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Research Letter

Spatial Response of Near-Surface Soil Water Contents to Newly Imposed Soil Management

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Core Ideas

- Reports on soil water content semivariograms among soil management practices are rare.
- Semivariogram ranges shifted after only 2 yr of newly imposed soil practices.
- Findings have implications for scaling remotely sensed soil water in agriculturally mosaic areas.

Abstract: Near-surface soil water content (SWC) and its spatial patterns are important for landscape hydrological responses to precipitation as well as our ability to remotely sense and model such responses. Our objective was to measure and evaluate near-surface SWC semivariograms of agricultural fields with newly imposed (i.e., <2 yr) side-by-side soil and residue management practices (i.e., reduced tillage systems and cover crops) in the midwestern United States. Range parameters were consistently smaller when cover crops were planted (20–25 m less) and tillage area and/or intensity was reduced (12–27 m less) compared with no cover crop and chisel plowing, respectively, except in a clayey Vertisol. Nugget and sill parameters did not have consistent trends across soil management practices or sites. These data, although brief and preliminary in scope, provide clear proof of concept that spatial pattern shifts can be clearly detected in newly imposed soil-management systems even though differences in SWC means are not always evident.

A landscape's capacity to infiltrate and store rainwaters as opposed to inducing overland flows and erosion is directly affected by antecedent near-surface soil water content (SWC). The literature on soil management effects on mean SWC, as well as on long-term ecosystem's spatial patterns of SWC (e.g., grassland, forest), is vast. Some seminal studies on SWC spatial patterns include the works by Western et al. (1998) and Western and Blöschl (1999) on grazed pastures in Australia. However, knowledge gaps still exist. For instance, literature on soil and residue management practice effects on SWC spatial variability is exceedingly rare (Hébrard et al., 2006). Moreover, literature on newly imposed management practices is nearly nonexistent.

A search of the scientific literature using Clarivate Analytic's Web of Science Core Collection on 29 May 2018 (Basic Search; Topics [i.e., title, abstract, and keywords]: "soil water content"*variogram or "soil water content"*semivariogram or "soil moisture"*variogram or "soil moisture"*semivariogram] resulted in 171 publications from 1992 to 2018. Of those papers, 107 reported SWC semivariograms, 19 compared SWC semivariograms within or among long-term land uses or ecosystem types (e.g., agricultural vs. grassland, forest vs. pasture), and only 2 compared SWC semivariograms among soil or residue management practices in crop production fields (Table 1). These two publications are Panosso et al. (2009) and Ribeiro et al. (2016), who evaluated long-term sugarcane (*Saccharum* L.) residue management and long-term tillage/cover-crop management of soybean [*Glycine max* (L.) Merr.], respectively, in Brazil.

To our knowledge, no study exists that directly evaluates near-surface SWC spatial patterns of newly imposed (i.e., within 1 or 2 yr) soil or residue management practices. However, some inferences and testable hypotheses can be formulated from the literature. For instance, flat landscapes with a mosaic of uses tend to lack SWC spatial patterns (i.e., pure nugget semivariogram) at scales greater than individual fields (Mohanty et al., 2000; Hébrard et al., 2006). Additionally, grasslands are reported to have lower SWC spatial dependence [i.e.,

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Abbreviations: SWC, soil water content.

Table 1. Publication year, study site country, and land uses reported in publications from the Web of Science Core Collection search on soil water content semivariograms.

Year	*n*	Country	*n*	Land Use	*n*
2018	2	Argentina	1	Agriculture	18
2017	4	Australia	6	Bare soil	6
2016	4	Austria	3	Barley	1
2015	8	Belgium	1	Bean	1
2014	5	Brazil	17	Bush	1
2013	9	Canada	6	Carrot	1
2012	7	China	18	Clover	1
2011	4	Cuba	1	Coffee	2
2010	6	England	4	Cotton	2
2009	6	France	1	Desert	2
2008	7	Germany	6	Fallow	5
2007	6	Hungary	2	Forest	50
2006	5	India	1	Fruit	1
2004	5	Indonesia	2	Golf Course	1
2003	5	Iran	1	Grassland	20
2002	4	Italy	1	Lettuce	1
2001	2	Japan	1	Maize	7
1999	7	Malaysia	1	Meadow	2
1998	4	Mexico	1	Millet	6
1997	1	Mongolia	1	Not reported	4
1996	3	Netherlands	2	Orchard	15
1994	1	New Zealand	2	Pasture	1
1993	1	Niger	1	Pea	1
1992	1	Nigeria	1	Potato	1
		Poland	1	Rice	1
		Russia	1	Savannah	2
		South Korea	1	Shrub	7
		Spain	1	Sorghum	1
		Sweden	2	Soybean	5
		Taiwan	1	Steppe	3
		Thailand	2	Sugarcane	3
		Tibet	2	Swamp	2
		United States	18	Tea	1
				Urban	1
				Vegetable	1
				Vineyard	2
				Wetland	4
				Wheat	6

equal to nugget/(nugget+sill); semivariogram parameters] and shorter distance of spatial autocorrelation when compared to neighboring crop fields (Jiongfeng and Wanchang, 2008; da Cunha et al., 2018). This may imply that plant root architectures and/or higher plant densities create smaller-scale, spatially variable mosaics in soil hydraulic properties/states. We can hypothesize that management practices that increase plant densities (e.g., fields with or without cover crops) create higher variability in soil pore networks, and thus higher variability in SWC at smaller scales. Similarly, we can hypothesize that mechanical mixing (i.e., tillage area and/or intensity) will have the opposite effect on SWC spatial variability due to the mechanical homogenization of soil pore networks near the soil surface. Our objective was to test these hypotheses and fill this knowledge gap using agricultural fields in the midwestern United States.

Procedures

Volumetric SWC were measured in 16 regular-interval linear transects at cropping system research sites in North Dakota and Iowa (Fig. 1). Decagon GS3 and Theta Probe model ML2 sensors (0–6 cm sensing depth) were used in North Dakota and Iowa, respectively. Soil-specific calibrations were applied to the measurements based on manufactures recommendations.

Each soil management system was in the second growing season of implementation when SWC values were measured. Measurements were obtained during the early summer months when the crops were in their rapid growth stages (i.e., SWC is mostly governed by soil evaporation and crop transpiration rates following 2–3 d after substantial rainfalls). Measurements were obtained at the mid-row position between plant rows, with transects running parallel to the plant row. Transect areas were relatively flat (slope < 1% with minimal microtopography) with no known subsurface characteristics (physical or chemical) to independently produce a priori spatially structured zones of high or low water drainage or plant growth from the soil management practice. Therefore, trends among near-surface SWC and their spatial variability structures are assumed to be due to the newly imposed soil management practices.

Cropping systems and their soil management included the following (Table 2):

1. Corn (*Zea mays* L.) phase of corn–soybean rotations with chisel plow, strip-till with shanks, strip-till with coulters, vertical-till, and no-till management near Barney, ND. Tillage system definitions can be found in DeJong-Hughes and Daigh (2017). Research plots (12.2-m-wide strips that extended the full length of a quarter section [480–560 m length]) were part of an on-farm experiment using full-sized equipment (Fig. 1A). Transect measurements were made on 9 July 2015, 12 d after a 2.0-cm rainfall. See Alghamdi (2017) for more site details.
2. Soybean phase of no-till soybean–barley (*Hordeum vulgare* L.) rotations with and without a winter cereal rye (*Secale cereale* L.) cover crop near Wahpeton, ND. Plots were part of an extension on-farm demonstration site using full-sized equipment. The farmer no-till drilled soybeans directly into strips of living rye cover crop that had been planted the previous fall after barley harvest. The rye was later terminated via glyphosate after soybean had emerged. Transect measurements were made on 9 July 2015, 8 d after a 0.5-cm rainfall.
3. Biofuel-based (grain + 50% stover harvest), no-till continuous corn (CC) with and without a winter cereal rye cover crop near Madrid, IA. Research plots were 27 m wide by 61 m long (Fig. 1A). The rye was no-till drilled the previous fall and terminated in the spring via glyphosate within 1 wk before the planting of corn. Transect measurements were made on 5 June, 2010, 4 d after a 2-cm rainfall. See Daigh et al. (2014a, 2014b) for more site details.

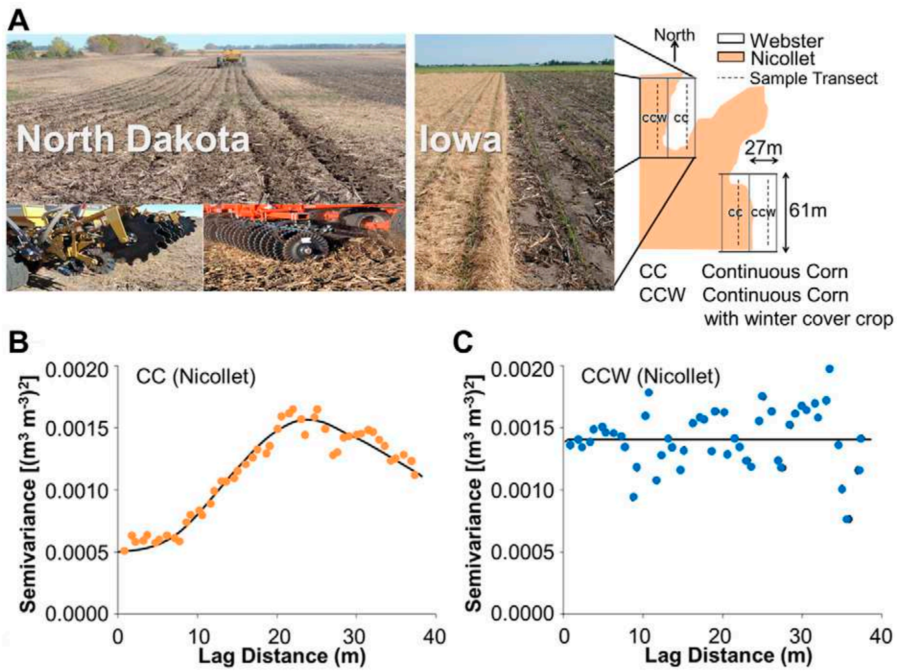

Fig. 1. Example photographs of soil management practices in North Dakota and Iowa. (A, left panel) Photograph of tillage research plots (plots left to right in photo: vertical till, no till, coulter strip till, and chisel plow) in North Dakota; bottom images are of the coulter strip till (left) and vertical tillage (right) implements. (A, middle panel) Photograph of 50% stover-harvested continuous corn with and without rye cover crops (CCW and CC, respectively) at plant emergence in Iowa. (A, right panel) Experimental plot layout over a soil series map with Webster and Nicollet soil series. Empirical semivariogram of (B) CC fitted with a sine hole function and of (C) CCW fitted with a pure nugget function from the Nicollet soil series.

Data groups within soil series and by management practices were confirmed to have similar variances and were stationary. Semivariogram models were then inversely parameterized using Proc Variogram in SAS 9.4 with model selection based on convergence and Akaike information criterion (SAS Institute, 2018a). Models included cubic, exponential, Gaussian, Matern, pentaspherical, power, sine hole, and spherical, which were also allowed to form nested functions (SAS Institute, 2018b). If no spatial structures were apparent, then a pure nugget function was evaluated using Vesper 1.6 (Minasny et al., 2006) against the other models for best fit. Model selections are reported in Table 2. See Grayson and Blöschl (2000) and Nielsen and Wendroth (2003) for use of geostatistics in hydrology and soil science.

Results and Implications

Range parameters (i.e., distance of spatial dependence) showed a decreasing trend when tillage area (i.e., strip till) or intensity (i.e., vertical till and no till) was reduced from chisel plowing in North Dakota (Table 2). Range parameters also went to <1 m when cover crops were included in cropping systems in Iowa (Table 2; Fig. 1B,C). These trends were consistent across soil series. However, an Epiaquert in North Dakota (Fargo series [fine, smectitic, frigid Typic Epiaquert]; 60% clay, 40% silt content) did not show the same trend when cover crops were added

Table 2. Volumetric soil water contents and semivariogram parameters of 16 regular-interval transects at research sites in North Dakota and Iowa.

Crop–soil management†	Soil series (texture‡)	Mean	SD	Model§	Nugget	Sill	Range	Spatial range shift with management¶
Soil tillage		m^3 m^{-3}	m^3 m^{-3}		σ^2	σ^2	m	
Cs–chisel plow	Wyndmere (SL)	0.13	0.02	SH	2.6×10^{-4}	3.1×10^{-4}	12	↓
Cs–strip till (shank)	Wyndmere (SL)	0.37	0.02	CUB(PEN)	0.1×10^{-4}	4.7×10^{-4}	3	
Cs–strip till (coulter)	Wyndmere (SL)	0.36	0.02	SHE(SPH)	1.9×10^{-4}	3.3×10^{-4}	4	
Cs–vertical till	Wyndmere (SL)	0.17	0.03	PN	9.3×10^{-4}	9.3×10^{-4}	<1	
Cs–no till	Wyndmere (SL)	0.40	0.02	PN	2.5×10^{-4}	2.5×10^{-4}	<1	
Cs–chisel plow	Delamere (SL)	0.12	0.03	SHE(SPH)	2.3×10^{-4}	1.3×10^{-3}	43	↓
Cs–strip till (shank)	Delamere (SL)	0.26	0.01	POW	1.1×10^{-4}	–	–	
Cs–strip till (coulter)	Delamere (SL)	0.23	0.02	SPH(SHE)	0.7×10^{-4}	3.5×10^{-4}	17	
Cs–vertical till	Delamere (SL)	0.20	0.03	SHE	5.3×10^{-4}	7.2×10^{-4}	17	
Cs–no till	Delamere (SL)	0.14	0.04	SHE(SHE)	7.4×10^{-4}	1.4×10^{-3}	16	
Cover crop								
Sb–no till	Fargo (SiC)	0.14	0.03	POW(SHE)	0.9×10^{-3}	1.1×10^{-3}	9	none
Sb–no till + cover crop	Fargo (SiC)	0.14	0.03	SHE	0.5×10^{-3}	0.8×10^{-3}	10	
CC–no till	Webster (CL)	0.27	0.03	SHE(SHE)	0.3×10^{-3}	1.0×10^{-3}	25	↓
CC–no till + cover crop	Webster (CL)	0.29	0.02	PN	0.5×10^{-3}	0.5×10^{-3}	<1	
CC–no till	Nicollet (CL)	0.28	0.03	SHE	0.5×10^{-3}	1.3×10^{-3}	20	↓
CC–no till + cover crop	Nicollet (CL)	0.20	0.04	PN	1.4×10^{-3}	1.4×10^{-3}	<1	

† CC = continuous corn; Cs = corn phase of corn–soybean rotation; Sb = soybean phase of soybean–barley rotation.

‡ CL = clay loam; SiC = silty clay; SL = sandy loam.

§ ( ) = nested function; CUB = cubic; PEN = pentaspherical; PN = pure nugget; POW = power; SHE = sine hole; SPH = spherical.

¶ Arrows indicate the direction of range parameter shifts to small values.

to a soybean–barley cropping system (Table 2). Nugget and sill parameters (i.e., small- and large-scale variances) did not tend to have any consistent trends across soil management practices or sites (Table 2).

These data, although brief and preliminary in scope, support our hypotheses and provide clear proof of concept that shifts in the range of spatially dependence for near-surface SWC can be clearly detected in newly imposed soil management systems even though apparent shifts in the experimental plots mean values are not always apparent (Table 2; Fig. 1B,C). These findings have implications for methodology used in upscaling and downscaling SWC at the land surface from point sensors to satellite sensing and may have consequences on hydrologic modeling. The apparent rapid shift in spatial dependence due to soil management should be considered during such scaling efforts in agricultural landscapes. This is particularly important since many agricultural landscapes have a mosaic of soil and residue management practices that often shift as farmers become more aware of and educated on new practices to increase soil and crop health. Other implications may include a researcher's ability to meet the statistical analysis assumptions often associated with agricultural experimental designs. Based on our findings, we suggest future research on (i) further testing of our hypotheses on agricultural fields with various plant types and planting densities (e.g., weed management, cover crop mixes, plant populations, and row spacing [Purcell et al., 2007]) and tillage management (e.g., inline deep zone tillage, plow pan prevalence, degree of soil settling [Daigh and DeJong-Hughes, 2017]) and (ii) sensitivity of pixel disaggregation methodologies and hydrologic model outputs to intra-pixel spatial variability of remotely sensed data (Dabney, 1998).

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