



# Energy Crops and Their Implications on Soil and Environment

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## ABSTRACT

Interest in producing cellulosic ethanol from renewable energy sources is growing. Potential energy crops include row crops such as corn (*Zea mays* L.), perennial warm-season grasses (WSGs), and short-rotation woody crops (SRWCs). However, impacts of growing dedicated energy crops as biofuel on soil and environment have not been well documented. This article reviews the (i) impacts of growing WSGs and SRWCs on soil properties, soil organic carbon (SOC) sequestration, and water quality, and (ii) performance of energy crops in marginal lands. Literature shows that excessive ( $\geq 50\%$ ) crop residue removal adversely impacts soil and environmental quality as well as crop yields. Growing WSGs and SRWCs can be potential alternatives to crop residue removal as biofuel. Warm-season grasses and SRWCs can improve soil properties, reduce soil erosion, and sequester SOC. Crop residue removal reduces SOC concentration by 1 to 3 Mg ha<sup>-1</sup> yr<sup>-1</sup> in the top 10 cm, whereas growing WSGs and SRWCs increase SOC concentration while providing biofuel feedstocks. The WSGs can store SOC between 0 and 3 Mg C ha<sup>-1</sup> yr<sup>-1</sup> in the top 5 cm of soil, while the SRWCs can store between 0 and 1.6 Mg ha<sup>-1</sup> yr<sup>-1</sup> of SOC in the top 100 cm. The WSGs and SRWCs have more beneficial effects on soil and environment when grown in marginal lands than when grown in croplands or natural forests. Indeed, they can grow in nutrient-depleted, compacted, poorly drained, acid, and eroded soils. Development of sustainable systems of WSGs and SRWCs in marginal lands is a high priority.

PRODUCING ETHANOL from lignocellulosic feedstocks is gaining an unprecedented interest to meet the 30 × 30 goal (30% replacement of fossil fuels by biofuel by the year 2030; USDOE, 2007a). Potential lignocellulosic energy crops include row crops such as corn, WSGs such as switchgrass (*Panicum virgatum* L.), and SRWCs such as poplar (*Populus* spp.) and willow (*Salix* spp.). Mixed native prairie grasses (Jefferson et al., 2004; Tilman et al., 2006) and cool-season grasses such as reed canarygrass (*Phalaris arundinacea* L.; Wrobel et al., 2009) are also being considered as potential energy crops. At present, crop residues, mainly corn stover, are considered as the prime lignocellulosic feedstock for producing ethanol. The goal of energy industries is to use crop residues as cellulosic ethanol feedstocks in the short term while other biomass sources from dedicated energy crops are being developed in the long term (Pacala and Socolow, 2004; Ragauskas et al., 2006; USDOE, 2007b; Abengoa Bioenergy, 2007).

Crop residues will soon be harvested as lignocellulosic feedstocks for the production of ethanol because technologies for the conversion of cellulose into liquid fuels are well advanced and cellulosic ethanol plants are being constructed. Indeed, production of ethanol from lignocellulosic feedstock materials,

known as second generation of biofuels, is expected to grow rapidly as the production of ethanol from grain may raise food prices. A number of ethanol plants are being constructed across the United States (USDOE, 2007b). One of the first cellulosic ethanol plants in the United States will be sited in southwestern Kansas and launch its operations in 2011. This plant will process large quantities of biomass, mainly corn stover, into ethanol (Abengoa Bioenergy, 2007).

While production of biofuel from renewable energy sources is a valuable initiative, the potential negative and positive impacts of removing crop residues and growing dedicated energy crops on soil and environmental quality must be, however, comprehensively assessed. Most of the current research on energy crops is focused on (i) developing technologies for conversion of cellulosic feedstocks into ethanol, and (ii) increasing production of biomass. As a result, impacts of energy crops such as growing herbaceous and woody plants on soil and environmental quality have not been widely documented. Little comparative analysis exists between crop residue removal and growing energy crops in regards to their differential effects on soil and water conservation, SOC dynamics, soil erosion, and other soil and environmental factors.

Therefore, the specific objectives of this article are to review the (i) potential impacts of growing WSGs and SRWCs on soil properties, SOC sequestration, sediment and nutrient loss in runoff, and wind erosion, and (ii) performance of growing energy crops in marginal lands. This paper presents a state-of-the-knowledge compendium of the available published information on the implications of growing energy crops on soil and

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**Abbreviations:**  $\psi$ , water potential; CRP, Conservation Reserve Program; EPIC, Erosion-Productivity Impact Calculator; GHG, greenhouse gas; NPS, nonpoint source; NT, no-till; RUSLE, Revised Universal Soil Loss Equation; SRWCs, short-rotation woody crops; SOC, soil organic carbon; SWAT, Soil and Water Assessment Tool; WSGs, perennial warm-season grasses.

environment. The potential impacts of crop residue removal on soil productivity (Wilhelm et al., 2004), SOC sequestration and net greenhouse gas (GHG) emissions (Blanco-Canqui and Lal, 2009a), and soil properties and soil erosion (Blanco-Canqui and Lal, 2009b) have been recently discussed. Thus, this article provides only a condensed discussion on this topic to compare impacts between crop residue removal and growing energy crops.

## CROP RESIDUE REMOVAL IMPACTS ON SOIL AND ENVIRONMENT

Data on long-term impacts of crop residue removal on soil properties, SOC dynamics, and GHG emissions for different scenarios of soil management and climates are few. Most of the previous studies were short term (<3 yr) and assessed only selected soil and agronomic factors (Unger, 1978; Doran et al., 1984; Karlen et al., 1984). Furthermore, studies have mostly focused on corn and not much on other crops such as wheat (*Triticum aestivum* L.) and sorghum [*Sorghum bicolor* (L.) Moench], which are also potential biofuel feedstocks (Sarath et al., 2008). Some studies have compared impacts of complete and zero crop residue removal (Karlen et al., 1994), but impacts resulting from a systematic removal of crop residues are not well documented (Blanco-Canqui and Lal, 2009b). The few studies indicate that indiscriminate residue removal adversely impacts soil properties, SOC dynamics, and water and wind erosion as well as crop production. The extent of impacts depends on soil-specific characteristics (e.g., texture and drainage), topography, tillage system, crop grown, management duration, and climate zones.

Indiscriminate removal of residues adversely affects soil physical, chemical, and biological properties. It increases the soil's susceptibility to compaction, crusting, and surface sealing. It reduces soil aggregation, macroporosity, aeration, and water infiltration (Wilhelm et al., 2004). Blanco-Canqui and Lal (2009c) observed that stover removal at rates as low as 25% reduced the stability of aggregates in nearly level silt loam and clayey soils. Residue removal also increases abrupt fluctuations in soil temperature and reduces plant available water content, which are the critical factors for plant growth (Unger, 1978). It increases evapotranspiration, reduces water storage, and alters biological activity and nutrient cycling.

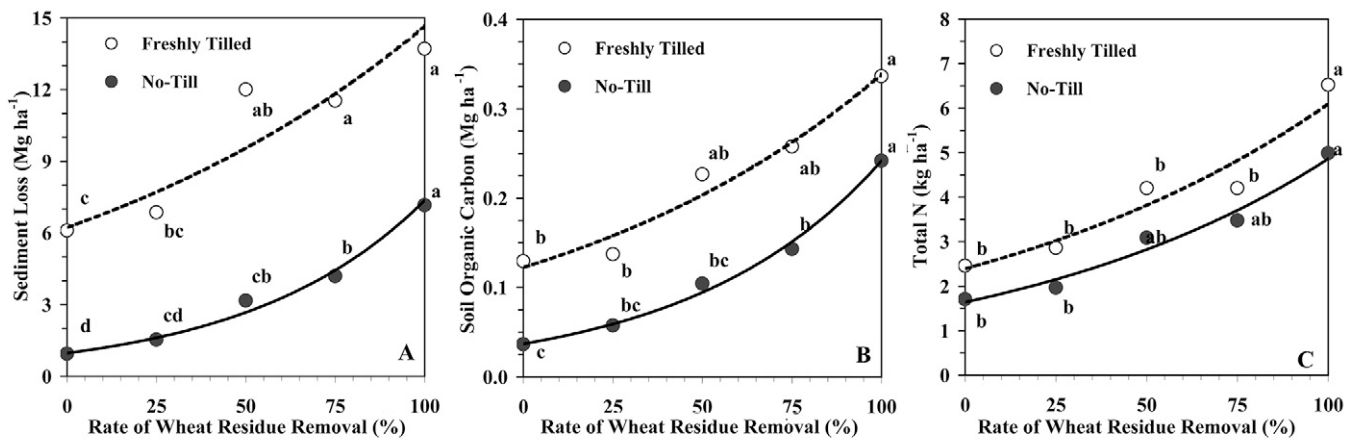
Residue removal also reduces crop yields by removing essential plant nutrients associated with residues (Wilhelm et al., 1986; Fixen, 2007; Hoskinson et al., 2007) and runoff sediment (Lindstrom, 1986; Blanco-Canqui and Lal, 2009a). Blanco-Canqui and Lal (2009c) found that stover removal at 50% reduced grain yield by 1.8 Mg ha<sup>-1</sup> yr<sup>-1</sup> and 100% removal reduced it by 3.3 Mg ha<sup>-1</sup> yr<sup>-1</sup> in three out of 4 yr after stover removal in a sloping soil. Because crop residues are rich in essential plant nutrients (e.g., C, N, P, K, Ca, and Mg), their removal directly reduces nutrient pools and alters chemical properties (e.g., pH, electrical conductivity, and cation exchange capacity).

Loss of SOC with residue removal can be high. The SOC pool changes are positive (gains) when stover is returned and negative (losses) when removed (Mann et al., 2002; Wilhelm et al., 2007). On clay loam, silt loam, and silty clay loam in Minnesota, Wilts et al. (2004) reported that complete stover

removal from long-term no-till (NT) soils reduced corn-derived SOC pool by 30% to 39% after 29 yr. On silt loam with 10% slope, silt loam with 2% slope, and clay loam with <1% slope, Blanco-Canqui and Lal (2009c) reported that stover removal at rates as low as 50% reduced SOC concentration by nearly 5.5 Mg ha<sup>-1</sup> in silt loams in the 0- to 10-cm soil depth after 4 yr of stover removal, showing that SOC pool was reduced by 1.4 Mg ha<sup>-1</sup> yr<sup>-1</sup>. On the clay loam, stover removal at 50% did not significantly reduce SOC concentration, but removal at 75% reduced SOC concentration by 6.5 Mg ha<sup>-1</sup> for the same soil depth, indicating a decrease of SOC pool by 1.6 Mg ha<sup>-1</sup> yr<sup>-1</sup>. Complete stover removal reduced SOC concentration by 3 Mg ha<sup>-1</sup> yr<sup>-1</sup> in the sloping silt loam, by 2.2 Mg ha<sup>-1</sup> yr<sup>-1</sup> in the nearly level silt loam, and by 1.6 Mg ha<sup>-1</sup> yr<sup>-1</sup> in the clay loam. In some soils, SOC pools under stover removal may be unaffected if the soils are at or near SOC saturation levels. After 29 yr of NT management in Connecticut, Hooker et al. (2005) reported no differences in SOC pool between soils with and without stover mulch. Changes in SOC concentration due to crop residue removal can be slower in nearly level clayey soils than in sloping and erosion-prone soils (Blanco-Canqui and Lal, 2007; Blanco-Canqui and Lal, 2009c). Crop residue requirements to maintain SOC and nutrient pools are higher than those required to control soil erosion (Wilhelm et al., 2007). Between 5.2 and 12.5 Mg ha<sup>-1</sup> of crop residue is needed to maintain SOC levels, depending on soil (Johnson et al., 2006; Varvel and Wilhelm, 2008).

Removal of crop residues can cause losses of nonpoint source (NPS) pollutants such as sediment and nutrients in runoff (Lindstrom, 1986; Pimentel and Lal, 2007). Indiscriminate residue removal can exacerbate the current high losses of sediment, which range between 2 and 6.8 billion Mg yr<sup>-1</sup> (Trimble and Crosson, 2000). Pimentel and Lal (2007) suggested that crop residue removal could increase sediment loss by 10- to 100-fold. A recent study by Blanco-Canqui et al. (2009a) under a single simulated rainstorm of high intensity found that a systematic removal of residues from NT winter wheat and plow till grain sorghum exponentially increased loss of sediment and sediment associated SOC and nutrient in runoff (Fig. 1). They found that residue removal rates as low as 50% increased loss of sediment over plots without removal, and that sediment losses between NT soils with ≥75% residue removed and freshly tilled soils with ≤25% removal did not differ (Blanco-Canqui et al., 2009a). Thus, benefits of NT for controlling soil erosion can be completely negated if residue cover is removed. Effects of residue removal on crop yields may be measurable 1 or 2 yr after removal, but the effects on soil erosion are immediate (Karlen et al., 1984; Blanco-Canqui et al., 2006). These losses would directly impair quality of downstream water bodies (e.g., ponds, wells, lakes, streams, and rivers). Indeed, hypoxia in coastal waters (e.g., Gulf of Mexico) is an ongoing problem due to the excess input of N from agricultural lands (Blanco and Lal, 2008). Increased use of N and P fertilizers to replace the nutrients lost by residue removed may concomitantly result in increased losses of N and P in runoff under continual removal of residues.

Residue removal can also cause losses of organic matter associated with sediment runoff. These losses can further accelerate



**Fig. 1. Sediment and sediment-bound soil organic carbon and nitrogen loss in runoff following wheat straw removal at variable rates from a long-term no-till and freshly plowed soil in western Kansas. Mean data points followed by the same lowercase letter within the same tillage system is not significantly different at the 0.05 probability level (after Blanco-Canqui et al., 2009a).**

off-site transport of NPS pollutants because soil organic matter is essential for filtration and adsorption of pollutants (Bollag et al., 1992). Blanco-Canqui et al. (2009a) reported that as much as  $0.1 \text{ Mg ha}^{-1}$  of sediment-associated SOC was lost in runoff under a single and intense simulated rainstorm following 50% residue removal from NT soils. This means that one single rainstorm could eliminate all the NT-induced gains in SOC pool if residues are removed at rates  $\geq 50\%$ . No-till management, on average, increases SOC pool by  $0.1 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ , depending on soil and climate (West and Post, 2002).

Residue left on the soil surface is also vital to protect soil from wind erosion, particularly in semiarid regions. If residues are completely removed, NT soils can be as erodible as or more than plowed soils during drought periods, because of absence of transient rough surface created by tillage. On a regional study in the central Great Plains, Blanco-Canqui et al. (2009b) reported that NT management did not increase dry aggregate stability, a main parameter of soil wind erodibility, over plow till, suggesting the strong need for maintaining surface residue cover to reduce wind erosion.

Literature reviewed herein shows that crop residue removal can adversely impact soil properties, water and wind erosion, SOC sequestration, and crop production. Only a small fraction (about 25%) of residue might be available for removal, depending on soil type and climate (Blanco-Canqui et al., 2009a). This small amount of crop residues is not economically feasible nor logistically possible. Thus, other alternative renewable feedstock sources for cellulosic ethanol production should be developed.

### IMPACTS OF WARM-SEASON GRASSES ON SOIL AND ENVIRONMENT

Extensive areas of the United States were under native WSGs before settlement, including switchgrass, Indian grass [*Sorghastrum nutans* (L.) Nash], big bluestem (*Andropogon gerardii* Vitman), and others. These native grasses have been, however, mismanaged (e.g., overgrazed) and eventually replaced by introduced cool-season grasses in many landscapes. Agricultural expansion contributed to the mismanagement of WSGs. At present, WSG are mostly grown in small areas and lands under the Conservation Reserve Program (CRP)

for erosion control, livestock forage, and wildlife habitat. In recent years, however, the potential use of WSGs as cellulosic ethanol feedstocks has generated an excitement and interest in reestablishing the WSGs.

Establishing WSGs as biofuels crops started in the early 1990s (Hohenstein and Wright, 1994). In 1992, the USDOE initiated a multiinstitution research program on switchgrass production for biofuel in various states (Tennessee, Texas, Virginia, Alabama, and Oklahoma) (Sanderson et al., 1996). These experiments indicated that WSGs, particularly switchgrass, offer a great potential as energy crops because of its higher biomass yield, deep-root system, rapid growth, low-maintenance, greater adaptability, and higher drought tolerance as compared with other common grass species. Warm-season grass performance is nevertheless soil- and region-specific (Sanderson et al., 1996).

Growing perennial WSGs can have potential benefits to improve soil and environment over row crops (e.g., corn) because growing WSGs does not require intensive cultivation or soil disturbance after establishment. Perennial grasses can improve soil properties, sequester SOC, reduce water and wind erosion, reduce net emissions of GHGs, and improve wildlife habitat. Because WSGs enhance nutrient cycling and storage, they may require lesser amounts of fertilizers and herbicides than row crops, reducing risks of water pollution. The magnitude of benefits of growing WSGs will depend, however, on soil type, topography, harvest frequency, cutting height, management duration, use of fertilizers and pesticides, and climate. At this point, data on the impacts of WSGs on soil and environment from field-scale plantations of WSGs for biofuel production are few. Research on WSGs when used in conservation buffer strips (e.g., switchgrass) shows the important role of WSGs in improving soil properties and controlling erosion (Kemper et al., 1992).

Tall WSGs consisting of tall grass species produce abundant above- and belowground biomass. Compared with row crops and short statured grasses, their permanent and extensive deep ( $>1.5 \text{ m}$ ) root systems in conjunction with the aboveground biomass returned can improve soil macroporosity, fluxes of water, air, and heat, water storage, microbial processes, and SOC storage. Active and decaying roots interact with soil

matrix under WSGs and improve soil physical, chemical, and biological properties. Increased SOC due to the continual above- and belowground C biomass input can maintain soil productivity.

### Soil Structural Properties

Growing WSGs generally improves soil structural properties (Table 1). For example, it reduces bulk density and increases soil porosity over row crops (Table 1). In a silt loam in Iowa, Rachman et al. (2004a) observed that switchgrass buffer strips reduced soil bulk density over NT corn-soybean [*Glycine max* (L.) Merr.] rotation in the 0- to 30-cm soil depth after 10 yr of switchgrass establishment. In a silt clay loam in Iowa, Bharati et al. (2002) observed that soil bulk density under switchgrass grown in a riparian buffer was 83% of that under corn. In northeastern Kansas, Murphy et al. (2004) observed that soils under WSGs had lower bulk density (0.68 Mg m<sup>-3</sup>) than under cool-season grass (0.76 Mg m<sup>-3</sup>). The lower soil bulk density under WSGs is due to the root perenniality, deep rooting system, and continued biomass input. The permanent surface cover and the extended roots provide resilience against both external (e.g., wheel traffic) and internal compactive forces (Clark et al., 1998). The high-biomass producing and deep-rooted grass species can also reduce the soil's susceptibility to compaction by increasing soil organic matter concentration (Thomas et al., 1996).

Soils under WSGs have more continuous macropores created by root channels and biological activity than under row crops. Rachman et al. (2004a) observed that soil macroporosity under switchgrass was about two times greater than under row crops. The higher proportion of macropores partly explains the lower bulk density under WSGs. The growing WSGs protects soil surface from raindrop impact, reduces surface sealing and crusting, maintains the integrity of open-ended macropores, and reduces risks of soil compaction and consolidation.

Growing WSGs can also improve soil aggregation. In a clayey soil in Texas, Acosta-Martínez et al. (2004) reported that perennial 'W.W.B. Dahl' old world bluestem [*Bothriochloa*

*bladhii* (Retz.) S.T. Blake] had 86% greater soil aggregate stability than cotton (*Gossypium hirsutum* L.). The abundant and dense network of WSG roots forms a skeleton to enmesh soil particles and form stable aggregates. The above- and belowground biomass also provides temporary, transient, and persistent organic binding agents (Tisdall and Oades, 1982). Residue-derived organic materials, on partial decomposition, produce organic mucilages, polymers, and other organic substances, which in interaction with fungal and mycorrhizal hyphae, form organo-mineral complexes responsible for aggregate formation and stabilization. Polysaccharides resulting from microbial processes and humic compounds from decomposition of roots bind and stabilize aggregates. In general, soils under WSGs are better aggregated than under row crops because of increased biomass return and reduced soil disturbance (Percival et al., 2000).

Growing WSGs also improves properties of soil aggregates, which are critical determinants of the behavior of the whole soil. Blanco-Canqui et al. (2005), while assessing the impacts of switchgrass plantations on soil structural properties across five ecosystems in the southeastern United States, observed that soils under switchgrass had lower aggregate strength by 60 to 70% and lower aggregate density by 10 to 20% than row crop systems in the 0- to 10-cm depth. The lower strength and density of aggregates indicate that soils under switchgrass plantations have better tilth and lower risks of compaction than in those under row crops. Accumulation of soil organic matter under switchgrass improves aggregate properties through the dilution effect. Tillage in row crops reduces macroporosity, compresses aggregates, and causes rapid consolidation of aggregates.

Warm-season grass-induced changes in soil properties, particularly in clayey soils, may not be, however, measurable in the short term (Clark et al., 1998). Acosta-Martínez et al. (2004) reported that soil bulk density in perennial old world bluestem was 27% greater than in cotton in a clayey soil after 5 yr in Texas. In the same region, Schwartz et al. (2003) observed that bulk density in WGSs was 6% greater than in croplands in the 0- to 10-cm depth. The frequent loosening and disturbance

**Table 1. Differences in soil physical properties between croplands and warm-season grasses (WSGs).**

Soil (location)	Management duration	Soil property	Cropland	WSGs	Reference
	yr				
Various soils in MN, ND, and SD	2–19	bulk density, Mg m <sup>-3</sup>	1.12a	1.07b	Liebig et al. (2005)
Silt loam (IA)	10		1.28a	1.22b	Rachman et al. (2004a)
Silt clay loam (IA)	5		1.34a	1.12b	Bharati et al. (2002)
Clayey soil (TX)	5		1.1b	1.4a	Acosta-Martínez et al. (2004)
Clay loam and silty clay loam (TX)	10		1.18b	1.25a	Schwartz et al. (2003)
Silt loam (MO)	12		1.41a	1.18b	Udawatta et al. (2008)
Loam (Blacksburg, VA)	12	aggregate bulk density, Mg m <sup>-3</sup>	1.54a	1.40b	Blanco-Canqui et al. (2005)
Loam (Orange, VA)	12		1.46a	1.22b	Blanco-Canqui et al. (2005)
Clayey soil (TX)	5	water-stable aggregates, %	21b	39a	Acosta-Martínez et al. (2004)
Silty clay loam (IA)	6		70.1a	73.6a	Anderson et al. (1997)
Loam (Blacksburg, VA)	12	aggregate tensile strength, kPa	276a	175b	Blanco-Canqui et al. (2005)
Loam (Orange, VA)	12		939a	546b	Blanco-Canqui et al. (2005)
Silt loam (MO)	12	macroporosity, m <sup>3</sup> m <sup>-3</sup>	0.005b	0.027a	Udawatta et al. (2008)
Silt loam (IA)	10		0.016b	0.038a	Rachman et al. (2004a)
Silt loam (IA)	10	volumetric water content at 0 MPa, m <sup>3</sup> m <sup>-3</sup>	0.50b	0.58a	Rachman et al. (2004a)
Silt loam (IA)	10	saturated hydraulic conductivity, mm h <sup>-1</sup>	115b	668a	Rachman et al. (2004a)
Silt loam (MO)	12		24b	61a	Udawatta et al. (2008)
Clay loam and silty clay loam (TX)	10	unsaturated hydraulic conductivity (ψ = -5 mm), mm h <sup>-1</sup> †	21.6a	11.3b	Schwartz et al. (2003)

† ψ is water potential.

effect of tillage can lower bulk density in cropped soils. Impacts of WSGs on soil aggregate stability can also take considerable time before changes are measurable. Anderson et al. (1997) found no differences in wet-aggregate stability between switchgrass and corn after 4 yr of management. Similarly, in a loamy soil in Iowa, Márquez et al. (2004) reported that a 7-yr switchgrass system did not increase mean weight diameter of soil aggregates over a row crop system.

The above studies indicate that impacts of WSGs on soil structural properties can be variable, depending soil type and management. In the long term, WSGs generally improve soil structural properties over row crops. Literature review also shows that data on soil properties under long-term plantations of WSGs are few, which hinders our ability to conclusively discern effects of WSGs on soil structural properties. Long-term monitoring of soil structure under field-scale plantation of WSGs is warranted to underpin the magnitude of impacts.

### Soil Hydraulic Properties

The greater macroporosity, more fibrous and extensive roots, and more abundant and interconnected macropore networks (e.g., root channels and earthworm burrows) under WSGs than under row crops improve soil hydraulic properties such as infiltration, saturated and unsaturated hydraulic conductivity, and water storage. Presence of water-conducting pores near the soil surface determines the amount of rainfall partitioning into infiltration and runoff. The gradual development of biopores, root growth, and macroaggregates following WSG establishment improves the rate at which water moves in lower soil profile depths. Roots and earthworm burrows under WSGs can penetrate consolidated and compacted soil matrix layers and change the pore structure, increasing water infiltration and storage at lower depths (Katsvairo et al., 2007). Bharati et al. (2002) observed that 60-min cumulative water infiltration was five times greater in switchgrass than in row crops and pasture after 6 yr of management. Warm-season grasses can also influence soil water retention and unsaturated water flow. Rachman et al. (2004a) reported that saturated hydraulic conductivity and volumetric water content (0 MPa) in switchgrass hedges was greater than in row crops.

Udawatta et al. (2008), using computed tomography, found that soils under WSGs with big bluestem, little bluestem [*Schizachyrium scoparium* (Michx.) Nash], prairie dropseed [*Sporobolus heterolepis* (A. Gray) A. Gray], and Indian grass had 83 pores, while soils in corn–soybean rotation had only 26 pores for a 2500 mm<sup>2</sup> area, and that the greater number of macropores explained about 40% of the variability in saturated hydraulic conductivity.

Switchgrass management effects on soil hydraulic properties can also be variable among soil types and ecosystem characteristics. Particularly in the short term, WSGs

may not always increase soil water retention and hydraulic conductivity. Soil aggregates under switchgrass retained 13% more water than those under row crops in one of two soils in the eastern United States. (Fig. 2; Blanco-Canqui et al., 2005). In clayey soils, Schwartz et al. (2003) observed that unsaturated hydraulic conductivity (water potential,  $\psi = -5$  cm) in croplands was about two times greater than in CRP lands planted to WSGs (Old World bluestem) after 10 yr of management. Soil consolidation after WSG establishment can offset short-term improvement in pore dynamics particularly in clayey soils. While changes in soil organic matter content and aggregation following establishment of WSGs may be measurable in less than 10 yr, changes in hydraulic properties are normally slower, particularly in semiarid regions. Growing WSGs may take as long as 15 yr to reach its potential for improving soil structural and hydraulic properties (Corre et al., 1999; Bharati et al., 2002). Warm-season grasses may require even longer time to improve soil properties at deeper depths in the soil profile. Improvement in water movement under WSGs depends on the length of management, grass species, soil type, and climate.

### Soil Organic Carbon Sequestration

Growing WSGs offers promise to displace fossil fuels and reduce net CO<sub>2</sub> emissions through SOC sequestration while improving soil properties (Robertson et al., 2008). Dedicated energy crops can reduce CO<sub>2</sub> emissions by 0.2 to 1.0 Gt yr<sup>-1</sup> (Sampson et al., 1993) by enhancing SOC sequestration (Tolbert et al., 2002). Mixture of herbaceous plants also has potential for storing SOC. Diverse mixture of grasses can sequester 4.4 Mg ha<sup>-1</sup> yr<sup>-1</sup> of CO<sub>2</sub> which is higher than the 0.32 Mg ha<sup>-1</sup> yr<sup>-1</sup> of net fossil CO<sub>2</sub> released from biofuel production (Tilman et al., 2006). McLaughlin and Walsh (1998) reported that SOC sequestration rates under switchgrass can be 20 to 30 times greater than under annual row crops. Indeed, WSGs can store SOC between 0 and 3 Mg C ha<sup>-1</sup> yr<sup>-1</sup> in the 0- to 5-cm soil depth (Lemus and Lal, 2005). In a clay loam in Iowa, switchgrass stored 0.82 Mg C ha<sup>-1</sup> yr<sup>-1</sup> in plant and litter biomass, which was higher than that in cool-season grass and row crops (Tufekcioglu et al., 2003). In a sandy loam in Alabama,

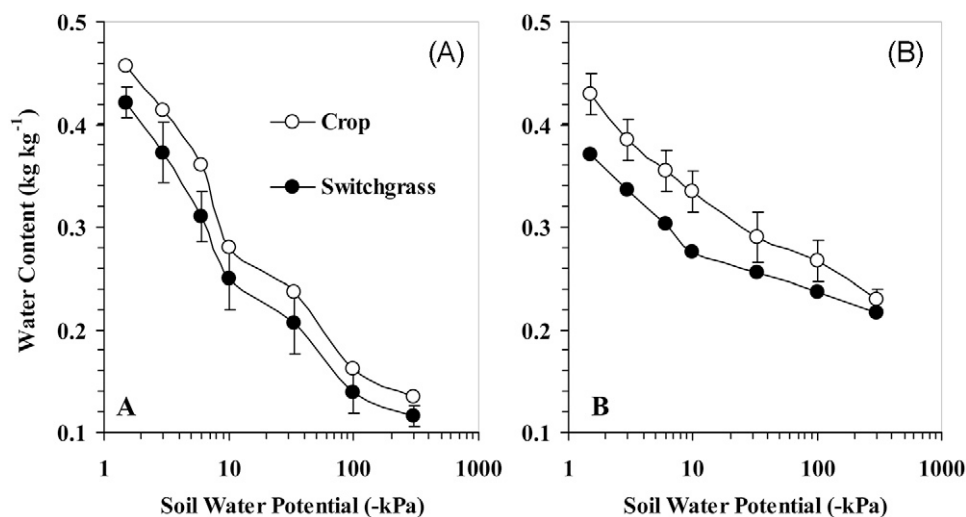


Fig. 2. Soil water retention characteristics under 12-yr switchgrass and row crops for two soils in (A) Blacksburg, VA, and (B) Orange, VA, in the 0- to 10-cm soil depth (after Blanco-Canqui et al., 2005). The error bars represent the LSD values to compare differences between crops and switchgrass at the each level of soil water potential.

the SOC content under switchgrass was 45% more than under plowed soils (Ma et al., 2000). These studies indicate that the amount of SOC sequestered by WSGs is generally greater than in row crops.

The SOC sequestration in WSGs can be large in deeper soil profile compared with row crops because of deeper rooting systems (Liebig et al., 2005; Omonode and Vyn, 2006). Warm-season grass root system, which often extends to near 3 m in the soil profile, enhances translocation of SOC to deeper layers, thereby reducing decomposition of SOC and promoting long-term SOC sequestration (Frank et al., 2004). Thus, WSGs can sequester SOC not only near the surface layers but also in deeper profile depths. On a regional study across 42 paired sites in Minnesota, North Dakota, and South Dakota, Liebig et al. (2005) observed that switchgrass fields stored more SOC than croplands in the 0- to 5-cm depth and also in the 30- to 90-cm depth. They reported that, when averaged across the 42 sites, switchgrass stored about 2 Mg ha<sup>-1</sup> of SOC in the 0- to 5-cm depth, 7.7 Mg ha<sup>-1</sup> in the 30- to 60-cm depth, and 4.35 Mg ha<sup>-1</sup> in the 60- to 90-cm depth more than cultivated soils. The fraction of SOC stored in deeper (>30 cm) soil profiles is critical for long-term SOC sequestration because this fraction has longer residence times and slower turnover due to reduced microbial processes and fluctuations in soil water content and temperature.

The greater SOC accumulation under WSGs is attributed to greater aboveground biomass input and root biomass concentration over cultivated soils (Brown et al., 2000; Frank et al., 2004). Below 30 cm, root biomass in switchgrass is normally greater than in row crops (Brown et al., 2000). Switchgrass produces about 6.7 Mg ha<sup>-1</sup> yr<sup>-1</sup> of total root biomass and half of this amount is found below the 30-cm depth (Frank et al., 2004). Indeed, about 10% of the total root biomass is found below the 60-cm soil depth. The root SOC content under 'Alamo' switchgrass, 5 yr after seeding, was higher than that under tall fescue (*Festuca arundinacea* Schreb.), corn, and mixed grasses in Tennessee, Kentucky, and Virginia (Garten and Wullschlegel, 1999). Jung (1986) reported that switchgrass had sevenfold greater root biomass than orchardgrass (*Dactylis glomerata*) in the 0- to 15-cm soil depth and switchgrass roots penetrated to depths below 60 cm unlike orchardgrass roots,

which were mostly concentrated in the upper 30 cm of soil profile.

Warm-season grasses as bioenergy crops generally increase the SOC pools, but, similar to their impacts on soil structural and hydraulic properties, the magnitude of increases depends on soil type, harvest cycles, and application of N fertilizers and manure (Garten and Wullschlegel, 2000). Reduction in frequency of harvest increases SOC sequestration because of greater C biomass return (Lee et al., 2007). Some studies suggest that increases in SOC pool under growing WSGs are only moderate (Bransby et al., 1998). While evaluating SOC sequestration in 5- to 8-yr-old WSGs across 10 sites in Indiana, Omonode and Vyn (2006) reported that SOC concentration in WSGs was greater (22.4 g C kg<sup>-1</sup>) than in croplands (19.8 g C kg<sup>-1</sup>) only in four of the 10 sites in the upper 15 cm of soil surface (Fig. 3). Addition of manure is a potential ecological practice for increasing SOC sequestration under WSGs while enhancing biological activity, improving soil properties, and soil productivity. Appropriate rates of manure application can replace or be an alternative to N fertilization for increasing biomass production and increasing SOC sequestration. Application of manure to WSG plantations may be environmentally and economically more beneficial than in cultivated soils because of lower runoff and soil erosion in WSG systems, which can reduce risks of water pollution. Manure application is an important strategy to increase SOC sequestration under WSG systems. Lee et al. (2007) reported that switchgrass in CRP lands stored 2.4 ± 0.9 Mg C ha<sup>-1</sup> yr<sup>-1</sup> with the addition of NH<sub>4</sub>NO<sub>3</sub> and 4.0 ± 1.0 Mg C ha<sup>-1</sup> yr<sup>-1</sup> in the 0- to 90-cm depth with the addition of manure in eastern South Dakota.

Growing WSGs increases SOC concentration by 0.3 to 0.5 Mg ha<sup>-1</sup> yr<sup>-1</sup>, whereas crop residue removal reduces SOC concentration by 1 to 1.5 Mg ha<sup>-1</sup> yr<sup>-1</sup> in the 0- to 30-cm soil depth (Anderson-Teixeira et al., 2009; Blanco-Canqui and Lal, 2009c). Growing WSGs can thus increase SOC concentration while providing alternative feedstocks for cellulosic ethanol production, unlike crop residue removal, which results in large losses of SOC. The increase in SOC with WSGs has large implications on soil and environment. It does not only reduce net emissions of GHGs (e.g., CO<sub>2</sub> and CH<sub>4</sub>) but also improves soil productivity, nutrient cycling and storage, soil properties,

and biological activity. Accumulation of SOC with WSGs can also be beneficial for trading C credits, particularly if WSGs are grown in marginal soils, which were not previously a sink for SOC. A marginal land is defined as a land currently unsuitable for producing economically viable commodity crops.

The amount of SOC sequestered by WSGs is a function of soil texture, length of management, antecedent SOC levels, and climate (Lemus and Lal, 2005; Blanco-Canqui et al., 2005). It can be greater in soils with initial low SOC levels than in those

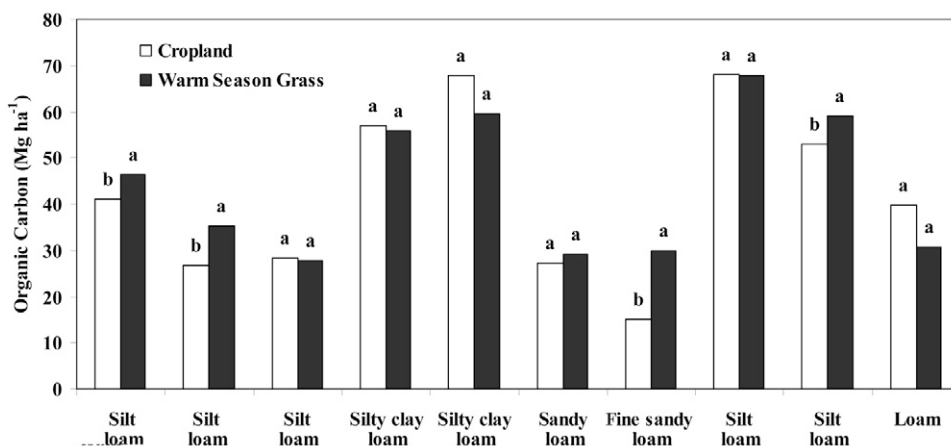


Fig. 3. Soil organic carbon storage for warm-season grasses and croplands in the 0- to 15-cm depth across 10 soils in Indiana (after Omonode and Vyn, 2006). Bars followed by the same lowercase letter within each soil are not significantly different at the 0.05 probability level.

that are about to reach their C saturation level. Thus, there is a high potential to sequester SOC in marginal or degraded lands where the soils are further from their C saturation level, relative to prime agricultural lands (Stewart et al., 2008). It is also important to note that SOC sequestration under WSGs is not infinite, and a soil will eventually become saturated with C. For example, changes in SOC concentration in soils under conservation tillage can approach a steady state after 50 yr (Lal et al., 1998). Changes in SOC concentration due to management are often rapid during the first 5 or 10 yr, followed by small changes after 10 yr (Adler et al., 2007; Novak et al., 2007). Assessment of SOC saturation and stabilization under WSGs across a wide range of soils and climates is a research priority to better understand the potential impacts of WSGs on SOC sequestration.

### Biological and Chemical Properties

Warm-season grasses alter soil chemical and biological properties by increasing soil organic matter content and biomass input over row crops. In loamy soils with exposed subsoil in Iowa, Al-Kaisi and Grote (2007) found that switchgrass had 200% more microbial biomass than either corn or soybean. Increased food supply (e.g., partly decomposed organic materials), adequate soil water content, and reduced fluctuations in soil temperature under growing WSGs and SRWCs promote proliferation of soil macro- and microorganisms. In a sandy loam in Alabama, earthworm numbers ( $6.3 \text{ m}^{-2}$ ) were greater under switchgrass than in the adjacent ( $0 \text{ m}^{-2}$ ) peanut (*Arachis hypogaea* L.)-cotton cropping system (Katsvairo et al., 2007). The greater earthworm population under WSGs, in association with the extensive active and decaying switchgrass roots, improves soil aggregation, macroporosity, and fluxes of water, air, and heat. Earthworms under trees and grass buffers are often more numerous than under croplands because of the abundant food source and cover (Bharati et al., 2002).

Warm-season grass-induced increase in soil organic matter content buffers acidity and alkalinity of soil. As discussed earlier, the SOM filters, adsorbs, and retains pollutants in soil (Bollag et al., 1992). The SOM and fine soil particles bind organic and inorganic pollutants and promote transformation and biodegradation of pollutants. Because growing WSGs generally requires lower amounts of fertilizer, herbicide, and pesticide, a reduction of water pollution by agricultural chemicals can be assumed with WSG usage compared with row crops.

Soils in WSGs can also accumulate more total N than those in row crops and cool-season grasses in the long term. In Iowa, Tufekcioglu et al. (2003) found that soils under switchgrass had greater N concentrations than under row crops after 7 yr of establishment. Across 10 paired soils in Indiana, Omonode and Vyn (2006) found that total soil N under 6- to 8-yr switchgrass was greater in one soil but lower in two soils compared with croplands in the 0- to 15-cm soil depth. After 25 yr of management in Iowa, Al-Kaisi and Grote (2007) observed that total soil N in switchgrass burned every 5 yr did not differ from that in corn-soybean rotation in the 0- to 15-cm depth, but it was greater for the 15- to 60-cm depth. The same study found no differences in total soil N between switchgrass and row crops when switchgrass was burned every year. Reduced biomass

removal or elimination of burning can increase total N in soils under switchgrass.

### Water Quality

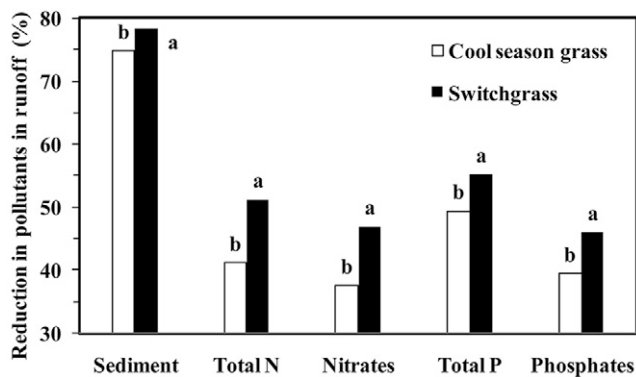
Limited research has assessed the soil erosion and water quality impacts of large-scale plantations of WSGs grown as biofuel. However, research on WSGs when used as conservation buffer strips shows that WSGs are an economical and ecological technology for reducing off-site transport of NPS pollutants and improving water quality (Daniels and Gilliam, 1996; Kemper et al., 1992; Eghball et al., 2000; Blanco-Canqui et al., 2004a). Switchgrass has been used in conservation buffer strips to control soil erosion from croplands (Eghball et al., 2000). Warm-season grass buffers remove sediment, nutrients, and other NPS pollutants from runoff. Even narrow (1-m) strips of WSGs, when planted perpendicular to the dominant field slope, can reduce off-site transport of NPS pollutants. Warm-season grass strips intercept, detain, and pond runoff sediment above and within them, form natural mini-terraces, and reduce interrill and concentrated-type flow (e.g., ephemeral gullies) (Dabney et al., 1999).

### Runoff

Warm-season grasses reduce runoff because of improved soil conditions. As discussed earlier, soils under WSGs generally have lower bulk density, and greater macroporosity, saturated hydraulic conductivity, and water infiltration rates (Rachman et al., 2004a, 2004b), which reduces the amount of rainwater available for runoff (Gilley et al., 2000). The deep-rooting system under WSGs helps reduce runoff by increasing water infiltration (Tufekcioglu et al., 1999). The abundant surface debris, biopores, and the dense network of roots intercept and filter runoff. Warm-season grasses are more effective at filtering sediment than at reducing runoff (Self-Davis et al., 2003). Blanco-Canqui et al. (2004a) reported that switchgrass hedges reduced runoff by 15% over plots without hedges. This means that more runoff infiltrates in soils under switchgrass. Lower runoff volumes under WSGs result in lower off-site delivery of NPS (e.g., sediment and nutrients) in runoff.

### Sediment

A number of studies have shown that WSGs reduce sediment transport in runoff. The slow movement and temporary ponding of runoff within grasses promote sediment deposition (Meyer et al., 1995). In some soils, soil loss in WSGs can be negligible (Kort et al., 1998). A plot study in Iowa found that switchgrass buffer strips ponded runoff above hedges and reduced off-site sediment transport from croplands (Gilley et al., 2000). On a silt loam with 5% slope in Mississippi, NT soils under cotton without switchgrass buffers lost  $5.2 \text{ Mg ha}^{-1}$  of sediment, while those with buffers lost only  $2.2 \text{ Mg ha}^{-1}$  (McGregor et al., 1999). Blanco-Canqui et al. (2004a, 2004b) found that narrow switchgrass hedges trapped 91% of sediment, leaving croplands compared with plowed plots without hedges. Effectiveness of switchgrass hedges for reducing sediment loss decreases with increase in soil slope because of increased runoff velocity and reduced opportunity time for water infiltration and sediment deposition. Gilley et al. (2000)



**Fig. 4.** Reduction in transport of pollutants in runoff under two types of buffer systems (after Lee et al., 1999). The lowercase letters (a, b) in each pair of bars indicate significant differences at the 0.05 probability level.

found that narrow switchgrass hedges trapped only 63% of the sediment on a silt loam with slopes of 8 to 16%.

Warm-season grasses can be more effective than cool-season grasses for reducing sediment and nutrient loss because WSGs often produce larger amounts of litter, have stiffer stems and roots, grow taller, and are thus more resistant against overtopping or becoming inundated with runoff sediment (Fig. 4). Lee et al. (1999) reported that 3-m switchgrass hedges reduced sediment loss by 69%, while an equal width of fescue filter strip reduced sediment loss by 62%. Blanco-Canqui et al. (2004a) also reported that 0.7-m switchgrass hedge trapped 91% of runoff sediment but an equivalent width of fescue filter strip trapped only 75% of sediment. They reported that sediment reduction by a 0.7-m switchgrass hedge was equivalent to reduction by 4 m of fescue filter strip. Performance of short-growing grasses for controlling concentrated flow under heavy rainfall may diminish more rapidly compared with WSGs.

Runoff sediment decreases linearly with increased width of WSGs. Foster (1982) found that sediment transport through grass buffers diminished exponentially with increasing grass width. Thus, field-scale plantations of WSGs can be more effective for controlling sediment and nutrient loss in runoff than narrow switchgrass because of their increased width (Dabney et al., 2006). Moreover, mixture of WSGs of various plant species is more effective at reducing soil erosion than single species because of root interaction and multi-story canopy cover (Sheridan et al., 1999).

### Nutrients

The effectiveness of WSGs for removing nutrients from runoff is also high. Eghball et al. (2000) reported that 0.8-m switchgrass reduced 57% of organic N, 81% of  $\text{NH}_4\text{-N}$ , 33% of  $\text{NO}_3\text{-N}$ , and 68% of particulate P losses. Loss of organic N and particulate P in runoff is correlated with sediment loss. As with sediment, WSGs are more effective than short-growing grasses for reducing loss of sediment and nutrients in runoff. Blanco-Canqui et al. (2004a) observed that a 0.7-m switchgrass hedge reduced 67% of organic N and between 50 and 68% of particulate P,  $\text{NO}_3\text{-N}$ ,  $\text{NH}_4\text{-N}$ , and  $\text{PO}_4\text{-P}$ , but fescue filter strips for equal width reduced only 55% of organic N and about 25% of particulate P,  $\text{NO}_3\text{-N}$ ,  $\text{NH}_4\text{-N}$ , and  $\text{PO}_4\text{-P}$ . Switchgrass buffer strips remove soluble nutrients through adsorption by soil organic matter and clay particles, immobilization,

biological and chemical transformation, and infiltration of runoff with colloidal particles (Groffman et al., 1991; Schmitt et al., 1999). Nutrient loss in runoff decreases exponentially with increase in switchgrass width (Foster, 1982; Blanco-Canqui et al., 2004a).

### Contaminants

Growing WSGs reduces transport of pesticides in runoff through filtration and adsorption. Studies have shown that narrow strips of WSGs planted below croplands perpendicular to the main slope reduce losses of herbicides and fertilizers. Thus, growing WSGs can improve water quality and reduce current concerns of surface and groundwater pollution with agricultural chemicals. Rankins et al. (2001) reported that loss of fluometuron in runoff was reduced by 63% in soils under big bluestem and by 86% under eastern gamagrass [*Tripsacum dactyloides* (L.) L.]. Belden and Coats (2004) reported that WSGs were 33 and 330% more effective than cool-season grasses for reducing leaching of metolachlor and atrazine, respectively, because WSGs are taller, and have stiffer stems and deeper root system than cool-season grasses. Warm-season grasses trap sediment-adsorbed herbicides, promote infiltration of sorbed chemicals, and enhance degradation of chemicals through microbial uptake and chemical transformations (Krutz et al., 2005). Reduction of pollutant transport in runoff by WSGs positively impacts water quality. The effectiveness of WSGs is a function of plantation width, grass species, soil type, topography, type, and concentration of pollutants.

### SHORT ROTATION WOODY CROPS AND SOIL AND ENVIRONMENT

Intensive management of tree species is another option to produce biofuel feedstocks. Unlike traditional forestry, management of short-rotation tree plantations mirrors agricultural crops because it involves seedbed preparation, fertilization, weed and pest control, and irrigation (Yin et al., 1998). Trees under SRWC can be harvested within 12 to 15 yr after establishment, which is a much shorter time than for traditional forestry (Miller, 2004). Poplar is one of most common and promising species used in SRWCs. Well and intensively managed plantations of SRWCs can benefit soil and environment. The high input of leaf and root litter, coupled with reduced soil disturbance, can improve soil properties and increase SOC storage under SRWCs. Because management of SRWCs is similar to agricultural systems, their benefits for improving soil properties may not parallel those of traditional forestry. Establishment and harvesting of SRWCs induce some soil disturbance, which can adversely affect soil compaction, soil erosion, SOC sequestration potential, and wildlife habitat.

### Soil Structural Properties

The SRWCs improve soil structural properties by reducing soil disturbance and increasing C biomass input. Tillage in agricultural soils creates more homogeneous and less stable soil aggregates than SRWCs. Presence of tree litter on the soil surface at various stages of decomposition protects soil against raindrop impact and minimizes crusting or surface sealing. Decomposed and partly decomposed organic materials reduce

risks of soil compaction by reducing internal friction and consolidation of soil aggregates.

Growing SRWCs influences soil aggregate stability, aggregate strength, soil porosity, soil water retention, and aeration (Fig. 5). Kahle et al. (2005) reported that conversion of cropland soils to fast-growing trees (*Salix* and *Populus* spp.) decreased soil bulk density while it increased soil porosity and microbial activities after 6 yr of conversion. On sandy and clayey soils, conversion of cropland to aspen (*Populus deltoides* W. Bartram ex Marshall) plantations improved soil water retention (Messing et al., 1997). Similarly, Devine et al. (2004) observed that SRWCs increased mean weight diameter of aggregates compared with row crops in a silt loam after 4 and 5 yr of management. Because of reduced traffic, soils in SRWCs are normally less compact than those in cultivation.

Differences in soil properties between croplands and SRWCs are generally larger than those among tree species. Blanco-Canqui et al. (2007) compared differences in soil physical properties among seven tree species [European larch (*Larix deciduas* Mill.), and five poplar taxa: aspen (*P. tremula* L. × *P. tremuloides* Michx.), NE-222 (*P. deltoids* × *P. nigra* 'Caudina'), DN-5 (*P. euramericana* 'Gelrica'), DN-34 (*P. euramericana* 'Eugenei'), and NM-6 (*P. nigra* × *P. maximowiczii*)] after 7 yr of plantation establishment under three levels of wood ash application on a fine sandy loam at the Upper Peninsula Tree Improvement Center in Escanaba, MI. They found that European larch and DN-34 increased soil aggregate mean weight diameter 40% more than N-222 and NM-6 at 0 Mg ha<sup>-1</sup> of ash application. At the 13 Mg ha<sup>-1</sup> of ash input, the mean weight diameter of soil aggregates among tree species was in the order: European larch > DN-34 = DN-5 > aspen = NM-6 > NE-222. Soil aggregates under SRWCs are more stable and require

higher kinetic energy for their disintegration than under croplands (Devine et al., 2004). The greater soil aggregate stability in SWRCs is due to the high presence of decomposed soil organic materials, which bind primary particles into stable aggregates. Blanco-Canqui et al. (2007) also found that soils under NM-6 poplar clone had lower soil aggregate strength and greater SOC concentration, implying that SOC accumulation under SRWCs reduce excessive soil compaction.

The forest litter, biological exudates, and particulate organic matter can also reduce wettability of soils in SWRCs. Particulate soil organic matter has hydrophobic characteristics and that derived from crop residues is more wettable than that derived from forest (Chenu et al., 2000). Partly decomposed organic materials in association with microbial processes can form mucilaginous films on aggregate surfaces, partially obstructing pores, retarding the advance of wetting front, and reducing air entrapment and rapid aggregate rupture in forest and manured soils. The slight reduction in aggregate wettability is important for reducing aggregate slaking and soil erosion.

### Soil Hydraulic Properties

Soils under managed forestlands generally have greater water infiltration and hydraulic conductivity than cultivated soils. Studies have found that SRWCs have much greater cumulative water infiltration than row crops and pasture (Bharati et al., 2002). Water infiltration in woody plants can be even greater than in WSGs due to greater number of macropores (e.g., root channels and earthworm burrows) under the trees. Soils under SRWCs retain more soil water than those under cultivation (Fig. 6). Greater evapotranspiration under SRWCs results in greater water infiltration and lower water table. The SRWCs can also improve soil water retention over cultivated soils due

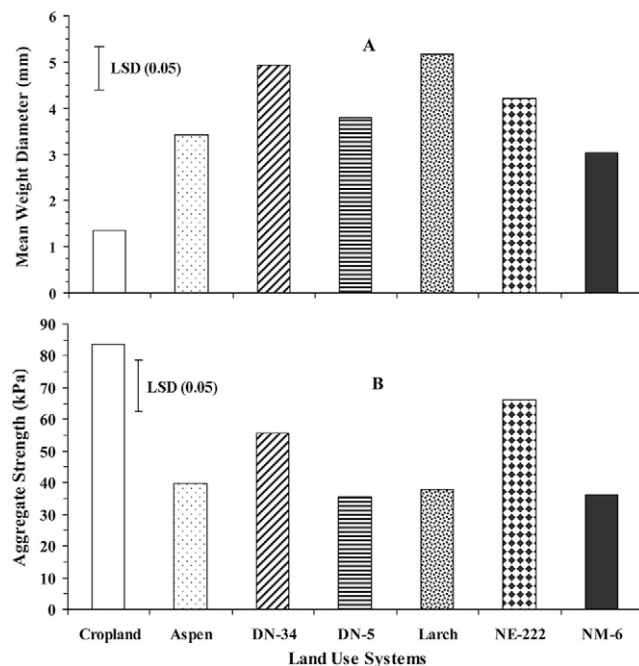


Fig. 5. (A) Mean weight diameter and (B) geometric mean of tensile strength of aggregates for agricultural soils and tree plantations at the Upper Peninsula Tree Improvement Center, Escanaba, MI. The LSD bars compare differences among the tree species including the agricultural soils at the 0.05 probability level (after Blanco-Canqui et al., 2007).

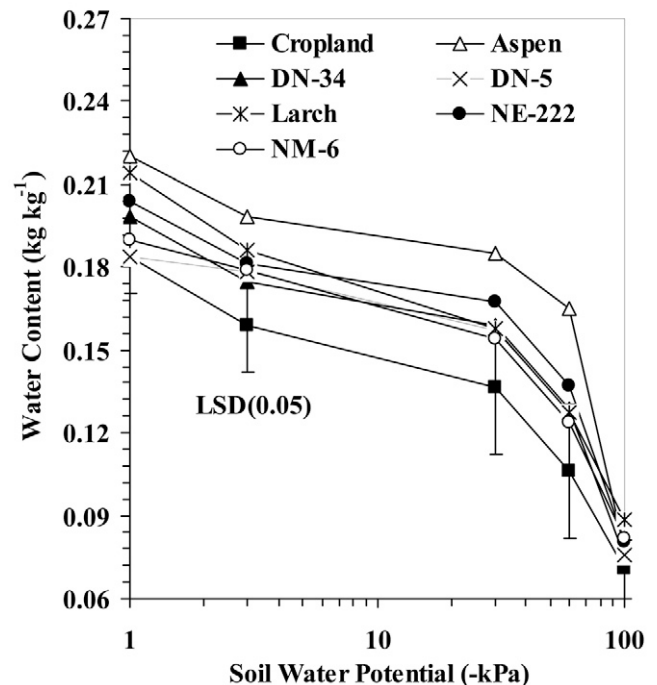


Fig. 6. Soil water retention curves for cultivated soils and tree plantations at the Upper Peninsula Tree Improvement Center, Escanaba, MI. The error bars signify the LSD values at the 0.05 probability level (after Blanco-Canqui et al., 2007).

to their greater soil organic matter concentration (Bharati et al., 2002). Hydraulic properties among tree species can differ, depending on the amount of above- and belowground biomass production. Blanco-Canqui et al. (2007) observed that soil water retention under aspen (*P. tremula* L. × *P. tremuloides* Michx.) was greater than under European larch and the NE-222 poplar clone for 0 to −66 kPa suctions. They found that the soil water retention capacity increased with an increase in SOC concentration. The increase in water retention with increase in SOC is due to the high specific surface area of soil organic matter, which adsorbs more water than inorganic particles.

### Soil Organic Carbon Sequestration

The SRWCs can store SOC due to the abundant above- and belowground biomass input. The SRWCs can store between 0 and 1.6 Mg ha<sup>-1</sup> yr<sup>-1</sup> of SOC in the 0- to 100-cm soil depth (Sartori et al., 2006). On relatively fertile soils in Canada, willow trees stored more SOC than either corn or switchgrass after 4 yr of establishment (Zan et al., 2001). In a regional study in the north-central United States, Coleman et al. (2004) found that gains in SOC under SRWCs were greater than in croplands when the initial SOC concentration was low. While assessing changes in SOC concentration under European larch, and five poplar clones under 0, 9, and 18 Mg ha<sup>-1</sup> of wood ash applications in the Michigan's Upper Peninsula, Sartori et al. (2007) observed that the NM-6 poplar clone accumulated the greatest concentration of SOC, while aspen (*P. tremula* L. × *P. tremuloides* Michx.) accumulated the lowest regardless of ash application after 7 yr of management. These differences in SOC concentration were attributed to differential C biomass input. For the same experiment, Miller (2004) reported that the NM-6 was the tallest (11.0 m) and had the highest survival rate (95%) and dry weight (9.03 Mg ha<sup>-1</sup> yr<sup>-1</sup>), while aspen (*P. tremula* L. × *P. tremuloides* Michx.) was the shortest (7.0 m) with one of the smallest diameters (6.3 cm) and had the lowest survival rate (76%) and dry weight (1.9 Mg ha<sup>-1</sup> yr<sup>-1</sup>). The higher tree weights, such as the case in NM-6, resulted in greater forest floor litter and root biomass, and thus greater SOC accumulation.

Short-rotation woody crop systems with trees that can fix N store more SOC than those without N-fixing trees. Some trees possess numerous nodules of N-fixing bacteria on the roots. Resh et al. (2002) reported that N-fixing *Albizia falcataria* (L.) Fosberg, *Leucaena leucocephala* (Lam.) DeWit stored about 1.1 Mg ha<sup>-1</sup> yr<sup>-1</sup> of SOC, whereas non-N-fixing *Eucalyptus* spp. stored zero. The SRWCs can store more SOC if fertilized and irrigated, but the production and transport of fertilizers as well as energy for pumping water may increase net CO<sub>2</sub> emissions, offsetting gains in SOC. Manure application can also increase SOC concentration by SRWCs. High rates of manure application can sequester SOC by as much as 4.5 Mg ha<sup>-1</sup> yr<sup>-1</sup> (Zan et al., 2001).

Most of the SOC under SRWCs tends to be concentrated near the soil surface due to greater accumulation of litter. The SOC pools under SWRCs can be lower than in natural forests, depending on management. Frequent harvesting of the aboveground biomass can reduce C biomass input and reduce gains in SOC. Increased biomass removal can cause abrupt fluctuations

in soil temperature, increase evaporation, and decrease soil water content, accelerating soil organic matter decomposition. The SOC levels in SRWCs can, however, approach to those in traditional forest soils over time if clear cutting is avoided and a dense permanent surface cover is maintained.

In the short term, SRWCs may not increase SOC storage over row crops because of soil disturbance during establishment. On a loamy sand, sandy clay loam, fine sandy loam, and clay loam in Minnesota, Grigal and Berguson (1998) observed an initial decline and then a gradual increase in SOC concentration, and differences in SOC between SRWCs and row crops after 6 to 15 yr of establishment were not significant. Greater accumulation of SOC under SRWCs will occur when trees are grown in marginal and degraded lands rather than in croplands or natural forests (Coleman et al., 2004). If a management strategy increases the above- and belowground biomass, then a net gain in SOC sequestration can result.

### Water Quality

Data on water quality impacts from plantations of SWRCs are sparse. Growing SRWCs in riparian buffers shows that trees contribute to reduction of soil erosion. Trees through their extended tree roots reduce runoff and soil erosion by increasing water infiltration, anchoring the soil, stabilizing streambanks, increasing soil organic matter concentration, and improving drainage. Trees intercept runoff, reduce sediment transport capacity, and increase infiltration of soluble chemicals into the soil. Trees also reduce runoff and improve drainage by increasing evapotranspiration. Poplar plantations have been used along erodible field areas to stabilize streambanks and reduce gully formation and sloughing of river banks (Kort et al., 1998). Thompson and Luckman (1993) planted poplar and willow in 136 sites affected by gullies and found that the SRWC plantations effectively controlled sediment loss in 42% of the sites.

Trees can be planted along streams, wetlands, and croplands to reduce off-site transport of pollutants (e.g., sediment and nutrients) to downstream waters and improve water quality. Lee et al. (2003) reported that combined strips of SRWCs and switchgrass plantations removed 97% of sediment, 94% of total N, 85% of NO<sub>3</sub>-N, 91% of total P, and 80% of PO<sub>4</sub>-P. Pimentel and Krummel (1987) reported that soil erosion loss from row crops areas was about 22 Mg ha<sup>-1</sup>, but it was only 2 Mg ha<sup>-1</sup> under SRWCs. Proper management (e.g., elimination of clear cutting) can provide long-term protection against erosion and water pollution. While soil erosion from SWRC plantations can be a concern during the first year of establishment, well-managed SRWCs rapidly improve soil conditions and lead to reduced runoff and soil erosion.

### HERBACEOUS AND WOODY PLANTS AND WIND EROSION

Both WSGs and SRWCs can also control wind erosion. Warm-season grasses such as switchgrass resist erosive forces of wind and reduce wind erosion because they grow tall and have stiff stems and deep rooting systems. Even a single row of switchgrass can be an effective barrier against wind

in semiarid regions (Bilbro and Fryrear, 1997). Switchgrass is a drought-tolerant species and can grow well in sandy and relatively windy environments. Growing WSGs can be particularly effective for controlling wind erosion near the soil surface, unlike trees, which can reduce wind velocity at increased heights above the soil surface (Blanco and Lal, 2008). Establishment of WSG plantations can be particularly beneficial in semiarid regions such as the Great Plains where wind erosion is of greater magnitude than water erosion. Warm-season grass buffers, when planted perpendicular to the dominant wind direction, have been shown to reduce downwind velocities and promote settlement of loose soil particles (Kemper et al., 1992). Thus, WSGs not only reduce water erosion, but also wind erosion. Perennial WSGs provide a permanent defense against wind erosion over croplands with reduced residue return.

### **Herbaceous and Woody Plants and Wildlife Habitat**

Growing WSGs and SRWCs can improve wildlife habitat and landscape aesthetics while providing biofuel feedstocks. The permanent vegetative cover and reduced soil disturbance in WSGs and SRWCs provide shelter and nesting cover for grassland animals (e.g., birds; Tolbert and Wright, 1998). Their abundant above- and belowground biomass also provide food for native ground animals. Pheasants, quail, rabbits, songbirds, ducks, geese, wild turkeys, and muskrats are abundant in areas under WSGs (Roth et al., 2005). The seeds are an important food resource for many birds and other animals. Row crops and short grasses have reduced the wildlife habitat in many farms and grasslands. More ground cover is present under WSGs if cutting height is above 0.15 m (Conover et al., 2007). Warm-season grasses can provide habitat for wildlife when cool-season grasses are dormant.

The benefits for biodiversity can be greater under larger-scale plantations of WSGs and SRWCs compared with those under narrow buffer strips of short growing grasses. Combined plantations of WSGs and SRWCs mixed with short-growing grass species simulating natural ecosystems may provide a better habitat for wildlife (Christian et al., 1997). Cunningham et al. (2004) observed that SRWCs improved diversity of flora and there were twice as many plant species in SRWCs as in agricultural lands. Diverse plant species attract game birds, butterflies, mammals, and soil organisms, which improve both wildlife and soil biological quality. In southwestern Wisconsin, harvesting switchgrass not only alters the vegetation structure but also composition of bird species (Roth et al., 2005). Birds which preferred short growing grass were found in harvested areas, while those preferring tall grasses such as sedge wren (*Cistothorus platensis*) and Henslow's sparrow (*Ammodramus henslowii*) were concentrated in unharvested parts of the switchgrass field. Proper balance among harvest frequency, cutting heights, and plant species is critical to wildlife habitat improvement under herbaceous and woody plants. Frequent harvesting and reduced cutting height of plants can reduce the wildlife habitat benefits. Some areas of the field could be left unharvested to enhance diversity of wildlife habitat under energy crops.

## **GROWING BIOENERGY CROPS IN MARGINAL AND DEGRADED LANDS**

Large-scale plantations of WSGs and SRWCs for biomass production may compete for land with agricultural crops. Use of marginal or degraded lands is thus an option. Establishment of WSGs and SRWCs in such lands can provide added benefits, including SOC sequestration, reduction in net CO<sub>2</sub> emissions, and improvement in soil properties and wildlife habitat, while still providing feedstocks for cellulosic ethanol production. Performance of WSGs and SRWCs in marginal and degraded lands has not been widely documented (Tolbert et al., 2002). The limited research data that exist indicate that WSGs and SRWCs are particularly suitable for adaptation to marginal lands (Frank et al., 2004). Producing WSGs and SRWCs in degraded lands can provide feedstocks with low production inputs of energy compared with crop residues.

### **Nutrient-Depleted Soils**

Production of energy crops for biofuel in marginal lands could restore previously unproductive or infertile soils. Warm-season grasses (e.g., switchgrass), once established, can grow in soils with low fertility and limited water supply (Ma et al., 2000). Potential of WSGs for sequestering SOC can be indeed high in degraded soils with low SOC caused by anthropogenic activities (Frank et al., 2004). *Miscanthus* (*Miscanthus* spp.) can accumulate about 0.5 Mg ha<sup>-1</sup> yr<sup>-1</sup> of C in soils of low productivity (Heaton et al., 2004). In a large-scale study across 27 sites distributed in Minnesota, Wisconsin, Iowa, and North Dakota, Coleman et al. (2004) reported that gains in SOC under SRWCs were generally greater when the SRWCs were grown in marginal lands than in fertile agricultural lands. The SOC concentration in SRWCs can be equal to or even lower than in croplands if SRWCs are grown in fertile agricultural lands (Coleman et al., 2004).

### **Compacted Soils**

The deep roots of WSGs can penetrate into relatively compacted layers (e.g., claypan, plowpan, and hardpan) and increase water movement, nutrient uptake, and groundwater recharge. In mid-Missouri, Clark et al. (1998) observed that roots of eastern gamagrass penetrated claypan or argillic horizons with high clay content (30–50%) to about 1.8 m depth. The claypan layer is found between 10 and 30 cm of soil depth. The ability of WSG roots to penetrate restricting soil layers can be essential to uptake water and nutrient from deeper layers in degraded soils. Most row crops have reduced ability to penetrate restrictive layers, and thus their roots are mostly confined to the soil depth above the restrictive layers (Gilker et al., 2002).

### **Poorly Drained Soils**

Warm-season grasses, particularly switchgrass and eastern gamagrass, can tolerate both saturated and unsaturated soil conditions, making them adaptable to restrictive environments (Gilker et al., 2002). Clark et al. (1998) reported that the eastern gamagrass improved soil drainage and air circulation at deeper profile depths attributed to extensive root channels and aerenchymous (air-filled) roots of the grass. The aerenchyma of WSG roots can permit root growth in water-logged soil layers by transporting O<sub>2</sub> and representing

a continued reservoir of O<sub>2</sub>. All WSGs exhibit aerenchyma property (Clark et al., 1998).

### Acid Soils

Warm-season grasses are acid-tolerant species and can grow in environments where soil acidity is a problem for conventional cropping systems. Krizek et al. (2003) reported that biomass yields from 'Pete' eastern gamagrass ranged from 4.3 to 6.6 Mg ha<sup>-1</sup> on an acid compact soil with shallow topsoil, low pH, and moisture deficits. Similarly, Gilker et al. (2002) found that eastern gamagrass was not inhibited by soils with low pH (3.5) and high Al-toxicity and bulk density (1.7 Mg m<sup>-3</sup>). Thus, WSGs penetrate compact soil layers and persist in toxic and acidic conditions, which are often barriers for row crops. In soils with exposed subsoil, switchgrass had greater root and microbial biomass than a corn-soybean rotation, indicating that growing WSGs can improve degraded soils due to their more extensive and deeper root system (Al-Kaisi and Grote, 2007).

### Concentrated Flow Erosion

Warm-season grasses have been shown to reduce concentrated runoff because they are tall and have stiff stems (Dosskey et al., 2002; Blanco-Canqui et al., 2004b). In a field study, Dabney et al. (2004) observed that switchgrass planted in series across concentrated flow channels stabilized and reduced formation of gullies. Vegetative barriers can also be effective for reducing sediment losses from highly eroded environments with steep slopes (Rey, 2004). Growing WSGs disperses concentrated runoff and reduces the runoff energy and velocity in sloping lands. Warm-season grasses such as switchgrass, miscanthus, and vetiver [*Vetiveria zizanioides* (Linn.) Nash] roots have high modulus of elasticity and bending angle at the elastic limit, which reflect their high ability to resist the increased hydrostatic pressure under concentrated runoff flow in gullies (Dunn and Dabney, 1996). Warm-season grasses have stiffer stems than cool-season grasses and can thus retard and disperse concentrated runoff more effectively (Dabney et al., 1995). Width of plantations, type of species, and stem strength, density, and elasticity are important factors for selecting WSGs to reduce concentrated flow erosion.

### Contaminated Soils

Warm-season grasses and SRWCs can also tolerate contaminated soils and be used as part of phytoremediation strategies (Kang et al., 2008). For example, switchgrass and big bluestem tolerate soil contaminated with trinitrotoluene better than cool-season grasses such as smooth bromegrass (*Bromus inermis* Leyss.) and tall fescue, where shoot and root growth are significantly reduced (Krishnan et al., 2000). Chekol et al. (2002) found that reed canarygrass and switchgrass were effective at remediating trinitrotoluene-contaminated soils but had little or no effects on pyrene remediation. Sedge (*Carex stricta*), switchgrass, and eastern gamagrass reduced residual total petroleum hydrocarbon in sediments by 70% after 1 yr of growth while willow, poplar, or no plants reduced only by 20% (Euliss et al., 2008). Similarly, big bluestem, Indian grass, and switchgrass have potential to remediate soils with high concentrations of atrazine and metolachlor (Zhao et al., 2003).

### Conservation Reserve Program Lands

There is a growing interest in establishing WSGs and SRWCs in lands currently enrolled in CRP lands, but implications of such strategy on soil and water resources, SOC sequestration, net GHG emissions, and wildlife habitat have not been accurately assessed (Malcolm and Aillery, 2009). Biomass can be grown and removed as biofuel from the CRP lands if proven to be inconsequential on soil and environment. The CRP was specifically implemented on marginal lands or erosion-prone soils, and thus any excessive removal of biomass or conversion of CRP lands to row crops may increase soil erosion, reduce SOC sequestration, and harm wildlife habitat to levels similar to preconversion levels. Moreover, the CRP lands are normally under mixed grasses. Replacing the CRP lands rich in plant species with monocrops or single grass species as biofuel may have negative consequences. Excessive removal of biomass from prairie native grasses may reduce SOC sequestration to levels similar to row crops (Skinner, 2008). Alternatively, if the CRP lands were more intensively managed with proper harvest frequency, cutting heights, and additions of manure and fertilizer, or planted to other more productive monocultures of perennials, a net increase in soil carbon sequestration, reduced GHG emissions, and improved soil properties and water quality might result. Well and intensively managed CRP lands may indeed improve the farm economy and conserve soil and water resources while supplying feedstocks for biofuel production. Guidelines for managing CRP lands under the new scenario for producing biofuel feedstocks should be established based on experimental and field-scale data. Performance of intensively managed WSGs and SRWCs on both existing marginal lands and CRP lands also needs to be documented.

### POTENTIAL OF DEDICATED ENERGY CROPS

Energy crops should not be grown in forest and prime agricultural lands if a sustainable renewable energy source is sought. First, converting forest lands into energy crops could accelerate net GHG emissions and increase risks of the projected global climate change (Campbell et al., 2008). Second, use of prime agricultural lands for producing energy crops may increase risks of food insecurity (Campbell et al., 2008). The most sustainable option for growing energy crops is the use of marginal, degraded, and abandoned lands. Campbell et al. (2008) estimated that global area of abandoned agricultural ranges between 385 and 472 million hectares, which, on average, can produce about 4.3 Mg ha<sup>-1</sup> yr<sup>-1</sup> of biomass and supply, depending on the nation, about 10% of energy demand. Bringing marginal lands (e.g., agricultural, forest, and grasslands) into biomass production for biofuel can thus be an additional strategy to reduce the energy demand. Development of technologies for increasing biomass production per unit area to meet the energy demands while still maintaining soil and environmental quality is also a priority.

Literature review shows that warm-season grasses and SRWCs can be good candidates for reclamation of marginal lands. The few previous studies show that WSGs can grow and persist in adverse conditions including compact, Al-toxic, poorly drained, acid, and relatively contaminated soils. The ability of WSGs to grow in soil conditions where conventional crops cannot persist suggests that agricultural lands that are

currently unproductive can be planted to WSGs to produce biofuel feedstocks and make them profitable. In a silty clay loam in Nebraska, ethanol yield from switchgrass grown in a marginal soil was greater than that from corn stover under the same rate of N fertilization after 5 yr of study (Varvel and Wilhelm, 2008). These results show that dedicated energy crops can be a viable option for producing renewable energy.

Simply planting and harvesting WSGs as biofuel do not guarantee soil and environment improvement. Proper management (harvest frequency, cutting heights) strategies must be implemented. Harvesting of WSGs as biofuel may significantly reduce or even negate the soil and environmental benefits if biomass cutting height is <0.10 m. Well-managed WSGs provide year-round permanent surface cover, which protects the soil from erosion.

## MODELING OF ENERGY CROPS

Models are important tools to assess soil and environmental (e.g., water quality and SOC dynamics) impacts of crop residue removal and growing energy crops. Use of models is becoming an important trend in management decision processes of energy crops. Robust and process-based models can predict the potential impacts on soil and environment for a specific geographic region. Modeling can also allow the extrapolation of results to other regions with similar management, soil, and climate. There is, however, limited information on modeling the effects of energy crops. To date, a major limiting factor for the calibration and use of process-based models is the lack of long-term measured data on soil properties, SOC dynamics, and biomass production.

A soil-crop model that can simulate the transformations in SOC, nutrient cycling, energy balance, and soil properties to predict corn yield and biomass is the Erosion-Productivity Impact Calculator (EPIC). This model allows the input of various rates of residue and biomass input to predict crop yields over time (Williams et al., 1984). Brown et al. (2000) modeled production of switchgrass and its impacts on the environment using the EPIC model in Missouri, Iowa, Nebraska, and Kansas. They reported that predicted switchgrass yields under different climate scenarios simulating the projected climate change increased when temperature increased by 3 to 8°C due to the more extended growing season and warmer conditions under the new climate. Precipitation increase with climate change increased runoff losses from the row crops but not from switchgrass.

Other models such as the Revised Universal Soil Loss Equation (RUSLE), the Soil and Water Assessment Tool (SWAT), and the Century are also potential models for energy crops. Nelson (2002) used RUSLE for predicting the maximum amount of crop residue that can be removed in the U.S. Corn Belt region based on soil erosion risks. The data indicated that the optimum crop residue removal rates vary by soil and climate. In northeastern Kansas, Nelson et al. (2006) using the SWAT model predicted that switchgrass plantings can reduce sediment yield by 99%, runoff by 55%, NO<sub>3</sub>-N by 34%, and edge-of-field erosion by 98%. The Century model has potential to predict SOC sequestration rates under bioenergy crops by incorporating plant-soil approaches and integrating specific management subroutines (Grogan and Matthews, 2002). The

Century model simulated SOC and N pools within ±5% of the observed data for 9 yr of continuous corn in eastern Canada (Liang et al., 1998). A similar study in Iowa by Manies et al. (2001) reported that Century model predicted satisfactorily the changes in SOC storage as affected by tillage and stover management in corn fields. Kiniry et al. (2005) used the ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) model in Texas, Arkansas, and Louisiana to predict switchgrass yield, showing that the model had limited ability for predicting year to year yield variability.

Pedotransfer functions are also potential tools to develop interrelationships among biomass production, SOC dynamics, and soil properties among different levels of residue removal and growing energy crops (Minasny and McBratney, 2002). These regression models are particularly useful to estimate site-specific changes. Long-term effects of energy crops on SOC dynamics can be predicted from the annual addition of root biomass and changes in soil properties. Further computer modeling should be done to develop a methodology for predicting maximum removable rates of crop residues as well as to determine performance of energy crops under different ecosystems conditions.

## RESEARCH NEEDS

The following points must be further addressed to gain a better understanding of the impacts of crop residue removal and growing energy crops on soil and environment: (i) Assess impacts of crop residue removal from corn, wheat, grain-sorghum, sweet (forage) sorghum, and other grain crops on soil properties, SOC sequestration, net emissions of GHGs, NPS water pollution, and wind erosion. (ii) Collect more data on crop residue removal impacts from field or watershed scale plots for different ecoregions and climate zones to establish definitive threshold levels of residue removal for biofuel production. (iii) Conduct long-term studies designed to assess the implications of field-scale plantations of growing WSGs and SRWCs on soil productivity, soil water conservation, and environmental quality under marginal lands. Impacts of growing SRWCs as biofuel on soil and environmental quality need scrutiny based on experimental data. (iv) Collect more data on biomass production potential, SOC dynamics, water quality (e.g., nonpoint-source pollution), water storage and use, GHG emissions, and wind erosion potential under WSGs and SRWCs grown on different soils and environments including marginal (i.e., steep and eroded) lands or CRP lands. (v) Establish WSGs and SRWCs in demonstration sites for the development and diffusion of management strategies. Well-designed experiments of energy crop plantations are needed to develop decision support systems and identify strategies for a sustainable management. Among the management strategies are harvesting frequency and heights, nutrient input, and soil management. (vi) Scrutinize the implications of growing WSGs and SRWCs on different soil types, ecoregions, and climate zones. Growing WSGs and SRWCs may, for example, increase water demands in regions with limited precipitation (e.g., semiarid regions) due to longer growing season and greater evapotranspiration and rooting depth. (vii) Increase studies on the selection and genetic improvement of herbaceous and woody plant species and varieties tolerant to adverse soil (e.g., shallow, compact,

acidity) and environmental (e.g., dry climate) conditions. (viii) Develop and calibrate models and pedotransfer functions capable of predicting impacts of growing WSGs and SRWC on SOC sequestration rates, water quality, and biomass production under different scenarios of production.

## CONCLUSIONS

Literature reviewed herein shows that studies assessing impacts of long-term crop residue removal and growing WSGs and SRWCs as cellulosic ethanol feedstocks on soil and environment are limited. The available studies show that indiscriminate crop residue removal harvesting for expanded uses has adverse impacts on soil properties, water quality, SOC sequestration, and crop production particularly in erodible and sloping soils. Alternatively, growing WSGs and SRWCs shows promise to provide a range of ecosystem services over crop residue removal. Short-rotation woody crops sequester SOC, reduce soil erosion, improve soil properties, and promote wildlife habitat. The benefits of WSGs and SRWCs are greater when grown in marginal, degraded, and abandoned lands than when grown in prime agricultural lands.

This review also reveals that gains in SOC and improvement in soil properties under WSGs and SRWCs can vary, depending on soil-specific characteristics (e.g., drainage, slope, and texture), harvest cycles, addition of amendments, previous land use and management, plant species, and climate. Impacts are often measurable with longer periods of management. Warm-season grasses and SRWCs as biofuel must be carefully managed to achieve the desired ancillary soil and environmental benefits. Growing WSGs and SRWCs as biofuel cannot replace natural forest and native prairie lands, but they can provide a number of ancillary benefits when managed properly. The potential benefits of growing energy crops on the environment will depend on how energy crops are grown and where they are grown. Mixture of plant species can be more effective than single species for controlling runoff, sediment, and nutrient loss. Well-managed energy crops can improve soil and environmental quality while supplying much-needed feedstocks for cellulosic ethanol production.

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