RESEARCH SECTION

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Crop rotation effect on selected physical and chemical properties of Wisconsin soils

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Abstract: In response to climate change, there is a need to adopt more resilient cropping systems for increased productivity. In this study, three corn (*Zea mays* L.)-based rotations—continuous corn (CC), corn–soybean (*Glycine max* [L.] Merr.; CS), and corn–soybean–wheat (*Triticum aestivum* L.; CSW), where all residues were retained on the field after harvest—were selected to study their effects on soil properties at three managed sites in Wisconsin—Arlington, Lancaster, and Marshfield. Soil core samples were collected at four depths (0 to 10, 10 to 20, 20 to 40, and 40 to 60 cm) in 2011. In 2013 and 2015, soil core samples were collected at the two top depths. Soil water retention (WR), plant available water (PAW), bulk density (BD), soil carbon (C), soil nitrogen (N), and C/N ratio were evaluated. Water retention was determined from 0 to 10 and 10 to 20 cm depths at five different matric potentials (Ψ = 0, −5, −10, −33, and −1,500 kPa). There was a significant location × depth interaction across soil properties, which could be associated with differences in management among locations. Averaged across location, CC and CSW rotations had greater water content and PAW across WR tensions than CS rotation at 0 to 10 cm depth, while no differences existed at 10 to 20 cm depth. Crop rotations had similar BD across locations and depths (1.37 to 1.41 g cm^{-3}). A significant three-way location × depth × rotation interaction for C and N amount was affected with generally higher C and N amount in CSW rotation at Lancaster and smaller differences among crop rotations at Arlington and Marshfield. Observed low soil C/N ratio values (<11) indicated potential for soil organic matter to provide some N to the crop. Results from this study indicate that long-term CC systems had similar soil properties to those found in the CS and CSW rotations, and differences among locations were attributed to the differences in management and the environments. However, there is a potential for higher WR under CSW rotation, which might be important under variable climatic conditions.

Key words: chemical properties—crop rotation—physical properties—soil carbon—water retention

Agriculture in the Midwest region of the United States is based on intensive corn (*Zea mays* L.) production. Agricultural practices that can help offset emissions of greenhouse gases, improve soil structure, reduce erosion, and increase soil water holding capacity might increase overall soil resilience to climate variability (IPCC 2007). Conservation practices that have been reported to address some of the above challenges include reduced or no-tillage (Bescansa et al. 2006), crop rotations (Aziz et al. 2011), cover crops (Abdalla et al. 2014), and nutrient management (Coulter et al. 2009).

Crop rotation is a practice of growing different crops on the same land in a particular order over multiple growing seasons (Bullock 1992; Karlen et al. 1994a). Current US agriculture is dominated by two crops—carbohydrate-rich corn and protein-rich soybean (*Glycine max* [L.] Merr.). These two crops complement each other and are usually grown in a two-year corn–soybean (CS) rotation. USDA estimated that 84% of corn and 94% of soybean were grown in some type of a rotational system in 2011. However, current crop prices and profit margins have led to monoculture cropping systems (USDA ERS 2013).

The effects of crop rotation on soil properties are not consistent over studies. There is mixed evidence on short- and long-term impact of crop rotations on soil properties. It is often reported that the effects of crop rotation on soil depends on the individual crop grown in a particular rotation since crops within rotation leave different quantity and quality of plant residues on the field (Sanford et al. 2012; Zuber et al. 2015). Leaving residues on the field has a positive effect on soils. In a 10-year no-tillage corn study, crop residues reduced water and wind erosion, increased earthworm population and available nutrients, and improved soil water retention (WR) (Karlen et al. 1994b). Since corn produces more residue than soybean or wheat (*Triticum aestivum* L.), one could assume that soil organic carbon (SOC) in a continuous corn (CC) scenario will increase more than in corn grown in a rotation. However, in a 15-year study in Illinois, Zuber et al. (2015) reported similar SOC concentrations in CC and corn grown in rotation with other crops and concluded it could be attributed to lower residue production due to a yield penalty after long-term CC production and a greater overall productivity of rotations including corn. In the same study, corn-based rotations lowered bulk density (BD) and SOC compared to continuously grown soybean, which leaves low quantities of residues.

Conservation tillage is an intensively studied management practice for soil improvement (Al-Kaisi and Yin 2005; Ogle et al. 2012; Olson and Al-Kaisi 2015). With technological improvements such as development of herbicide resistant crops, it is easier now than in the past to control weeds, leading to an increase in conservation tillage management. It has been estimated that the use of conservation tillage will increase 40% by 2020 compared to 1995 (Lal 2001). This is a positive trend since conventional tillage is a practice that impacts soil structure and modifies soil pore distribution leading to significant soil, air, and water relationship changes (Hubbard et al. 2013). Practices such as no-tillage, strip tillage, deep rip, or chisel plow have proved to sequester more carbon (C) and emit less carbon dioxide (CO_2) compared to moldboard under CS rotation (Al-Kaisi and Yin 2005). However, some studies reported higher SOC amounts in moldboard plow systems compared to

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no-tillage systems. Higher SOC in the lower depths of moldboard systems can destabilize aggregates and translocate C-rich upper horizon materials to lower levels (Olson and Al-Kaisi 2015). Ogle et al. (2012) in an analysis performed on a national scale estimated that no-tillage has a potential to increase SOC only when the yield penalty of residues production is less than 15%.

Several studies have investigated an interaction of crop rotations and tillage and their influence on many soil properties (Aziz et al. 2015; Havlin et al. 1990; Katsvairo et al. 2002; West and Marland 2002; Zuber et al. 2015). In an analysis of 67 long-term agriculture experiments with 267 paired treatments, West and Post (2002) concluded that the transition from conventional tillage to no-tillage in long-term CS rotation results in high C sequestration rates. These authors estimated that if both practices are applied, then an increase in SOC will have two phases: (1) short term of 15 to 20 years driven by changes in tillage and (2) long term of 40 to 60 years due to rotation enhancement and stabilization in residue amounts. However, the majority of experiments had a maximum sampling depth of less than 20 cm and none of them exceeded 30 cm depth. Baker et al. (2007) in their work provided scientific evidence of no difference between conventional and conservational tillage methods on C sequestration when studies consider deeper sampling depths. Also, different studies found that significant effects of both tillage and rotations on SOC are detectable in shorter periods of time when high residue producing crops were used (Havlin et al. 1990). Havlin et al. (1990) studied nitrogen (N) fertilizer rates in conjunction with tillage and rotations and found that SOC was increased under high N fertilizer rates. Evaluating different soil properties, Katsvairo et al. (2002) found that different corn rotations did not interact with tillage and had no effect either on BD or air-filled porosity during vegetative stages of corn development at the 15 cm soil depth. However, in the same study, the extended soybean–wheat/clover (*Trifolium pretense* L.)–corn rotation had greater earthworm density and greater water infiltration compared to other rotations, which contributed to higher yields.

Water scarcity is a major environmental challenge for agriculture. It is predicted that extreme weather conditions, such as prolonged droughts, are going to be more common in the future (IPCC 2014). In fact, since the beginning of global surface temperature recordkeeping in 1880, 9 out of the 10 warmest years have been recorded in the last 13 years with 2014 being the warmest ever recorded (NOAA 2015). There is a high risk that these events will reduce water availability for plants, thus reducing yields. Water retention is the ability of soil to retain water, which is then available for plant production (Gupta and Larson 1979). It is important to keep SOC at the highest possible level since it often promotes greater WR (Arriaga and Lowery 2003; Bescansa et al. 2006). Therefore, management practices that supply C into the soil are of particular interest. A strong correlation has been reported between SOC and water content at saturation and 20 kPa of suction in the top 7.6 cm of soil (Arriaga and Lowery 2003). Also, there is a strong relationship between WR and soil pore-size allocation. Bescansa et al. (2006) found that under a no-tillage system, small pores (0.2 to 6 μm) occupied around 60% of the total pore volume in the top 15 cm of soil, and the opposite was true under reduced and moldboard tillage where large pores (>9 μm) occupied the majority of the pore space. This difference in pore size distribution is attributed to the higher water holding capacity under no-tillage. Erodible soils tend to have less soil aggregates due to reduced C input from the soil surface, and it might also lead to increase in BD and lower WR (Arriaga and Lowery 2003). The advantage of conservation tillage over traditional tillage to store more water has been well documented under prolonged dry conditions. In Argentina, higher WR in no-tillage was advantageous during critical corn growing stages in summer; moreover, no-tillage corn yields were similar to conventionally tilled treatments with the same N rate, which provided an advantageous management alternative for Argentinian farmers (Fabrizzi et al. 2005).

Application of long-term crop rotations and changing from conventional tillage to conservation tillage without removing crop residues changes soil properties. Often the effect is positive, which in the long-run can improve the resiliency of cropping systems to climate change. Thus, it is necessary to understand how different rotations will affect soil properties. No studies to our knowledge have examined the effects of the same long-term crop rotations on a wide array of soil physical and chemical properties across different environments and management practices. Also, there is little information available on how the addition of winter wheat with fine and dense roots affects soil changes to the common two-year CS rotation. Therefore, our objectives were to compare changes in BD, C, N, C/N ratio, WR, and plant available water (PAW) following simultaneous use for 5 to 10 years of CC, CS, and CSW rotations in three unique sites in Wisconsin. We hypothesized that regardless of the environment, increased rotation complexity will improve these soil properties.

Materials and Methods

Sampling Locations. This study was conducted at the University of Wisconsin's Agricultural Research Station at Arlington (43°18´ N, 89°20´ W), Lancaster (42°50´ N, 90°47´ W), and at Marshfield (44°76´ N, 90°09´ W). At each location, CC, CS, and corn–soybean–wheat (CSW) rotations were selected to study their effects on soil physical properties and soil C and N after 5 to 10 years use when all rotation treatments were present. The experimental design was a randomized complete block with three replications at Arlington and Marshfield and two replications at Lancaster. Only those phases with corn grown during the sampling year were sampled in the CC, CS, and CSW rotations. Soil samples were collected and evaluated twice, in 2011 and 2013, at depths 0 to 10, 10 to 20, 20 to 40, and 40 to 60 cm. All experiments were established prior to sample collection. The study at Arlington was established in 2002 on Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudolls) with slopes ranging from 2% to 6%. The Plano series consists of deep and well drained silty soils formed in loess or similar silty materials on uplands under tall prairie grasses. They are characterized as having moderate permeability with slopes ranging from 0% to 12%. The study at Lancaster was established in 1966 on a Fayette silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs). The CSW rotation treatment was added in 2005. The Fayette series consists of deep, well drained soils formed in loess on convex crests and side slopes on uplands and on treads and risers on high stream terraces. With the slopes ranging from 0% to 60%, the surface runoff potential varies from negligible to high.

The study at Marshfield was established in 2007 on Marshfield silt loam (fine-loamy, mixed, superactive, frigid Mollic Epiaqualfs) with 0% to 2% slope. Marshfield soils form a drainage sequence with Loyal silt loam (fine-loamy, mixed, superactive, frigid Oxyaquic Glossudalfs). These soils are deep and poorly drained with moderate permeability formed in loess or silty alluvium under deciduous water-tolerant trees (Soil Survey Staff 2015). In Wisconsin, the large-scale conversion of prairies into agricultural lands began in the 1840s. For many years, continuous wheat and then forage systems based on corn, wheat, oat (*Avena sativa* L.), and alfalfa (*Medicago sativa* L.) used to support the fast growing dairy industry were dominant (Posner et al. 1995).

Field Management. Applied management practices were different at each location, with tillage practices varying among locations and rotations. All plots at Arlington were under no-tillage. At Lancaster, both CS and CSW rotations were no-tillage, and CC was fall chisel plow, spring disking, and cultimulching. Tillage operations at Marshfield in all rotations included fall chisel plow, spring disking, and field cultivation. Crop hybrids used in this experiment were adapted high-performing hybrids based upon previous research at each location. Corn and soybean were planted in April or May each year. Corn was seeded in 76 cm rows at all locations and soybean in 76, 38, and 19 cm rows at Arlington, Lancaster, and Marshfield, respectively. Winter wheat was drilled in 19 cm rows after soybean harvest in late September to early October. The seeding rates were 82,745 to 86,450 seeds ha^{-1} of corn, 370,500 to 444,600 seeds ha^{-1} of soybean, and 4.2 to 4.9 million seeds ha^{-1} of wheat. Nitrogen application to corn occurred after planting as 28% urea ammonium nitrate (NH_4NO_3) at a rate of 224 kg N ha^{-1} at Arlington, and 34% NH_4NO_3 and the same rate at Lancaster. At Marshfield, 28% urea NH_4NO_3 was applied to corn as a N source at a rate of 134.5 kg N ha^{-1} in CC and 90 kg N ha^{-1} in CS and CSW rotations. Winter wheat was treated with N fertilizer in the form of urea at a rate of 113 kg N ha^{-1} in 2011 to 2012 and 134 kg N ha^{-1} in 2013 to 2014 at Arlington and at a rate of 97 kg N ha^{-1} in 2012 and 73 kg N ha^{-1} in all other years at Marshfield. Winter wheat at Lancaster was fertilized with NH_4NO_3 at a rate of 34 kg N ha^{-1}. No N fertilizer was applied to soybean. Weeds were controlled by following best recommended practices for each environment. If needed, crops were also treated with insecticides following best recommended practices. Soil fertility samples were collected and analyzed annually at Arlington and every three years at Lancaster and Marshfield. Phosphorus (P) and potassium (K) fertilizers were applied as recommended using soil nutrient information from soil tests. Specific crop varieties and other agronomic practices used in this study are reported in Kazula and Lauer (2017, in review).

Soil Sampling and Analysis. In the spring of 2011 and 2013, soil samples were collected from corn plots of CC, CS, and CSW rotations at four depths (0 to 10, 10 to 20, 20 to 40, and 40 to 60 cm) from every plot. Samples were collected in the approximate center of each depth interval from the quarter row position free of wheel tracks. At Arlington, soil samples were also collected in 2015, only from the two top depths (0 to 10 and 10 to 20 cm). However, soil sampling frequency, sampling depths, and sampling methods differed across studied soil properties.

Three soil cores (3.1 cm in diameter and 6 cm long) were collected for WR measurements from each plot. Water retention was measured for 0 to 10 and 10 to 20 cm depths. Immediately after collection, soil cores were sealed and transported to the laboratory and stored at 4°C. Water retention was measured at the following matric potentials: 0, −5, −10, −33, and −1,500 kPa. The first three points characterize the so-called "wet end" of the WR curve up to the field capacity (–33 kPa). The last point (–1,500 kPa), the so-called "dry end," determines the permanent wilting point. Prior to WR analysis, samples were saturated with tap water. A fine nylon screen was installed on the bottom of each core with a rubber band to prevent soil losses. Cores were placed in a tub, which was then filled with tap water to about half of the core height and allowed to equilibrate for at least eight hours. Afterwards, more water was added to the top edge of the cores, but water was not allowed to flow over the soil surface. Samples were allowed to equilibrate again for at least eight hours. Saturated weights were recorded and WR analysis followed. Different methods were applied between years to measure the "wet end" of the WR curve. A hanging water column apparatus designed by McGuire and Lowery (1992) was used on samples collected in 2011, and a water tension apparatus (Dane and Hopmans 2002) was used on samples collected in 2013. Both methods were based on similar assumptions and procedures. After completing "wet end" suction points, the samples were dried at 105°C for least 24 hours, and the last point of the WR curve at –1,500 kPa "dry end" was measured with a WP4 dew point potentiometer (Decagon Devices, Pullman, Washington). This method required a fine-sized material; therefore, dried samples were passed through a 2 mm screen of a mill design to grind soil. The method included placing 3 to 4 g of finely ground soil from each core into four separate cups (2 cm diameter). Deionized water was poured into the cups at 100, 200, 300, and 400 μL increment rates. Prepared samples were covered and allowed to equilibrate for 24 hours and then analyzed. Plant available water (cm) was calculated by subtracting the water content at the "dry end" from the water content at the "wet end" and multiplied by the length of the measured depth.

For BD calculations, undisturbed oven-dried core weights were recorded and divided by the core's volume (Blake and Hartge 1986). In 2011, BD was measured at four depths (0 to 10, 10 to 20, 20 to 40, and 40 to 60 cm) and in 2013 on the two top depths (0 to 10 and 10 to 20 cm). In 2015, BD was measured on the two top depths only at Arlington. Core samples collected in 2011 from 20 to 40 and 40 to 60 cm depths were used for BD determination without WR measurement.

Each year a minimum of 12 push-probe (1.9 cm diameter) samples from all four depths (0 to 10, 10 to 20, 20 to 40, and 40 to 60 cm) were collected and composited into one bag per depth for standard soil fertility analysis including available P, available K, cation exchange capacity (CEC), and pH. The composites were collected from the same plots where the core samples were collected. These soil samples were also used for particle size analysis using the hydrometer method to determine sand, silt, and clay fractions (Gee and Bauder 1986). Particle size analyses were performed on samples collected in 2011.

Carbon and N concentration analyses were performed with the composite samples after drying and grinding. Approximately 8 to 10 mg of soil were packed into 5 × 9 mm tin capsules, and the concentrations were determined with a dry combustion method

Table 1
Significance of analysis of variance for the effects of location, depth, and their interactions on bulk density, soil concentration and amount of carbon (C) and nitrogen (N), and the key chemical analysis at three crop rotation experiments conducted in Wisconsin.

		Soil					Chemical analysis			
Source	Bulk density	N (%)	C (%)	C (kg ha^{-1})	N (kg ha^{-1})	C/N	pH	K	P	CEC
Location (L)	0.612	<0.001	<0.001	<0.001	<0.001	0.004	0.002	0.105	<0.001	<0.001
Rotation (R)	0.842	0.895	0.633	0.756	0.998	0.437	0.178	0.269	0.309	0.577
L × R	0.892	0.157	0.229	0.019	<0.001	0.044	0.559	0.151	0.348	0.903
Depth (D)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
L × D	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
R × D	0.118	0.318	0.602	0.061	0.246	0.983	0.931	0.742	0.684	0.239
L × R × D	0.690	0.598	0.393	0.014	0.018	0.091	0.302	0.516	0.723	0.319

Notes: K = potassium. P = phosphorus. CEC = cation exchange capacity.

using a Flash EA 1112 CN Automatic Elemental Analyzer (Thermo Finnigan, Milan, Italy). Paul et al. (2001) measured negligible amounts of inorganic C in these soils; therefore, it was assumed that inorganic C had no effect on C concentration estimation. These data served to calculate C/N ratio as well as C and N amounts expressed in kilograms per hectare at each depth and accounting for differences in BD.

Data Analysis. Linear mixed effects models were developed using the MIXED procedure of SAS software version 9.3 (2011) to analyze soil chemical (pH, P, K, and CEC) as well as physical (BD, soil C and N concentration and amount data, C/N ratio, WR, and PAW) properties as a function of year (2011 to 2015), location (Arlington, Lancaster, and Marshfield), rotation (CC, CS, and CSW), depth (0 to 10, 10 to 20, 20 to 40, and 40 to 60 cm), and WR (0, –5, 10, –33, and –1,500 kPa). Location, rotation, depth, and tension and their interactions were treated as fixed effects, while year, rep(year × location), and rep × rotation(year × location) were treated as random effects. Least square means were separated using the PDIFF option of LSMEANS. This option uses Fisher's protected F-test at $p \leq 0.05$. The Kolmogorov-Smirnov test was applied to check for normality assumption but no transformations were needed. Differences in management across locations may influence soil properties. However, since crop rotations were the main focus in this study, we allowed for this known source of variability in order to compare the responses of long-term crop rotations on soil properties across typically practiced management practices in Wisconsin.

Results and Discussion

Chemical Analysis. There was a significant effect of location on soil pH, available P, and CEC, but not on K concentration (table 1). The main effect of rotation similarly affected all variables. There were no significant differences among rotations and in any interaction that included rotation. However, the analysis of variance revealed significant effects of depth and location × depth interaction.

Differences in pH were observed in all depths across locations that oscillated near neutral (pH ranged from 6.7 to 7.2), except in the moderately acidic conditions of the 40 to 60 cm depth in Marshfield (pH = 5.7) (table 2). Potassium concentrations were highest at the 0 to 10 cm depth (127 to 169 ppm) and decreased with the depth ranging from 60 to 101 ppm across locations and other depths. Phosphorus concentrations varied across locations and ranged from 8.3 to 19.6, 10.3 to 24.5, and 16.2 to 51.6 ppm at Arlington, Lancaster, and Marshfield, respectively. Cation exchange capacity increased with the depth at Arlington and Lancaster and decreased at Marshfield.

Soil Carbon and Nitrogen. There were significant effects of location, depth, and their interaction on soil C and N expressed either in concentration (percentage) or amount (kilogram per hectare) units as well as C/N ratio calculated from measured concentration data (table 1). In addition, significant location × rotation and location × rotation × depth interactions were observed in C and N expressed in amount units. Separation of the means that highlights the above F-test results is presented in table 3, and the significant three-way interaction is presented in table 4.

Soil C and N concentrations decreased with depth and when averaged across depths were the lowest at Lancaster (table 3). The significant location × depth interaction was influenced with no difference in C and N concentration at the two lowest depths at Lancaster. Soil C and N expressed in amount at each depth had different patterns across locations. Soil at Arlington contained significantly more C (2,224 kg ha^{-1}) than that of either Marshfield (1,989 kg ha^{-1}) or Lancaster (1,346 kg ha^{-1}). However, the averaged N amounts were similar at Arlington (236 kg ha^{-1}) and Marshfield (229 kg ha^{-1}) and lower at Lancaster (170 kg ha^{-1}). At Lancaster, the CSW rotation had more C than either CC or CS rotation at three top depths (0 to 10, 10 to 20, and 20 to 30 cm), and all rotations had similar C at 40 to 60 cm depth. The Fayette soil series at Lancaster is located on slope surfaces and is prone to surface runoff (Soil Survey Staff 2015), and this may partially explain much lower C concentrations.

Crop rotation did not affect BD, N, and C when averaged across locations, but some differences were found for C and N amount units among crop rotations within a location (table 3). Arlington CC plots had higher C amounts at 20 to 40 cm depth than the Arlington CSW rotation. Soils at Arlington had the highest C amounts at 40 to 60 cm depth across locations. Marshfield had C amounts similar to Arlington at the three top depths, with the exception of the 20 to 40 cm depth in CC, which was much lower. At Lancaster, CSW rotation generally had higher C amounts at all three top depths; however, all Lancaster rotations had similar C amounts at 40 to 60 cm and were similar to 40 to 60 cm at Marshfield. Sanford at al. (2012), during a 20 year period of study, compared various cropping systems and reported that the greatest C losses were under intense CC (–2 Mg ha^{-1} y^{-1}) in 0 to 90 cm depth, and this was more than half of C losses from CS or CSW rotations. The only C increase in the same study was found under a rotational pasture system (6.5 Mg ha^{-1} y^{-1}) up to 15 cm depth. The authors concluded that this was mainly attributed to the differences of

Table 2
Interaction effect of location and depth on soil pH, available potassium (K), available phosphorus (P), and cation exchange capacity (CEC) at four different soil depths at Arlington, Lancaster, and Marshfield, Wisconsin (2011 to 2015).

	Chemical analysis			
Effect	**pH**	**K (ppm)**	**P (ppm)**	**CEC (cmol kg^{-1})**
Location by depth (cm)				
Arlington				
0 to 10	7.0	140.6	19.6	12.1
10 to 20	7.1	87.8	14.6	12.8
20 to 40	7.0	65.9	8.3	13.6
40 to 60	7.0	72.1	15.4	15.0
Lancaster				
0 to 10	6.7	126.7	24.5	8.5
10 to 20	7.0	67.4	10.3	9.1
20 to 40	7.2	60.9	12.1	13.0
40 to 60	6.9	66.6	23.8	15.3
Marshfield				
0 to 10	7.1	169.2	51.6	11.3
10 to 20	7.0	101.1	45.1	10.5
20 to 40	6.7	59.6	20.0	8.3
40 to 60	5.7	64.4	16.2	9.8
LSD (0.05)	0.3	19.1	6.7	1.4
Location means				
Arlington	7.0	91.6	14.5	13.4
Lancaster	6.9	80.4	17.6	11.5
Marshfield	6.6	98.6	33.2	10.0
LSD (0.05)	0.2	NS*	6.4	1.4

Note: LSD = least significance difference.
*NS = not significant.

the estimated belowground biomass inputs since the majority of fine perennial grass root biomass is located close to the surface. Much lower variation in C was recorded in our study among crop rotations. In this experiment, at Arlington all rotations were under no-tillage management, whereas CC in the Sanford et al. (2012) study was chisel plowed, which greatly offsets the C contribution from corn aboveground residues. This may also be reflected in our results, where the chisel-plowed CC at Lancaster had lower mean soil C in the upper layers than the other rotations. However, the difference between the rotations was not significant.

The pattern of soil N amount was more equally distributed through the soil profile across locations than that of C. At Arlington, across rotations, soils had similar N amounts at the two top depths; however, rotations showed some difference at the deeper soil horizon. At the 20 to 40 cm depth, CC had much higher N amounts, and the CSW rotation had much lower N amounts compared to CS (table 4). At Lancaster, across depths, rotations had similar N amounts except the CSW rotation at 20 to 40 cm depth, which was significantly higher compared to the other rotations at this depth. At Marshfield, CC at 20 to 40 cm depth had lower N than that of other crop rotations.

Differences in soil C contributed to observed differences in BD, WR, or PAW (figures 1 through 4). Also, it has been observed that clay particles interact more with soil organic matter than larger soil particles (Arriaga and Lowery 2003). Comparatively, soils at Arlington had more clay particles up to 20 cm depth and Marshfield had more sand particles at all depths (table 5). Differences in texture could, in addition to higher surface runoff potential, explain lower C amounts at Lancaster, but they were poor in explaining high C level in Marshfield. Soils at Marshfield were subjected to intense chisel plow management and contained as much C at the two top depths as the full depth of no-tilled soils at Arlington. This may be related to the land history of the two sites where the transition of native prairies into highly cultivated grain crops at Arlington has contributed to significant losses of C, and may yet to have reached soil C equilibrium (Posner et al. 1995; Sanford et al. 2012). Moreover, part of the reason why Marshfield, the northernmost location, had more C can be attributed to lower drainage capacity and slightly cooler temperatures in Marshfield, relative to Lancaster and Arlington.

Carbon to N ratio decreased with depth at Lancaster and Marshfield and was relatively stable in the three top depths at Arlington. This difference across locations contributed to a significant location × depth interaction (table 3). Carbon to N ratio varied slightly across rotations, but there was no significant main effect of rotation on soil C/N ratios. In general, low soil C/N ratio values across locations indicated a potential for the soil organic matter in these systems to provide some N to the crop.

Bulk Density. Crop rotations showed a similar BD across locations and depths. However, depths were found to have different BD across locations due to the significant location × depth interaction (table 1 and figure 1). At Arlington, no differences were found across depths for BD, which ranged from 1.35 to 1.40 g cm^{-3}, where surprisingly BD values at the top and the deepest depths were almost identical. At two other locations, BD was the lowest and not different at the first depth and ranged from 1.23 to 1.27 g cm^{-3}. At the 10 to 20 cm depth BD increased more at Lancaster (1.39 g cm^{-3}) compared to Marshfield (1.30 g cm^{-3}) and then continued to increase at the 40 to 60 cm depth.

Organic matter promotes aggregation, which often leads to BD reduction (Arriaga and Lowery 2003; Jordahl and Karlen 1993). Therefore, practices that supply C into the soil are of particular interest. Arriaga and Lowery (2003) reported that continuously repeated manure application significantly decreased BD from eroded soil up to 23 cm soil depth, and these BD changes were negatively correlated with total soil C increases. There are a couple of factors that may explain the lack of differences in BD among crop rotations within locations (table 1). First, even though corn out-competes soybean and wheat in residue abundance after harvest, the long-term CC practice reduces the residue inputs compared to rotated corn due to total yield decline, which might offset to a certain extent the differences (Zuber et al. 2015). There is a large body of literature that confirms yield depression under continuously grown crops compared to rotated crops (Crookston et al. 1991; Pedersen

Table 3
Bulk density, soil carbon (C), and nitrogen (N) expressed in concentration and amount units, and C/N ratio calculated from soil concentration data at Arlington (ARL), Lancaster (LAN), and Marshfield (MAR), Wisconsin (2011 to 2015).

Location	Rotation	Depth (cm)	Bulk density (g cm^{-3})*	C (%)	N (%)	C/N	C (kg ha^{-1})	N (kg ha^{-1})
ARL			1.37	1.28	0.13	9.41	2,224	236
LAN			1.39	0.84	0.10	8.12	1,346	170
MAR			1.39	1.24	0.14	8.12	1,989	229
LSD (0.05)			NS	0.12	0.01	0.81	224	24
	CC		1.39	1.11	0.12	8.56	1,844	211
	CS		1.38	1.10	0.12	8.37	1,825	212
	CSW		1.38	1.15	0.12	8.73	1,890	212
	LSD (0.05)		NS	NS	NS	NS	NS	NS
		0 to 10	1.28	1.83	0.18	10.00	2,343	234
		10 to 20	1.36	1.51	0.16	9.38	2,036	216
		20 to 40	1.45	0.70	0.09	7.98	1,923	232
		40 to 60	1.45	0.43	0.06	6.85	1,110	163
		LSD (0.05)	0.02	0.06	0.01	0.42	115	15
ARL	CC		1.37	1.33	0.14	9.00	2,412	265
	CS		1.38	1.21	0.13	9.23	2,177	235
	CSW		1.37	1.29	0.13	10.01	2,083	207
LAN	CC		1.40	0.81	0.09	8.33	1,319	162
	CS		1.39	0.76	0.09	7.52	1,202	162
	CSW		1.39	0.94	0.11	8.52	1,517	184
MAR	CC		1.41	1.18	0.13	8.34	1,800	206
	CS		1.38	1.32	0.14	8.35	2,097	238
	CSW		1.39	1.21	0.14	7.66	2,070	244
	LSD (0.05)		NS	NS	NS	1.07	323	32
ARL		0 to 10	1.35	1.84	0.18	10.32	2,473	241
		10 to 20	1.39	1.63	0.16	10.18	2,262	225
		20 to 40	1.40	1.01	0.11	9.35	2,561	277
		40 to 60	1.36	0.64	0.08	7.81	1,601	200
LAN		0 to 10	1.27	1.52	0.16	9.76	1,947	199
		10 to 20	1.39	1.02	0.12	8.48	1,413	167
		20 to 40	1.46	0.44	0.06	7.06	1,153	174
		40 to 60	1.45	0.37	0.05	7.19	871	139
MAR		0 to 10	1.23	2.13	0.21	9.92	2,610	263
		10 to 20	1.30	1.88	0.20	9.48	2,433	257
		20 to 40	1.50	0.66	0.09	7.52	2,054	247
		40 to 60	1.54	0.28	0.05	5.55	859	150
		LSD (0.05)	0.05	0.14	0.01	0.91	247	30

Notes: CC = continuous corn. CS = corn–soybean. CSW = corn–soybean–wheat. NS = not significant. LSD = least significance difference.

* The first two depths were measured in 2011 and 2013 at all stations, where Arlington had additional measurement taken in 2015. Depths 20 to 40 cm and 20 to 60 cm measured only in 2011, since it is not expected to change over short periods of time.

and Lauer 2002; Pedersen and Lauer 2003; Stanger and Lauer 2008). Also, West and Post (2002) in a large meta-analysis comparison concluded that it could take over 40 years to stabilize and detect differences in SOC under different crop residues. These crop rotation experiments were 5 to 10 years old when the first soil samples were collected in 2011, and all rotations were present within each location, which may suggest that more time would have to elapse to detect any differences since C buildup is a slow process. Significant differences that occurred among depths across locations could be attributed to differences in soils as well as management. Soils at Arlington and Marshfield had similar C amounts at 0 to 10 and 10 to 20 cm depths (table 3). However, the tillage operations at Marshfield may additionally explain lower BD at the two top depths because the two lowest depths had the highest BD among all locations, possibly due to relatively lower C amounts and soil series type, which is described as poorly drained. No-tillage and C rich soils at Arlington resulted in consistent BD across all depths.

Water Retention, Water Content, and Plant Available Water. There was no difference in averaged water content across locations and crop rotations and their inter-

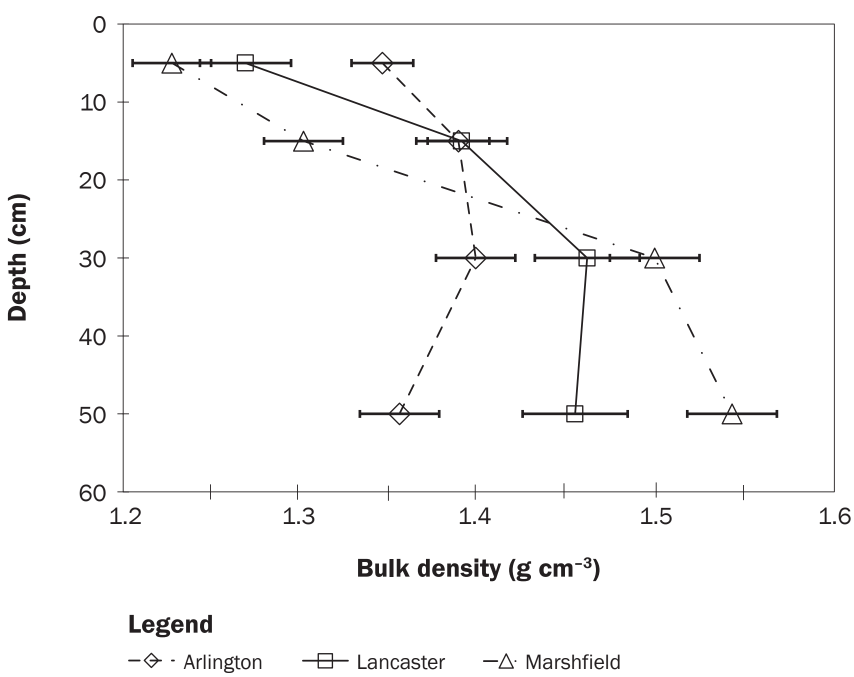
Table 4
Soil carbon (C) and nitrogen (N) amounts by rotation and depth within rotation at Arlington (ARL), Lancaster (LAN), and Marshfield (MAR), Wisconsin (2011 to 2015).

	Carbon (kg ha^{-1})*			Nitrogen (kg ha^{-1})*		
Effect, depth (cm)	**ARL**	**LAN**	**MAR**	**ARL**	**LAN**	**MAR**
Rotation × depth (cm)						
CC						
0 to 10	2,582	1,790	2,564	250	183	261
10 to 20	2,395	1,470	2,327	252	165	253
20 to 40	2,824	1,074	1,405	322	157	177
40 to 60	1,848	943	904	235	144	135
CS						
0 to 10	2,431	1,926	2,631	243	199	269
10 to 20	2,156	1,141	2,514	214	150	256
20 to 40	2,593	923	2,396	277	152	278
40 to 60	1,528	816	848	205	148	147
CSW						
0 to 10	2,407	2,123	2,636	229	214	260
10 to 20	2,234	1,628	2,458	209	185	261
20 to 40	2,264	1,462	2,363	230	212	285
40 to 60	1,426	854	823	161	126	167
LSD (0.05)		420			48	

Notes: CC = continuous corn. CS = corn–soybean. CSW = corn–soybean–wheat.

*Collected in 2011 and 2013 at all locations. At Arlington, the two top depths where additionally sampled in 2015.

Figure 1
Bulk density at four soil depths (0 to 10, 10 to 20, 20 to 40, and 40 to 60 cm) presented in the middle of each depth range at Arlington, Lancaster, and Marshfield, Wisconsin. Data represent average across years and crop rotation within locations. The first two depths were measured in 2011 and 2013 at all stations, where Arlington had additional measurement taken in 2015. Depths 20 to 40 and 20 to 60 cm had bulk density measured only in 2011.



action; however, besides significant effects of depth and tension, significant rotation × depth, location × tension, depth × tension, and three-way location × depth × tension interactions were observed (table 6).

Water retention curves of each rotation at each location are presented for depth 0 to 10 cm in figure 2 and for 10 to 20 cm depth in figure 3. Crop rotations influenced WR in a similar manner at each location regardless of management methods. The two-year CS rotation had noticeably lower water contents at the field capacity tension point (–33 kPa) at each location in the first depth (0 to 10 cm), while at the second depth all rotations had similar lower water content. Extending the CS rotation with winter wheat that has a dense and fine root system might explain this tendency of improved WR at the first depth. These differences were too small to be captured statistically, however, they were large enough to influence the differences in PAW calculated as a difference of the field capacity (–33 kPa) and permanent wilting point (–1,500 kPa) (table 6). Averaged across locations at the 0 to 10 cm depth, CC and CSW rotations had greater PAW than the CS rotation, where at the 10 to 20 cm depth all rotations equalized PAW (figure 4).

Water retention decreased with depth, but the differences were marginal (table 7). Water retention at the 0 to 10 cm (0 to 3.9 in) depth was only different from the 10 to 20 cm depth at the first tension point, which represented the saturation water content (0 kPa), except at Arlington where it was also higher at –5 kPa tension point. Also soils at Marshfield had the highest WR at the 0 kPa at both depths and Arlington generally had the highest WR at the –1,500 kPa tension point, representing permanent wilting point.

The decrease of WR across tensions and PAW with depth can be mainly attributed to higher C content at the top depth since it promotes soil aggregate formation (Arriaga and Lowery 2003; Bescansa et al. 2006). However, the differences in C content among rotations were relatively small and inconsistent across rotations and depths to explain why WR and PAW were the lowest in CS rotation regardless of tillage management method across location. Therefore, there must be other significant factors contributing to those differences. One potential explanation may lay in the differences of root systems between crops. Corn and wheat have denser root systems than soybean, promot-

Figure 2
Water retention curves at 0 to 10 cm depth of continuous corn, corn–soybean, and corn–soybean–wheat rotation at (a and d) Arlington, (b and e) Lancaster, and (c and f) Marshfield, Wisconsin, where (a) through (c) show the "wet end" of the curve up to the field capacity (–33 kPa), and (d) through (f) show the complete curve up to the permanent wilting point (–1,500 kPa) presented on log scale.

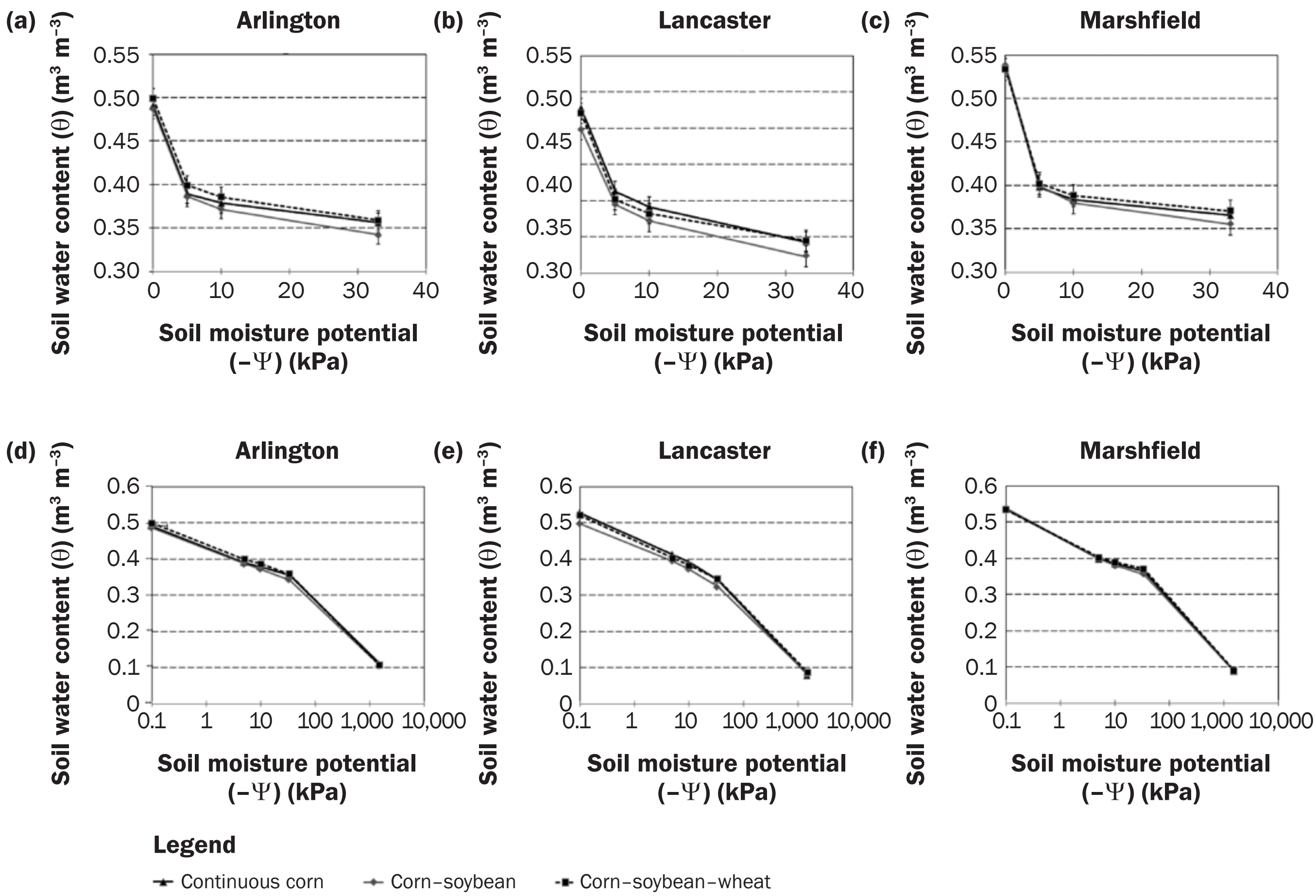


Table 5
Soil texture at different depths at Arlington, Lancaster, and Marshfield, Wisconsin (2011). Standard error provided in parentheses.

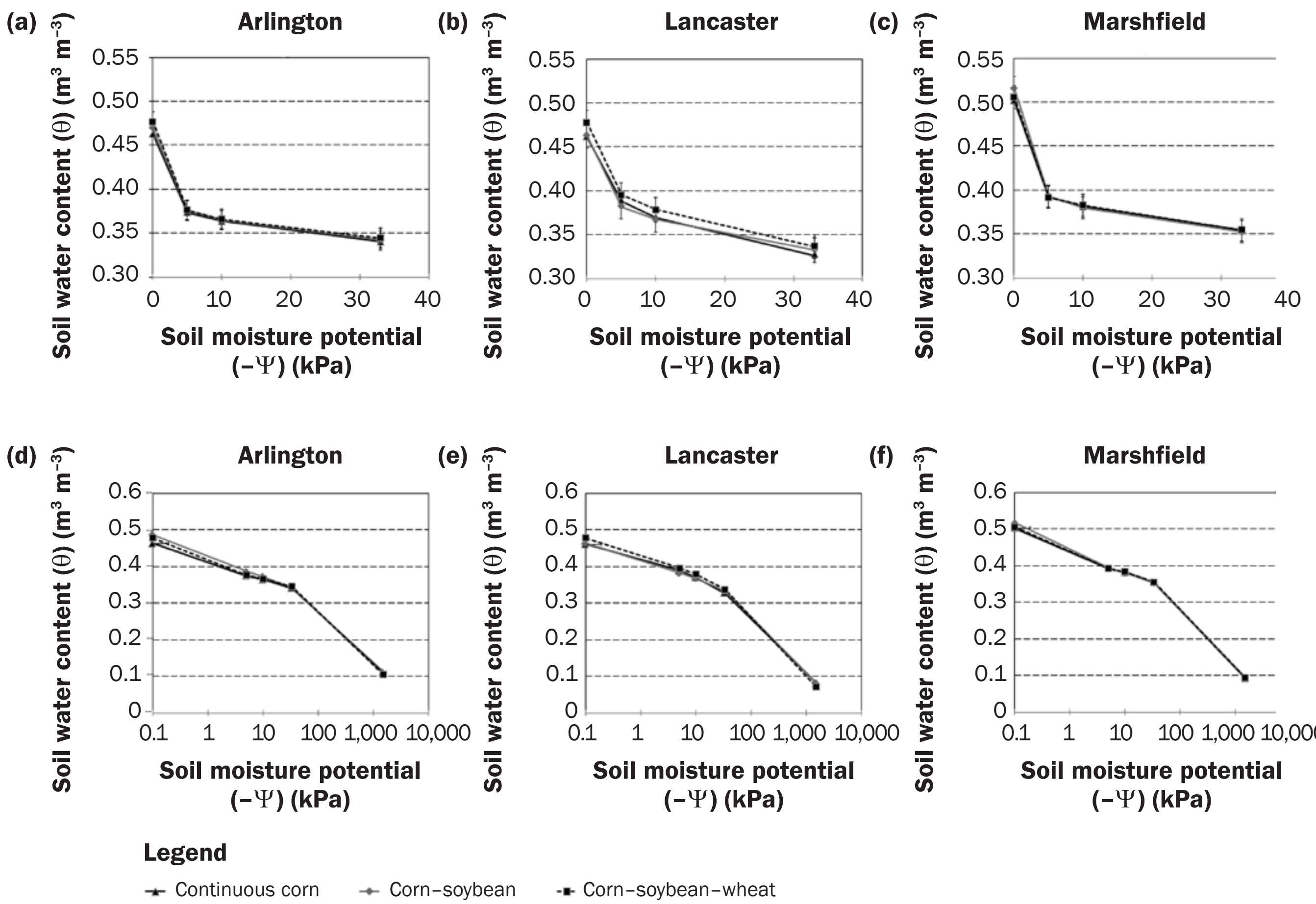
Location	Depth (cm)	Sand (%)	Silt (%)	Clay (%)
Arlington	0 to 10	7.9 (±0.4)	70.4 (±0.6)	21.7 (±0.5)
	10 to 20	7.2 (±0.6)	69.4 (±0.7)	23.3 (±1.0)
	20 to 40	4.1 (±0.4)	66.6 (±1.1)	29.3 (±1.2)
	40 to 60	3.9 (±0.5)	64.0 (±0.9)	32.1 (±1.2)
Lancaster	0 to 10	9.2 (±0.7)	79.0 (±0.5)	11.8 (±0.7)
	10 to 20	7.3 (±0.7)	76.7 (±1.5)	16.0 (±1.3)
	20 to 40	5.5 (±0.3)	67.3 (±0.8)	27.2 (±0.9)
	40 to 60	4.2 (±0.3)	64.2 (±0.3)	31.7 (±0.4)
Marshfield	0 to 10	16.1 (±0.8)	69.1 (±0.5)	14.8 (±0.5)
	10 to 20	16.2 (±1.0)	69.4 (±0.7)	14.3 (±0.7)
	20 to 40	16.2 (±1.3)	66.6 (±0.9)	17.2 (±0.8)
	40 to 60	20.1 (±1.6)	54.2 (±3.0)	25.7 (±2.1)

ing sites for aggregate formation capable of retaining more water. Blanco-Canqui et al. (2010) reported reduced BD, increased water infiltration, and higher SOC at all studied depths. Their study indicated that the presence of winter wheat in a system may improve WR at certain tensions.

Summary and Conclusions

The negative effects of climate change, such as more frequent and persistent droughts, flooding, or extreme rainfall events, highlight a systematical need to address agricultural vulnerability to those events and search for better adaptation strategies. In this study, practiced at the same time for 5 to 10 years prior to first soil collection, CC and CSW rotation showed a slight trend of increasing soil WR and PAW only at 0 to 10 cm compared to a CS rotation. Therefore, add-

Figure 3
Water retention curves at 10 to 20 cm depth of continuous corn, corn–soybean, and corn–soybean–wheat rotation at (a and d) Arlington, (b and e) Lancaster, and (c and f) Marshfield, Wisconsin, where (a) through (c) show the "wet end" of the curve up to the field capacity (–33 kPa), and (d) through (f) show the complete curve up to the permanent wilting point (–1,500 kPa) presented on log scale.



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ing wheat to the two-year CS rotation has a potential to retain more water. Generally, differences in the soil properties measured were small among crop rotations, but were high among locations due to differences in management and the environments. For example, soil under no-tillage at Arlington had the most stable C amounts and BD, while soils prone to erosion at Lancaster had lowest C amounts. However, at Lancaster, CSW rotation resulted in a slight trend of retaining more C. There is a potential that with extending growing season length, growing conditions are becoming more suitable for implementing cover crops, which could provide additional benefits to the soils. Here, the application of either long-term, two-year CS or three-year CSW rotation affects in similar ways most soil properties compared to higher residue production in CC across a range of management practices in Wisconsin.

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Figure 4
Comparison of plant available water (PAW) among (a) continuous corn (CC), (b) corn–soybean (CS), and (c) corn–soybean–wheat (CSW) measured at two soil depths. Data are averages across three locations and years (2011 to 2015). The different lowercase letters indicate significant differences ($p < 0.05$, LSD) among crop rotations and depth.

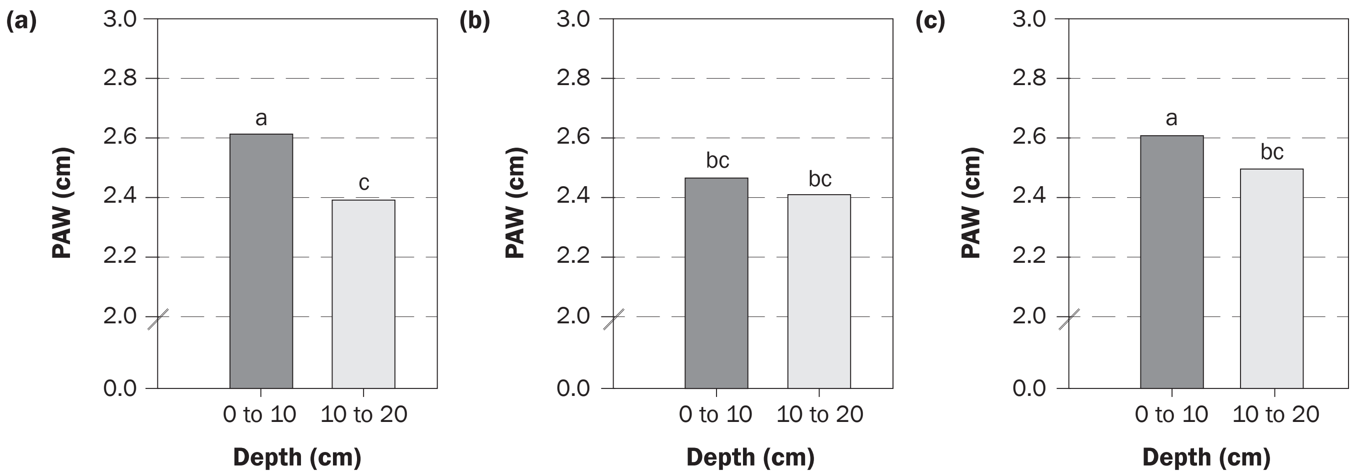

Table 6
Significance of analysis of variance for the effects of location, rotation, depth, tension, and their interactions on water retention and plant available water at three crop rotation experiments conducted in Wisconsin.

Source	Water retention	Plant available water
Location (L)	0.235	0.334
Rotation (R)	0.191	0.030
L × R	0.839	0.852
Depth (D)	<0.001	<0.001
L × D	0.084	0.749
R × D	0.003	0.038
L × R × D	0.525	0.463
Tension (T)	<0.001	—
L × T	<0.001	—
R × T	0.498	—
D × T	<0.001	—
L × R × T	0.824	—
L × D × T	0.040	—
R × D × T	0.614	—
L × R × D × T	0.993	—

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Table 7

Interaction effects of rotation × depth and location × depth × tension at Arlington, Lancaster, and Marshfield, Wisconsin (2011 to 2015).

	Water content ($m^3\ m^{-3}$)	
Effect	**0 to 10 cm**	**10 to 20 cm**
Rotation × depth		
CC	0.350	0.333
CS	0.341	0.335
CSW	0.351	0.337
LSD (0.05)	0.007	
Location × depth × tension (kPa)		
Arlington		
0	0.492	0.470
−5	0.392	0.375
−10	0.379	0.365
−33	0.352	0.342
−1,500	0.107	0.108
Lancaster		
0	0.515	0.467
−5	0.403	0.389
−10	0.382	0.372
−33	0.337	0.332
−1,500	0.082	0.078
Marshfield		
0	0.536	0.508
−5	0.400	0.392
−10	0.384	0.381
−33	0.364	0.354
−1,500	0.088	0.093
LSD (0.05)	0.016	

Note: LSD = least significance difference.