and retain water because it reduces the specific surface area of the soil. Organic particles have a greater specific surface area and water adsorption capacity than soil inorganic particles (Rawls et al., 2003). Hudson (1994) found that soils containing 4% organic matter retained plant available water twice more than soils containing 1% organic matter. Olness and Archer (2005) found that change in plant available water ranged between 2.5 and 5% for each 1% change in SOC concentration for soils with <2.5% SOC and 40% clay concentrations. Recently, Kvaerno and Haugen (2011), while assessing the performance of a number of pedotransfer functions in predicting soil water characteristics based on particle-size distribution, organic matter content, and bulk density across 540 soil horizons on cultivated lands in Norway, found that pedotransfer functions which included organic matter content as one of the input parameters were the best predictors of soil water retention under low suctions.

size distribution to influence soil compaction, structural, and hydraulic properties. The SOC buffers risks of excessive soil compaction, increases soil aggregate stability and strength, promotes macroporosity, induces slight water repellency, and improves water retention.

The mechanisms by which SOC influences soil physical properties are numerous and complex. Organic particles stabilize soil aggregates by binding individual particles into stable units and strengthening the inter-particle cohesion within and among aggregates. Organic films can also induce some hydrophobic properties to soil, reducing aggregate slaking. Because crop residues have elastic properties, residue-derived organic materials provide elasticity, spring-like behavior, and rebounding capacity to the whole soil. Organic particles also have lower density than mineral particles, which dilutes the soil bulk density, reducing risks of excessive compression and compaction of the soil. Presence of a network of fine roots, fungal hyphae, and other biological components can enmesh mineral particles and increase friction forces among soil particles. Organic particles can also impart slight electrical charge to the soil similar to clay particles to react and develop complex chemical bonds among soil particles to further improve soil physical properties. These myriad benefits of SOC-enriched materials can be readily altered by management practices such as crop residue removal.

Crop residue removal adversely impacts soil physical properties by depleting SOC, but C input through high-biomass producing crop rotations (e.g., continuous cropping systems) may maintain and improve soil physical characteristics. Residue management strategies (e.g., no-till) that increase SOC concentration improve soil structural, compaction, and hydraulic properties. Particularly, an increase in SOC concentration is strongly correlated with maximum soil compactibility and critical water content, indicating that cultivated soils with increased SOC concentration are less susceptible to compaction and can be trafficked at greater soil water content without the risks of soil compaction compared with soils low in SOC concentration.

The numerous beneficial effects of SOC on different soil physical parameters support the need for maintaining optimum levels of SOC through annual crop residue return and use of no-till farming to maintain or improve soil functions. Because excessive removal of crop residues for off-farm uses readily reduces SOC concentration, it can adversely affect soil physical behavior. Residue mulch improves soil physical properties not only by increasing SOC concentration but also by protecting the soil surface from the erosive forces of raindrops, and reducing abrupt fluctuations of soil temperature, freezing and thawing, and wetting and drying cycles. Overall, increasing SOC concentration through proper crop residue management may not only reduce net emissions of C to the

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