

Physical Properties of an Alfisol Under Biofuel Crops in Ohio

Catherine Bonin* and Rattan Lal[#]

Carbon Management and Sequestration Center, The Ohio State Univ., 210 Kottman Hall, 2021 Coffey Rd., Columbus, OH, 43210, USA

Abstract: There is an increasing need to develop renewable energy sources from biofuel crops to replace fossil fuels. Biofuel crops may also enhance ecosystem functions such as soil quality, water availability, and nutrient reserves. Therefore, the effects of four biofuel crops (corn (*Zea mays*), switchgrass (*Panicum virgatum*), indiangrass (*Sorghastrum nutans*) and willow (*Salix* spp.) were evaluated on soil quality at three sites in Ohio to assess the effects of crop species on soil bulk density (ρ_b), soil moisture characteristics (SMC), water stable aggregate distribution (WSA), and aggregate tensile strength (TS) to 40 cm depth. Overall, results were site-specific, with most differences occurring for the clayey soil at the Northwest site. At the Jackson site, soil in the 0-10 cm layer under switchgrass had a higher moisture content (θ) between 0 and 100 kPa than that under indiangrass. At the Western site, θ under corn at 1500 kPa was higher at 30-40 cm depth. At the Northwest site, soils under corn in the 0-10 cm depth tended to have the lowest θ at 0 and 3 kPa, while soils under switchgrass and willow had 50% more large macroaggregates and fewer small microaggregates than that under corn. Soil TS in the 0-10 cm depth under corn was nearly 160% more than that under other perennial crops. These results suggest that management of perennial biofuel crops can improve soil physical quality. Changes over seven years occur first in the surface soil layers, but further differences may evolve in subsoil layers with increase in time.

Keywords: Soil quality, biofuel feedstock, tensile strength, water stable aggregate, bioenergy.

INTRODUCTION

The search for renewable and sustainable energy sources has been driven by the rising cost of fossil fuel, as well as increasing atmospheric greenhouse gas (GHG) concentrations and the threat of climate change and environmental degradation. In the US, corn grain is the primary crop for ethanol production, with over 52 billion liters of corn grain ethanol produced in 2011 [1]. However, the Energy Independence and Security Act of 2007 (EISA) has capped corn grain contributions and requires that other crops be increasingly used to supply ethanol, such as perennial grasses, trees, algae, etc.

Until recently, biofuel research has focused mainly on comparing bioenergy yields of different feedstocks and potential carbon (C) sequestration by biofuel crops. The implementation of life-cycle assessments (LCA) has helped to quantify and contrast the energy and GHG balances of crop options by providing estimates of energy and GHG costs for crop and biofuel production, as well as biofuel consumption. Although LCAs provide a method of determining crop costs and benefits, results have been equivocal, even within the same crop due to factors such as uncertainties in quantification and by-product allocation methods [2]. Even with these uncertainties, most LCAs suggest that

corn and other annual crops have a lower net energy balance (NEB; the ratio of energy produced to energy used), and a lower GHG balance than perennial species such as grasses and trees [3-6].

What is less understood is how managing for different bioenergy crops may affect soil physical properties. Soil is a vital resource whose quality and ecosystem services can be strongly influenced by vegetation and management practices. Biofuels and management practices can improve soil physical properties such as bulk density (ρ_b), porosity (ϕ), soil strength, and aggregate stability [7]. Improvements in soil quality may enhance resource use efficiency, maintain biomass productivity, reduce risks of accelerated erosion and runoff, increase soil water retention, improve aggregate stability, as well as sequester soil organic carbon (SOC) [8,9]. For example, aggregation influences soil structure, which is an important factor in maintaining soil quality and sustaining agricultural productivity [10]. Likewise, soil strength impacts root elongation, seedling emergence, and plant growth. In this manner biofuel crops may augment multiple ecosystem services: produce energy, reduce atmospheric GHG release, and improve soil quality.

Plant growth and potential ethanol yields are also affected by soil hydrological properties. Adequate moisture must be retained in the soil for water uptake by roots, and water stress can elicit a variety of plant responses that reduce photosynthesis, lower transpiration rates, and can decrease agronomic yields

*Address corresponding to this author at the Carbon Management and Sequestration Center, The Ohio State Univ., 210 Kottman Hall, 2021 Coffey Rd., Columbus, OH, 43210, USA; Tel: (608) 335-6750; Fax: (614) 292-7432; E-mail: bonin.8@osu.edu

[#]Co-Author. Rattan Lal: E-mail: lal.1@osu.edu

[11,12]. Water is a resource that will become increasingly limited from increases in anthropogenic demands and global climate change [13]. Soil moisture properties are correlated with soil texture, ρ_b , and soil organic matter (SOM) content [14]. Enhancing soil quality to increase soil moisture and plant available water (PAW) may reduce irrigation needs and sustain biofuel crop production.

Plant lifeform and chemical composition can also affect nutrient cycling and C dynamics in soil [15,16]. Longer-lived, deeply rooted perennial systems may also store more SOC in deeper sub-soil than shorter-lived and shallow-rooted annual crops could [17]. Texture can also play a role in affecting soil properties, but when grasslands, forests, and cropland have similar soil textures, the perennial ecosystems can have higher SOM concentrations, lower soil ρ_b , more water stable soil aggregates (WSA), and greater PAW capacity [18]. Finally, soil properties change slowly over time, such that differences may take years or decades to appear [19,20], although in some cases positive changes in SOC to 150 cm depth have been observed within nine years under both switchgrass (*Panicum virgatum*) and corn (*Zea mays*) [21].

Each biofuel crop may have different effects on soil characteristics based on plant attributes such as life habit, root mass and rooting distribution, and plant tissue composition. Annual crops, such as corn, may have a shorter growing period than perennials. Annuals also require replanting each year, which could further impact soil properties. In contrast, perennial grasses and trees can have extensive and deep root systems. Up to 80% of switchgrass biomass may occur belowground [22]. Switchgrass and willow (*Salix* spp.) produce more fine root biomass than corn (8.8 Mg ha⁻¹ and 5.8 Mg ha⁻¹, respectively, versus 0.9 Mg ha⁻¹ for corn), and have a greater proportion of roots below 35

cm [23]. Likewise, soils under grass and forest buffers have lower ρ_b , more porosity, and can potentially store more water than soils under cropland [24]. Rooting properties can also lower soil tensile strength (TS) under switchgrass [25].

The objective of this research was to examine soil properties under four biofuel crops, namely corn, willow, switchgrass, and indiangrass (*Sorghastrum nutans*), and compare how the soils under each crop treatment have differentiated in the seven years since establishment of this biofuel crop experiment. The hypothesis tested was that soil under the grass and tree species would have better soil quality as indicated by lower ρ_b , higher WSA, lower TS, and would have favorable soil moisture retention characteristics with high PAW.

MATERIALS AND METHODS

The study was conducted at three Ohio Agricultural Research and Development Center (OARDC) sites: the Northwest (41° 13' 49" N, 83° 45' 34" W), Western (39° 51' 21" N, 83° 40' 40" W), and Jackson (39° 1' 39" N, 82° 36' 17" W) branches (Table 1). The soil series at the Northwest site are Hoytville silty clay loam and Hoytville clay loam (Fine, illitic, mesic Mollic Epiaqualfs). At the Western site, soils are primarily Kokomo silty clay loam (fine, mixed, superactive, mesic Typic Argiaquoll) and Strawn-Crosby complex (fine-loamy, mixed, active, mesic Typic Hapludalf; fine, mixed, active, mesic Aeric Epiaqualf). In Jackson, the soil series are Rarden-Wharton silt loams (Fine, mixed, active, mesic Aquultic Hapludalfs, Fine-loamy, mixed, active, mesic Aquic Hapludults) and Shelocta-Rarden association, steep (Fine-loamy, mixed, active, mesic Typic Hapludults, Fine, mixed, active, mesic Aquultic Hapludalfs) [26,27].

Table 1: Historical Site Characteristics and Prior Land Use of the Three Sites in Ohio where the Biofuel Experiment was Established

Site	Location	Temperature (°C)	Precipitation (cm)	Prior land use	Crops
Northwest	41° 13' 49" N 83° 45' 34" W	9.9	85.6	Sod	Switchgrass Corn Willow
Western	39° 51' 21" N 83° 40' 40" W	10.9	105.7	Corn-soybean rotation	Switchgrass Indiangrass Corn Willow
Jackson	39° 1' 39" N 82° 36' 17" W	11.4	109.2	Forage grasses	Switchgrass Indiangrass

Switchgrass, indiangrass, willow, and no-till (NT) corn plots were established in spring 2004. The Western site was the only location where all four biofuel crops were planted (Table 1). Soils were plowed before sowing or planting to facilitate stand establishment. Corn and switchgrass plots were 6 x 6 m, while willow plots were 12 x 6 m, and all treatments were replicated four times, with the exception of indiangrass at the Western site (replicated twice). Willow seedlings were planted at a rate of 2400 trees ha⁻¹, in six rows of three trees per plot, and 28 g N was spread in a 15-cm circle around each tree seedling (67 kg N ha⁻¹). In spring of 2007 and 2008, 69 g N (168 kg N ha⁻¹) and 23 g P (56 kg P ha⁻¹) were applied around each tree. The NT corn was sidedressed with 110 kg N ha⁻¹ annually. Willow trees have not been harvested since establishment.

Switchgrass was sown into plots at a seeding rate of 11.2 kg pure live seed ha⁻¹, with 56 kg N ha⁻¹ applied at establishment. No other fertilizers were applied to switchgrass plots until initiation of a fertilizer experiment in 2008 and 2009. For these two years, each switchgrass plot was divided into four quarters and sub-plot received one of four rates of N fertilizer. The current analysis was conducted on sub-plots that received 50 kg N ha⁻¹ annually for the two years, as this application rate approximates the amount of N that switchgrass removes annually from soils at this site [28]. Each year after establishment, switchgrass plots and indiangrass were harvested at ~15 cm stubble height in late fall, and the cut biomass was removed.

Soil Sampling and Analysis

Bulk samples were collected using a shovel in the summer of 2011 from plots at all three sites to 0- to 10-cm and 10- to 20-cm depths. Soil samples were collected between rows in corn and willow plots, and randomly within the grass plots. Intact soil cores were also collected with a core sampler at four (0-to 10-cm, 10-to 20-cm, 20-to 30-cm, and 30-to 40-cm) depths. Due to the availability of cores, one core size was used at the Western site, and a slightly larger core size was used at the Northwest and Jackson sites. Cores collected at the Western site were 4.75 cm in diameter by 5 cm deep, while those collected at the Northwest and Jackson sites were 5.35 cm in diameter by 6 cm deep. All cores collected within a site were the same size, allowing for comparison among crop treatments within sites. Bulk samples were air dried and passed through 8- and 4.75-mm mesh screens to collect soil aggregates with sizes between 4.75- and 8-mm. Cores

were trimmed, wrapped in plastic and stored at 4°C pending analysis.

Bulk Density and Soil Moisture Characteristics

Soil ρ_b was calculated for each of the four depths using the core method [29]. Since cores were kept intact for soil moisture characteristic (SMC) analysis, a portion of the core trimmings was oven-dried at 105°C for 48-72 hours and used to estimate oven-dry core weight. The ρ_b was calculated by dividing oven-dry soil weight by its volume.

After cores were weighed, a piece of cheesecloth was fixed to the bottom of each core using a rubber band. Cores were completely saturated for 2-3 days used to assess SMC:

$$\theta = f(\Phi)$$

where θ is volumetric moisture content ($\theta = w * \rho_b / \rho_w$, where w is the gravimetric water content and ρ_w is the density of water) and Φ is soil moisture potential (kPa) measured using both the tension table and pressure plate extractors [30]. The SMC were calculated by measuring soil water retention at 0, 3, 6, 33, 100, and 1500 kPa. Intact soil cores were used for the first five Φ , while sieved soils were used at 1500 kPa 2 mm. Field water capacity (FWC) and the permanent wilting point (PWP) were computed as θ at 33 kPa and 1500 kPa, respectively. Plant available water (PAW) was calculated as the difference between FWC and PWP. The θ held by spore size classes was calculated as the difference in θ between two pore sizes. Pore size was determined based on capillary rise [31]:

$$r = 0.15 / h$$

where r is the radius of pores (cm) and h is the height of the water column or Φ (cm). Six pore size classes were defined: > 300 μm , 50-300 μm , 9-50 μm , 3-9 μm , 0.02- 3 μm , and < 0.02 μm in pore diameter.

Water Stable Aggregates

Air-dry aggregates from bulk soils were used to measure size distribution and percent of WSA using the wet sieving method [32]. Approximately 50 g of aggregates (4.75-8 mm) were placed into a Yoder apparatus containing five nested sieves of 4.75, 2.00, 1.00, 0.425, and 0.162 mm diameter [33]. Aggregates were slowly wetted by capillary action for 15 minutes and then oscillated mechanically for 30 minutes at 60 oscillations min⁻¹. Soil aggregates retained on each

sieve were transferred to beakers and dried at 40°C for 2 days, and weighed. Soil passing through the 0.162 mm sieve was also collected, dried, and weighed. The % WSA was calculated on six size classes: >4.75 mm, 4.75-2.00 mm, 1.00-2.00 mm, 0.425-1.00 mm, 0.162 mm-0.425 mm, and <0.162 mm. The data were used to calculate the mean weight diameter (MWD) according to Youker and McGuinness [34].

Aggregate Tensile Strength

The TS for each of the 0-10 cm and 10-20 cm depths were tested in a crushing apparatus similar to that described by Horn and Dexter [35]. Five aggregates (4.75-8 mm) were selected from each plot and depth and tested in using a crushing test (indirect tension). Using the method by Dexter and Kroesbergen [36], three diameters were taken for each aggregate to calculate the average diameter (D_{agg}). The TS was calculated as:

$$TS = 0.576 \cdot (F / D_{agg}^2)$$

where F is the force needed to rupture the aggregate measured by the crushing apparatus [37].

Soil Texture and pH

Soil texture and pH were measured for 0-10, 10-20, 20-30, and 30-40 cm depths. Once SMC analyses were completed on the soil cores, the soil was air-dried and ground to pass through a 2-mm sieve. The particle size analysis (PSA) was determined by using the pipette method [38]. The pH was calculated by mixing

10 g of soil with 10 mL distilled water (1:1 ratio). Samples were vortexed for one minute, then allowed to rest for one hour. After the rest period, samples were quickly vortexed again and pH was measured with a glass electrode.

Statistical Analysis

Soils from each site were analyzed separately using PROC MIXED of SAS (Version 9.2, SAS Institute, Cary, NC) [39]. Biofuel crop and depth were treated as fixed variables and replication as a random variable. For TS, the five aggregates measured for each crop and depth were treated as subsamples. Responses for each treatment were separated using the test for least significant differences (LSD), with $\alpha = 0.05$.

RESULTS

The three sites differed in climate, soil texture, soil pH, and soil ρ_b (Tables 1 and 2). Both precipitation and temperature increased from the northern to the southern research stations. The Northwest site, which had the highest clay content, also had the highest pH. Surface soil ρ_b was the highest at the Western site and the lowest at the Jackson site.

Bulk Density

Although the size of cores collected varied, which could impact ρ_b measurements, results were similar to those calculated by Jung [28] in 2008 and 2009, suggesting that different core sizes had little effect on variations in ρ_b . While soil ρ_b was affected by site and

Table 2: Soil Properties for the 0-10, 10-20, 20-30, and 30-40 cm Depths Under Biofuel Crops at Three Sites in Ohio

Site	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	pH	Bulk density (Mg m ⁻³)
Northwest	0-10	21.1	42.5	36.5	Clay Loam	6.71	1.39
	10-20	20.2	42.1	37.8	Clay Loam	6.93	1.51
	20-30	20.4	40.6	39.1	Clay Loam	7.07	1.55
	30-40	19.0	39.0	42.0	Clay	7.30	1.58
Western	0-10	24.1	58.8	17.2	Silt Loam	5.42	1.47
	10-20	23.6	57.8	18.6	Silt Loam	5.49	1.66
	20-30	23.1	58.5	18.4	Silt Loam	5.38	1.65
	30-40	22.2	57.0	20.8	Silt Loam	5.71	1.64
Jackson	0-10	18.7	62.7	18.6	Silt Loam	6.54	1.29
	10-20	16.5	63.5	20.1	Silt Loam	6.63	1.48
	20-30	13.5	62.1	24.5	Silt Loam	6.67	1.53
	30-40	12.2	59.0	28.8	Silty Clay Loam	6.48	1.60

soil depth, biofuel crop species had little effect. Where differences did occur, it was in the surface layer only. At the Jackson site, soil in the 0-10 cm depth under switchgrass had a lower ρ_b compared to that under indiangrass, at 1.23 Mg m^{-3} versus 1.35 Mg m^{-3} ,

respectively ($P = 0.0084$). At the Northwest site, soil ρ_b in the 0-10 cm layer tended to be higher under corn (1.49 Mg m^{-3}) than under switchgrass (1.33 Mg m^{-3}), with soil ρ_b under willow (1.35 Mg m^{-3}) being intermediate of the two crops ($P = 0.0588$).

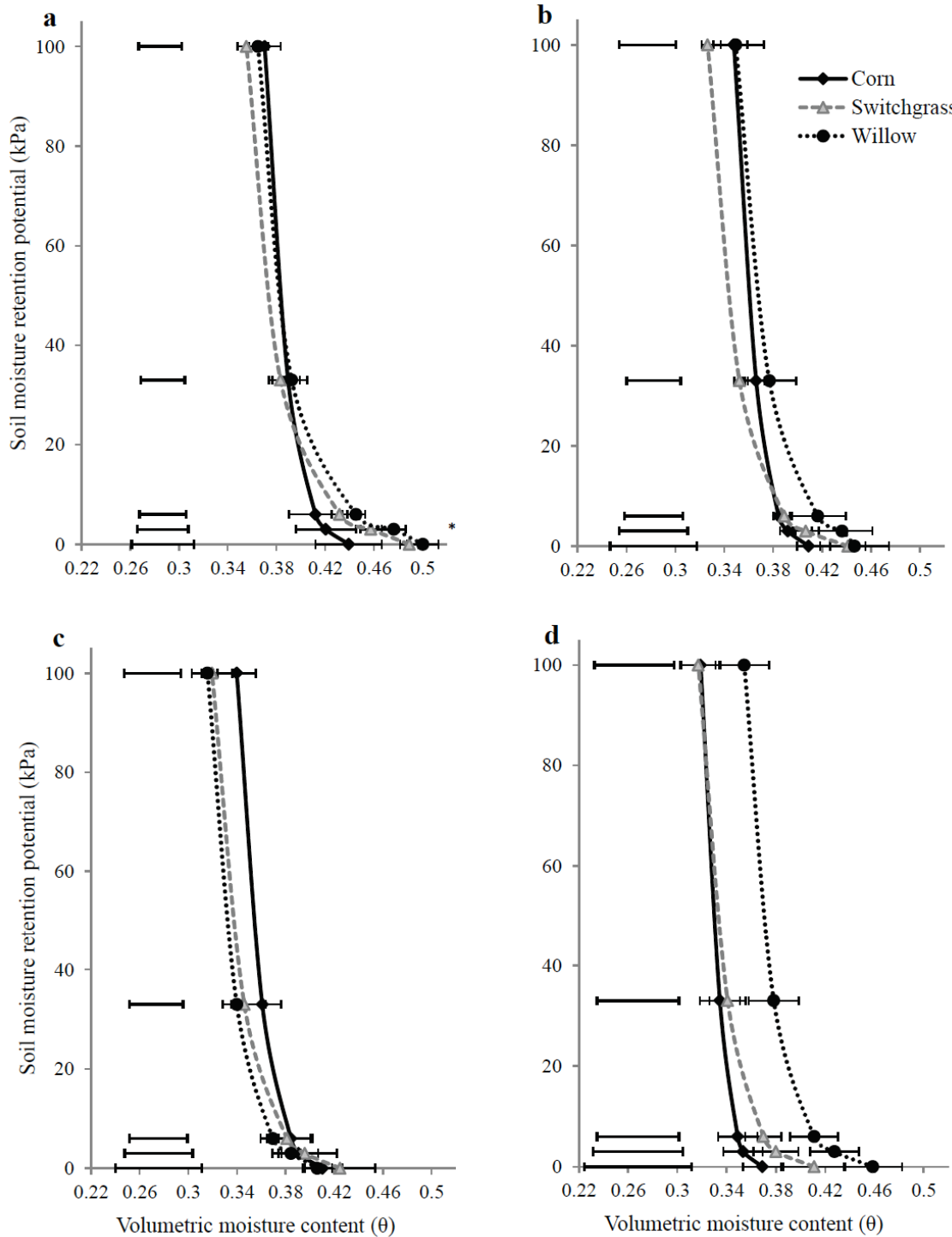


Figure 1: Soil moisture characteristic curves under biofuel crops at four depths at the Northwest site (mean \pm s.e. for each soil moisture potential Φ). The bars to the left of the curves indicate the LSD (0.05) values for each Φ within each depth. A “*” indicates where the volumetric water content (θ) at the particular soil moisture retention potential under biofuel crops differs significantly ($P < 0.05$).

Soil Moisture Characteristics

Differences in SMCs occurred primarily at the Jackson site, and in the 0-10 cm soil depth (Figures 1-3). At this depth, soil under switchgrass held more moisture than that under indiangrass for all Φ except

1500 kPa ($P < 0.015$ at each Φ). In addition, Jackson soils under switchgrass tended to have a higher PAW than that under indiangrass ($P = 0.0559$). In the 0-10cm depth at the Northwest site, corn tended to have the lowest θ and those under willow the highest θ at 0 kPa and 3 kPa ($P = 0.0576$ and $P = 0.0437$,

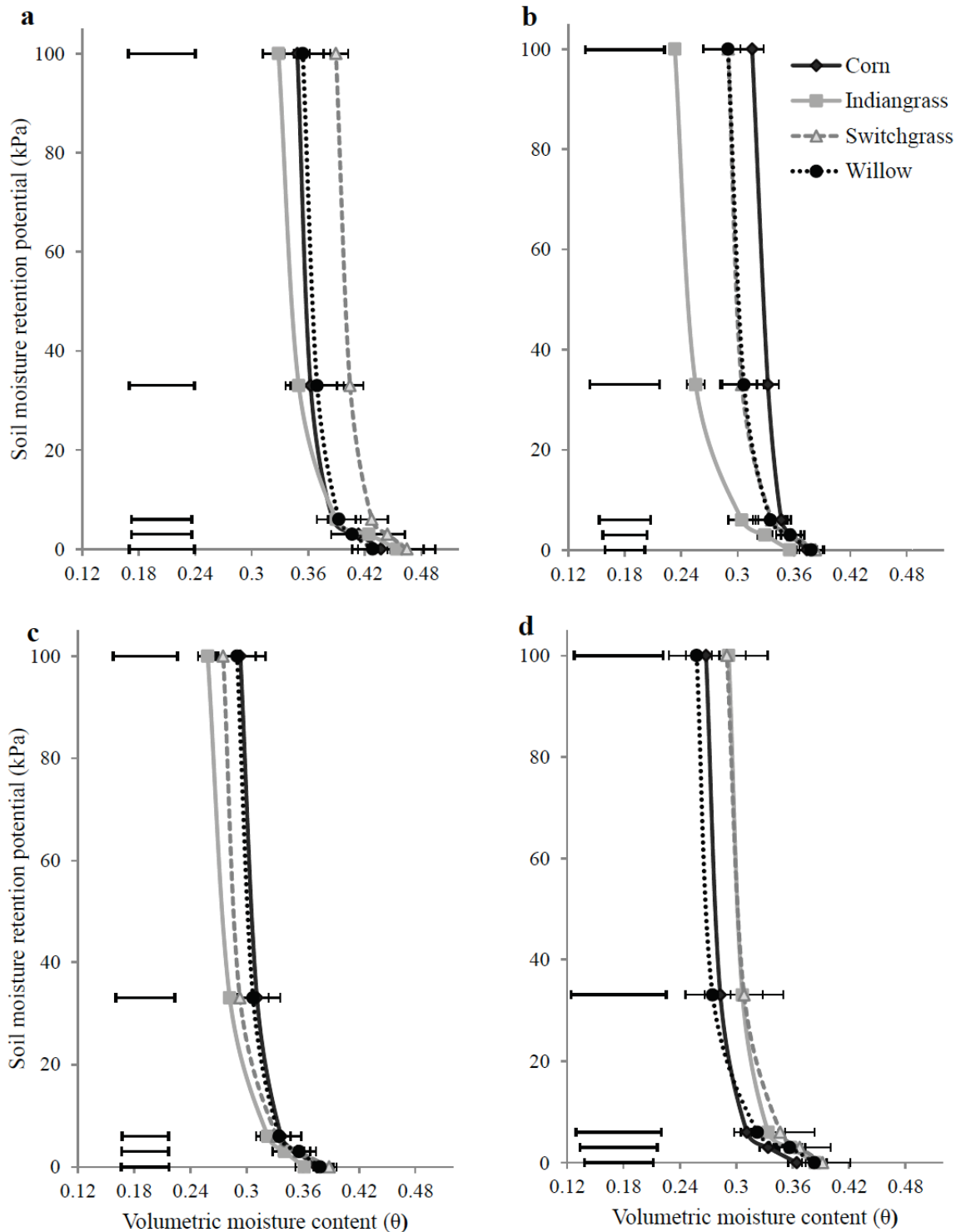


Figure 2: Soil moisture characteristic curves under biofuel crops at four depths at the Western site (mean \pm s.e. for each soil moisture potential Φ). The bars to the left of the curves indicate the LSD (0.05) values for each Φ within each depth.

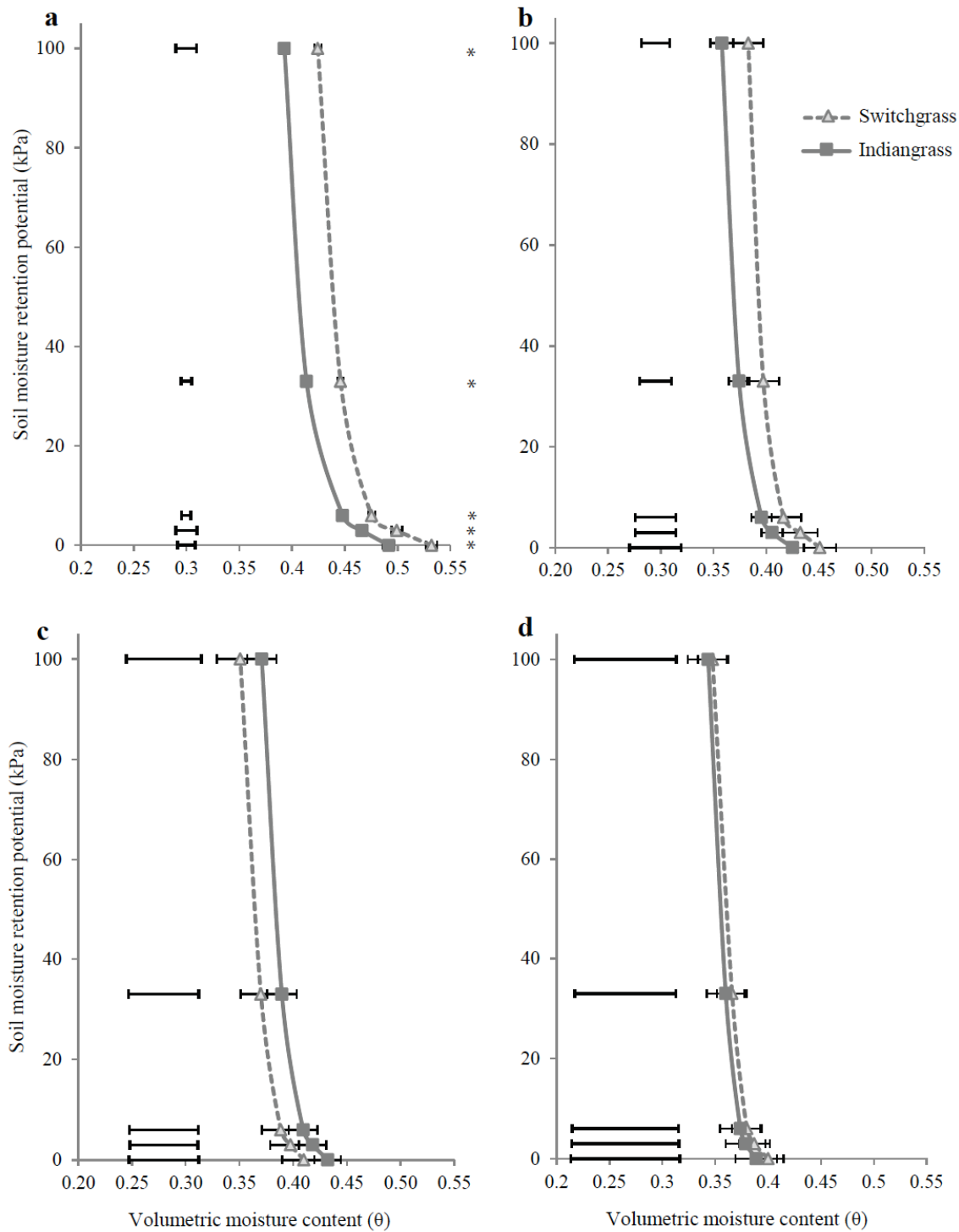


Figure 3: Soil moisture characteristic curves under biofuel crops at four depths at the Jackson site (mean \pm s.e. for each soil moisture potential Φ). The bars to the left of the curves indicate the LSD (0.05) values for each Φ within each depth. A “*” indicates where the volumetric water content (θ) at the particular soil moisture retention potential under biofuel crops differs significantly ($P < 0.05$).

respectively), but there were no other differences in SMCs. At the Western site, soil under corn tended to have higher θ at 1500 kPa than that under other biofuel crops, but this was only significant at the 30-40 cm depth ($P = 0.0051$).

Evaluation of θ held by pore size classes produced similar results (Figure 4). At the Northwest site, the primary differences occurred among pores between 3 and 300 μm . Where differences were present, soil under willow held the most water within a pore size

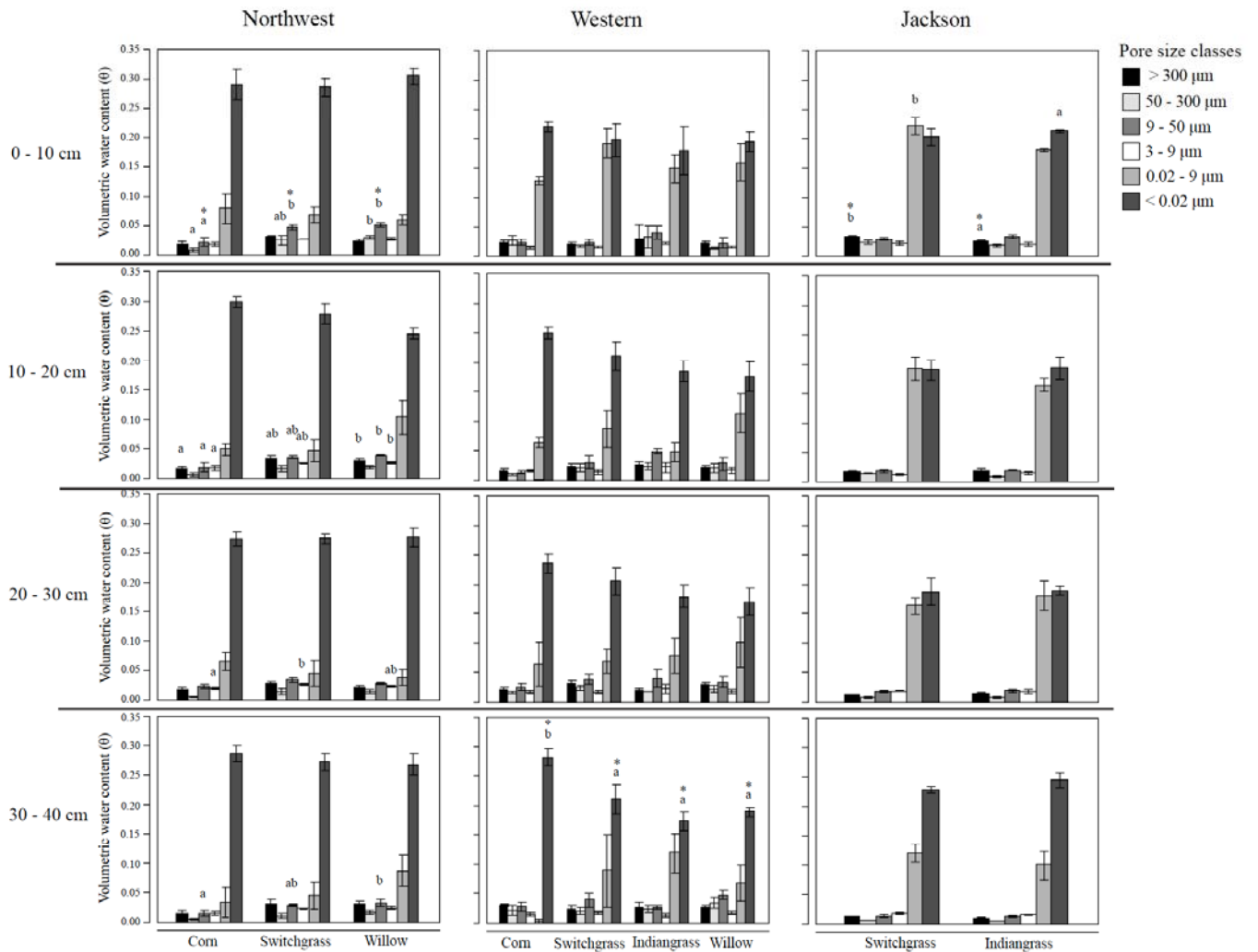


Figure 4: Soil moisture content (θ) held within size pore size classes under biofuel crops at four soil depths in three sites in Ohio. Different letters signify where θ for the particular pore size class differs among soils under biofuel crops at $P < 0.10$. Letters with a “*” above them signify that the difference is significant at $P < 0.05$.

class, and that under corn the least, with soil under switchgrass being intermediate. One exception was in the 10-20 cm soil layer, where soil under corn tended to have a higher θ than that under willow ($P = 0.0875$). The only difference at the Western site was in the smallest pore class ($< 0.02 \mu\text{m}$), where soil under corn in the 30-40 cm layer held more water than those under the grasses or willow ($P = 0.0051$). At the Jackson site, soil under switchgrass and indiangrass tended to have similar θ , with two exceptions in the top 0-10 cm soil depth. At this depth, large pores ($> 300 \mu\text{m}$) in soils under switchgrass had a higher θ than those under indiangrass ($p = 0.0177$), which was also a trend for pores 0.2 to $3 \mu\text{m}$ ($p = 0.0609$).

Water Stable Aggregates and Tensile Strength

The size of WSA generally decreased with increase in depth at all three sites. The only differences in

%WSA and MWD occurred at the Northwest site, where soils under switchgrass and willow had more large macroaggregates than those under corn (Table 3). In comparison with soil under corn, those under the two perennial crops had 50% more macroaggregates $> 4.75 \text{ mm}$, but 600% more microaggregates $< 0.162 \text{ mm}$ in the 0- 10 cm depth. Similarly, the 10-20 cm depth showed that soil under corn had a greater proportion of small aggregates. The MWD of aggregates under switchgrass and willow was nearly 30% higher than that under corn at the 0-10 cm depth ($P = 0.0272$), with a similar trend of lower MWD under corn at the 10-20 cm depth ($P = 0.0695$).

The soils at the Northwest site has the largest aggregate TS and were 50 to 100% stronger than those under the same biofuel crop at the other two sites. Soil TS was similar under crops at the Western

Table 3: Distribution of Water-Stable Aggregates (WSA, by %) and Mean Weight Diameter (MWD, mm) in the 0-10 and 10-20 cm Soil Depths Under Four Crop Species at Three Sites in Ohio

Northwest site														
Crop†	0-10 cm depth						10-20 cm depth							
	>4.75 mm	4.75-2.00 mm	1.00-2.00 mm	0.425-1.00 mm	0.162-0.425 mm	<0.162 mm	MWD	>4.75 mm	4.75-2.00 mm	1.00-2.00 mm	0.425-1.00 mm	0.162-0.425 mm	<0.162 mm	MWD
Corn	61.7 ^a	16.3	8.7 ^b	5.9 ^b	3.5 ^b	3.9 ^b	4.67 ^a	60.4	15.8	9.2 ^b	6.2 ^b	4.0 ^b	4.3 ^b	4.58
SG‡	93.9 ^b	4.0	0.8 ^a	0.5 ^a	0.4 ^a	0.5 ^a	6.13 ^b	73.9	13.8	5.2 ^a	2.9 ^a	1.9 ^a	2.3 ^a	5.28
Willow	89.5 ^b	6.6	1.6 ^a	0.9 ^a	0.5 ^a	0.8 ^a	5.96 ^b	78.0	11.9	4.2 ^a	2.6 ^a	1.5 ^a	1.8 ^a	5.46
p-value	0.031	0.0734	0.015	0.0129	0.0235	0.0429	0.0272	0.145	0.7553	0.0422	0.0173	0.0028	0.0188	0.0695
Western site														
Corn	64.1	9.5	6.5	8.3	5.1	6.5	4.59	57.0	6.3	8.0	10.2	8.7	9.9	4.07
SG	77.9	5.0	3.5	4.9	3.1	5.6	5.24	78.9	5.2	3.9	5.1	2.8	4.1	5.31
IG	93.6	1.8	0.8	0.9	0.9	2.0	6.05	63.2	6.9	5.0	9.4	8.6	7.0	4.43
Willow	84.9	6.2	2.3	1.9	1.5	3.3	5.67	57.6	7.9	6.7	10.8	9.4	7.5	4.15
p-value	0.3836	0.3938	0.3358	0.1267	0.1711	0.3395	0.3042	0.4178	0.6442	0.3481	0.3929	0.3959	0.6667	0.4179
Jackson site														
SG	71.3	11.3	6.4	5.9	2.2	2.9	5.12	57.5	12.0	8.4	8.7	5.7	7.7	4.13
IG	72.3	11.1	5.7	5.2	2.7	2.9	5.07	54.8	12.4	8.7	9.1	7.0	8.1	4.28
p-value	0.9274	0.9628	0.8361	0.824	0.6042	1.00	0.9205	0.6341	0.9198	1.00	0.8361	0.5791	0.8523	0.6785

[†]Means with different letters within a pore class and site are significantly different at $P < 0.05$.

[‡]SG: switchgrass; IG: indiagrass.

and Jackson sites. Overall, aggregate TS increased with increase in soil depth under biofuel crops. At both the Northwest and Western sites, soil in the 0-10 cm depth under corn had the largest aggregate TS, compared with that under other biofuel crops (Table 4). Soil aggregate TS under corn increased nearly 160%, compared to aggregates under switchgrass and willow. There were no differences in TS at the Jackson site, or at the 10-20 cm soil depth at any of the three sites.

DISCUSSION

Soil aggregation and TS are integral parts of soil structure, and may impact soil porosity, stabilization and protection of SOM, and microfaunal habitat [40]. Seven years since establishment of biofuel crops, some differences in soil physical and hydrological properties were observed, primarily in the top 10 cm layer. In most instances, each site has distinct soil physical properties due to soil texture, site history, and climate: compared to the Jackson and Western sites, the Northwest site has the largest pH and soils with the highest TS, larger MWD and WSA. Differences among soils under biofuel crops occurred most often at the

Northwest site, which had clayey soils, cooler temperatures, and less precipitation than the other two locations, suggesting that soil and environmental conditions are important controls of changes in soil physical properties.

Soil ρ_b

With one exception, differences in soil ρ_b were absent at all depths. Dividing the top 10 cm layer into two, 5-cm segments might affect conclusions, since soil changes typically begins near the surface. The analysis of the entire 0-10 cm depth could have obscured some near soil differences that might be statistically significant. The lone difference was at the Jackson site, where soil ρ_b in the 0-10 cm layer was less in soil under switchgrass than under indiagrass. Both of these are perennial, warm-season grasses with similar growth habits, but it is possible that species differences in shallow rooting biomass could have caused the difference in soil ρ_b . For example, another study reported that soil ρ_b can be less under switchgrass than that under cropland in the 0-5 cm layer, but equal in the 5-10 cm layer [17], and similarly, soil ρ_b in the top 3 cm under switchgrass or trees was less than that under

Table 4: Mean Tensile Strength (kPa) of Aggregates (4.75-8 mm) of the 0-10 and 10-20 cm Soil Depths Under Four Crop Species at Three Sites in Ohio

Northwest	Tensile Strength (kPa)	
	0-10 cm	10-20 cm
Corn†	549 ^b	561
Switchgrass	347 ^a	443
Willow	410 ^{ab}	424
p-value	0.0360	0.1512
Western		
Corn	372 ^b	367
Switchgrass	274 ^a	345
Indiangrass	200 ^a	266
Willow	219 ^a	259
p-value	0.0013	0.1283
Jackson		
Switchgrass	193	202
Indiangrass	224	238
p-value	0.2167	0.3184

†Means with different letters within a soil depth and site are significantly different at $P < 0.05$.

corn [41]. Differences in ρ_b have been observed in other crop studies, but are also often site-specific [25,42].

Hydrological Properties

There were few differences in SMCs under crops at two of the three sites in Ohio. Interestingly, at the Jackson site, soils in the 0-10 depths under switchgrass held more water than that under indiangrass at Φ between 0 and 100 kPa, and soil under switchgrass also tended to have more PAW than that under indiangrass. The soil under switchgrass also tended to have a higher θ than that under indiangrass at the Western site, but due to small sample size (only two indiangrass plots at the site), differences were not significant. This result was unexpected, as both species are perennial, warm-season grasses. Root biomass and root-shoot ratios of switchgrass are comparable or higher than those of indiangrass, and switchgrass root biomass responds more to N fertilization than does indiangrass [43]. The differences in soil moisture between these grasses could be a result of prior fertilization history, where switchgrass plots received 50 kg N ha⁻¹ in 2008 and 2009, while indiangrass was unfertilized.

At the Northwest site, differences in soil θ were only present at low Φ (less negative) in the 0-10 depths, where soil under corn held less water than those under switchgrass or willow. At the Western site, PAW tended to be the lowest under corn, and was significant at the 30-40 cm depth. The PAW has been used as a factor in productivity indices [44], and a high PAW may help stabilize yields across years and maintain yields even during droughts [45]. In addition, PAW has also been positively correlated with SOC, suggesting that soils with greater moisture storage may also store more C and enhance C sequestration goals [46]. The slightly elevated PAW in soils under perennial grasses and trees may therefore be a result of increased root biomass that is converted into SOC. Overall, the results suggest that soil under corn may have less PAW than perennial species by either having lower θ at low Φ (i.e., at FWC) or having higher θ at PWP. However, changes in hydrological properties due to changes in bulk density and pore size distribution can take decades to occur, as a study comparing croplands with restored grasslands and native grasslands suggests [47].

Aggregate Stability

The contribution of SOM from grasses can increase WSA, MWD, and also improve soil moisture retention at low Φ (less negative) [48]. Larger root mass, root exudates, and the presence of fungal hyphae in soils under grasses and willow also improve the stability of macroaggregates [49]. Differences in WSA were only observed in one location (the Northwest site). However, these results are in accord with other studies in that perennial species had greater numbers of large aggregates than in soils under annual crops [50,51].

Site-specific differences may have occurred because of differences in soil texture: the WSA of soil under corn can be lower than that under a perennial forage species for clayey soils [52], similar to the results of the present study. The conversion of pasture to cropland can gradually decrease aggregate stability, while the reverse may slowly increase it, although it may take decades for lands converted to pasture to attain the WSA and MWD of long-term grasslands [14]. Increased WSA has been associated with increased SOC, contributed from both plant roots and microbial inputs [49, 51]. At the Western site, where the previous land use was cropland, and it is possible that conversion to perennial grasses and trees enhanced aggregate stability and that significant differences may develop in the future. In contrast, the other two sites

were managed under perennial cover (native grasses and sod), so conversion to biofuel crops may have had less of an impact on WSA.

Aggregate Tensile Strength

The TS was the largest under corn, compared to that under grasses or willow at both sites where corn, grasses, and willow were established. The data suggest that TS is lower under switchgrass than in soil under corn. Soil penetration resistance (SPR), another measure of soil mechanical resistance, was measured to 10 cm at the Western site: similarly, soils under corn have greater SPR [19]. These results are in accord with those of Blanco-Canqui et al. [25], where soils under switchgrass and forest had lower TS than those under crops. Lower soil TS under switchgrass is likely due to dense and prolific root systems near the surface. Switchgrass can produce >20 mg roots cm⁻³ in the top 15 cm of soil [53], while NT corn root density is < 3 mg cm⁻³ to the same depth [54]. An increase in SOM may improve aggregate stability and porosity, resulting in less compacted aggregates and lower soil TS.

CONCLUSIONS

While significant differences in soil ρ_b , θ , WSA, and TS occurred only occasionally, where differences in soil properties occurred, it generally agreed with the hypothesis that soils under perennial grasses and willow would have improved soil properties compared to that under corn. It is likely that increased organic inputs in soils under perennial biofuel crops from plant roots and microbial activity may play a large role in explaining differences observed among the perennial species and the annual crop corn. Overall, there were few differences in soil physical properties among the two warm-season grasses, suggesting that both grasses are equally beneficial to soil qualities. Willow and indiangrass co-occurred only at one site (Western), making comparison of soil properties more difficult. Soil physical properties under willow and switchgrass tended to be similar, suggesting that perennial crops may enhance soil quality more than does corn. While changes in soil properties begin in the soil surface, it is possible that additional changes may occur over time in subsoil layers as well.

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