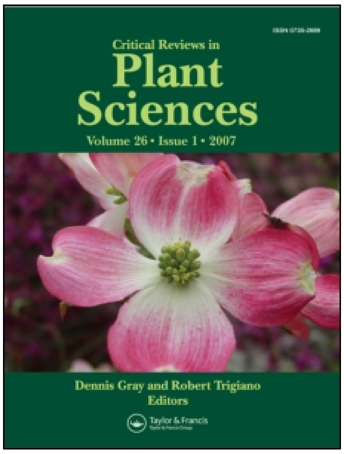

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Humberto Blanco-Canqui[a]; R. Lal[b]
[a] Western Kansas Agricultural Research Center-Hays, Kansas State University, Hays, Kansas [b] Carbon Management and Sequestration Center, FAES/OARDC, School of Natural Resources, The Ohio State University, Columbus, Ohio

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Crop Residue Removal Impacts on Soil Productivity and Environmental Quality

Humberto Blanco-Canqui[1] **and R. Lal**[2]

[1]*Kansas State University, Western Kansas Agricultural Research Center-Hays. 1232 240th Ave., Hays, Kansas 67601-9228*
[2]*The Ohio State University, Carbon Management and Sequestration Center, FAES/OARDC, School of Natural Resources, Columbus, Ohio 43210-1085*

Referee: Donald C. Reicosky, USDA-ARS, North Central Soil Conservation Research Laboratory, 803 Iowa Ave., Morris, MN 56267, USA

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Address correspondence to Humberto Blanco-Canqui, Kansas State University, Western Kansas Agricultural Research Center-Hays, 1232 240th Ave., Hays, Kansas 67601-9228. E-mail: hblanco@ksu.edu

Crop residues are a potential source of renewable feedstocks for cellulosic ethanol production because of their high cellulose content and easy availability. Indiscriminate removal as biofuel may, however, have adverse impacts on soil, environment, and crop production. This article reviews available information on the impacts of crop residue removal on soil properties, crop yields, and soil erosion across a wide range of soils and ecosystems. It explicitly synthesizes data on the independent impacts of crop residue removal on soil and environment rather than on the interrelated tillage-crop-residue management impacts. Published literature shows that residue removal adversely impacts near-surface soil physical, chemical, and biological properties. Unmulched soils are prone to particle detachment, surface sealing, crusting, and compaction. Residue removal reduces input of organic binding agents essential to formation and stability of aggregates. It also closes open-ended biochannels by raindrop impacts and reduces water infiltration, saturated/unsaturated hydraulic conductivity, and air permeability, and thereby increases runoff/soil erosion and transport of non-point source pollutants (e.g., sediment and chemicals). Residue removal accelerates evaporation, increases diurnal fluctuations in soil temperature, and reduces input of organic matter needed to improve the soils' ability to retain water. It reduces macro- (e.g., K, P, N, Ca, and Mg) and micronutrient (e.g., Fe, Mn, B, Zn, and S) pools in the soil by removing nutrient-rich residue materials and by inducing losses of soil organic matter (SOM)-enriched sediments in runoff. Residue removal drastically reduces earthworm population and microbial carbon (C) and nitrogen (N) biomass. It adversely affects agronomic production by altering the dynamics of soil water and temperature regimes. The short-term (<10 yr) data show nevertheless that residue removal may not always degrade soil physical properties and decrease crop yields in the short term depending on the soil type, topography, and fluctuations in annual weather conditions. Sloping and erosion-prone soils are more rapidly and adversely affected by residue removal than those on flat terrains with heavy texture and poorly drained conditions. Sloping terrains are not only highly susceptible to water and wind erosion but also to tillage erosion. In these soils, therefore, a fraction of the total crop residue produced may be available for biofuel production and other expanded uses. Standard guidelines on when, where, and how much residues to remove need to be, however, established. Modeling rates of residue removal are presently based on the needs of soil cover to control erosion without consideration to maintaining SOM and nutrient pools, enhancing soil physical, chemical, and biological quality, and sustaining crop production. Threshold levels of residue removal must be assessed for principal soil types based on the needs to maintain or enhance soil productivity and improve environmental quality. For those soils in which some residues are removed, best management practices (e.g., cover crops, diverse crop rotations, and manure application) must be adopted to minimize adverse impacts of residue removal. Because indiscriminate harvesting of crop residues for biofuel may deteriorate soil properties, reduce crop yields, and degrade the environment, there exists an urgent research need for developing alternative sustainable renewable energy feedstocks (e.g., warm season grasses and short-rotation woody crops).

Keywords crop residues, cellulosic ethanol, soil organic matter, dedicated energy crops, soil properties, nutrient pools, runoff and soil loss, crop yields, best management practices, soil carbon

I. INTRODUCTION

Crop residues have been identified as principal renewable feedstocks for ethanol production. Crop residues for biofuel will most likely be harvested in large scale as technologies for the transformation of the high-cellulose biomass into biofuel (i.e., ethanol) develop and demands for ethanol intensify. Any crop residue, which has high cellulose content, is suitable for ethanol production. At present, because of its easy availability and high cellulosic content, corn (*Zea mays L.*) stover is the preferred choice for cellulosic ethanol until other renewable energy feedstocks (e.g., warm-season grasses and short-rotation woody crops) are grown on a large scale. Among the main crops which produce large amounts of residues are corn, wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L.), and rice (*Oryza sativa* L.). In the U.S. Corn Belt region, corn stover represents nearly 80% (245 million $\mathrm{Mg}^{-1}\ \mathrm{yr}^{-1}$) of the total crop residue production (Kadam and McMillan, 2003; Perlack *et al.*, 2005), constituting the prime candidate for biofuel production in the region. In the Great Plains, wheat straw and sorghum stover are potential biofuel feedstocks (Sarath *et al.*, 2008). Research on new varieties of plant species (e.g., sorghum) with unique genetic characteristics capable of producing large amounts of biomass is being pursued (Bouton, 2007; Torney *et al.*, 2007).

While crop residues are potential as feedstock for biofuel production, their removal can, however, adversely impact soil and environment quality, with attendant decline in net primary productivity (NPP) and water quality, etc. Thus, there is an urgent need to review and synthesize the available information on the implications of crop residue removal on soil processes and properties, NPP, and environmental quality prior to initiating large-scale residue removal programs. The few previous reviews on the residue management on soil and agronomic productivity have mostly focused on the interrelated tillage-residue-cropping management implications whereby effects of residue management are often confounded with those of tillage and cropping systems (Mann *et al.*, 2002; Wilhelm *et al.*, 2004; Wilhelm *et al.*, 2007). A comprehensive review of the impacts of residue management independent from those of tillage and cropping systems is needed to strengthen our understanding of the role of crop residues in sustaining soil and agronomic productivity, mitigating climate change, and supporting other ecosystem services.

The objective is to review and synthesize the available information on the impacts of crop residue removal on soil physical, chemical, and biological properties, crop yields, and runoff and soil loss as well as to identify any research needs in relation to the use of crop residues as biofuel feedstocks. An objective analysis of available data on the effects of crop residue removal on the ecosystem services is warranted to determine whether removal of residues for expanded uses is economically feasible and environmentally compatible. These analyses are needed to develop a decision support system for management of agricultural residues for diverse and competing uses such as soil amendment, animal fodder, industrial raw material, and biofuel feedstocks. This review differs from others in that it explicitly discusses the independent impacts of residue removal across a wide range of soils, ecosystems, and climatic zones. While crop residues generally comprise of above- and below-ground biomass, the term "crop residues" in this review refers to the measured above-ground biomass left on the field after harvest. The term "stover" refers to the above-ground biomass left on the soil surface after corn and sorghum harvest (Wilhelm *et al.*, 2004). Regardless of terminology (e.g., residues, stover, straw, fodder, and others) used for describing the plant biomass, any above- and below-ground plant material other than grain is a valuable form of C and provide a number of essential ecosystem services.

II. CROP RESIDUES ARE NOT A WASTE

Crop residues are often mistakenly regarded as "agricultural waste" or something of little or no value (McKinney, 2004). Some view the use of crop residues for biofuel production as an opportunity to give these "agricultural wastes" an economic value while reducing the overdependence on fossil fuels without consideration of maintaining soil carbon. Crop residues are not a "waste" (Lal, 2004). They are valuable assets when returned to soil (Wilhelm *et al.*, 2007). Crop residues are 40–46% C and provide innumerable ecosystem services including reduction in soil erosion and water pollution, improvement in soil physical, chemical, and biological properties, increase in agronomic production, and sequestration of soil organic carbon (SOC) with the attendant mitigation of the global climate change. Among numerous benefits of leaving crop residue are the following:

- maintaining agronomic productivity by replenishing nutrients in the soil, increasing the soil organic matter (SOM) concentration, conserving soil water, reducing excessive evaporation, promoting biological activity, enhancing soil aggregation, strengthening nutrient cycling, reducing abrupt fluctuations in soil temperature, and improving soil tilth (Wilhelm *et al.*, 1986; Wilhelm *et al.*, 2007);
- improving water and air quality by reducing soil erosion and non-point source pollution, absorbing agricultural chemicals, filtering runoff, and buffering against the impact of air pollutants (Lindstrom, 1986; Mickelson *et al.*, 2001); and
- mitigating global climate change by sequestering SOC and off-setting emissions of CO_2 and other greenhouse gases (GHGs) (Lal, 2008a).

III. IMPACTS OF CROP RESIDUE REMOVAL FOR INDUSTRIAL USES

Impacts of indiscriminate and large scale removal of crop residues for industrial uses on soil, environment, and NPP are not fully understood. While importance of crop residues for protecting soil and water conservation has long been recognized (Wischmeier and Smith, 1978), information with regards to impact on soil properties and NPP due to the independent effects of crop residue removal has not been widely documented or considered. Such impacts must be assessed for different cropping systems, soil types, soil functions, and ecosystem services. Implications of residue removal on soil intrinsic attributes, nutrient and carbon pools, soil erosion, and crop yields need to be specifically discussed. For example, the amount of crop residue required for maintaining SOC pools and enhancing soil quality can be higher than that required to control soil erosion (Wilhelm *et al.*, 2007).

IV. SOIL PHYSICAL, CHEMICAL, AND BIOLOGICAL PROPERTIES

A. Soil Physical Properties

1. Structural Stability

Crop residue mulch serves as a natural blanket to protect the soil surface against insolation and erosive impacts of raindrops and blowing wind. It buffers the soil surface from excessive compaction, surface sealing, and crusting while reducing the breakdown and dispersion of soil aggregates. Used as surface mulch, crop residues improve soil structural properties by increasing SOM concentration. The effectiveness of crop residue cover is a function of percent of soil surface cover, soil textural class, topography, intensity of rainfall, and velocity of wind (Ruan *et al.*, 2001). The larger the amount of crop residue returned to soil, the more the surface covered, the greater the protection of soil structure against natural and anthropogenic perturbations (Blanco-Canqui *et al.*, 2006a). Surface sealing, crusting, and decline in aggregate stability are among the adverse impacts of residue removal on soil structure.

1.1. Surface Sealing and Crusting. Surface seals are thin layers that are formed when raindrops strike the surface of bare soils and disperse soil aggregates, causing the release, movement, and orientation of fine particles that clog the pores near the soil surface. Surface sealing modifies the soil hydrological properties by lowering the saturated/unsaturated hydraulic conductivity, reducing water infiltration/rate, and increasing runoff rate and amount. Benyamini and Unger (1984) observed that crusts reduced water infiltration rate by 10-fold compared to uncrusted soils. Upon drying, surface seals develop crusts of high strength. Some crusts can be 5 cm thick depending on rainfall intensity, soil disturbance, and soil intrinsic properties (USDA-NRCS, 1996). The higher density and lower hydraulic conductivity of crusts compared to the underlying soil layers restrict seedling emergence, reduce water, air, and heat fluxes, and increase soil erosion. Seedlings must break through or push the crust away in order to emerge and grow (Baumhardt *et al.*, 2004).

Maintaining a complete and continuous cover with crop residue mulch on the soil surface is essential to reduce formation of surface seals (Ruan *et al.*, 2001). Cassel *et al.* (1995) reported that tillage practices such as no-till (NT), which leave crop residues on the soil surface, eliminate surface sealing and crusting. A soil surface protected with heavy crop residue mulch does not seal or crust even in soils of high silt and low SOM contents (Kladivko, 1994). Blanco-Canqui *et al.* (2006b) reported that soils without crop residue mulch developed continuous crusts with a thickness of 3 ± 0.7 cm and cracks of 0.6 ± 0.5 cm width during dry periods in Ohio. Direct impact of raindrops on soils with little or no residue cover causes densification and consolidation of surface layers and formation of surface crusts.

1.2. Aggregate Stability. Aggregate stability is one of the soil properties most sensitive to crop residue removal. It decreases with decrease in surface residue cover (Table 1). Surface aggregates in soils without residue mulch are readily dispersed under the erosive forces of impacting raindrops. Input of organic matter is the main mechanism by which crop residues form and stabilize aggregates. Stability of aggregates is positively correlated with SOM concentration (Rhoton *et al.*, 2002; Bossuyt *et al.*, 2005; Blanco-Canqui *et al.*, 2006a). Crop residues, upon decomposition, provide temporary, transient, and persistent binding organic agents (Tisdall and Oades, 1982). There are three mechanisms (physical, chemical, and biological) by which mulching with crop residues stabilize soil aggregates. Physically, crop residue mulch insulates the soil surface, intercepts the raindrops impacting the soil surface, and moderates freezing-thawing and wetting-drying cycles of surface soil (Kladivko, 1994). Chemically, it releases substances and compounds such as polysaccharides, humic compounds, and organic mucilages, which enmesh and glue the primary and secondary soil particles into stable aggregates. Biologically, it stimulates activity of macro- (e.g., earthworms) and microorganisms (e.g., fungi) to promote formation and stabilization of aggregates.

Adverse changes in aggregate stability caused by removal of crop residues can be rather rapid. Blanco-Canqui *et al.* (2006a) observed that stover removal from NT continuous corn systems reduced soil aggregate stability by 50 to 80% with 50% removal, and by 100 to 300% with 100% removal within a short period of one year. A follow-up study by Blanco-Canqui and Lal (2009a) after four years showed that stover removal did not necessarily reduce aggregate stability more than that observed after one year of stover removal, which indicates the rapid changes in aggregate stability. In soils prone to structural degradation, stover removal at rates as low as 25% can reduce aggregate stability; but the severe reduction usually occurs with complete removal (Table 1).

While most studies have reported a large decrease in aggregate stability with increasing rates of crop residue removal (Morachan *et al.*, 1972; Black, 1973; Singh and Malhi, 2006; Blanco-Canqui and Lal, 2009a), some have not (Karlen *et al.*, 1994; Roldán *et al.*, 2003). Even with 10 consecutive years of stover removal, Karlen *et al.* (1994) reported that complete stover removal did not reduce wet aggregate stability in silt loams, but doubling the stover amount over the normal stover treatment increased aggregate stability. Systematic removal of stover from NT soils by 0, 33, 66, and 100% for 5 consecutive year did not reduce aggregate stability in a sandy loam (Roldán *et al.* ,2003). Thus, the magnitude of impacts of crop residue removal on soil structural properties is most probably governed by differences in soil type (texture and mineralogy), cropping system, climate, and drainage conditions (Table 1).

Impacts of crop residues on aggregate stability differ, depending on the quality (e.g., decomposition rates, chemical composition, and C/N ratio) and quantity of mulch application (Heal *et al.*, 1997). Gantzer *et al.* (1987) observed that soils incubated with corn stover generated less splash and had higher aggregate stability than those incubated with soybean residues. Soybean residues decompose more rapidly than corn stover because of

TABLE 1
Crop residue removal affects soil structural and compaction parameters.

Soil (Slope)	Tillage (Duration, years)	Crop	Residue Cover	Bulk Density Mg m^{-3}	Aggregate Stability	Cone Index MPa
			%		MWD (mm)†	
[1]Silt loam (10%)	No-till (3)	Corn	0	1.23a	1.92c	1.18a
			25	1.22a	3.25b	1.12a
			50	1.23a	3.2b	1.13a
			75	1.20b	3.32b	0.94b
			100	1.10b	3.70b	0.95b
[1]Silt loam (2%)	No-till (3)	Corn	0	1.34a	1.82c	1.06a
			25	1.36ab	1.75c	1.03ab
			50	1.30ab	1.77c	0.89ab
			75	1.26b	2.21bc	0.81ab
			100	1.19c	3.20b	0.79b
[1]Clay loam (<1%)	No-till (3)	Corn	0	1.20a	0.89c	0.93a
			25	1.16a	1.42c	0.95a
			50	1.12a	1.72c	0.93a
			75	1.08a	1.73bc	0.88a
			100	1.10a	2.60b	0.84a
[2]Loam	Plow Till (6)	Barley (Hordeum vulgare L.)	0	1.15a	4.5b	0.68a
			100	1.13a	6.2a	0.47b
					WSA (%)‡	
[3]Silt loam (10 to 13%)	No-till (10)	Corn	0	1.38a	41.9b	ns
			100	1.33a	45.9b	ns
			200	1.24a	60.0a	ns
			Mg ha^{-1}			
[4]Silt loam (2%)	No-till (10)	Wheat	0	1.28a	0.9c	0.50a
			8	0.7b	3.4b	0.48a
			16	0.6b	5.4a	0.45a
					(> 0.42 mm) §	
[5]Sandy loam (2 to 4%)	Plow Till (8)	Wheat	0	1.38a	58.2	
			1.68	1.31b	60.4	
			3.36	1.29b	68.0	
			6.73	1.27b	77.8	
					GMD¶	
[6]Silty clay loam (6%)	Plow Till (13)	Corn	0	0.90a	1.2b	
			2	0.89a	1.2b	
			4	0.90a	1.3b	
			8	0.88a	1.3b	
			16	0.86a	1.8a	
			32	0.77b	—	

† Mean weight diameter, ‡Water-Stable Aggregates, §Dry Aggregate size, ¶Geometric mean diameter.

[1]Blanco-Canqui and Lal (2007a) and Blanco-Canqui and Lal (2009a); [2]Singh and Malhi (2006); [3]Karlen et al. (1994); [4]Blanco-Canqui and Lal (2007b); [5]Black (1973); [6]Morachan et al. (1972).

lower C:N ratio. Crop residues that decompose easily (e.g., soybean) generate binding or glue-like substances in the short term while those that decompose slowly (e.g., corn stover) provide both surface cover and binding agents over long term. Stover is rich in polysaccharides and phenolic/lignin compounds important to soil aggregate stabilization (Johnson *et al.*, 2004). Additionally, crops that produce large amounts of residues (e.g., sorghum) result in greater soil aggregation than those with lower biomass (e.g., wheat) production because of differences in decomposition rates (Skidmore *et al.*, 1986).

2. *Soil Compaction: Bulk Density and Cone Index*

Bulk density and cone index are two critical indicators of soil compaction. Crop residue removal generally increases bulk density and cone index because residue mulch absorbs and dissipates any compactive forces of wheel and animal traffic. Braida *et al.* (2006), using a Proctor test, observed that application of stover mulch at rates of 2, 4, 8, and 12 Mg ha^{-1} reduced the maximum density and dissipated the compactive energy by up to 30 %. Residue mulch imparts resilience and elastic properties to soil by increasing SOM concentration. Removal of residues exposes soil to the raindrop impacts, which causes densification and consolidation of surface layers. Aggregate dispersion at the soil surface clogs macropores and reduces the proportion of surface-connected macropores (e.g., earthworm and roots channels). Greater earthworm density and activity observed in mulched than in unmulched soils contribute to the reduction in soil compaction (Blanco-Canqui and Lal, 2007a). Consolidation of bare soils reduces the roughness of the soil surface. Soil surface of mulched fields is looser, more heterogeneous, wetter, and more porous than that of fields without mulch cover. Decomposed crop residues reduce bulk density because SOM has lower density than mineral fraction. In NT soils, the magnitude of reduction in bulk density due to residue removal is the greatest near the soil surface where residues are usually concentrated. Increased biological activity (e.g., earthworm activity) may transfer some decomposed residues to sub-soil (Bohlen *et al.*, 1997; Lorenz and Lal, 2005).

Application of 32 Mg ha^{-1} of stover to a silty clay loam (Morachan *et al.*, 1972) and 6.7 Mg ha^{-1} of wheat straw to a sandy loam (Black, 1973) reduced bulk density. Increases in soil compaction due to residue removal can be rapid (Table 1). Complete removal of sorghum residues for two-year increased cone index from 0.5 to 1.0 MPa in a NT clay loam (Sow *et al.*, 1997) whereas stover removal at rates of 50% increased bulk density by 0.15 Mg m^{-3} and cone index by 0.20 MPa in NT silt loams in Ohio after one (Blanco-Canqui *et al.*, 2006b) and three (Blanco-Canqui and Lal, 2007a) years of stover removal. In a similar short-term study conducted in western Nigeria, Lal *et al.* (1980) monitored changes in soil bulk density 6, 12, and 18 months following a systematic application of rice straw mulch to bare tropical soils and observed that bulk, density decreased from 1.22 to 1.05 Mg m^{-3} when 12 Mg ha^{-1}of rice straw mulch was applied. The same study suggested that at least 6 Mg ha^{-1} of rice straw is needed to maintain soil structural properties and reduce excessive compaction. In some soils, the high spatial and temporal variability in compaction parameters can mask the impacts of residue removal even within the same soil. Karlen *et al.* (1994) reported no impacts of complete stover removal on bulk density and cone index in the 0 to 5 cm soil depth in NT continuous corn systems after stover removal from two silt loams for 10 consecutive years.

Magnitude of impacts of crop residue removal on soil compaction varies with soil, tillage, residue type, and cropping systems (Table 1). Blanco-Canqui and Lal (2007a) reported that complete stover removal increased cone index from 0.9 to 1.2 MPa in a sloping silt loam and from 0.8 to 1.1 MPa in a nearly level silt loam but had no effects on a level clay loam. These cone index values are below the crop limiting threshold level, which is about 3 MPa for silt loams. Gupta *et al.* (1987) observed that changes in soil strength following the application of stover at rates of 0.0, 3.4, 6.7, and 10.1 Mg ha^{-1} were smaller on a clay loam than on sandy and silt loam soils. The reviewed literature shows that changes in soil compaction due to stover removal can be small in clayey soils and that complete removal of residues has greater adverse impacts than partial removal. The greater the amount of residue mulch cover, the greater is its capacity to buffer the soil against compaction.

3. *Hydraulic Properties*

3.1. Total Porosity, Soil Water Retention, and Plant Available Water. Total soil porosity generally decreases with increase in the rate of crop residue removal. For example, data

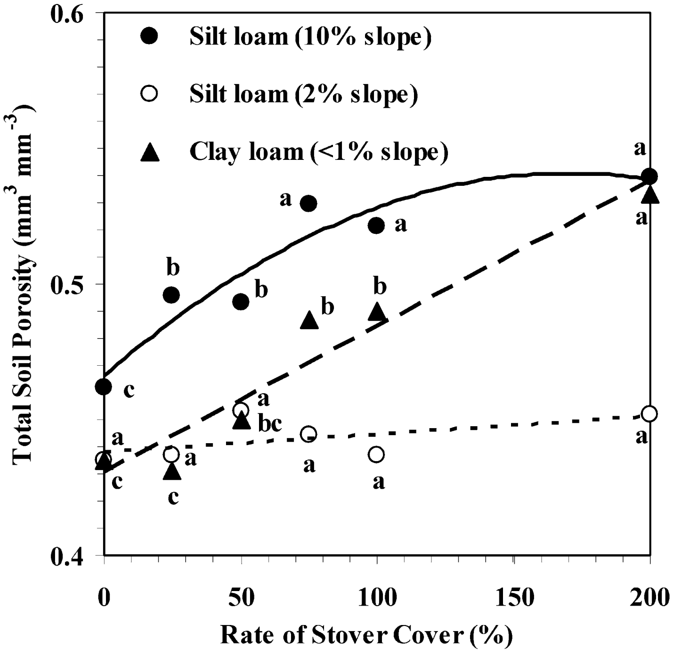

FIG. 1. Response of soil porosity to stover cover in three no-till soils in Ohio. Means within the same soil followed by the same letter do not significantly differ at the 0.05 probability level.

in Figure 1 show that total porosity increased with the increase in rate of stover mulch cover on a sloping silt loam and flat clay loam but had no effects on a level silt loam in Ohio. In Nigeria, Lal *et al.* (1980) reported that mean total porosity was 0.49 mm^3 mm^{-3} under 0 and 2 Mg ha^{-1} of rice straw, 0.55 mm^3 mm^{-3} under 4 and 6 Mg $ha^{-1}$of straw, and 0.59 mm^3 mm^{-3} under 12 Mg ha^{-1}. Increase in straw mulch cover from 0 to 12 Mg ha^{-1} increased macropores from 0.18 to 0.38 mm^3 mm^{-3} and mesopores from 0.07 to 0.08 mm^3 mm^{-3} whereas it decreased micropores from 0.23 to 0.13 mm^3 mm^{-3}. Mulched soils often have more macropores (e.g., biopores) and thus drain faster than unmulched soils. Soils supporting those cropping systems with high NPP normally have higher total soil porosity than those with low NPP. Shaver *et al.* (2002) reported that continuous cropping systems increased total porosity (0.54 mm^3 mm^{-3}) more than wheat-fallow systems (0.50 mm^3 mm^{-3}) in a 12-yr NT system in the Great Plains. In contrast, Karlen *et al.* (1994) observed no differences in total porosity among soils mulched with 0, 100, and 200% of corn stover mulch.

Soil water content is one of the most sensitive parameters to crop residue removal. Bare soils lose moisture soon after the protective mulch cover is removed. Mulched soils are normally wetter in spring and summer than unmulched soils (Shaver *et al.*, 2002). Wilhelm *et al.* (1986) reported that mulch/stover cover explained 84% of variations in water storage in a NT silty clay loam. Mulching with crop residues improves soil water storage by: 1) increasing infiltration rate and decreasing runoff losses, 2) reducing evaporation and abrupt fluctuations in soil surface temperature, and 3) increasing SOM concentration, which increases water retention capacity of the soil. Residue-derived SOM interacts with soil matrix and increases the specific surface area of soil essential to adsorb and retain water molecules. Thus, soil water content and plant available water capacity decrease with increase in residue removal because of the deterioration in soil structure, depletion of residue-derived organic materials, and high losses by evaporation (Blanco-Canqui *et al.*, 2007a).

Impacts of residue removal on soil water retention have been widely documented (Table 2). Blanco-Canqui *et al.* (2007a) reported that water retention decreased with increase in stover removal rates across three NT soils in Ohio within one year following removal. They observed that mulched soils retained 20 to 50% more water than unmulched soils for 0 to −6 kPa soil water potential. Stover removal at rates as low as 25% reduced water retention in silt loams. In contrast, Morachan *et al.* (1972) reported that continued application of 16 Mg ha^{-1} of stover for 13 consecutive years did not increase soil water retention (−30 kPa) over unmulched plots in a plowed silty clay loam. Similarly, Karlen *et al.* (1994) observed no differences in water retention and plant available water content between soils with 0% and 100% stover cover, but soils with 200% stover cover retained more than those with 0% cover at −9.8 kPa in silt loams. Available data show that residue removal impacts on soil water retention can be large in some soils and small on others, depending on soil texture, terrain, drainage, and climate.

3.2. Saturated Hydraulic Conductivity. Residue removal impacts on saturated hydraulic conductivity (K_{sat}) are somewhat inconsistent because of its high spatial and temporal variability. The use of small cores for its characterization may be the cause for the large variations in K_{sat}. For example, Karlen *et al.* (1994) observed that differences in geometric mean K_{sat} values among NT soils with 0% stover cover (5.4 mm h^{-1}), 100% cover (21.9 mm h^{-1}), and 200% cover (68.0 mm h^{-1}) were large but were not statistically significant after 10 years of stover management. Similarly, Sharratt *et al.* (2006) observed no statistical differences in K_{sat} between soils with mulch rates of 0% and 100% cover of barley straw mulch in a 20-yr NT silt loam (Table 2). In contrast, other studies have reported significant impacts of residue removal K_{sat} (Table 2). For example, Findeling *et al.* (2003) reported a linear decrease in K_{sat} with increase in rates of stover removal on a sandy loam after 4 years of stover management. Blanco-Canqui *et al.* (2007a) also reported decrease in K_{sat} in the short term when stover was removed at 0, 25, 50, 75, and 100% from NT systems in a clay loam and two silt loams (Table 2). Under plowed soils, Singh *et al.* (1996) observed that complete removal of barley straw reduced K_{sat} by about 5-fold after 9 years of straw management.

Table 2 shows two trends in response of K_{sat} to residue removal. One, changes in K_{sat} can be rapid soon after the residue removal. Two, the K_{sat} data are highly variable with no consistent trends. Response of K_{sat} to residue removal may also differ depending on the nature and quality of crop residues and duration of tillage and crop residue management. Bordovsky *et al.* (1999) observed that complete removal of sorghum and wheat straw removal decreased K_{sat} from 5.5 to 3.2 mm h^{-1} in an irrigated sandy loam but not on a dryland soil. Stover removal may impact soil hydrology differently because such as wheat and soybean residues are less coarse and more decomposable than stover, which remains longer on the soil surface. Large numbers of continuous biochannels in soils of temperate climates may lead to greater K_{sat} than in dry environments with reduced earthworm activity (Singh *et al.*, 1996).

3.3. Water Infiltration. Similar to K_{sat}, impacts of residue removal on water infiltration rates also depend on soil type. Soil surface sealing, crusting, and consolidation due to residue removal are the main causes of reduction in water infiltration rate. Abundant surface-connected macropores (e.g., earthworm burrows) in mulched soils improve water infiltration rate (Shipitalo and Butt, 1999). Thus, decrease in water infiltration rate by residue removal is often due to the clogging of open-ended biopores. Crop residue removal drastically decreases the earthworm population (as discussed later). A 3-yr study in Ohio showed that adverse impacts of stover removal on decreasing water infiltration rates were large on a sloping silt loam, small on a nearly flat silt loam, and nonsignificant on clay loam (Blanco-Canqui and Lal, 2007a; Table 2). The data from their experiments showed that stover removal reduced cumulative

TABLE 2
Influence of crop residue removal on soil hydraulic properties across a number of soils.

Soil and Slope	Tillage System (Duration, years)	Type of Residue	Residue Cover	K_{sat} mm h^{-1}	Cumulative water infiltration cm	Water Retention (−33 kPa) mm^3 mm^{-3}	Plant Available Water mm^3 mm^{-3}
			%				
[1]Silt loam (10%)	No-till (3)	Corn	0	0.43b	18.2b	0.28c	0.114b
			25	0.43b	19.9b	0.35bc	0.17b
			50	1.01ab	33.7b	0.40b	0.22ab
			75	2.20ab	52.5ab	0.42ab	0.23ab
			100	2.40a	70.2a	0.43ab	0.23ab
[1]Silt loam (2%)	No-till (3)	Corn	0	0.05c	28.4b	0.20b	0.06b
			25	0.04c	21.6b	0.19b	0.04b
			50	0.05c	14.6b	0.24ab	0.07b
			75	5.19b	42.7a	0.25ab	0.06b
			100	1.44b	36.4ab	0.30ab	0.09b
[1]Clay loam (<1%)	No-till (3)		0	0.48	13.7a	0.24c	0.06b
		Corn	25	0.24b	2.3a	0.25c	0.07b
			50	1.29b	15.0a	0.25c	0.06b
			75	3.61a	22.1a	0.35b	0.12ab
			100	5.41a	9.8a	0.43a	0.17a
[2]Silt loam	No-till (20)	Barley	0	612a	8.4b	0.58b	
			100	648a	10.4a	0.60a	
[3]Clay loam	Plow Till (9)	Barley	0	40.7b	425a	0.36a[†]	0.16a
			100	220.3a	276a	0.35a[†]	0.18a
			Mg ha^{-1}				
[4]Silt loam	No-till (10)	Wheat	0	53b	164a	0.32b	0.20a
			8	6213a	117a	0.52a	0.16a
			16	6883a	64a	0.57a	0.16a
[5]Sandy loam	Bare soil (2)	Rice straw	0	300c	110c		
			2	450c	150c		
			4	700b	200b		
			6	1320a	240b		
			12	1290a	350a		

[†] values correspond to -10 kPa.
[1]Blanco-Canqui et al. (2007a, 2007b); [2]Sharratt et al. (2006); [3]Singh et al. (1996); [4]Blanco-Canqui and Lal (2007c); [5]Lal et al. (1980).

water infiltration by 2.5 times and at 50% compared with 4 times by 100% removal in the sloping silt loam. In nearly level silt loam, however, complete stover removal reduced cumulative water infiltration by only about 30%. These data suggest that flat silt loams and clayey soils may respond at a slower pace to stover removal compared to soils on sloping terrains. Lal *et al.* (1980) observed that application of rice straw mulch at 4 to 6 Mg ha^{-1} increased water infiltration rate by 100% and that of 12 Mg ha^{-1} increased it by 300% in a sandy loam in Nigeria. Sharratt *et al.* (2006) reported that removal of barley straw from a NT silt loam reduced cumulative water infiltration by about 20% in subarctic Alaska. Other studies have, however, reported little or no impacts of residue mulch cover on water infiltration rate. Application of stover mulch at rates as high as 16 Mg ha^{-1} (Morachan *et al.*, 1972) to a plowed silty clay loam and wheat straw (Blanco-Canqui and Lal, 2007c) to a NT silt loam did not increase water infiltration in ≥10-yr experiments in Ohio. Likewise, Unger (1992) on a clay loam in Texas and Singh and Malhi

(2006) on a loam in Canada did not observe any differences in water infiltration rate between mulched and unmulched soils under NT.

There are several reasons for the inconsistent impacts of residue mulch on water infiltration reported in the literature. In some soils, water infiltration rates do not decrease with residue removal in spite of the significant decrease in earthworm population. This is probably because of the lack of incorporation of residue mulch in NT soils that limits earthworm activity (e.g., shallow-dwelling endogenic earthworms) to near-surface layers only and reduces the development vertical and continuous water-conducting burrows. Stratification of changes in soil properties and earthworm population under NT management is common. Presence of poorly drained subsoil horizons beneath the residue mulch may also offset increases in water infiltration rate by mulching. Lower antecedent water content, higher rates of evaporation, and lower hydrophobic properties may increase water infiltration rate in unmulched soils to a level similar to that observed in mulched soils. The build-up of a stratified surface layer of SOM under heavily mulched soils may tend to restrict water infiltration rate in soils of cool and temperate climates (Sharratt *et al.*, 2006) by imparting water repellent or hydrophobic properties to soil. For example, Blanco-Canqui and Lal (2007c) found no differences in water infiltration but higher water repellency in mulched than unmulched soils. The lower water repellency in unmulched soils may have enhanced infiltration in unmulched soils. Contrary to the general view that agricultural soils are non-water repellent (Wallis and Horne, 1992), heavily mulched soils may exhibit some water repellent properties, known as subcritical water repellency, depending on the quantity and quality of residue-derived SOM compounds (Hallet *et al.*, 2001; Goebel *et al.*, 2004). This topic is discussed later in physical properties of soil aggregates. Published data highlight the complexity of the impact of residue mulch and the large variability of water infiltration characteristics.

4. *Soil Thermal Properties*

Soil temperature regime is a key dynamic property moderating numerous physical, hydrological, chemical, and biological processes in the soil. It determines seed germination, seedling emergence and growth, plant height and physiological development, evaporation rates, soil water storage and flux, soil air composition and gaseous (e.g., CO_2, CH_4, and N_2O) fluxes, microbial activities, nutrient availability and cycling, and many other soil processes (van Donk *et al.*, 2004; Parkin and Kaspar, 2003). Quantity of crop residue mulch retained on the soil surface determines the soil temperature regime (Larney *et al.*, 2003). Thus, any removal or addition of crop residues can rapidly change the soil temperature dynamics. Residue mulch insulates the soil surface from abrupt fluctuations in air temperature, but the amount of residue retained on the soil surface determines the degree of insulation (Kladivko, 1994). Mulch cover moderates temperature exchange and dynamics between the soil and the atmosphere (Sauer *et al.*, 1996; Sharratt, 2002), in a way that mulched soils are normally cooler during the day and warmer during the night than unmulched soils.

Removal of crop residues creates different microclimatic conditions (Gupta *et al.*, 1981). Mulched soils are cooler in summer and thus have lower evaporation losses than unmulched soils. In contrast, higher soil temperature in unmulched soils accelerates evaporation and reduces available water storage for plant growth (Hu and Feng, 2003). In cool and temperate regions, because mulched NT soils are considerably cooler in spring than mulched soils (Drury *et al.*, 2003), they can retard seed germination and delay stand establishment (Arshad and Azooz, 2003). During winter, however, mulched soils can accelerate microbial processes in winter and early soil thawing because of warmer conditions (Benoit *et al.*, 1986). In the Corn Belt region, Sharratt (2002) observed that near-surface temperature in soils with 60-cm-tall corn stubble was about 2°C higher than those in without stover and stubble during winter. Partial removal of residue mulch may be an option to reduce excessive cooling of NT soils during spring. Models have been used to predict and understand changes in diurnal and annual temperature variations in response to partial removal of stover (Gupta *et al.*, 1981). Effects of crop canopy and residue cover on soil temperature have been modeled for a range of soils and environments (Van Wijk and De Vries, 1963; Cruse *et al.*, 1980; Ghorman and Lal, 1984; van Donk *et al.*, 2004; Elias *et al.*, 2004).

In a study across two silt loams and a clay loam in Ohio, Blanco-Canqui *et al.* (2006c) observed that stover management had a strong effect on soil temperature (Fig. 2). Soil temperature decreased with increase in rates of stover cover, except during winter. The bare soil without stover had consistently the highest soil temperature for all stover rate treatments. The temperature from June to October decreased with increase in rate of stover removal. Stover removal at rates $>25\%$ strongly altered the soil temperature regime. On average, there was a drop of 5°C when stover removal rate increased from 0 to 75% regardless of soil type. No significant differences in soil temperature were observed for stover removal rates of 75% and 100%. The effect of stover management on soil temperature during winter time when the soil was covered with about 15 cm of snow was the opposite of that during summer. Soil temperature in winter decreased with decrease in rate of stover removal (Fig. 3).

Lower soil temperature in soils with residue retention is attributed to the fact that mulch cover significantly alters the radiation balance. Light colored stover cover has high albedo and reflects the incoming solar radiation at the soil surface (Horton *et al.*, 1994). Residue removal effects on soil temperature are also large in cold regions. Complete removal of stover from NT increased soil temperature by 2.2°C and soil thermal diffusivity by about 15% in Canada (Arshad and Azooz, 1996). Similarly, Sharrat *et al.* (1998) observed that standing stubble and stover reduced soil freezing and increased snow cover thickness in a loam in the northern U.S. Corn Belt. Stover mulch

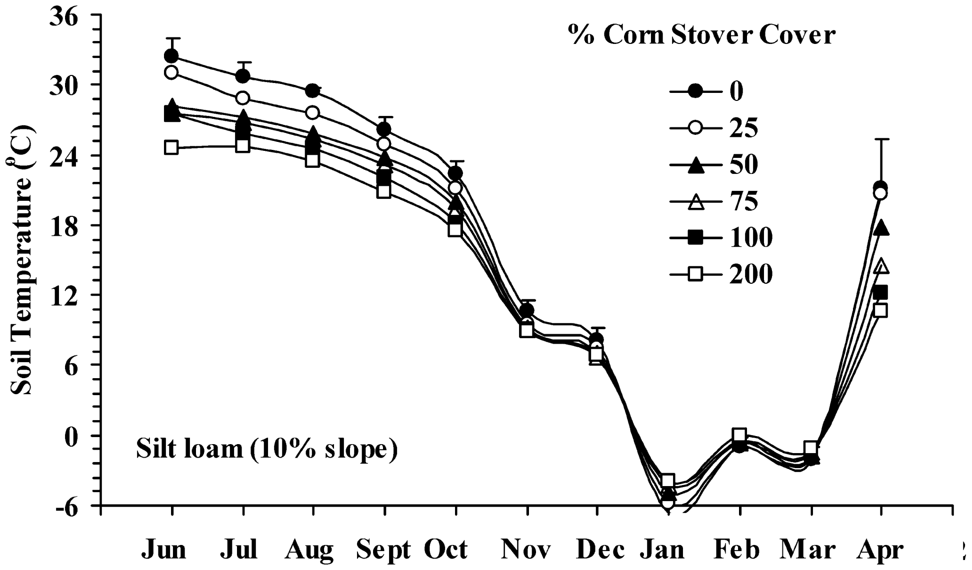

FIG. 2. Response of soil temperature to varying rates of stover cover in a no-till corn in Ohio. The error bars represent the LSD values of the mean.

increases the soil surface roughness and enhances the snow accumulation/trapping as compared to bare soils. The reduced soil freezing by stover mulch can reduce soil freezing and may accelerate early spring thawing as compared with removing stover. In general, stover removal can greatly alter the soil temperature dynamics.

5. *Aeration and Gaseous Flux*

Adequate aeration is essential to soil and rhizospheric processes. Proper aeration promotes plant root development, nutrient uptake, heat movement, and crop growth. Aerobic soil organisms also require oxygen for respiration and nutrient cycling, and transformations. Reduction in air permeability can impede drainage and increase risks of runoff and soil erosion. Crop residue removal reduces air permeability by decreasing macroporosity. Stover removal at rates $\leq$25% can reduce air flow and inhibit gaseous exchange. Blanco-Canqui *et al.* (2007a) observed that stover removal explained about 98% of the variability in gaseous flux across three soils in Ohio. The air flux under soils with 75, 100, and 200% of stover cover was 1.3 times higher than those in soils with 0, 25, and 50% of stover retention. Impacts of crop residue removal on air flux are similar to those on K_{sat} because both are influenced by changes in soil macroporosity. Similar to water, air flows preferentially through large and continuous macropores in accordance with Pouseuille's Law (Iversen *et al.*, 2003).

6. *Micro-Scale Soil Physical Properties*

Crop residue removal affects soil properties at macro- and micro-scale (Blanco-Canqui and Lal, 2008), thus maintaining crop residues on the soil surface is important to moderating soil properties and functions at all scales. Data on the impacts of crop residue removal on soil properties at the aggregate or micro-scale level are, however, few because most of the studies on residue removal have primarily focused on macro-scale soil properties (Lal *et al.*, 1980; Karlen *et al.*, 1994; Sharratt *et al.*, 2006; Singh and Malhi, 2006). Yet, understanding the impacts of residue removal on micro-scales is also important because soil aggregate dynamics influence the macro-scale behavior of the whole soil (Horn *et al.*, 1994; Blanco-Canqui *et al.*, 2005a). Properties of individual aggregates reflect those of the soil matrix and influence root growth (Reuss *et al.*, 2001), SOM storage and dynamics (e.g., encapsulation of SOM) (Urbanek *et al.*, 2007), water flux and retention (Carminati *et al.*, 2007), nutrient cycling and storage (Wang *et al.*, 2001), and soil erosion risks (e.g., detachment and slaking) (Blanco-Canqui *et al.*, 2007b). For example, soil erodibility is influenced by the strength and stability of individual aggregates against erosive forces of raindrops and shearing forces of runoff.

Aggregates often differ in their properties from the whole soil because of differences in the mechanisms of their formation and turnover. Unlike the whole soils, microaggregates may remain undisturbed during plowing (Horn, 1990). Tensile strength and density of aggregates tend to be higher than those of the bulk soil because aggregates are more cohesive and compact. Some of the aggregate properties sensitive to crop residue management are density, stability, strength, pore-size distribution, and water repellency, sorptivity, and retention. Perpetual removal of crop residues can drastically alter the structural and hydrological properties of individual aggregates (Blanco-Canqui and Lal, 2008).

6.1. Aggregate Disintegration and Tensile Strength. In general, less raindrop kinetic energy is required to disintegrate

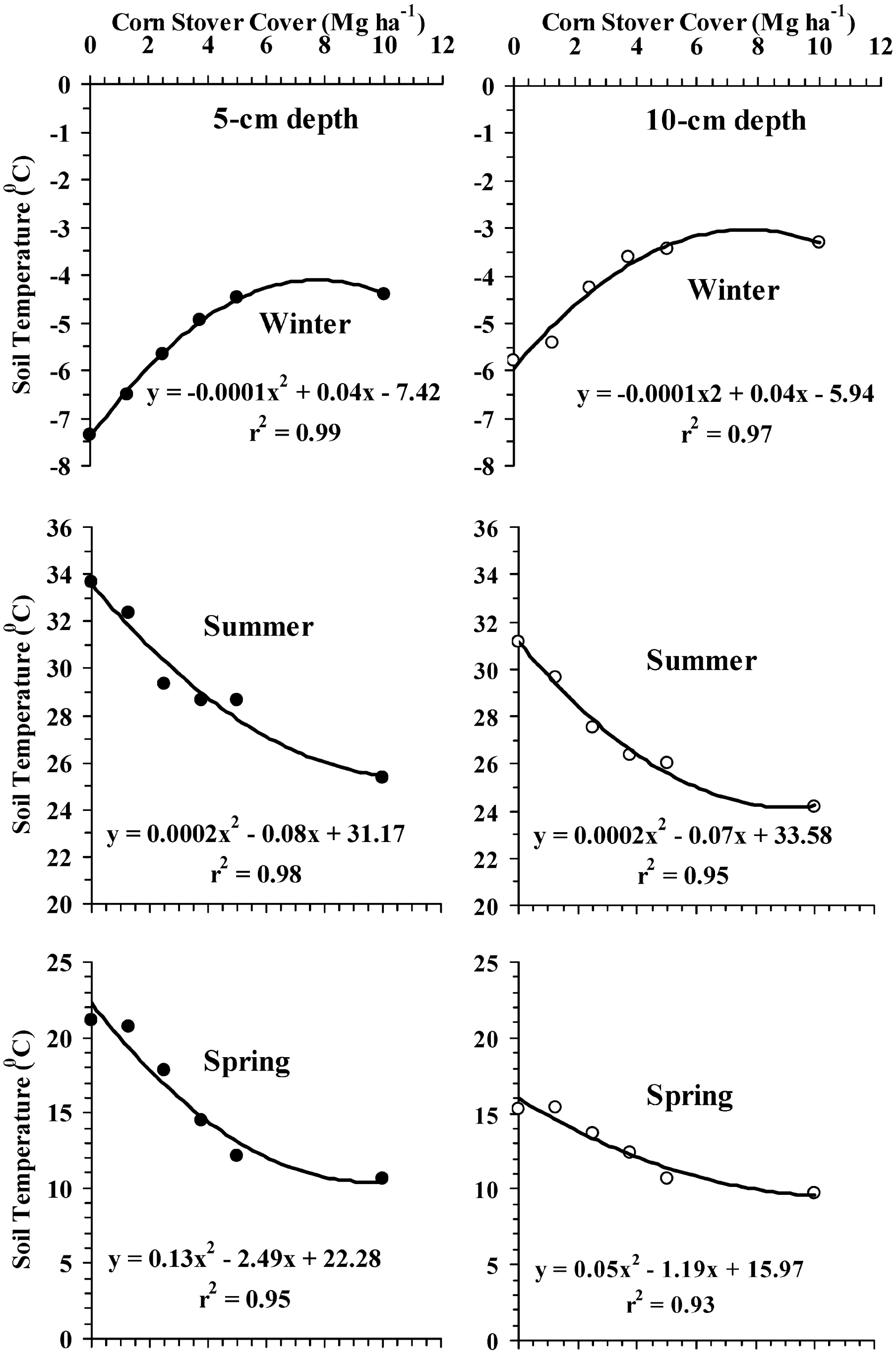

FIG. 3. Soil temperature as a function of stover cover for no-till corn in Ohio.

aggregates from unmulched soils. In a study with individual soil aggregates, Blanco-Canqui and Lal (2008) observed that complete stover removal reduced the kinetic energy needed to break aggregates by 2 to 20 times regardless of the soil type. Furthermore, stover removal at rates ≤25% reduced tensile strength by 10% to 30% for aggregates equilibrated at a range of water potentials. Impacts of stover removal on tensile strength were more pronounced on 2.0- to 3.3- and 4.75- to 8-mm aggregates than on 1- to 2-mm sized aggregates. Reduction in SOM concentration due to residue removal decreased the formation of strong and cohesive aggregates. Residue-derived organic compounds (e.g., polysaccharides) react with clay particles and create strong interparticle bonds of aggregates, acting as cementing agents upon drying (Zhang, 1994). Residue removal also increases aggregate density because of reduction in intraggregate macroporosity.

6.2. Aggregate Water Retention and Subcritical Water Repellency. Crop residue removal also affects the hydraulic properties of aggregates, especially the water retention. On a sloping silt loam, complete removal of stover reduced the aggregate water retention by about 30% for −0.1 and −30 kPa and by about 30% to 80% for −30 to −1500 kPa water potentials (Blanco-Canqui and Lal, 2008). However, the effects of residue removal were smaller on nearly level silt loam and clayey soils. Residue removal also reduces the ability of a soil to repel water entry. Subcritical water repellency, ability to slightly repel water, is an important and intrinsic property of aggregates. It impacts water sorption, infiltration, aggregate detachment, SOM storage, and susceptibility to accelerated runoff and soil erosion (Hallet *et al.*, 2001; Goebel *et al.*, 2004; Eynard *et al.*, 2004). Residue removal reduces the aggregate water repellency by decreasing input of organic materials and activity of soil organisms. Earthworms, for example, can induce some water repellency by excreting some organic compounds. Organic films coat aggregates and impact their hydrophobic properties. Blanco-Canqui and Lal (2007b) reported that aggregates from a NT silt loam without wheat straw had lower water repellency than those from mulched soils.

The presence of subcritical water repellency favors the stability and strength of aggregates. Non-water repellent aggregates are dispersed more easily than those that exhibit some degree of water repellency because the rapid entry of water into soil slakes aggregates by entrapping air and causing rapid pressure release (Hallet *et al.*, 2001). Mulching can delay water entry into the aggregates by 5 to 15% compared to unmulched soils (Blanco-Canqui and Lal, 2008). The small delay in water penetration has important implications in reducing susceptibility to aggregate slaking and soil erodiblity. Water drop penetration test (WDPT), capillary rise method (CRM), Wilhelmy plate method, and repellency index (ethanol: water ratio) are some of the techniques used to characterize water repellency of soils (Letey *et al.*, 2000). Using the WDPT, water repellency in aggregates can be classified as non-water repellent (WDPT $<$1s), very low repellency ($1 <$ WDPT $<$10 s), and low repellency ($10 <$ WDPT < 60 s) (King, 1981).

There is a strong interaction among soil texture, water content, and residue-derived hydrophobic organic materials in imparting water repellency. Clayey soils tend to be more water repellent than silt loams under similar amounts of crop residue mulch (De Gryze *et al.*, 2006). Blanco-Canqui and Lal (2008) showed that stover removal reduced water repellency by 2-fold with 50%, 7-fold with 75%, and 9-fold with 100% of stover removal at −0.01, −0.1, and −0.03 MPa water potentials in a sloping silt loam. In comparison, stover removal at rates ≥50% on a relatively flat silt loam reduced water repellency by 3 to 10 times at the same water potentials. On a clay loam, stover removal reduced water repellency by 1.5 times for 25% removal, and by 1.8 times by 50% removal, and by about 3.5 times by ≥75% removal at −0.1, −0.3, and −1.5 MPa water potential. Aggregate sorptivity, a property related to water repellency, is also affected by rates of residue removal. On a clay loam, complete stover removal increased aggregate sorptivity by 2.8 times compared with normal residue rates (Blanco-Canqui and Lal, 2008).

B. Chemical Properties

1. pH, Cation Exchange Capacity, and Electrical Conductivity

Impacts of crop residue removal on pH, cation exchange capacity (CEC), and electrical conductivity (EC) are generally small, at least over a decadal scale. Morachan *et al.* (1972) reported that soil pH decreased in a silty clay loam by 0.2 (from 5.3 to 5.1) and 0.5 (from 5.3 to 4.8) units with mulch application rate of 4 and 16 Mg ha^{-1} of stover, respectively. In contrast, Karlen *et al.* (1994) observed no impacts of stover removal on soil pH in silt loams. High rate of mulch application tends to decrease soil pH near the surface layers (Karlen *et al.*, 1984). Blanco-Canqui and Lal (2009a) observed that CEC decreased and pH and EC slightly increased with increase in rate of stover removal in the three soils in Ohio, but the magnitude of changes depended on soil type. Shaw and Mask (2003) also reported that residue removal from NT corn-soybean-wheat rotation systems increased EC by 5% in a loam-textured soil.

2. Macro- and Micro-Nutrients

Removal of crop residues reduces soil fertility because residues are an important reservoir of essential macro- (e.g., K, P, N, Ca, and Mg) and micronutrient (e.g., Fe, Mn, B, Zn, and S) pools (Table 3). all the residues at harvest is indispensable for recycling SOM and essential nutrients. The SOM decreases in direct proportion to the rate of residue removal although the magnitude of the decrease is a function of the antecedent SOM concentration, soil type, topography, and climate (Larson *et al.*, 1972; Karlen *et al.*, 1994; Salinas-Garcia *et al.*, 2001; Potter *et al.*, 2007) (Fig. 4). of crop residue removal on SOC storage and dynamics have been reviewed in another report (Blanco-Canqui *et al.*, 2009b).

Many studies have shown that crop residue removal reduces nutrient pools. Fixen (2007) estimated that stover removal at about 40% can reduce N pool by 20%, P by 14%, and K by 110% in the U.S. Corn Belt region. The adverse impacts of crop residue removal on total C and N pools are often larger than those on other nutrients. Karlen *et al.* (1994) reported that complete stover removal drastically reduced total C and N, and NO_3-N concentrations but had no effects on P, K, Ca, and Mg concentrations in silt loams after 10 years of stover management. Similarly, Karlen *et al.* (1984) observed no significant impacts of residue removal on P, K, Ca, Mn, and Zn in a sandy loam soil. Larson *et al.* (1972) also found smaller impacts of stover removal on available P as compared with those on C and N pools.

TABLE 3
Influence of crop residue removal on soil chemical properties for different soils.

Soil (Slope)	Tillage (Duration, years)	Crop	Residue Cover	pH	Organic C g kg^{-1}	Total N g kg^{-1}	Available P mg kg^{-1}	Exchangeable K mg kg^{-1}	Ca mg kg^{-1}	Mg mg kg^{-1}	CEC	EC
			%									
[1]Silt loam (10%)	No-till (4)	Corn	0	7.15a	18.9b	1.9b	32	331	1513	457	12	0.36a
			25	7.12a	23.3ab	2.3ab	37	332	1648	502	13	0.34a
			50	7.07a	23.0ab	2.3ab	38	351	1573	482	13	0.35a
			75	7.04a	24.9a	2.4a	46	383	1541	475	13	0.25b
			100	7.06a	27.1a	2.5a	52	389	1663	525	14	0.25b
			200	7.05a	28.3a	2.6a	55	395	1650	530	14	0.24b
[1]Silt loam (2%)	No-till (4)	Corn	0	7.16a	21.4b	2.0b	107	230	2305	566	17	0.13a
			25	7.01a	20.4b	1.9ab	101	220	2003	524	18	0.13a
			50	7.26a	25.1ab	2.2ab	137	293	2253	566	16	0.15a
			75	6.76a	24.1ab	2.3ab	134	284	2145	555	17	0.17a
			100	6.7a	28.0a	2.6a	140	333	2208	585	17	0.16a
			200	6.6a	28.6a	2.7a	145	339	2210	600	18	0.15a
[1]Clay loam (<1%)	No-till (4)	Corn	0	5.96a	21.2b	2.4a	52	279	2187	390	20	0.40a
			25	5.76ab	22.8ab	3.2a	59	292	2316	391	18	0.47a
			50	5.73ab	24.0ab	2.7a	54	302	2316	415	21	0.25b
			75	5.52ab	25.7a	2.7a	50	318	2251	411	22	0.17b
			100	5.63a	26.8a	2.7a	50	370	2328	413	22	0.15b
			200	5.50a	27.5a	2.8a	53	380	2390	420	23	0.15b
[2]Sandy loam	No-till (5)	Corn	0	5.93ab	32.0d	1.3b	13.5a	437ab				0.20a
			33	6.05a	34.5c	1.5ab	10.7b	370b				0.19a
			66	5.79bc	38.0b	1.7a	10.1b	401ab				0.22a
			100	5.65c	42.0a	1.7a	13.8a	478a				0.24a
[3]Sandy loam	No-till (4)	Corn	10	5.8a			77a	126a	424a	94a		
			33	5.8a			70a	108a	419a	93a		
			100	5.9a			66a	108a	383a	95a		
			Mg ha^{-1}									
[4]Sandy loam (2 to 4%)	Plow Till (8)	Wheat	0		10.4b	0.89b		277c	1182a	259a		
			1.68		11.5b	0.97b		320bc	1160ab	246a		
			3.36		12.2ab	0.96b		355ab	1128ab	244a		
			6.73		12.8a	1.02a		394a	1114b	260a		
[5]Sandy loam	Bare Soil (1.5)	Rice	0	5.8b	14.0c		10b	78c	1100a	468a		
			2	5.9b	14.0c		12b	117bc	1080a	507a		
			4	5.9b	15.0bc		11b	156ab	1080a	507a		
			6	6.2a	17.0ab		15ab	195a	1060a	585a		
			12	6.2a	18.0a		18a	195a	1120a	546a		

[1]Blanco-Canqui and Lal (2009a); [2]Roldán et al. (2003); [3]Karlen et al. (1984); [4]Black (1973); [5]Lal et al. (1980).

Blanco-Canqui and Lal (2009a) reported that stover removal reduced total C, N, P, K, Ca, and Mg pools on a sloping silt loam after three years of continued stover removal but its impacts were smaller on nearly level silt loam and clay loam soils in Ohio. Complete stover removal reduced total N pool by 1.1 Mg ha^{-1} and available P concentration by 20 mg kg^{-1} on the sloping silt loam in the 0- to 20-cm soil depth, while it reduced total N by 0.80 Mg ha^{-1} on the nearly level silt loam.

Rate of removal, rate of residue decomposition, quality of residue, rate of fertilizer application, soil characteristics, and climate determine the amount of nutrients depleted with residue removal. In a tropical region of Mexico, Salinas-Garcia *et al.*

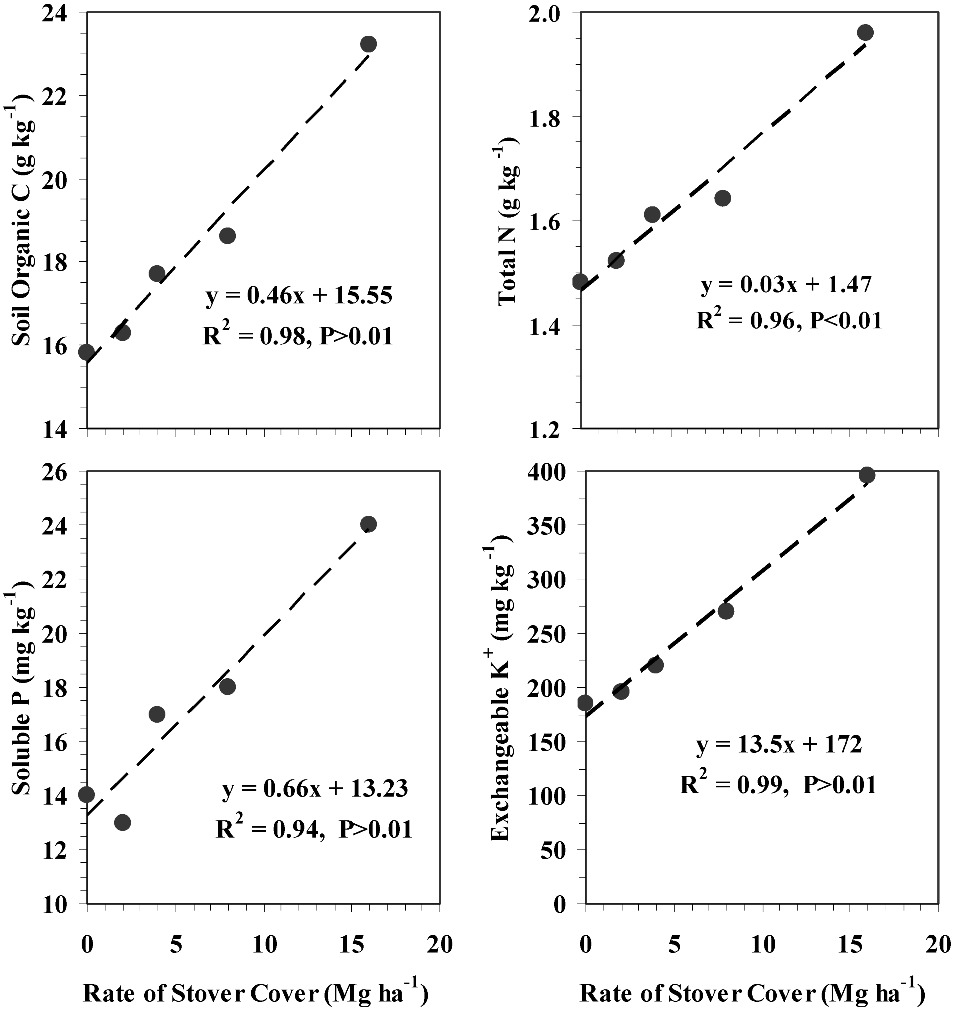

FIG. 4. Stover removal reduced soil nutrient pools on a silt clay loam under 11-yr NT continuous corn management in Iowa (After Larson *et al.*, 1972).

(2001) observed that stover removal drastically reduced total C and N pools and extractable P from a clay and silty clay under NT. On the silty clay, total N concentration plots with 100% stover retention was 1.09 Mg ha^{-1}, but residue removal by 33% reduced total N by about 25% while complete removal reduced it by about 55%. On the clayey soil, 33% of stover removal reduced total N concentration by about 20% and complete removal reduced it by about 36% when the total N concentration in plots with 100% stover retention was 0.39 Mg ha^{-1}. Salinas-Garcia and colleagues observed that stover removal by 33 and 66% from the silty clay did not decrease extractable P but complete removal reduced it by about 20%, whereas, removal at rates <33% from the clay loam reduced extractable P by about 33%.

Residue removal reduces nutrient pools by: 1) removing the nutrients contained in the residues, 2) increasing risks for runoff and soil erosion which removes nutrients, and 3) accelerating SOM mineralization under the bare soil surface because of alterations in soil temperature and moisture regimes. Large amounts of these nutrients are removed along with residue. For example, the average concentration of total C and N in stover is 42 and 10 g kg^{-1}, respectively while the concentration of the rest of elements in mg kg^{-1} is 993 for P, 5056 for K, 5127 for Ca, 2386 for Mg, 8 for B, 7 for Cu, 196 for Fe, and 43 for Mn (Blanco-Canqui and Lal, 2009a). Thus, any removal of residue directly removes residue-derived nutrients. The reduction in nutrient pools by residue removal is positively correlated with the reduction in crop yields (Blanco-Canqui and Lal, 2009a). The amount of crop residue required for maintaining the essential nutrients is more than required for reducing soil erosion to tolerable limits (Wilhelm *et al.*, 2007). The reduction of nutrient pools by residue removal can increase the need for additional N, P, and K fertilizers to offset the losses of nutrients. The excessive use of chemical fertilizers or animal manure can increase risks of non-point source pollution of surface and ground waters (e.g., hypoxia). Nutrients are also removed with grain removal, but this fact, while highly important, is not discussed in this paper because our main focus was on crop residue removal.

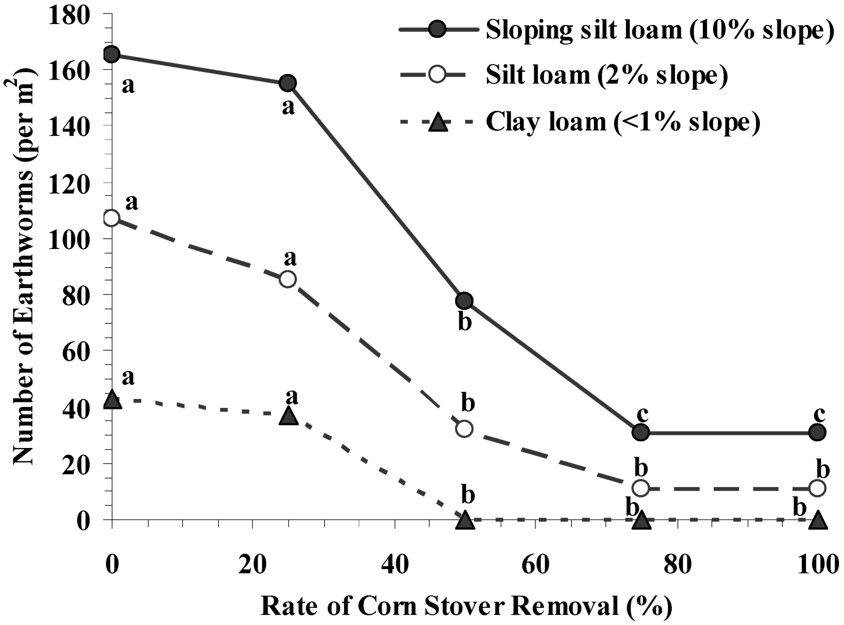

FIG. 5. Earthworm density decreases with stover removal regardless of soil type in the surface 0- to 15-cm depth (After Blanco-Canqui and Lal, 2007a). Means within the same soil followed by the same letter do not significantly differ at the 0.05 probability level.

C. Biological Properties

1. Earthworm Population

Removal of crop residues reduces earthworm population and the number of surface-connected macropores because residues are a food source and habitat to soil macro- and microorganisms (Bohlen *et al.*, 1997; Butt *et al.*, 1999; Shipitalo and Butt, 1999). Earthworms are essential to soil structural development, nutrient recycling, SOM turnover, and fluxes of water, air, and heat across the entire soil profile (Bohlen *et al.*, 1997). Residue mulch preserves surface macropores and promotes the development of macropore network. In general, the earthworm population decreases with increase in rate of residue removal regardless of the type of crop residues. Blanco-Canqui and Lal (2007a) observed that plots without wheat straw mulch had no earthworms (0 per m^2) in comparison with 158 ± 52 worms m^2 in plots mulched with 8 Mg ha^{-1} of straw and 267 ± 58 worms m^2 in plots mulched with 16 Mg ha^{-1}. Karlen *et al.* (1994) observed that soils mulched with 100 and 200% of stover had more (78 per m^2) earthworms than unmuched treatment (53 per m^2) in two NT silt loams. Blanco-Canqui and Lal (2007a) reported that stover removal at rates as low as 25%reduced the earthworm population across three contrasting Ohio soils. Soils mulched with 100 and 75% of stover had on average 3 times more earthworms per m^2 than those mulched with 0, 25, and 50%of stover cover in a sloping silt loam stover removal at rates > 50% eliminated all earthworms in a clayey soil (Fig. 5).

Earthworm activity creates microenvironments through formation of dynamic fabric of residue-enriched middens (Fig. 5). A network of surface-connected and vertical burrows is often observed under the middens (Shipitalo and Butt, 1999). Removal of residue causes the migration of earthworms to neighboring mulched soils or to lower soil depths. Unlike the surface-feeding and midden-building species, earthworms below the surface feed on root-derived residues and SOM. Thus, a shift in earthworm species composition may occur with residue removal. The decrease in earthworm population with increase in rate of residue removal is attributed to the decrease of food supply, lack of protective surface cover, and increase in fluctuations in soil temperature (Shaver *et al.*, 2002). Reduction in the number of earthworms often results in a concomitant decrease in water infiltration rate and amount, which increases risks of runoff and soil erosion. It also impairs essential soil processes such as aggregate formation and stability, aeration, SOM decomposition and humification, nutrient cycling, and microbial activity (Karlen *et al.*, 1994).

2. Microbial Biomass

Crop residue removal also influences the dynamics of soil microorganisms. Karlen *et al.* (1994) reported higher fungal biomass (e.g., ergosterol) in soils with 200% of stover cover compared with unmulched control, and the decrease in fungal biomass with stover removal partly explained the lower aggregate stability in unmulched soils. Higher microbial activity stabilizes soil aggregates by producing organic binding agents. Salinas-Garcia *et al.* (2001) observed that soil microbial biomass C and N concentrations were higher near the soil surface of plots mulched with 33, 66, and 100% of stover compared with unmulched control. Abundant food supply, optimum soil water content, and favorable soil temperature contribute to an increase in microbial biomass in mulched soils. Roldán *et al.* (2003) reported that plots with $\leq$33% of stover cover had lower (322 mg kg^{-1}) microbial biomass C than those with 66 (426 mg kg^{-1}) and 100 (654 mg kg^{-1}) % of cover.

V. RUNOFF AND SOIL LOSS

Many have documented the benefits of residue mulch cover to reducing runoff and soil erosion (Adams, 1966; Meyer *et al.*, 1970; Lal *et al.*, 1980; Khan *et al.*, 1988; Dabney *et al.*, 2004; Wilson *et al.*, 2004; Doring *et al.*, 2005). Indeed, estimates of threshold levels of crop residue removal for alternative (e.g., biofuel feedstocks) uses are being established mostly based on the data on residue requirements for reducing soil erosion rates to tolerable limits (Nelson, 2002; Kim and Dale, 2004; Graham *et al.*, 2007). Removal of residue cover exacerbates soil erosion (Mickelson *et al.*, 2001) but also deteriorates environmental quality (Mann *et al.*, 2002). Runoff and soil loss increase exponentially with decrease in surface cover on increase in rate of crop residue removal (Figs. 6 and 7). Studies conducted on silt loams (Seta *et al.*, 1993; Wilson *et al.*, 2004) and loam (Mickelson *et al.*, 2001) in the U.S. Corn Belt region shown that runoff and soil losses from unmulched soils were higher than those from mulched soils. Crop residues are the most economic and effective means to protect soil from water and wind erosion (Kladivko, 1994). Some estimates indicate that removal of 30 or 50% of stover cover may not significantly increase soil erosion, but removal above these levels can exacerbate the soil erosion hazard (Nelson, 2002; Kim and Dale, 2004).

Reduction in runoff from soils with residue mulch is attributed to improved soil structure, high water infiltration rate (Blough *et al.*, 1990) and increased macroporosity (Butt *et al.*, 1999). Blanco-Canqui and Lal (2007a) reported that a systematic removal of stover at rates of 0, 25, 50, 75, and 100% reduced both rates of water infiltration and number of earthworms. In some soils, however, residue removal may not always decrease the water infiltration rate (Unger, 1992; Singh and Malhi, 2006)

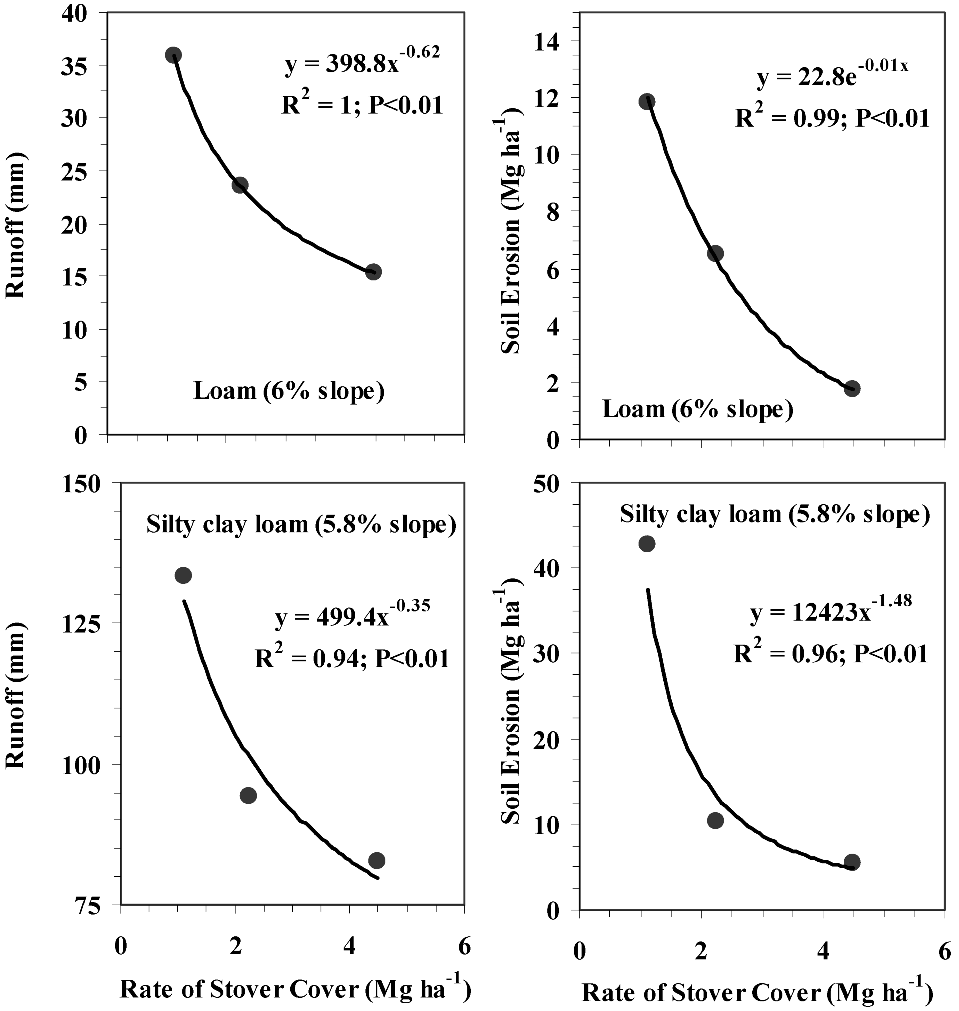

FIG. 6. Runoff and soil loss decrease in an exponential or power function with increase in rate of stover cover (After Lindstrom, 1986).

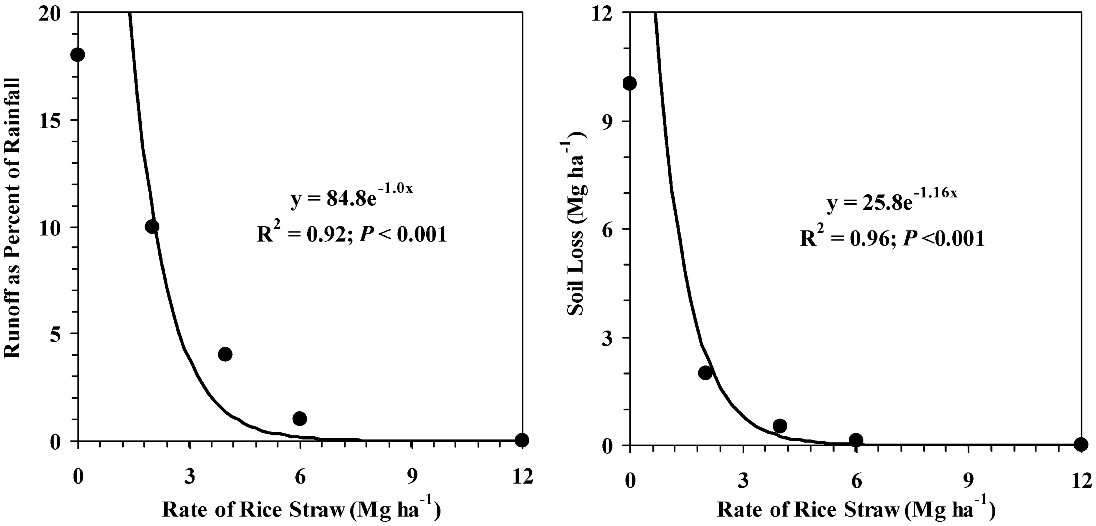

FIG. 7. Application of rice straw reduced runoff and soil erosion in a tropical sandy loam in Nigeria (After Lal *et al.*, 1980).

and increase runoff (Blevins *et al.*, 1983; Ghidey and Alberts, 1998). The effectiveness of crop residue mulch in reducing soil erosion is often greater than that for reducing runoff.

The reduction in runoff and soil erosion in mulched soils has positive implications on the environment because it reduces risks of non-point source pollution and hypoxia of coastal waters. Sediment losses in runoff from mulched soils are lower than those from unmulched soils because crop residues intercept and filter runoff and sediment-borne pollutants (Potter *et al.*, 1995; Torbert *et al.*, 1996). Uncontrolled runoff and sediment transport can carry large amounts of non-point source pollutants (e.g., fertilizers, pesticides, and herbicides) to downstream waters. Shock *et al.* (1997) observed that application of 0.90 Mg ha^{-1} of wheat straw to irrigated furrows reduced cumulative sediment loss from 333 to 17 Mg ha^{-1} after 17 irrigations, total N lost from 230 to 33 kg ha^{-1} in the first 6 irrigations, and total P lost from 215 to 18 kg ha^{-1} after 6 irrigations. Maintaining crop residue cover also significantly reduces losses of NO_3-N, NH_4-N, and PO_4-P in runoff (Torbert *et al.*, 1999). Total N transport in runoff often increases linearly with increase in rate of residue removal (Mostaghimi *et al.*, 1992).

VI. TILLAGE EROSION

Tillage erosion, which refers to the gradual soil displacement downhill due to intensive tillage operations and crop residue removal, can be a major component of total soil erosion in sloping terrains (Lindstrom *et al.*, 1990). This type of erosion has not been, however, studied in as much detail as water and wind erosion. Soil loss through tillage erosion rates can range between 15 and 600 Mg ha^{-1} annually and represent as much as 70% of total soil erosion in hilly croplands (Lobb *et al.*, 1999).

One of the best management strategies to control tillage erosion is the use of no-till technology with crop residue mulch because it eliminates or minimizes soil disturbance (Blanco and Lal, 2008). No-till systems not only reduce water and wind erosion but also tillage erosion. While crop residue mulch alone may not control tillage erosion, residue mulch cover combined with reduced tillage or no-tillage management can control tillage erosion. Moldboard plow causes greater tillage erosion than chisel and disk plows because it inverts and causes large movement of loose soil. Cultivating on the contour, reducing tillage frequency and depth, reducing tractor speed to about 1 m s^{-1}, adopting reduced tillage, establishing vegetative barriers on the contour, and establishing terraces and stone bunds are additional strategies to reduce tillage erosion (Blanco and Lal, 2008).

VII. CROP PRODUCTION

One of the most far-reaching impacts of crop residue removal for alternative uses is the reduction in crop growth and NPP. Decline in crop production by residue removal could adversely impact sustainability of land use and cropping systems. Crop production integrates all the complex and dynamic factors influenced by residue removal and which also influence plant growth by altering soil temperature regimes and radiation balance, increasing soil compaction, and reducing plant available water content, aeration, soil aggregation, soil tilth, SOM concentration, and nutrient storage and cycling. Site-specific research is needed to assess the magnitude of decline in NPP and agronomic yield by long-term removal of crop residues.

A. Crop Growth and Height

Thick crop residue cover can reduce crop emergence particularly in temperate climates with cool and wet soils during the spring (Mehdi *et al.*, 1999). Thus, a judicious removal of residue mulch can promote early emergence. Blanco-Canqui *et al.* (2006c) observed that compared to soils without stover cover, corn emergence was delayed in silt loams by 3 days in soils with 100% residue cover, and by 2 days in those with 75% cover whereas, on a clay loam soil, corn emergence was delayed by 3 days with 75% of residue cover. Delay in seedling emergence is directly reflected in seedling height. Early-emerging plants under unmulched soils often grow taller than late emerging plants under mulched soils. However, depending on local conditions, the late emerging plants under mulched soils can catch up in height with the early-emerging plants and even grow taller by the silking stage because of higher available water content and favorable temperature regimes under mulched soils. As discussed earlier, mulched soils retain more water than unmulched soils (Table 2). Blanco-Canqui and Lal (2007a) reported that mean daytime soil temperature during growing season was 23.6 ± 0.5°C (Mean ± SD) in soils with 100% stover cover, 25.6 ± 0.7°C with 75% cover, 27.4 ± 0.8°C with 50% cover, 29.4 ± 0.7°C with 25% cover, and 30.7 ± 0.5°C with 0% cover on a sloping silt loam, showing that complete removal increased soil temperature by about 6°C. The same study showed that stover-removal induced increases in soil compaction, and fluctuations in temperature explained about 45% of the variability in corn yield.

Delayed seedling emergence in mulched soils may not always translate into lower crop yields. Indeed, Dam *et al.* (2005) observed that heavy stover mulch cover reduced corn emergence by 18 to 30% compared to unmulched plots in a loamy sand, but grain yield in mulched soils did not differ from that in unmulched soils. Yet, in some environments, delayed emergence can reduce crop yields. For example, Liu *et al.* (2004) observed that a delayed corn emergence due to slow soil warming in spring and wet soil conditions in mulched soils reduced crop yields by 35 to 50% compared to unmulched soils. Corn emergence is positively correlated with soil temperature and negatively with soil water content, but at silking, plant height is often negatively correlated with soil temperature and positively with soil water content. Residue removal-induced changes in soil temperature and soil water content may have greater adverse effect on plant growth on sloping and erodible soils than on deep soils and glaciated terrains (Blanco-Canqui and Lal, 2007a).

B. Grain and Biomass Yields

Several short- and long-term studies have been conducted to assess the impacts of residue removal on crop yields (Morachan *et al.*, 1972; Wilhelm *et al.*, 1986; Karlen *et al.*, 1994; Sow *et al.*, 1997; Linden *et al.*, 2000). On a silty clay loam in Iowa, retention of stover mulch to NT soils at rates as high as 16 Mg ha^{-1} reduced yields in 2 yr, increased yields in 1 yr, and had no effects on corn yield in 10 out of 13 years (Morachan *et al.*, 1972). Another study in South Carolina from 1980 to 1982 showed that removal of stover at rates as high as 90% from a sandy loam under conservation tillage had no effects on corn yield in 1980, reduced it by 0.88 Mg ha^{-1} in 1981, and increased it by 0.52 Mg ha^{-1} in 1982 under rainfed conditions. Under irrigated conditions, residue removal by 90% increased yield by 0.66 Mg ha^{-1} in 1980 but had no effects in 1981 and 1982 (Karlen *et al.*, 1984). On a silty clay loam in Nebraska, Wilhelm *et al.* (1986) and Power *et al.* (1986) observed that stover removal at rates as low as 50% reduced corn grain yield in 2 out of 4 years by about 0.80 Mg ha^{-1}, while complete stover removal reduced stover yield in all years by 1.5 to 3.0 Mg ha^{-1} in a NT system. Both studies also reported that complete residue removal reduced soybean grain yield in 2 out of 4 years by about 0.9 Mg ha^{-1} and soybean residue yield by 1.0 to 2.3 Mg ha^{-1} in all years. Wilhelm *et al.* (1986) reported that stover removal explained between 88 and 99% of the yield variability in corn grains and between 82 and 96% in soybean yield.

In two silt loams in Wisconsin, Karlen *et al.* (1994) observed that complete stover removal from NT continuous corn systems had no effect on grain yield in 8 out of 10 years. In the remaining two years, complete stover removal increased grain yield by 0.5 Mg ha^{-1} in one years and reduced it by 2.8 Mg ha^{-1} in the other years compared to mulched soils. On a NT clay loam in Texas, Sow *et al.* (1997) observed that removal of sorghum straw reduced crop yield from 4.69 to 4.02 Mg ha^{-1}. On a silt loam in Minnesota, stover removal reduced corn grain yield by 1.0 Mg ha^{-1} during 3 of a 12-yr in NT, by 0.5 to 1.0 Mg ha^{-1} during 8 out of 12 years in chisel plow, and by about 0.5 to 2.0 Mg ha^{-1} during 4 out of 12 years in moldboard plow system under continuous corn cultivation (Linden *et al.*, 2000). In eastern Ohio, Blanco-Canqui and Lal (2007a) observed, in a 3-yr study in Ohio, that corn grain and stover yields decreased consistently every year with increase in rate of stover removal on a sloping silt loam. Corn grain yield was reduced by ∼ 20% with 50% of stover removal and by ∼ 30% with 100% stover removal (Fig. 8). The effects of stover removal were not, however, significant on a relatively flat silt loam and clay loam soil in glaciated terrains. On a silt loam in Indiana, corn grain yield was unaffected by complete stover removal, complete stover return, and double stover retention in a 6-yr NT continuous corn systems (Barber, 1979).

The reviewed literature shows that impacts of residue removal on crop yields are highly variable, and depend on the tillage method, cropping systems, duration of tillage and crop management, soil-specific characteristics (e.g., texture and drainage), topography, and climate during the growing season. Crop residue removal can increase, decrease, or have no effect on crop yields depending on site-specific conditions. The year-to-year variability in weather conditions (e.g., precipitation amount) can mask the impacts of residue removal on crop yields. Fluctuations in annual rainfall can have greater impacts on crop yields than residue removal (Linden *et al.*, 2000). On two silt loams in Wisconsin, seasonal weather accounted for about 90% of the variability in corn yield (Swan *et al.*, 1994). Crop residue removal may have particularly adverse effects on yields during dry years and not as much in wet years because of higher soil water conservation under residue mulch in dry years.

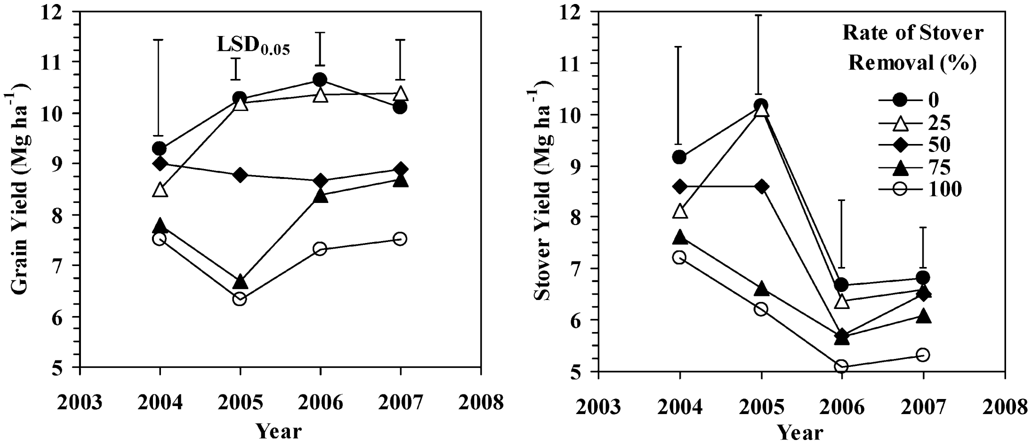

FIG. 8. Impacts of stover removal on grain and stover yields on a sloping silt loam during 4 years of stover management (After Blanco-Canqui *et al.*, 2006c; Blanco-Canqui and Lal, 2007a).

In some soils, use of fertilizers and organic amendments (e.g., manure) can counteract the adverse effects of residue removal on crop yields.

The reduction in crop yields in mulched soils in temperate climates is mostly due to excessively cold and wet soils during seedling stage. Crop yield is also affected by incidence of weeds and pests, soil acidification, and nutrient immobilization under high rates of residue retention (Linden *et al.*, 2000; Mann *et al.*, 2002). In contrast, the reduction in crop yields by residue removal is mainly due to low plant available water reserves, high fluctuations in soil temperature, high soil compaction, surface sealing, and low input of nutrients. Residue removal can cause rapid changes in soil water and temperature regimes as well as soil compaction. Differences in soil texture, drainage, and topography are probably the major factors affecting the magnitude of adverse impacts of residue removal on crop yields. A 3-yr study by Blanco-Canqui and Lal (2007a) clearly indicated that crop yields under unglaciated, sloping terrain, erosion-prone and well drained soils were more adversely affected by residue removal than under glaciated, deep, clayey soils on relatively flat terrains. The large decline in grain yield on sloping NT soils by residue removal suggest that the benefits of NT systems for sustaining crop production can be rapidly lost through indiscriminate removal of crop residues.

VIII. PERMISSIBLE LEVELS OF CROP RESIDUE REMOVAL

The data reviewed in this article support the conclusion that a fraction of the crop residue produced may be available for removal from some soils where either adverse changes occur only after excessive or complete residue removal or changes due to removal are not significant. Nonetheless, it remains to be determined where, when, and how much of crop residue can be removed without causing serious adverse impacts on soil, NPP, and the environment (Wilhelm *et al.*, 2007). The few studies conducted to establish the threshold levels of crop residue removal for alternative uses, specifically in the U.S. Corn Belt region, indicate that about 30% to 50% of the total stover produced can be removed without causing severe adverse impacts on soil (Lindstrom *et al.*, 1979; Nelson, 2002; Kim and Dale, 2004; Graham *et al.*, 2007). These estimates are, however, based only on the residue cover requirements for controlling soil erosion and do not consider the residue requirements to sustain soil and agronomic resources and improve the environment. The threshold levels of crop residue removal must be established based on the residue needs to: (i) conserve soil and water, (ii) maintain or increase crop production, (iii) increase SOM pools, (iv) reduce net GHG emissions, and (v) minimize non-point source pollution (Graham *et al.*, 2007).

Therefore, there is a strong need to refine the models by considering the site specificity of soil and crop response to residue removal. Some soils, depending on the ecoregion, may not be drastically affected by moderate levels of residue removal in the short term. For example, a site-specific study by Karlen *et al.* (1984) suggested that some of the crop residues produced in a NT sandy loam soil in the Atlantic Coastal Plains could be used for bioenergy production because residue removal induced small or no changes in soil nutrient pools after 4 years, and that the nutrient pool removed with residues can be compensated by proper fertilization. In contrast, a study by Blanco-Canqui and Lal (2009a) reported drastic decline in crop yields and nutrient pools by stover removal from erosion-prone soils on sloping terrains, but moderate or no impacts on nearly flat silt loam and clay loam soils after 4 years of residue management. Conclusions drawn from these studies support the need for site-specific establishment of threshold levels of crop residue removal for industrial uses. Crop residues can be removed from select soils provided that the problems of soil erosion, SOM and nutrient depletion, hypoxia and non-point source pollution and decline in NPP and crop yield are effectively mitigated.

IX. ALTERNATIVE SOURCES OF BIOFUEL FEEDSTOCKS

Available data also show that indiscriminate and excessive crop residue removal can have, in general, negative impacts on soil properties, SOM and nutrient pools, NPP and thus crop production (Karlen *et al.*, 1994; Blanco-Canqui *et al.*, 2009a). In some soils, a small fraction of crop residue produced may be available for removal. Because harvesting a small fraction of crop residues is neither logistically feasible nor economically viable to produce large volumes of ethanol, other renewable energy feedstocks must be identified and developed as possible alternatives. Warm-season grasses (Sanderson *et al.*, 2006), prairie grasses (Tilman *et al.* 2006), and short-rotation woody crops (Sartori *et al.*, 2006) are some of dedicated energy crops that can be used as biofuel feedstocks. Growing bioenergy crops such as switchgrass (*Panicum virgatum* L.) and miscanthus (*Miscanthus sinensis* L.) and short-rotation woody crops would not only provide cellulosic feedstocks but also provide ancillary benefits to soil and environment. Warm-season grasses improve soil properties (Bharati *et al.*, 2002; Rachman *et al.*, 2004), reduce soil erosion (Kemper *et al.*, 1992), improve water quality (Blanco-Canqui *et al.*, 2006d), sequester SOC (Liebig *et al.*, 2005; Al-Kaisi and Grote, 2007), and reduce net emissions of GHGs (McLaughlin and Kszos, 2005) while providing cellulosic biomass for biofuel production. Likewise, short-rotation woody crops sequester C (Sartori *et al.*, 2006) and improve soil properties (Blanco-Canqui *et al.*, 2007c).

Such biofuel plantations must be grown on marginal and degraded lands to minimize both competition for prime agricultural lands and negative impacts on soil and environment. Some studies have shown that converting croplands to dedicated bioenergy plantations on prime agricultural soils may increase emissions of GHGs (Scharlemann and Laurance, 2008). For example, Searchinger *et al.* (2008) reported that producing biofuels from switchgrass grown on croplands increase of net emissions of GHGs by 50% and generate large C debt. Increases in net GHGs can be even more dramatic if rainforests and grasslands are cleared for the production of crops for biofuel production (Scharlemann and Laurance, 2008). Based on these considerations, the alternative is to produce biofuel feedstocks on lands that do not compete for agricultural production, and are either marginal or degraded.

Understanding of management of bioenergy crops on marginal soils is a high priority. One of the challenges is to identify biofuel tree and grass species which have recalcitrant biomass and grow well on marginal and degraded lands. Molecular breeding techniques and genetic diversity of plant species with biofuel qualities must be improved and energy production potential of bioenergy crops documented (Sarath *et al.*, 2008). Standard guidelines for the site-specific establishment and management of dedicated energy crops on marginal lands must be developed for principal ecoregions and predominant soils. Producing biofuel from dedicated energy crops is timely and offers an opportunity to lessen over reliance on food crops as biofuel.

X. USE OF RESIDUE FERMENTATION CO-PRODUCTS

Using by-products of bioethanol as amendments for soil and water conservation must also be considered. Conversion of biomass to ethanol generates a residue or co-product of fermentation. The co-product of stover fermentation is very high in lignin (600 to 7000 g kg^{-1}) and N (20 g kg^{-1}) content (Johnson *et al.*, 2004). It also contains some unprocessed cellulose and hemicellulose rich in C content (Mosier *et al.*, 2005). Using these co-products to soil as amendments may partially offset the negative impacts of residue removal on soil properties, SOM, and nutrient pools. Johnson *et al.* (2004) reported that addition of stover fermentation co-product at rates of 0.75, 3.0, and 6.1 g kg^{-1} to severely eroded soils increased both soil aggregate stability and humic compounds. Because the fermented residues contain stable C or refractory C (Reijnders, 2008), its application to soil may promote some long-term C sequestration while stabilizing aggregates and improving soil fertility. The fermentation co-products must be, however, tested to determine the presence of undesirable or toxic substances which would adversely impact soil productivity and microbial activity. Presence of high amounts of phenolic compounds and heavy metals reacting with lignin may limit the use of co-products (Reijnders, 2008). Return of fermented residues, however, neither provides the surface protective cover like coarse crop residues nor has all the properties of the unprocessed residues left on the soil surface. The potential benefits of using fermentation residues to soil and crop production must be comprehensively tested under plot, field, and watershed scales.

XI. BIOCHAR

Biochar, also called charcoal or black C, is a co-product of slow pyrolysis of biomass. Pyrolysis is a thermal conversion biomass into biochar and other co-products under low levels of oxygen. Biochar, similar to fermentation co-products (Johnson *et al.*, 2004), can be used as soil amendment (Laird, 2008; Lal, 2008b). It has a great potential to make bioenergy systems C negative (Laird, 2008b; Mathews, 2008). Biochar is an impure form of recalcitrant C that has a long residence time of about 1000 yr (Glaser *et al.*, 2002). Estimates show that about 10% (Laird, 2008) to 45% (Skjemstad *et al.*, 2002) of the total soil C, depending on the soil and climate, is biochar. Because C in biochar is not as active as soil organic C, addition of biochar to soil can promote long-term C sequestration. Buried biochar not only sequesters C but also improves soil aggregation, increase water retention, and enhance nutrient cycling (Glaser *et al.*, 2002), thereby improving crop production (Laird, 2008). Producing biochar from crop residues and returning it to soil is an option to offset the depletion of soil organic C by crop residue removal for biofuel production (Lal, 2008b). Further assessment of the benefits of biochar to soil, environmental quality, and crop production as well as potential problems associated with biochar handling or management is urgently needed.

XII. USE OF BEST MANAGEMENT PRACTICES

In soils where some residue removal is feasible, best management practices (BMPs) must be adopted to offset the possible adverse impacts of residue removal. Among the potential BMPs are growing cover crops, adopting diverse crop rotations including agroforestry, using manure, establishing conservation buffers, using soil conditioners, and adopting integrated nutrient management. These practices not only reduce risks of soil erosion and water pollution but also enhance SOC sequestration, reduce nutrient depletion, and improve crop production. The BMPs (e.g., crop rotations and cover crops) when used in combination with NT practices can improve soil properties and increase SOC pools (Kim and Dale, 2005). Also, adoption of perennial and deep-grass rooted species can increase SOC pools in deeper soil profile unlike NT systems which tend to confine gains in SOC to surface layers only. Blanco-Canqui *et al.* (2005b) observed that NT receiving 14 Mg $\text{ha}^{-1}\text{yr}^{-1}$ of beef cattle manure increased soil aggregate stability, water retention capacity, and SOM concentration more than NT without manure when compared to plowed soils. Villamil *et al.* (2006) reported that winter cover crops including hairy vetch (*Vicia villosa* Roth) and cereal rye (*Secale cereale* L.) when used in combination with corn-soybean rotations reduced soil compaction, increased aggregate stability, enhanced SOM concentration, and improved soil water retention capacity and nutrient pools compared to either corn- or soybean-fallow systems. Significant improvements in soil attributes with adoption of BMPs suggest that their combination with NT may permit some residue removal. No-till systems which rely solely on crop residues for soil and water conservation and other environmental services must be exempt from crop residue removal for expanded uses.

XIII. RESEARCH NEEDS

There is a strong need to conduct further research on the response of soil, environment, and crop production to crop residue removal. Some of the specific research needs are:

1. Establish site-specific threshold levels of residue removal rates for principal soils and predominant ecoregions based on the residue requirements to maintain NPP and crop yields, crop production, SOM storage, and environmental quality. A comprehensive analysis is needed to assess the residue requirements for maintaining soil productivity, reducing risks of pollution of surface water, and sustaining agricultural productivity.
2. Conduct comprehensive field experiments to determine the maximum permissible of residue removal without increasing runoff and soil erosion. While impacts of complete stover removal on runoff and soil erosion are obvious and well known, impacts of a partial removal of residues are little documented. This information is urgently needed to establish the threshold levels of residue removal for different soils and ecosystems.
3. Develop alternative sources of biofuel feedstocks such as warm-season grasses and short-rotation woody crops to reduce the overreliance on crop residues essential to soil and agronomic production. Research on the production and management practices of these dedicated energy crops in degraded and marginal lands is needed.
4. Develop robust database on the degree to which soil properties, SOM pools, and crop grain and biomass yields change over short (<3 yr), medium (5 to 10 yr)-, and long-term (>10 yr) following complete and partial residue removal across a broad range of soils, tillage and cropping systems, and climatic conditions.
5. Initiate specific studies on the rates of runoff and soil loss for a range of crop residues types (e.g., stover and wheat straw) to establish the threshold levels of residue removal based on the measured data. Current estimates of threshold levels of crop residue removal in relation to soil erosion are based mostly on model-based estimates.
6. Assess the independent impacts of residue removal on soil and environments rather than the interactive effects of tillage-cropping system-residue management systems. Well-designed and long-term experiments of crop residue removal at variable rates on soils managed under similar tillage and cropping system are required.
7. Perform SOC and nutrient budget analyses for various scenarios of residue management across different soils. Models to study C or nutrient dynamics must be improved or developed to predict the implications residue removal on soil fertility and SOC/SOM sequestration.
8. Evaluate of the potential use of fermentation residues and pyrolysis co-products (e.g., biochar) for improving soil properties, C sequestration, and crop production under on-farm conditions. The amount of co-products produced and its beneficial impacts on soil physical, chemical, and biological properties and crop production must be understood.

XIV. CONCLUSIONS

The data reviewed herein show that impacts of residue removal on soil attributes and crop production are highly site specific. Differences in soil texture, drainage, slope, duration of residue management, rate of residue removal, tillage and cropping system, application of fertilizers, use of organic amendments, and climate determine the magnitude of residue removal impacts soil and agronomic productivity. While reduction in SOM pool with increase in residue removal is rapid and consistent even with small removal rates (e.g., 25%), impacts of residue removal on soil physical properties and crop yields are inconsistent, even with complete crop residue removal. In some soils, crop yields vary more from year to year due to weather fluctuations, which make the determination of the effects of residue removal difficult (Linden *et al.*, 2000). Available data clearly suggest the need for further documentation of the response of crop yields or soil productivity to residue removal or principal soils over a long period of time (>10 yr).

The large decrease in SOM pool with residue removal observed in most soils could, however, have severe negative implications because SOM is important to improving soil structure, improving soil water retention capacity, reducing soil erosion, increasing soil fertility and productivity, and filtering non-point source pollutants. Based on the rapid response of SOM and nutrient pools, reviewed studies suggest that indiscriminate residue removal can be detrimental to future soil productivity and environmental quality (e.g., water pollution and GHG emissions) in most soils in the long term. Unless threshold levels of residue removal are established and BMPs implemented in combination with NT systems, indiscriminate removal of crop residue would increase soil erosion, reduce SOC sequestration and nutrient pools, and eventually decrease crop production. A shift from crop residues to dedicated energy crops (e.g., warm-season grasses and short-rotation woody crops) is needed to produce alternative sources of biofuel feedstocks without adversely affecting soil and environmental quality and agronomic production.

A large scale removal of residues could also have many social and environmental consequences. Economic incentives for producers due to increased demand for crop biomass may increase the land area under monocrops (e.g., corn and sorghum) and reduce the land enrollment in conservation programs (e.g., Conservation Reserve Programs in the USA), which would result in increased soil erosion and fertilizer input. Reduced crop diversification would cause the degradation of soil and water quality through eutrophication of downstream water bodies (e.g., rivers, streams, and lakes) development of hypoxic zones in coastal waters. Increase in land area for monocropping can also accelerate emissions of GHGs through high fuel use and fertilizer production and low SOM storage in soils. Increased use of N fertilizers, for example, may increase production of nitrous oxides, which represents about 5% of the total GHG emissions in the USA (EIA, 2007). Environmental impacts through soil erosion and agricultural emissions of GHGs can be large. Increased demand for crop biomass can propel farmers shifting from environmentally friendly tillage (e.g., NT) and cropping systems (e.g., diverse crop rotations) to less benign management systems (e.g., monocropping of corn, wheat, and sorghum, plow tillage). All these concerns must be addressed before recommending the use of any crop residue for biofuel production.

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