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Site-specific effects of winter cover crops on soil water storage

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Core Ideas

As part of the submission process, we ask authors to prepare highlights of their article. The highlights will consist of 3 to 5 bullet points that convey the core findings of the article and emphasize the novel aspects and impacts of the research on scientific progress and environmental problem solving.

The purpose of these highlights is to give a concise summary that will be helpful in assessing the suitability of the manuscript for publication in the journal and for selecting appropriate reviewers. If the article is accepted the highlights may also be used for promoting and publicizing the research.

Core Idea 1: Cover crop effects on soil water storage at 10-18 cm soil depth were not consistent

Core Idea 2: Cover crops increased water held at field capacity in two of four trials

Core Idea 3: Cover crops did not affect water held at saturation or increase percentage of macropores

Core Idea 4: Causal model suggests cover crop roots may be a key driver of variable results

Core Idea 5: CUST_CORE_IDEA_5 :No data available.

Site-specific effects of winter cover crops on soil water storage~~Effect of Winter Cover Cropping on Soil Water Storage Varies by Site~~

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Abbreviations:

CC, cover crop

USDA, United States Department of Agriculture

Core ideas

- Cover crop effects on soil water storage at 10-18 cm soil depth were not consistent
- Cover crops increased water held at field capacity in two of four trials
- Cover crops did not affect water held at saturation or increase percentage of macropores
- Causal model suggests cover crop roots may be a key driver of variable results

ABSTRACT

Addition of an over-wintering cereal rye (*Secale cereale* L.) cover crop (CC) to Midwestern maize (*Zea mays* L.)-based systems offers several environmental benefits, but the long-term effects of this practice on soil hydrological properties are not well-understood. We utilized four long-term (10+ year) trials (two commercial fields, two research plots) in Iowa, USA that included a replicated winter rye CC and no-cover treatment in no-till maize/soybean (*Glycine max* [L.] Merr) systems. We took intact 7.62 cm diameter soil samples from a 10-18 cm depth shortly after cash crop planting in the spring. We measured the soil water retention curve using matric potentials ranging from saturation to -500 cmH_2O. Additionally, we measured organic matter, textural composition, and bulk densities of the soil samples. At the depth sampled, CCs did not meaningfully affect bulk density, water contents at saturation, or air-entry potentials at any trial, nor increase the percentage of macropores. At two trials, soil water content at field capacity (-100 cmH_2O) in the CC treatments was 2.5 vol% (SE: 1.2%; commercial field) and 2.4 vol% (SE: 1.3%; research plot) higher~~, respectively,~~ compared to the no-cover treatments. This increase could meaningfully reduce the amount of water drained from a field after a saturating rain and should be considered when assessing CC impacts on landscape hydrology. The presence or absence of a CC effect on field capacity was not related to CC above-ground biomass production, previous cash crop, or soil texture at the trial sites. Based on our results, a causal

model, and previous literature we hypothesize ~~;~~ CC root characteristics are~~may be~~ key to understanding variable effects of CCs on soil water storage. Our results indicate it is possible for CCs to meaningfully affect soil water storage, but more research is needed on the mechanisms by which these changes occur.

INTRODUCTION

Addition of an over-wintering cereal rye (*Secale cereale* L.) cover crop (CC) to Midwestern maize (*Zea mays* L.)-based systems potentially offers several environmental benefits including reduced soil erosion and nutrient pollution (Strock et al., 2004; Kaspar et al., 2007; Kaspar and Singer, 2011; Kladivko et al., 2014). On average, rye CCs have no effect on maize yields compared to winter fallow in the short term (Marcillo and Miguez, 2017), but it is possible repeated use of CCs could stabilize cash crop yields over time (Williams et al. 2018). In Midwestern rain-fed systems, crops rely on stored soil water and often suffer from drought stress (Campos et al., 2006). Using CCs may induce changes in soil characteristics such as increased organic matter, lower bulk densities, increased water-stable aggregates, and more macro-pores (Blanco-Canqui and Jasa, 2019; Haruna et al., 2020). In theory, these changes could result in more water storage capacity (Hudson, 1994; Minasny and McBratney, 2018; King et al., 2020), and therefore buffer crop yields against drought stress (Williams et al., 2016; Kane et al., 2021). Cover crops might also benefit crop-water relations by increasing water infiltration or reducing evaporation through a mulching effect (Unger and Vigil, 1998; Leuthold et al., 2021). Two global meta-analyses suggest that on average, CCs increase soil's capacity to store water and increase infiltration rates (Basche and DeLonge, 2017, 2019). However, to our knowledge there are few studies supporting these findings in Midwestern cover cropping contexts, and the few existing studies report contradictory results (Villamil et al., 2006; Haruna and Nkongolo, 2015; Basche et al., 2016; Rorick and Kladivko, 2017; Irmak et al., 2018). Region-specific studies are needed, as climatic and management constraints of maize-soybean rotations can limit CC options and growth potential (Strock et al., 2004; Baker and Griffis, 2009; Nichols et al., 2020a). Furthermore, to our knowledge there are no studies that report results from fields of commercial farms, and it is therefore unclear whether results observed in a controlled research setting are transferable to large-scale production fields.

In addition to regional differences in CC effects, the number of years that CCs have been used in a field may also influence whether changes in soil are detected. Long-term studies on tillage practices have shown significant, but slow changes to the soil after implementing no-till (Al-Kaisi et al., 2014; Cusser et al., 2020). Addition of CCs might likewise require several years before changes in soil hydrological properties can be detected, necessitating data collection from long-term experiments.

On average, 75% of both maize and soybean root mass is located in the top 30 cm of the soil profile (Nichols et al. 2019), indicating soil water storage in this increment will have important implications for crop water use. Shallow soil depths (0-10 cm) may be more responsive to CC effects compared to deeper soil layers (e.g. Atwood and Wood, 2021; Kaspar et al., 2006; Moore et al., 2014), but modelling and isotope studies suggest soil water below 10 cm may be more important when considering the soil's contribution to a crop's water supply (Williams et al., 2008; Asbjornsen et al., 2008; Rizzo et al., 2018). In general, there is less information available about CC effects on soil at depths greater than 10 cm, particularly about soil water retention curve parameters. Therefore, measurements taken from 10-30 cm depth ranges at multiple sites would provide valuable information about whether cover cropping can potentially affect crop yield stability through crop-water relations.

Lastly, to our knowledge the causal relationships between CCs and soil water storage have not been explicitly presented. Causal models can help identify gaps in the literature and help target data collection. ~~data needs, and w~~When sufficient data are available, causal models ~~-~~can be used to construct structural equation models that estimate the relative strength of causal factors~~paths~~ (Smith et al., 2014). Causal modelling can also be used to frame hypotheses, resulting in more targeted research questions that directly test the presence or absence of causal links (Pearl, 2010). Therefore, a credible causal model can aid in advancing future research.

Given (i) the need to quantify long-term benefits of cover cropping in both research and commercial production settings, (ii) the scarcity of Midwest-specific data at depths relevant to crop water-use, and (iii) the lack of a framework for organizing relevant knowledge, the objectives of our study were to:

(1) Determine what aspects of a soil's hydrological characteristics are affected by long-term cover cropping at a depth relevant to crop production
(2) Identify factors that affect the soil's response to cover cropping
(3) Propose a causal model connecting CCs to changes in soil properties to aid in targeting future research.

To achieve our objectives, we collected soil samples at a 10-18 cm depth increment from four long-term (10+ years) no-till cover crop trials located in Iowa, USA. Two trials were on commercial farm fields, and two trials were part of a United States Department of Agriculture (USDA) research experiment. We assessed the effects of long-term cover cropping on soil water content at saturation, soil water content at matric potentials approximating field capacity (-100 cm H_2O; Moore 2021), and the soil water retention curve. To complement and contextualize these data, we also measured soil texture, soil organic matter, and bulk densities of the soil samples. We used our results in combination with previous literature to construct a proposed causal model.

MATERIALS AND METHODS

Site descriptions

Three long-term sites that had been in place for at least 10 years were used for this study (**Supplemental material S1**), with one site having two trials. Therefore, a total of four trials were sampled (**Table 1**). Each trial consisted of two treatments that had been in place for at least 10 years: (1) a maize/soybean rotation (either grain- or silage-based) with a winter rye CC planted yearly in the fall following cash crop harvest and terminated in the spring, and (2) the same rotation without a CC. The West-grain and East-grain trials were production fields on commercial farms, and only one phase of the maize/soybean rotation was present each year. The Central site was a larger research study managed by the USDA and included both phases of each rotation (Korucu et al. 2018). For the present study, one commercial trial was sampled following the soybean phase (West-grain), one commercial trial following the maize phase (East-grain), and the USDA site samples were only taken following the maize or maize-silage phase due to time constraints. ~~For the present study, at the USDA site samples were only taken following the maize or maize-silage phase due to time constraints.~~ Every trial was arranged in a randomized complete block design with four (commercial trials) or five (USDA trials) replicates. The plots within each trial were managed identically except for the planting of the CC in the fall. The exact herbicide and nutrient programs varied by site, reflective of their managers and contexts (**Supplemental material S2**). More detailed accounts of agronomic management practices at the sites have been published elsewhere (Moore et al., 2014; Nichols et al., 2020b). All sites had sub-surface tile drainage at approximately 1.2 m depth and had been managed without tillage since initiation of the trials.

Table 1. Geographical, experimental, soil, weather, and sampling information for the four trials

Plot Size and Average Slope*	Treatment Replications	Dominant Soil Types, Depth to Water Table*	Sand/Silt/Clay, Organic Matter Content**	30-year Annual Mean		Mean Cover Crop Biomass		2018 Crop	2019 Sample Date
				Air Temperature	*Cumulative Precipitation*	*5-year*	*10-year*		
m			*%*	*°C*	*mm*	*Mg ha^{-1}*	*Mg ha^{-1}*		
West-grain (commercial farm), 41°55’N 94°36’W, initiated in 2008									
25 x 250 (1-3%)	4	Nicollet loam; 67 cm	29/43/28 2.86%	9.5	880	0.24	0.45	Soybean	May 23
East-grain (commercial farm), 41°18’N 92°48’W, initiated in 2009									
25 x 275 (0-2%)	4	Taintor silty clay loam; 0 cm	11/56/33 3.62%	10.2	947	1.73	1.32	Maize	June 10
Central (USDA research plots), 42°00’N 93°48’W									
Silage-based, initiated in 2002									
3.8 x 55 (1-3%)	5	Clarion loam; 100 cm	30/41/29 2.57%	9.8	907	2.38	1.98	Maize silage	June 6
Grain-based, initiated in 2009									
3.8 x 55 (1-3%)	5	Clarion loam; 100 cm	32/40/28 2.42%	9.8	907	1.53	0.88	Maize	June 6

** From Web Soil Survey data using map unit area weighted estimates*
*** Field measurements averaged by trial, see Materials and Methods*

Cover crop biomass sampling occurred each spring at every trial by removing two or four aboveground biomass samples from an area ranging from 0.25-0.36 m^2 from each plot, depending on the trial. Details about methodology are reported elsewhere (Nichols et al., 2020b) and historical values are available in both supplementary material and in a published dataset (Nichols et al. 2020c). Maize grain, maize silage, and soybean grain yields were measured yearly. Results from the commercial fields showed the effect of cover cropping on grain yields varied by trial and by year (Practical Farmers of Iowa, 2018). While understanding how long-term use of cover crops affects crop yields in different weather-years is a valuable topic of research, it is not the focus of the present study.

Soil Sampling

An aluminum ring 7.62 cm in diameter and 7.62 cm in length was used to extract intact soil samples. Sampling occurred in May or June of 2019 after maize (West-grain) or soybean (East-grain, Central-grain, Central-silage) emergence at each site. Sampling was conducted immediately following crop emergence to minimize the effects of live roots in the samples and was done two to four days following a rain to ensure the soil was fully drained, but wet enough to remain in the ring during sampling (Al-Shammary et al., 2018).

At all trials, one sample was taken in the middle of the plot between planted rows in a non-traffic area in order to minimize the effects of soil changes related to planting activities (wheel-row compaction, drill disturbance) on the results. To get intact soil cores from a 10-18 cm depth increment, a hole 10 cm deep was dug, and soil was smoothed by hand to create a flat area approximately 30 cm square. The ring was placed on the soil surface in the center of the flat area, a hollow metal cap was placed on it, and a 15 kg weight was used to evenly drive the ring into the undisturbed soil. Once the ring was fully inserted into the soil, a hole was dug around the ring. A flat sheet of metal was slid under the ring to extract it, and a knife was used to remove soil from the top and bottom of the ring by sawing in a Z-cutting motion (three sawing motions per core). The ring was wrapped in aluminum foil with the soil orientation (top, bottom) marked. The foil-wrapped ring was then placed in an individual plastic container in a cooler. This process was repeated for each plot (eight plots at East-grain, eight at West-grain, 10 at Central-silage, and 10 at Central-grain; Table 1). Samples remained in the cooler for no more than four hours before being placed in a refrigerator.

Soil-water-retention curve

Analytical equipment could accommodate 12 samples at a time, so each trial's samples were run together in a batch for a total of four batches (e.g., the eight samples from the West-grain trial were run together in one batch). Our interest was in comparing relative effects within a trial, so variation between runs was included statistically in variation between trials. The samples were analyzed in the order they were collected. A given trial's cores had cheesecloth taped to the bottom of each core and an additional ring taped to the top. The batch of samples was then placed in a vacuum chamber for at least 12 hours in a solution of 0.01 M $CaCl_2$ filled to the top of the first ring, allowing the samples to saturate with minimal air entrapment. Following saturation, the top ring was removed from the cores. The cores were weighed, then transferred to a custom-built pressure cell apparatus (Ankeny et al. 1992). Measurements were made according to the protocol described by Kool et al. (2019). Cores were drained at atmospheric pressure for 12 hours to obtain a measurement for gravity-drained matric potential (Ψ_m = -3.8 cmH_2O). Subsequent measurements were taken at Ψ_m of -10, -25, -50, -100, -200, and -500 cmH_2O. The samples were then oven dried at 60 ^{0}C for at least 48 hours, then weighed. Bulk densities were estimated by dividing the oven-dried weight of soil by the ring volume (347.5 cm^3; Grossman et al., 2002). A water balance was constructed for each core individually as quality control, resulting in the removal of one replicate from the no-cover treatment of the Central-silage trial, which had a large hole visible in the center of the core upon destructive inspection, confirming its justified removal from the dataset.

Soil texture and organic carbon

The oven-dried soil was ground and passed through a 2 mm sieve. Two teaspoons of soil (~10 grams) from each core were used for soil texture measurements. Soil texture was quantified using laser diffractometry (Miller and Schaetzl, 2012) with a Malvern Mastersizer 3000 and a HydroEV attachment (Malvern Panalytical Ltd, UK), producing estimates for the percentage of the soil that was sand (50-2000 µm), silt (6-50 µm), and clay (0.1-6 µm). Half of the remaining oven-dried soil cores were sent for organic matter analysis (Agsource, Ellsworth Iowa, USA) using the loss-on-ignition method (Nelson and Sommers, 1996). While this method may not produce reliable absolute estimates of organic matter (Hoogsteen et al., 2015), our interest was in pairwise comparisons of treatments rather than in obtaining absolute estimates of organic matter.

Statistical analysis

All data analysis, figure creation, and model fitting were done using *R* version 4.0.3 (R Core Team, 2020) and the *tidyverse* meta-package (Wickham et al., 2019). Non-linear models were fit using the *nlraa* (Miguez, 2021) package functionality, with specific equation fits from the *HydroMe* (Omuto et al., 2021) and *soilphysics* (de Lima et al., 2021) packages. Linear models were fit and summarized using the *lme4* (Bates et al., 2015) package, which fits mixed effects models, and the *emmeans* (Lenth et al., 2018) package, which estimates both marginal and conditional means and confidence intervals and performs pairwise comparisons.

We fit the Gardner (Gardner, 1958) and van Genutchen (van Genuchten, 1980) models to describe the relationship between soil moisture and soil water matric potential in our datasets. We found the models produced similar Akaike's Information Criteria (AIC; Bozdogan, 1987) values, with the Gardner model showing a slightly better fit. The Gardner equation is as follows:

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{1 + a\psi^n}$$

where θ is the volumetric moisture content at a given soil water potential ψ; the remaining variables are fitted parameters. θ_r and θ_s are the residual and saturated water contents, respectively; a approximates the inverse of the pressure at which the retention curve is steepest (e.g., air-entry potential; van Genutchen 1980); and n is an index for the pore size distribution, with higher values indicating a broader distribution of pore sizes. We fit the Gardner model to each experimental unit, then analyzed the air-entry and pore-size distribution parameters as response variables, described below. Residual water contents (θ_r) are estimated by the model, and can occur at suction pressures greater than -15,000 cmH_2O (SSSA, 2008). The highest suction presssure applied to samples in this study was -500 cmH_2O, which could lead to less stable model fits due to lack of an anchoring value (Groenevelt and Grant, 2004). To determine whether the model produced reasonable estimates without these anchoring values, we compared (1) the model-estimated saturated water contents with the measured values, and (2) the pore-size distribution parameter estimate against values estimated using capillary rise equations, which assumes the mean pore neck diameter (in cm) of drained pores at a given pressure is equal to 0.3 divided by the head pressure (cmH_2O). Pores with mean neck diameters greater than 30 μm were considered macropores (Kirkham, 2014). The percent macropores was assessed as a response variable, described below.

Volumetric water contents at saturation were extracted directly from the measured values. Volumetric water contents at field capacity were estimated as the measured volumetric water content at a matric potential of -100 cmH_2O (Moore 2021). We used this approximation because the matric potential that approximates field capacity depends on the depth to the water table. The trials sampled all had artificial tile drainage installed at ~1.2 meter depths and had shallow water tables (**Table 1**), meaning field capacity will be at matric potentials less negative than the commonly assumed value of -330 cmH_2O (Bonfante et al., 2020). Soil water retention curve data from Moore (2021) suggest that -100 cmH_2O is a better approximation for field capacity in mollic epipedons with shallow water tables, such as those sampled in the present study.

The effects of trial, CC treatment, and their interaction on response variables (soil texture, organic matter, water contents at saturation and field capacity, air-entry pressures, pore-size distribution index, percent macropores) were assessed using mixed-effect models. Trial, CC treatment, and their interaction were included as fixed effects. Percent sand was investigated as a covariate in appropriate models because texture is the dominant driver of water retention curve parameters (de Jong et al., 1983; Saxton and Rawls, 2006), has a large influence on bulk densities, and can affect soil organic matter accumulation. Models without a sand covariate had random intercept effects for replicates nested within location (East, Central, West), and models that included a sand covariate had fixed effects only. Models were compared using AIC. All statistical results are available in S**upplementary material S3**.

RESULTS AND DISCUSSION

Soil texture, organic matter, and bulk density

Within~~In~~ certain trials, the CC treatment was coincident with differences in sand, silt, as well as clay percentages ($p<0.001$). The percent sand did not vary by CC treatment in the Central-silage trial, but varied significantly ($p<0.01$) at the other three trials (**Supplementary material S3, S4**). Likewise, the percent clay varied by CC treatment in three of the four trials while the percent silt varied by CC treatment in only one trial (West-grain). However, the significant differences between CC and no-cover plots were only of a meaningful magnitude (>1% difference) at the two commerical farm trials (East-grain, West-grain; **Table 2).** In the East-grain trial, the CC plots had 3% more sand compared to the no-cover plots ($p<0.001$). In the West-grain trial, the CC plots had 5% more sand compared to the no-cover plots ($p<0.001$). The increased sand in the CC plots was compensated for by a decrease in clay (East-grain) or a decrease in both clay and silt (West-grain). At both of the Central trials, texture components of the CC and no-cover plots were within 1% of each other.

Table 2. Summary of soil texture components for rye cover crop (CC) and no-cover treatments at each trial, bolded text indicates significant differences at p<0.01 greater than 1% in magnitude; totals may not add to 100% due to rounding, see Supplemental material S4 for more precise values.

Trial	Sand	Silt	Clay
	Rye CC /No-cover	*Rye CC/No-cover*	*Rye CC/No-cover*
West-grain (commercial farm)	**31/26%**	**42/45%**	**27/30%**
East-grain (commercial farm)	**13/10%**	56/56%	**32/35%**
Central-silage	30/29%	41/41%	29/30%
Central-grain	32/32%	40/40%	28/28%

While the plots in the commercial farm fields (East-grain, West-grain) were randomly assigned a CC treatment, the treatments were close to regularly alternating strips, with the four blocks laid out side-by-side. If a field has a uniform texture gradient perpendicular to the blocking, this regularly alternating pattern could result in one treatment having significantly different textures compared to the other, as we observed. Additional samples taken at a later date from East-grain trial confirmed the soil texture pattern we observed in the present study (unpublished data), providing further evidence our observations were not due to chance, but rather refelected a true soil texture gradient at the sites. The Central site had six treatments in small plots and the five blocks were located in two rows within the field, with each treatment being randomly assigned within the block; this arrangement may have better randomized treatments with respect to natural patterns of soil texture within the site. Based on these results, sand was included as a covariate in statistical models for response variables potentially affected by soil texture.

Soil organic matter contents ranged from 1.8 to 4.6%, with a signficant trial-by-CC treatment interaction ($p<0.001$). Soil organic matter accumulation may be affected by soil texture (Scott et al., 1996; Bosatta and Agren, 1997), so statistics were run both with and without a sand co-variate to account for the different soil textures in the CC and no-cover treatments observed in some trials. The Central-silage trial showed a significant ($p<0.01$) but small (+0.25%) absolute increase in organic matter with cover cropping, regardless of inclusion of a sand covariate. In the other three trials, the results depended on whether sand was included as a co-variate. Without a sand co-variate, organic matter was estimated to decrease with cover cropping compared to no-cover in three trials (p-values ranging from 0.001-0.048). When a sand co-variate was included in the statistical analysis, organic matter either did not change (Central-grain) or significantly ($p<0.01$) increased with cover cropping by small amounts (+0.19% and +0.26% in the East-grain and West-grain trials, respectively). Due to the sensitivity of the results and the small effect sizes, we conclude cover cropping did not meaningfully affect soil organic matter at this depth in the three grain trials, but may have resulted in a slightly higher organic matter content in the Central-silage trial. This is consistent with a previous study at this same trial, which found higher organic matter in the top 5 cm of soil in CC treatments compared to no-cover, but small differences below that depth (Moore et al., 2014).

Bulk densities varied from 1.2 g cm^{-3} to 1.7 g cm^{-3}. The large size of sand particles reduces packing efficiencies compared with clay, meaning a sandy soil may have lower bulk densities simply due to packing arrangements. However, regardless of the statistical model fit, all estimated CC effects were less than measurement precision of the core method for measuring bulk density (±0.12 g cm^{-3}, Han et al., 2016), rendering their interpretation questionable. A recent summary of research on the effects of CCs on bulk densities likewise found few studies where an overwintering rye CC grown in the US reduced bulk densities more than typical measurement errors (Haruna et al., 2020). We therefore found no evidence that CCs meaningfully affected soil bulk density at 10-18 cm soil depths at any trial.

Soil hydrological properties

Soil texture is the dominant factor determining soil water retention (de Jong et al., 1983; Saxton and Rawls, 2006), particularly under wet conditions (i.e. saturation and field capacity; Manns and Berg, 2014). Because soil texture varied by CC treatment in the two commercial field trials (East-grain, West-grain), sand was included as a co-variate in statistical models assessing the effects of cover cropping on these response variables.

Air-entry potential and pore distribution

The Gardner equation fitting process converged for all experimental units (**Figure 1**), with *a* (an estimate of the inverse of air-entry potential) ranging from 0.001 to 0.284, and *n* (pore-size distribution index) ranging from 0.45 to 1.49.

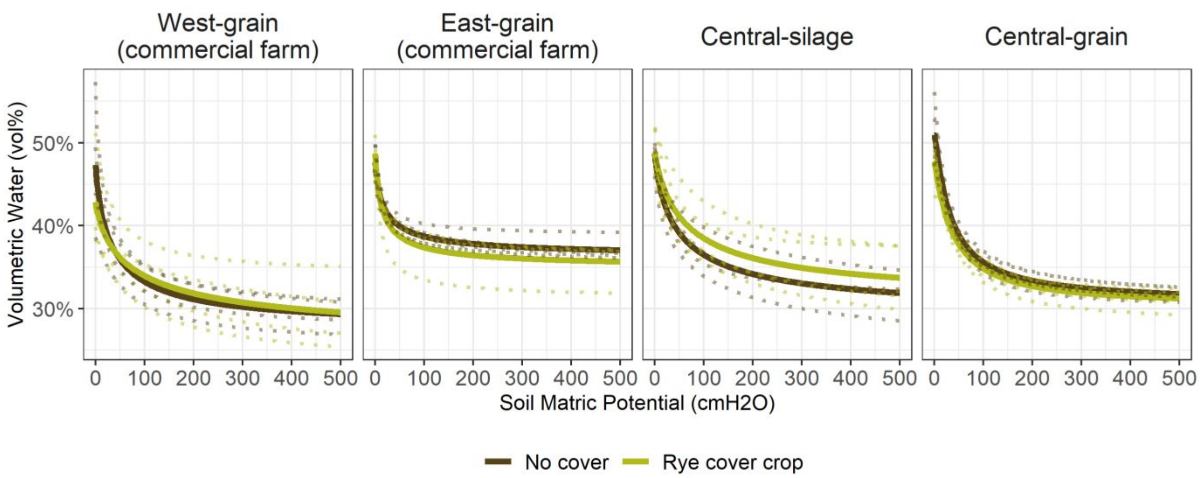

Figure 1. The Gardner equation was fit to each experimental unit (dotted lines); mean values (solid lines) for each trial and cover crop treatment are presented to aid in interpretation.

There was not a significant interaction between trial and CC treatment for either parameter. While both parameters differed significantly by trial ($p<0.001$), cover cropping did not significantly affect either parameter, with or without a sand covariate (**Table 3; Supplemental material S3**).

Table 3. Summary of estimated mean values, standard error of the mean (SE), and significance of the comparison between rye cover crop (CC) and no-cover treatments within a trial (p-value) for Gardner parameters and percent macropores.

Cover crop (CC) treatment	Inverse air-entry potential (Gardner model parameter *a*)		Pore-size distribution (Gardner model parameter *n*)		Percent macropores (capillary rise equation)	
	mean(SE)	p-value	mean(SE)	p-value	mean(SE)	p-value
	cmH_2O^{-1}		*unitless*		%	
West-grain (commercial farm)						
Rye CC	0.03(0.01)	0.15	0.83(0.09)	0.60	48(5)	0.05
No cover	0.05(0.01)		0.90(0.09)		61(5)	
East-grain (commerical farm)						
Rye CC	0.11(0.01)	0.14	0.83(0.09)	0.96	73(5)	0.75
No cover	0.08(0.01)		0.82(0.08)		71(5)	
Central-grain						
Rye CC	0.02(0.01)	0.97	1.15(0.08)	0.67	59(4)	0.61
No cover	0.02(0.01)		1.10(0.08)		62(4)	
Central-silage						
Rye CC	0.03(0.01)	0.32	0.90(0.08)	0.52	54(4)	0.40
No cover	0.04(0.01)		0.82(0.09)		59(5)	

When compared across trials, the *a* parameter was strongly related to the percentage of sand in the trial's soil, with the East-grain trial having the lowest sand content (mean of 11%) and highest *a* estimate (mean of 0.09), and the Central-grain trial having the highest sand content (mean of 32% sand) and lowest *a* estimate (mean of 0.02). This inverse relationship is consistent with empirical equations relating air-entry potential to soil texture (Saxton and Rawls 2006). However, even with a sand co-variate, cover cropping did not significantly affect air-entry pressures nor pore-size distributions.

Consistent with the lack of CC effect on the Gardner equation's pore-size distribution parameter (*n*) manual estimation of the pore-size distribution confirmed CCs did not increase the percentage of macropores in any trial (**Table 3**; **Supplemental material S5.** In a review of published studies, Haruna et al. (2020) found the effect of CCs on macropore makeup of the soil highly variable, but with an overall average increase. The wide variation may be partially due to varying cut-offs in pore sizes for macropore categorization (Luxmoore, 1981), but the variability in combination with our results again demonstrates using literature averages to predict CC impacts in Midwestern systems may be inappropriate.

Soil water at saturation and field-capacity

For these analyses we assigned significance at p-values less than 0.10. With or without a sand covariate, no trial exhibited a significant increase in water held at saturation with the use of cover cropping (**Figure 2**). Water held at saturation is largely dependent on bulk density, so these findings are consistent with the lack of meaningful effect of CCs on bulk densities in our study. Field capacities were signifiantly higher in the cover cropped plots at one commercial farm (West-grain; $p = 0.07$) and one USDA trial (Central-silage; $p = 0.05$). At the West-grain trial, the soil water at field capacity increased (after sand correction) from 33.6 to 36.0 vol%, and at the Central-silage trial from 38.1 to 40.6 vol%, respectively. An increase in the soil's ability to hold water after gravity drainage may also contribute to peak water flow regulation. By increasing volumetric water content at field capacity by 2 vol% in the 0-20 cm profile, CC fields could hold an additional 40,000 L of water in each 20-cm hectare slice, which could meaningfully reduce the amount of water drained from a field after a saturating rain. For comparison, evapotranspiration rates in an over-wintered rye cover crop with modest biomass production can be ~ 24,000 L ha^{-1} day^{-1} (Qi and Helmers, 2010), and peak flows from sub-surface drainge tiles in central Iowa can be ~22,000 L ha^{-1} $hour^{-1}$ (Daigh et al. 2014). To our knowledge there are limited studies examining the potential for CCs to reduce flood damage in the Midwest, but the one we are aware of accounts for only the increased evapo-transipiration with the use of CCs (Antolini et al., 2020). Our study suggests that in addition to reducing run-off (Korucu et al. 2018), considering how CC-induced increases in the amount of water held in a soil at field capacity affect flood incidence and severity would be worth investigating. Furthermore, as other studies have noted, an increase in the amount of water held at field capacity results in more precipitation being stored for cash crop use (Basche et al. 2016; Leuthold et al. 2021), meaning in some cases long-term use of CCs could lead to more stable cash crop yields (Williams et al. 2018).

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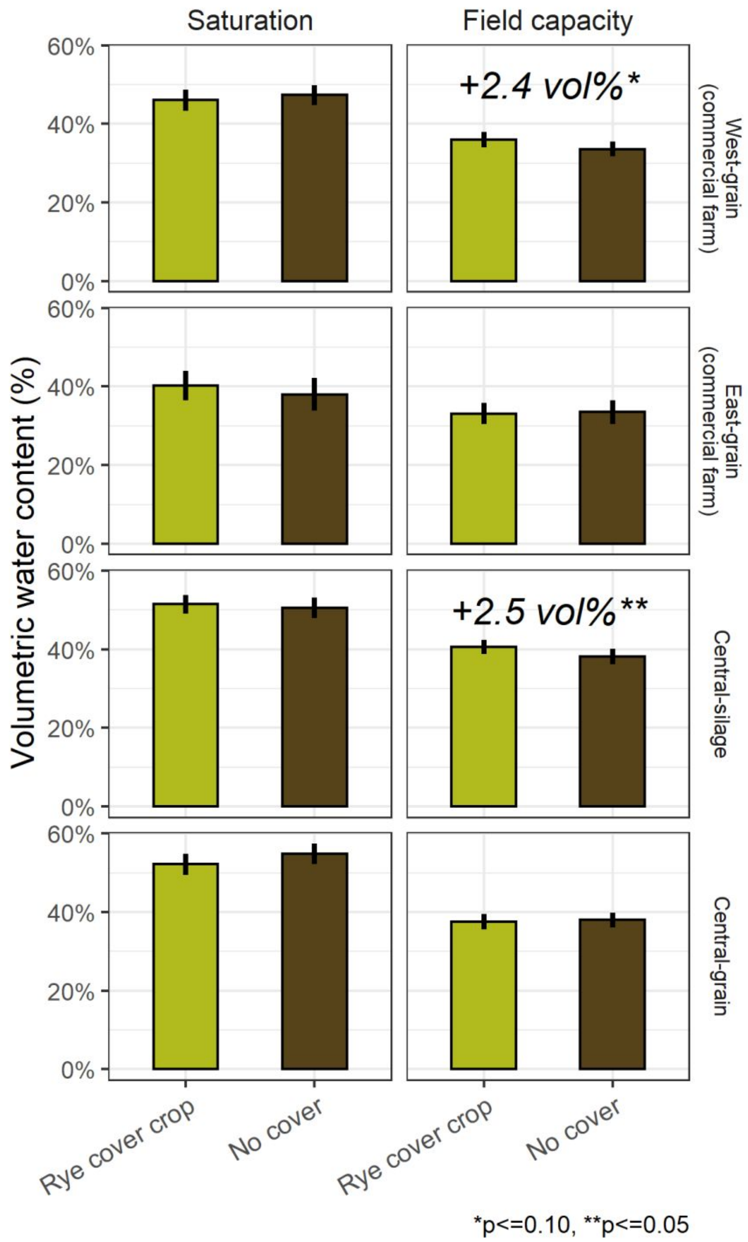

Figure 2. Soil volumetric water contents at saturation and field capacity (-100 cmH2O) with 10+ years of winter rye cover cropping (green) or winter fallow (brown) in a maize-soybean rotation at four trials. Bars show estimated means, line ranges are the 95% confidence intervals around the mean. Text

presents the estimated effect of cover cropping on volumetric water content in instances of a significant effect.

Factors explaining variable results

The West-grain and Central-silage trials both exhibited significantly higher soil water at field capacity with the use of cover cropping compared to winter fallows. However, the West-grain trial consistently produced the lowest above-ground CC biomass, and the Central-silage trial the highest (**Table 1**), indicating the changes in water held at field capacity are likely not associated with CC above-ground biomass production. Although a previous study suggested soil texture could mediate the effects of long-term CC-use (Blanco-Canqui and Jasa, 2019), in our dataset there was no pattern between soil textural characteristics and the magnitude of CC effect on water held at field capacity. This means knowledge of a soil's texture did not help predict whether a CC would affect water held at field capacity in our study.

The West-grain trial was sampled following a soybean crop, and the Central-silage following a silage crop, while the two trials without significant CC effects were both sampled following a maize-grain crop (**Table 1**). Soybean and maize-silage crops would leave less residue compared to a preceeding maize-grain crop, however this study did not measure residue amounts at the time of sampling. Given the lack of insight into what may be driving the variable effects given the available data, we explored potential causes for our variable results and identified additional measurements that may aid in identifying drivers of the variable effects of CCs on soil hydrological properties.

Causal model

There are several pathways by which CCs might affect a soil's capacity to hold water (**Figure 3**). The causal model was built using literature relevant to Midwestern systems, and when applicable was limited to evidence drawn from research conducted with a cereal rye cover crop (**Supplemental material S6**). The model was simplified to exclude the effects of soil erosion, soil texture, tillage, and landscape position, which are all factors that could potentially influence how soil responds to cover cropping (Moore 2021). Rather, we present this simple casusal model to provide a base from which to build.

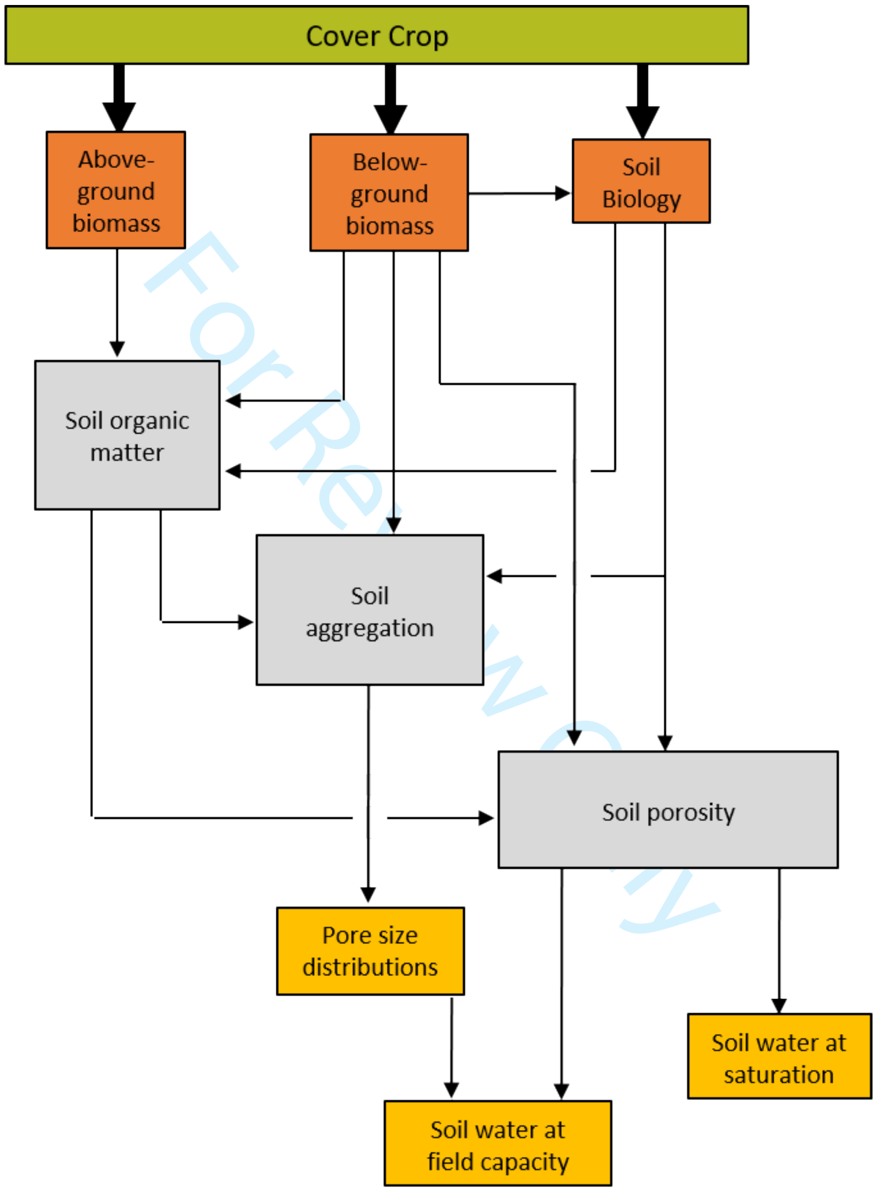

Figure 3. Pathways by which cover crops may affect the soil pore size distributions, the amount of water stored at field capacity, and the amount of water at saturation in no-till systems. The effects of soil erosion are not included. X→Y should be read as 'X affects Y'.

Causal diagrams such as **Figure 3** are the basis for constructing structural equation models, which can greatly enhance researchers' ability to address complex research questions in agriculture (Smith et al., 2014; Wade et al., 2020). For example, in our proposed causal diagram, below-ground biomass measurements are necessary for estimating direct effects of cover cropping on pore size distributions, field capacity, and saturation. This is further supported by recent studies and reviews that identify CC roots as being a crucial component to understanding CC effects on soil properties (Williams and Weil, 2004; Haruna et al., 2020; Ogilvie et al., 2021). While there is limited data available pairing above- and below-ground biomass of CCs, data collected in Iowa over a five-year period showed no relationship between above- and below-ground rye biomass, with root-to-shoot ratios varying from 0.16-1.94 at similar levels of aboveground biomass production (Martinez-Feria et al., 2016). Therefore, above-ground biomass production cannot be used as a proxy for below-ground production with much confidence, and studies that pair above- and below-ground CC biomass with soil measurements would be advantageous in enhancing our understanding of CC effects on soil.

CONCLUSIONS

We found CCs increased water held at field capacity at the 10-18 cm soil range in two of the four trials sampled. The observed increases were of a meaningful magnitude that could contribute to cash crop water needs, and may have implications for flooding severity in agricultural regions and should be considered when modelling cover crop effects on landscape water balances. We were unable to explain the trial-dependent effects using the available measurements and information. Based on a proposed causal model, we suggest researchers measure CC root biomass in addition to above-ground biomass when examining the effects of CCs on soil properties. Effects of growing over-wintering CCs need to be explicitly investigated in the

Midwestern US, as the constraints of maize-soybean systems may render the effects smaller in magnitude compared to averages reported by global meta-analyses.

SUPPLEMENTAL MATERIAL

S1 - A map of trial locations

S2 - Detailed description of management practices and historical cover crop biomass production for each trial

S3 - Statistical summaries

S4 – Detailed soil texture results

S6 – Causal model literature support

DATA AVAILABILITY

The data are available as downloadable csv files in supplementary material. Additionally, all data are available in an R package (https://github.com/vanichols/PFIswhc) and the R code used in processing and summarizing data for this publication is available in a github repository (will be created once paper is accepted).

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTIBUTIONS

VN contributed to conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, writing of original draft, and review/editing. ML contributed to funding acquisition, project administration, supervision, and review/editing of draft. SG contributed to project administration, resources, and review/editing. EM contributed to methodology, resources, and review/editing.

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Site-specific effects of winter cover crops on soil water storage~~Effect of Winter Cover Cropping on Soil Water Storage Varies by Site~~

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Abbreviations:

CC, cover crop

USDA, United States Department of Agriculture

Core ideas

- Cover crop effects on soil water storage at 10-18 cm soil depth were not consistent
- Cover crops increased water held at field capacity in two of four trials
- Cover crops did not affect water held at saturation or increase percentage of macropores
- Causal model suggests cover crop roots may be a key driver of variable results

ABSTRACT

Addition of an over-wintering cereal rye (*Secale cereale* L.) cover crop (CC) to Midwestern maize (*Zea mays* L.)-based systems offers several environmental benefits, but the long-term effects of this practice on soil hydrological properties are not well-understood. We utilized four long-term (10+ year) trials (two commercial fields, two research plots) in Iowa, USA that included a replicated winter rye CC and no-cover treatment in no-till maize/soybean (*Glycine max* [L.] Merr) systems. We took intact 7.62 cm diameter soil samples from a 10-18 cm depth shortly after cash crop planting in the spring. We measured the soil water retention curve using matric potentials ranging from saturation to -500 cmH_2O. Additionally, we measured organic matter, textural composition, and bulk densities of the soil samples. At the depth sampled, CCs did not meaningfully affect bulk density, water contents at saturation, or air-entry potentials at any trial, nor increase the percentage of macropores. At two trials, soil water content at field capacity (-100 cmH_2O) in the CC treatments was 2.5 vol% (SE: 1.2%; commercial field) and 2.4 vol% (SE: 1.3%; research plot) higher~~, respectively,~~ compared to the no-cover treatments. This increase could meaningfully reduce the amount of water drained from a field after a saturating rain and should be considered when assessing CC impacts on landscape hydrology. The presence or absence of a CC effect on field capacity was not related to CC above-ground biomass production, previous cash crop, or soil texture at the trial sites. Based on our results, a causal

model, and previous literature we hypothesize ~~;~~ CC root characteristics are~~may be~~ key to understanding variable effects of CCs on soil water storage. Our results indicate it is possible for CCs to meaningfully affect soil water storage, but more research is needed on the mechanisms by which these changes occur.

INTRODUCTION

Addition of an over-wintering cereal rye (*Secale cereale* L.) cover crop (CC) to Midwestern maize (*Zea mays* L.)-based systems potentially offers several environmental benefits including reduced soil erosion and nutrient pollution (Strock et al., 2004; Kaspar et al., 2007; Kaspar and Singer, 2011; Kladivko et al., 2014). On average, rye CCs have no effect on maize yields compared to winter fallow in the short term (Marcillo and Miguez, 2017), but it is possible repeated use of CCs could stabilize cash crop yields over time (Williams et al. 2018). In Midwestern rain-fed systems, crops rely on stored soil water and often suffer from drought stress (Campos et al., 2006). Using CCs may induce changes in soil characteristics such as increased organic matter, lower bulk densities, increased water-stable aggregates, and more macro-pores (Blanco-Canqui and Jasa, 2019; Haruna et al., 2020). In theory, these changes could result in more water storage capacity (Hudson, 1994; Minasny and McBratney, 2018; King et al., 2020), and therefore buffer crop yields against drought stress (Williams et al., 2016; Kane et al., 2021). Cover crops might also benefit crop-water relations by increasing water infiltration or reducing evaporation through a mulching effect (Unger and Vigil, 1998; Leuthold et al., 2021). Two global meta-analyses suggest that on average, CCs increase soil's capacity to store water and increase infiltration rates (Basche and DeLonge, 2017, 2019). However, to our knowledge there are few studies supporting these findings in Midwestern cover cropping contexts, and the few existing studies report contradictory results (Villamil et al., 2006; Haruna and Nkongolo, 2015; Basche et al., 2016; Rorick and Kladivko, 2017; Irmak et al., 2018). Region-specific studies are needed, as climatic and management constraints of maize-soybean rotations can limit CC options and growth potential (Strock et al., 2004; Baker and Griffis, 2009; Nichols et al., 2020a). Furthermore, to our knowledge there are no studies that report results from fields of commercial farms, and it is therefore unclear whether results observed in a controlled research setting are transferable to large-scale production fields.

In addition to regional differences in CC effects, the number of years that CCs have been used in a field may also influence whether changes in soil are detected. Long-term studies on tillage practices have shown significant, but slow changes to the soil after implementing no-till (Al-Kaisi et al., 2014; Cusser et al., 2020). Addition of CCs might likewise require several years before changes in soil hydrological properties can be detected, necessitating data collection from long-term experiments.

On average, 75% of both maize and soybean root mass is located in the top 30 cm of the soil profile (Nichols et al. 2019), indicating soil water storage in this increment will have important implications for crop water use. Shallow soil depths (0-10 cm) may be more responsive to CC effects compared to deeper soil layers (e.g. Atwood and Wood, 2021; Kaspar et al., 2006; Moore et al., 2014), but modelling and isotope studies suggest soil water below 10 cm may be more important when considering the soil's contribution to a crop's water supply (Williams et al., 2008; Asbjornsen et al., 2008; Rizzo et al., 2018). In general, there is less information available about CC effects on soil at depths greater than 10 cm, particularly about soil water retention curve parameters. Therefore, measurements taken from 10-30 cm depth ranges at multiple sites would provide valuable information about whether cover cropping can potentially affect crop yield stability through crop-water relations.

Lastly, to our knowledge the causal relationships between CCs and soil water storage have not been explicitly presented. Causal models can help identify gaps in the literature and help target data collection. ~~data needs, and w~~When sufficient data are available, causal models can be used to construct structural equation models that estimate the relative strength of causal factors~~paths~~ (Smith et al., 2014). Causal modelling can also be used to frame hypotheses, resulting in more targeted research questions that directly test the presence or absence of causal links (Pearl, 2010). Therefore, a credible causal model can aid in advancing future research.

Given (i) the need to quantify long-term benefits of cover cropping in both research and commercial production settings, (ii) the scarcity of Midwest-specific data at depths relevant to crop water-use, and (iii) the lack of a framework for organizing relevant knowledge, the objectives of our study were to:

(1) Determine what aspects of a soil's hydrological characteristics are affected by long-term cover cropping at a depth relevant to crop production
(2) Identify factors that affect the soil's response to cover cropping
(3) Propose a causal model connecting CCs to changes in soil properties to aid in targeting future research.

To achieve our objectives, we collected soil samples at a 10-18 cm depth increment from four long-term (10+ years) no-till cover crop trials located in Iowa, USA. Two trials were on commercial farm fields, and two trials were part of a United States Department of Agriculture (USDA) research experiment. We assessed the effects of long-term cover cropping on soil water content at saturation, soil water content at matric potentials approximating field capacity (-100 cm H_2O; Moore 2021), and the soil water retention curve. To complement and contextualize these data, we also measured soil texture, soil organic matter, and bulk densities of the soil samples. We used our results in combination with previous literature to construct a proposed causal model.

MATERIALS AND METHODS

Site descriptions

Three long-term sites that had been in place for at least 10 years were used for this study (**Supplemental material S1**), with one site having two trials. Therefore, a total of four trials were sampled (**Table 1**). Each trial consisted of two treatments that had been in place for at least 10 years: (1) a maize/soybean rotation (either grain- or silage-based) with a winter rye CC planted yearly in the fall following cash crop harvest and terminated in the spring, and (2) the same rotation without a CC. The West-grain and East-grain trials were production fields on commercial farms, and only one phase of the maize/soybean rotation was present each year. The Central site was a larger research study managed by the USDA and included both phases of each rotation (Korucu et al. 2018). For the present study, one commercial trial was sampled following the soybean phase (West-grain), one commercial trial following the maize phase (East-grain), and the USDA site samples were only taken following the maize or maize-silage phase due to time constraints. ~~For the present study, at the USDA site samples were only taken following the maize or maize-silage phase due to time constraints.~~ Every trial was arranged in a randomized complete block design with four (commercial trials) or five (USDA trials) replicates. The plots within each trial were managed identically except for the planting of the CC in the fall. The exact herbicide and nutrient programs varied by site, reflective of their managers and contexts (**Supplemental material S2**). More detailed accounts of agronomic management practices at the sites have been published elsewhere (Moore et al., 2014; Nichols et al., 2020b). All sites had sub-surface tile drainage at approximately 1.2 m depth and had been managed without tillage since initiation of the trials.

Table 1. Geographical, experimental, soil, weather, and sampling information for the four trials

Plot Size and Average Slope*	Treatment Replications	Dominant Soil Types, Depth to Water Table*	Sand/Silt/Clay, Organic Matter Content**	30-year Annual Mean		Mean Cover Crop Biomass		2018 Crop	2019 Sample Date
				Air Temperature	*Cumulative Precipitation*	*5-year*	*10-year*		
m			*%*	*°C*	*mm*	*Mg ha⁻¹*	*Mg ha⁻¹*		
West-grain (commercial farm), 41°55'N 94°36'W, initiated in 2008									
25 x 250 (1-3%)	4	Nicollet loam; 67 cm	29/43/28 2.86%	9.5	880	0.24	0.45	Soybean	May 23
East-grain (commercial farm), 41°18'N 92°48'W, initiated in 2009									
25 x 275 (0-2%)	4	Taintor silty clay loam; 0 cm	11/56/33 3.62%	10.2	947	1.73	1.32	Maize	June 10
Central (USDA research plots), 42°00'N 93°48'W									
Silage-based, initiated in 2002									
3.8 x 55 (1-3%)	5	Clarion loam; 100 cm	30/41/29 2.57%	9.8	907	2.38	1.98	Maize silage	June 6
Grain-based, initiated in 2009									
3.8 x 55 (1-3%)	5	Clarion loam; 100 cm	32/40/28 2.42%	9.8	907	1.53	0.88	Maize	June 6

** From Web Soil Survey data using map unit area weighted estimates*
*** Field measurements averaged by trial, see Materials and Methods*

Cover crop biomass sampling occurred each spring at every trial by removing two or four aboveground biomass samples from an area ranging from 0.25-0.36 m^2 from each plot, depending on the trial. Details about methodology are reported elsewhere (Nichols et al., 2020b) and historical values are available in both supplementary material and in a published dataset (Nichols et al. 2020c). Maize grain, maize silage, and soybean grain yields were measured yearly. Results from the commercial fields showed the effect of cover cropping on grain yields varied by trial and by year (Practical Farmers of Iowa, 2018). While understanding how long-term use of cover crops affects crop yields in different weather-years is a valuable topic of research, it is not the focus of the present study.

Soil Sampling

An aluminum ring 7.62 cm in diameter and 7.62 cm in length was used to extract intact soil samples. Sampling occurred in May or June of 2019 after maize (West-grain) or soybean (East-grain, Central-grain, Central-silage) emergence at each site. Sampling was conducted immediately following crop emergence to minimize the effects of live roots in the samples and was done two to four days following a rain to ensure the soil was fully drained, but wet enough to remain in the ring during sampling (Al-Shammary et al., 2018).

At all trials, one sample was taken in the middle of the plot between planted rows in a non-traffic area in order to minimize the effects of soil changes related to planting activities (wheel-row compaction, drill disturbance) on the results. To get intact soil cores from a 10-18 cm depth increment, a hole 10 cm deep was dug, and soil was smoothed by hand to create a flat area approximately 30 cm square. The ring was placed on the soil surface in the center of the flat area, a hollow metal cap was placed on it, and a 15 kg weight was used to evenly drive the ring into the undisturbed soil. Once the ring was fully inserted into the soil, a hole was dug around the ring. A flat sheet of metal was slid under the ring to extract it, and a knife was used to remove soil from the top and bottom of the ring by sawing in a Z-cutting motion (three sawing motions per core). The ring was wrapped in aluminum foil with the soil orientation (top, bottom) marked. The foil-wrapped ring was then placed in an individual plastic container in a cooler. This process was repeated for each plot (eight plots at East-grain, eight at West-grain, 10 at Central-silage, and 10 at Central-grain; Table 1). Samples remained in the cooler for no more than four hours before being placed in a refrigerator.

Soil-water-retention curve

Analytical equipment could accommodate 12 samples at a time, so each trial's samples were run together in a batch for a total of four batches (e.g., the eight samples from the West-grain trial were run together in one batch). Our interest was in comparing relative effects within a trial, so variation between runs was included statistically in variation between trials. The samples were analyzed in the order they were collected. A given trial's cores had cheesecloth taped to the bottom of each core and an additional ring taped to the top. The batch of samples was then placed in a vacuum chamber for at least 12 hours in a solution of 0.01 M $CaCl_2$ filled to the top of the first ring, allowing the samples to saturate with minimal air entrapment. Following saturation, the top ring was removed from the cores. The cores were weighed, then transferred to a custom-built pressure cell apparatus (Ankeny et al. 1992). Measurements were made according to the protocol described by Kool et al. (2019). Cores were drained at atmospheric pressure for 12 hours to obtain a measurement for gravity-drained matric potential (Ψ_m = -3.8 cmH_2O). Subsequent measurements were taken at Ψ_m of -10, -25, -50, -100, -200, and -500 cmH_2O. The samples were then oven dried at 60 ^{0}C for at least 48 hours, then weighed. Bulk densities were estimated by dividing the oven-dried weight of soil by the ring volume (347.5 cm^3; Grossman et al., 2002). A water balance was constructed for each core individually as quality control, resulting in the removal of one replicate from the no-cover treatment of the Central-silage trial, which had a large hole visible in the center of the core upon destructive inspection, confirming its justified removal from the dataset.

Soil texture and organic carbon

The oven-dried soil was ground and passed through a 2 mm sieve. Two teaspoons of soil (~10 grams) from each core were used for soil texture measurements. Soil texture was quantified using laser diffractometry (Miller and Schaetzl, 2012) with a Malvern Mastersizer 3000 and a HydroEV attachment (Malvern Panalytical Ltd, UK), producing estimates for the percentage of the soil that was sand (50-2000 µm), silt (6-50 µm), and clay (0.1-6 µm). Half of the remaining oven-dried soil cores were sent for organic matter analysis (Agsource, Ellsworth Iowa, USA) using the loss-on-ignition method (Nelson and Sommers, 1996). While this method may not produce reliable absolute estimates of organic matter (Hoogsteen et al., 2015), our interest was in pairwise comparisons of treatments rather than in obtaining absolute estimates of organic matter.

Statistical analysis

All data analysis, figure creation, and model fitting were done using *R* version 4.0.3 (R Core Team, 2020) and the *tidyverse* meta-package (Wickham et al., 2019). Non-linear models were fit using the *nlraa* (Miguez, 2021) package functionality, with specific equation fits from the *HydroMe* (Omuto et al., 2021) and *soilphysics* (de Lima et al., 2021) packages. Linear models were fit and summarized using the *lme4* (Bates et al., 2015) package, which fits mixed effects models, and the *emmeans* (Lenth et al., 2018) package, which estimates both marginal and conditional means and confidence intervals and performs pairwise comparisons.

We fit the Gardner (Gardner, 1958) and van Genutchen (van Genuchten, 1980) models to describe the relationship between soil moisture and soil water matric potential in our datasets. We found the models produced similar Akaike's Information Criteria (AIC; Bozdogan, 1987) values, with the Gardner model showing a slightly better fit. The Gardner equation is as follows:

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{1 + a\psi^n}$$

where θ is the volumetric moisture content at a given soil water potential ψ; the remaining variables are fitted parameters. θ_r and θ_s are the residual and saturated water contents, respectively; a approximates the inverse of the pressure at which the retention curve is steepest (e.g., air-entry potential; van Genutchen 1980); and n is an index for the pore size distribution, with higher values indicating a broader distribution of pore sizes. We fit the Gardner model to each experimental unit, then analyzed the air-entry and pore-size distribution parameters as response variables, described below. Residual water contents (θ_r) are estimated by the model, and can occur at suction pressures greater than -15,000 cmH_2O (SSSA, 2008). The highest suction presssure applied to samples in this study was -500 cmH_2O, which could lead to less stable model fits due to lack of an anchoring value (Groenevelt and Grant, 2004). To determine whether the model produced reasonable estimates without these anchoring values, we compared (1) the model-estimated saturated water contents with the measured values, and (2) the pore-size distribution parameter estimate against values estimated using capillary rise equations, which assumes the mean pore neck diameter (in cm) of drained pores at a given pressure is equal to 0.3 divided by the head pressure (cmH_2O). Pores with mean neck diameters greater than 30 μm were considered macropores (Kirkham, 2014). The percent macropores was assessed as a response variable, described below.

Volumetric water contents at saturation were extracted directly from the measured values. Volumetric water contents at field capacity were estimated as the measured volumetric water content at a matric potential of -100 cmH_2O (Moore 2021). We used this approximation because the matric potential that approximates field capacity depends on the depth to the water table. The trials sampled all had artificial tile drainage installed at ~1.2 meter depths and had shallow water tables (**Table 1**), meaning field capacity will be at matric potentials less negative than the commonly assumed value of -330 cmH_2O (Bonfante et al., 2020). Soil water retention curve data from Moore (2021) suggest that -100 cmH_2O is a better approximation for field capacity in mollic epipedons with shallow water tables, such as those sampled in the present study.

The effects of trial, CC treatment, and their interaction on response variables (soil texture, organic matter, water contents at saturation and field capacity, air-entry pressures, pore-size distribution index, percent macropores) were assessed using mixed-effect models. Trial, CC treatment, and their interaction were included as fixed effects. Percent sand was investigated as a covariate in appropriate models because texture is the dominant driver of water retention curve parameters (de Jong et al., 1983; Saxton and Rawls, 2006), has a large influence on bulk densities, and can affect soil organic matter accumulation. Models without a sand covariate had random intercept effects for replicates nested within location (East, Central, West), and models that included a sand covariate had fixed effects only. Models were compared using AIC. All statistical results are available in S**upplementary material S3**.

RESULTS AND DISCUSSION

Soil texture, organic matter, and bulk density

Within~~In~~ certain trials, the CC treatment was coincident with differences in sand, silt, as well as clay percentages ($p<0.001$). The percent sand did not vary by CC treatment in the Central-silage trial, but varied significantly ($p<0.01$) at the other three trials (**Supplementary material S3, S4**). Likewise, the percent clay varied by CC treatment in three of the four trials while the percent silt varied by CC treatment in only one trial (West-grain). However, the significant differences between CC and no-cover plots were only of a meaningful magnitude (>1% difference) at the two commerical farm trials (East-grain, West-grain; **Table 2).** In the East-grain trial, the CC plots had 3% more sand compared to the no-cover plots ($p<0.001$). In the West-grain trial, the CC plots had 5% more sand compared to the no-cover plots ($p<0.001$). The increased sand in the CC plots was compensated for by a decrease in clay (East-grain) or a decrease in both clay and silt (West-grain). At both of the Central trials, texture components of the CC and no-cover plots were within 1% of each other.

Table 2. Summary of soil texture components for rye cover crop (CC) and no-cover treatments at each trial, bolded text indicates significant differences at $p<0.01$ greater than 1% in magnitude; totals may not add to 100% due to rounding, see Supplemental material S4 for more precise values.

Trial	Sand	Silt	Clay
	Rye CC /No-cover	*Rye CC/No-cover*	*Rye CC/No-cover*
West-grain (commercial farm)	**31/26%**	**42/45%**	**27/30%**
East-grain (commercial farm)	**13/10%**	56/56%	**32/35%**
Central-silage	30/29%	41/41%	29/30%
Central-grain	32/32%	40/40%	28/28%

While the plots in the commercial farm fields (East-grain, West-grain) were randomly assigned a CC treatment, the treatments were close to regularly alternating strips, with the four blocks laid out side-by-side. If a field has a uniform texture gradient perpendicular to the blocking, this regularly alternating pattern could result in one treatment having significantly different textures compared to the other, as we observed. Additional samples taken at a later date from East-grain trial confirmed the soil texture pattern we observed in the present study (unpublished data), providing further evidence our observations were not due to chance, but rather refelected a true soil texture gradient at the sites. The Central site had six treatments in small plots and the five blocks were located in two rows within the field, with each treatment being randomly assigned within the block; this arrangement may have better randomized treatments with respect to natural patterns of soil texture within the site. Based on these results, sand was included as a covariate in statistical models for response variables potentially affected by soil texture.

Soil organic matter contents ranged from 1.8 to 4.6%, with a signficant trial-by-CC treatment interaction ($p<0.001$). Soil organic matter accumulation may be affected by soil texture (Scott et al., 1996; Bosatta and Agren, 1997), so statistics were run both with and without a sand co-variate to account for the different soil textures in the CC and no-cover treatments observed in some trials. The Central-silage trial showed a significant ($p<0.01$) but small (+0.25%) absolute increase in organic matter with cover cropping, regardless of inclusion of a sand covariate. In the other three trials, the results depended on whether sand was included as a co-variate. Without a sand co-variate, organic matter was estimated to decrease with cover cropping compared to no-cover in three trials (p-values ranging from 0.001-0.048). When a sand co-variate was included in the statistical analysis, organic matter either did not change (Central-grain) or significantly ($p<0.01$) increased with cover cropping by small amounts (+0.19% and +0.26% in the East-grain and West-grain trials, respectively). Due to the sensitivity of the results and the small effect sizes, we conclude cover cropping did not meaningfully affect soil organic matter at this depth in the three grain trials, but may have resulted in a slightly higher organic matter content in the Central-silage trial. This is consistent with a previous study at this same trial, which found higher organic matter in the top 5 cm of soil in CC treatments compared to no-cover, but small differences below that depth (Moore et al., 2014).

Bulk densities varied from 1.2 g cm^{-3} to 1.7 g cm^{-3}. The large size of sand particles reduces packing efficiencies compared with clay, meaning a sandy soil may have lower bulk densities simply due to packing arrangements. However, regardless of the statistical model fit, all estimated CC effects were less than measurement precision of the core method for measuring bulk density (±0.12 g cm^{-3}, Han et al., 2016), rendering their interpretation questionable. A recent summary of research on the effects of CCs on bulk densities likewise found few studies where an overwintering rye CC grown in the US reduced bulk densities more than typical measurement errors (Haruna et al., 2020). We therefore found no evidence that CCs meaningfully affected soil bulk density at 10-18 cm soil depths at any trial.

Soil hydrological properties

Soil texture is the dominant factor determining soil water retention (de Jong et al., 1983; Saxton and Rawls, 2006), particularly under wet conditions (i.e. saturation and field capacity; Manns and Berg, 2014). Because soil texture varied by CC treatment in the two commercial field trials (East-grain, West-grain), sand was included as a co-variate in statistical models assessing the effects of cover cropping on these response variables.

Air-entry potential and pore distribution

The Gardner equation fitting process converged for all experimental units (**Figure 1**), with *a* (an estimate of the inverse of air-entry potential) ranging from 0.001 to 0.284, and *n* (pore-size distribution index) ranging from 0.45 to 1.49.

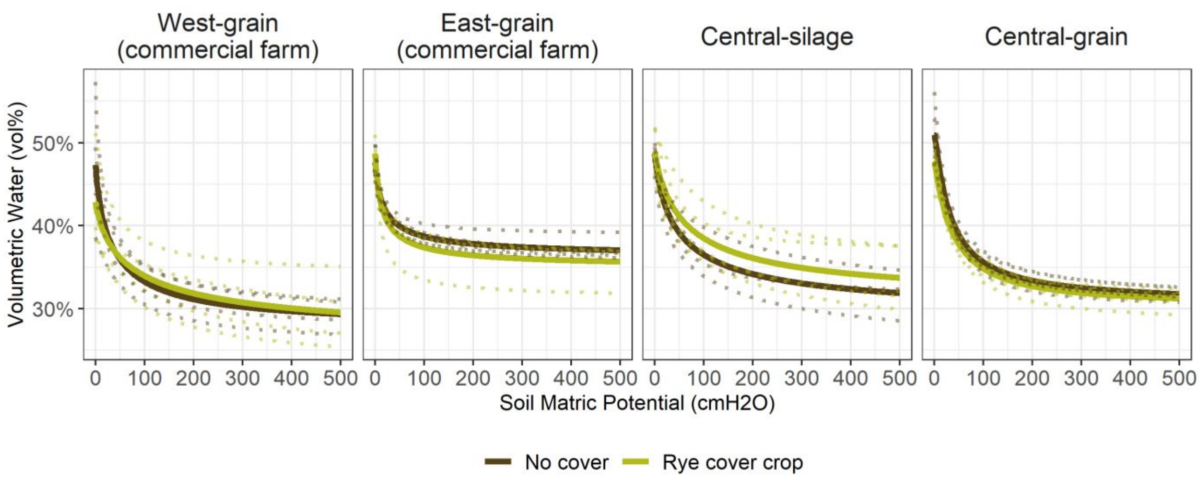

Figure 1. The Gardner equation was fit to each experimental unit (dotted lines); mean values (solid lines) for each trial and cover crop treatment are presented to aid in interpretation.

There was not a significant interaction between trial and CC treatment for either parameter. While both parameters differed significantly by trial ($p<0.001$), cover cropping did not significantly affect either parameter, with or without a sand covariate (**Table 3; Supplemental material S3**).

Table 3. Summary of estimated mean values, standard error of the mean (SE), and significance of the comparison between rye cover crop (CC) and no-cover treatments within a trial (p-value) for Gardner parameters and percent macropores.

Cover crop (CC) treatment	Inverse air-entry potential (Gardner model parameter *a*)		Pore-size distribution (Gardner model parameter *n*)		Percent macropores (capillary rise equation)	
	mean(SE)	p-value	mean(SE)	p-value	mean(SE)	p-value
	cmH_2O^{-1}		*unitless*		%	
West-grain (commercial farm)						
Rye CC	0.03(0.01)	0.15	0.83(0.09)	0.60	48(5)	0.05
No cover	0.05(0.01)		0.90(0.09)		61(5)	
East-grain (commerical farm)						
Rye CC	0.11(0.01)	0.14	0.83(0.09)	0.96	73(5)	0.75
No cover	0.08(0.01)		0.82(0.08)		71(5)	
Central-grain						
Rye CC	0.02(0.01)	0.97	1.15(0.08)	0.67	59(4)	0.61
No cover	0.02(0.01)		1.10(0.08)		62(4)	
Central-silage						
Rye CC	0.03(0.01)	0.32	0.90(0.08)	0.52	54(4)	0.40
No cover	0.04(0.01)		0.82(0.09)		59(5)	

When compared across trials, the *a* parameter was strongly related to the percentage of sand in the trial's soil, with the East-grain trial having the lowest sand content (mean of 11%) and highest *a* estimate (mean of 0.09), and the Central-grain trial having the highest sand content (mean of 32% sand) and lowest *a* estimate (mean of 0.02). This inverse relationship is consistent with empirical equations relating air-entry potential to soil texture (Saxton and Rawls 2006). However, even with a sand co-variate, cover cropping did not significantly affect air-entry pressures nor pore-size distributions.

Consistent with the lack of CC effect on the Gardner equation's pore-size distribution parameter (*n*) manual estimation of the pore-size distribution confirmed CCs did not increase the percentage of macropores in any trial (**Table 3**; **Supplemental material S5.** In a review of published studies, Haruna et al. (2020) found the effect of CCs on macropore makeup of the soil highly variable, but with an overall average increase. The wide variation may be partially due to varying cut-offs in pore sizes for macropore categorization (Luxmoore, 1981), but the variability in combination with our results again demonstrates using literature averages to predict CC impacts in Midwestern systems may be inappropriate.

Soil water at saturation and field-capacity

For these analyses we assigned significance at p-values less than 0.10. With or without a sand covariate, no trial exhibited a significant increase in water held at saturation with the use of cover cropping (**Figure 2**). Water held at saturation is largely dependent on bulk density, so these findings are consistent with the lack of meaningful effect of CCs on bulk densities in our study. Field capacities were signifiantly higher in the cover cropped plots at one commercial farm (West-grain; $p = 0.07$) and one USDA trial (Central-silage; $p = 0.05$). At the West-grain trial, the soil water at field capacity increased (after sand correction) from 33.6 to 36.0 vol%, and at the Central-silage trial from 38.1 to 40.6 vol%, respectively. An increase in the soil's ability to hold water after gravity drainage may also contribute to peak water flow regulation. By increasing volumetric water content at field capacity by 2 vol% in the 0-20 cm profile, CC fields could hold an additional 40,000 L of water in each 20-cm hectare slice, which could meaningfully reduce the amount of water drained from a field after a saturating rain. For comparison, evapotranspiration rates in an over-wintered rye cover crop with modest biomass production can be ~ 24,000 L ha^{-1} day^{-1} (Qi and Helmers, 2010), and peak flows from sub-surface drainge tiles in central Iowa can be ~22,000 L ha^{-1} $hour^{-1}$ (Daigh et al. 2014). To our knowledge there are limited studies examining the potential for CCs to reduce flood damage in the Midwest, but the one we are aware of accounts for only the increased evapo-transipiration with the use of CCs (Antolini et al., 2020). Our study suggests that in addition to reducing run-off (Korucu et al. 2018), considering how CC-induced increases in the amount of water held in a soil at field capacity affect flood incidence and severity would be worth investigating. Furthermore, as other studies have noted, an increase in the amount of water held at field capacity results in more precipitation being stored for cash crop use (Basche et al. 2016; Leuthold et al. 2021), meaning in some cases long-term use of CCs could lead to more stable cash crop yields (Williams et al. 2018).

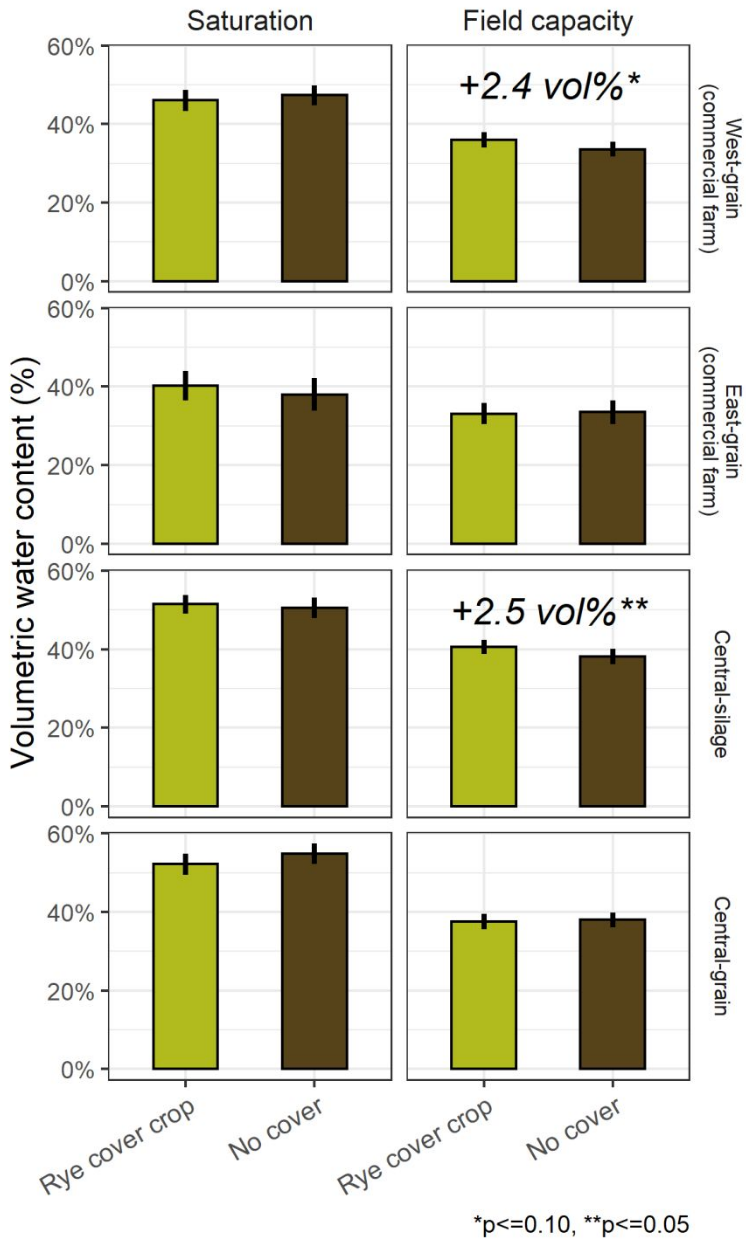

Figure 2. Soil volumetric water contents at saturation and field capacity (-100 cmH2O) with 10+ years of winter rye cover cropping (green) or winter fallow (brown) in a maize-soybean rotation at four trials. Bars show estimated means, line ranges are the 95% confidence intervals around the mean. Text

presents the estimated effect of cover cropping on volumetric water content in instances of a significant effect.

Factors explaining variable results

The West-grain and Central-silage trials both exhibited significantly higher soil water at field capacity with the use of cover cropping compared to winter fallows. However, the West-grain trial consistently produced the lowest above-ground CC biomass, and the Central-silage trial the highest (**Table 1**), indicating the changes in water held at field capacity are likely not associated with CC above-ground biomass production. Although a previous study suggested soil texture could mediate the effects of long-term CC-use (Blanco-Canqui and Jasa, 2019), in our dataset there was no pattern between soil textural characteristics and the magnitude of CC effect on water held at field capacity. This means knowledge of a soil's texture did not help predict whether a CC would affect water held at field capacity in our study.

The West-grain trial was sampled following a soybean crop, and the Central-silage following a silage crop, while the two trials without significant CC effects were both sampled following a maize-grain crop (**Table 1**). Soybean and maize-silage crops would leave less residue compared to a preceeding maize-grain crop, however this study did not measure residue amounts at the time of sampling. Given the lack of insight into what may be driving the variable effects given the available data, we explored potential causes for our variable results and identified additional measurements that may aid in identifying drivers of the variable effects of CCs on soil hydrological properties.

Causal model

There are several pathways by which CCs might affect a soil's capacity to hold water (**Figure 3**). The causal model was built using literature relevant to Midwestern systems, and when applicable was limited to evidence drawn from research conducted with a cereal rye cover crop (**Supplemental material S6**). The model was simplified to exclude the effects of soil erosion, soil texture, tillage, and landscape position, which are all factors that could potentially influence how soil responds to cover cropping (Moore 2021). Rather, we present this simple casusal model to provide a base from which to build.

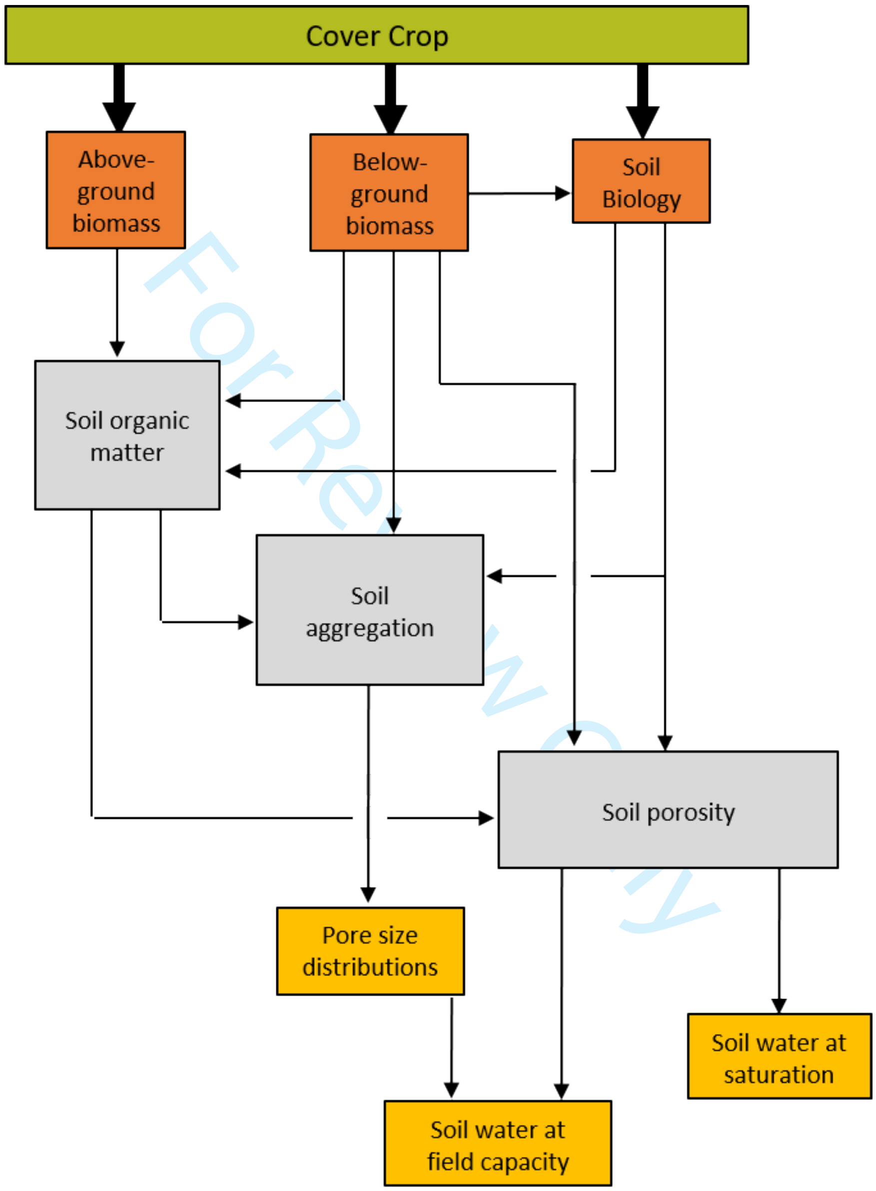

Figure 3. Pathways by which cover crops may affect the soil pore size distributions, the amount of water stored at field capacity, and the amount of water at saturation in no-till systems. The effects of soil erosion are not included. X→Y should be read as 'X affects Y'.

Causal diagrams such as **Figure 3** are the basis for constructing structural equation models, which can greatly enhance researchers' ability to address complex research questions in agriculture (Smith et al., 2014; Wade et al., 2020). For example, in our proposed causal diagram, below-ground biomass measurements are necessary for estimating direct effects of cover cropping on pore size distributions, field capacity, and saturation. This is further supported by recent studies and reviews that identify CC roots as being a crucial component to understanding CC effects on soil properties (Williams and Weil, 2004; Haruna et al., 2020; Ogilvie et al., 2021). While there is limited data available pairing above- and below-ground biomass of CCs, data collected in Iowa over a five-year period showed no relationship between above- and below-ground rye biomass, with root-to-shoot ratios varying from 0.16-1.94 at similar levels of aboveground biomass production (Martinez-Feria et al., 2016). Therefore, above-ground biomass production cannot be used as a proxy for below-ground production with much confidence, and studies that pair above- and below-ground CC biomass with soil measurements would be advantageous in enhancing our understanding of CC effects on soil.

CONCLUSIONS

We found CCs increased water held at field capacity at the 10-18 cm soil range in two of the four trials sampled. The observed increases were of a meaningful magnitude that could contribute to cash crop water needs, and may have implications for flooding severity in agricultural regions and should be considered when modelling cover crop effects on landscape water balances. We were unable to explain the trial-dependent effects using the available measurements and information. Based on a proposed causal model, we suggest researchers measure CC root biomass in addition to above-ground biomass when examining the effects of CCs on soil properties. Effects of growing over-wintering CCs need to be explicitly investigated in the

Midwestern US, as the constraints of maize-soybean systems may render the effects smaller in magnitude compared to averages reported by global meta-analyses.

SUPPLEMENTAL MATERIAL

S1 - A map of trial locations

S2 - Detailed description of management practices and historical cover crop biomass production for each trial

S3 - Statistical summaries

S4 – Detailed soil texture results

S6 – Causal model literature support

DATA AVAILABILITY

The data are available as downloadable csv files in supplementary material. Additionally, all data are available in an R package (https://github.com/vanichols/PFIswhc) and the R code used in processing and summarizing data for this publication is available in a github repository (will be created once paper is accepted).

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTIBUTIONS

VN contributed to conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, writing of original draft, and review/editing. ML contributed to funding acquisition, project administration, supervision, and review/editing of draft. SG contributed to project administration, resources, and review/editing. EM contributed to methodology, resources, and review/editing.

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Supplementary Material for 'Winter Cover Cropping Effects on Soil Water-Holding Capacity Vary by Site'

Nichols et al. 2021

6/15/2021

Supplemental material S1. Map of sites

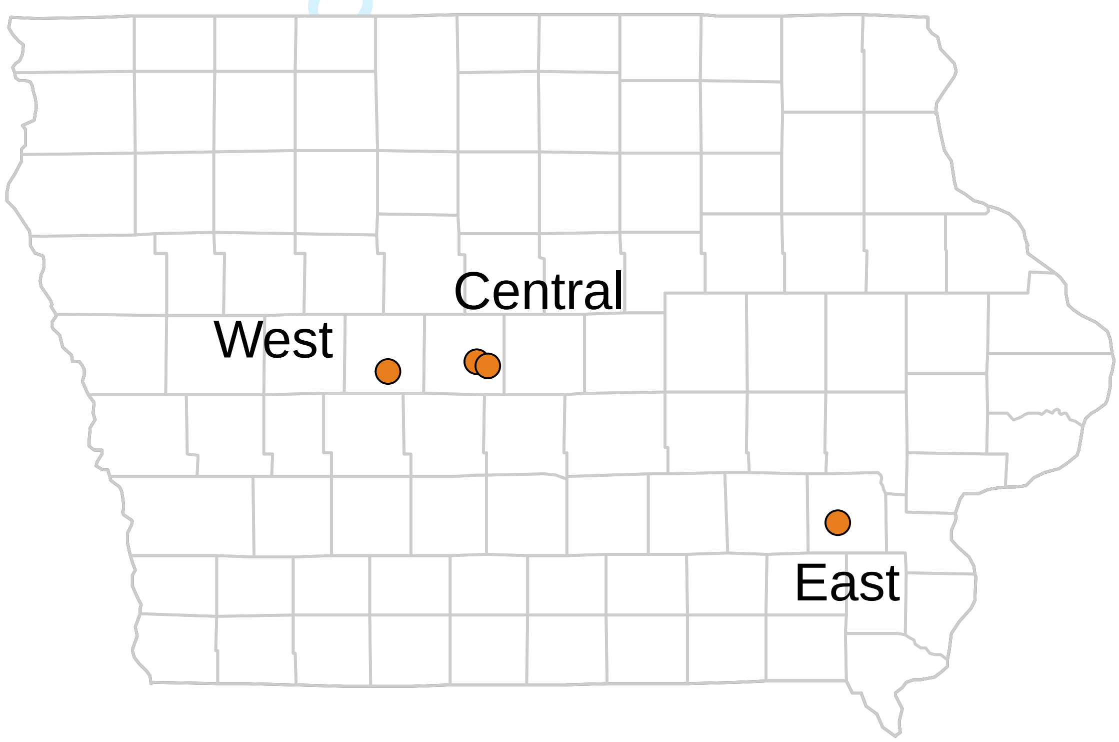

Figure 1: Map of site locations in Iowa

Supplemental material S2. General Site Management Summary

Table 1: General Site Description

Site Description	General Location	Treatment Description	Year of Initiation	Crop Planted in 2019	Number of Treatment Replicates	Sampled in 2019
Central Grain	Boyd Farm, Boone, field 44	maize/soybea grain rotation, with and without rye cover crop	2009	maize	5	Y
	Boyd Farm, Boone, field 42	maize/soybean grain rotation, with and without rye cover crop	2009	soy	5	Y
Central Silage	Boyd Farm, Boone, field 44	maize silage/soybea grain rotation, with and without rye cover crop	2002	maize silage	5	Y
	Boyd Farm, Boone, field 42	maize silage/soybean grain rotation, with and without rye cover crop	2002	soy	5	N
West	Jefferson, IA	maize/soybea grain rotation, with and without rye cover crop	2008	maize	4	Y
East	Washington, IA	maize/soybean grain rotation, with and without rye cover crop	2009	soybeans	4	Y

Table 2: 2018-2019 Herbicide Use

Site Description	Herbicides Used in 2018 Growing Season	Herbicdes Used in Fall 2018	Herbicides Used in Spring 2019
Central Grain	glyphosate 1 week before soybean planting	none	glyphosate 1 week before maize planting; metalochlor, atrazine, and mesotrione at planting
Central Grain	glyphosate 1 week before maize planting; metalochlor, atrazine, and mesotrione at planting	none	glyphosate 1 week before soybean planting
Central Silage	glyphosate 1 week before soybean planting	none	glyphosate 1 week before maize planting; metalochlor, atrazine, and mesotrione at planting
Central Silage	glyphosate 1 week before maize planting; metalochlor, atrazine, and mesotrione at planting	none	glyphosate 1 week before soybean planting
West	glyphosate before planting; glyphosate and fluthiacet-methyl at planting	none	glyphosate before planting; glyphosate and fluthiacet-methyl at planting
East	glyphosate and acetochlor before planting (April 15), atrazine, acetochlor at planting (May 14); acetochlor and glyphosate after planting (June 15)	none	chlorimuron-ethyl, flumioxazin, pyroxasulfone, and glyphosate before planting, dicamba and acetochlor after planting

Table 3: General Management

Site Description	General Herbicide Regime	General Date of Cover Crop Termination	General Date of Crop Planting	Inorganic Fertilizer Used	Organic Fertilizer Used	Tillage Used
Central Grain	burndown, residual herbicide at maize planting	15-Apr	26-Apr	Y	NA	N
Central Grain	burndown, residual herbicide at maize planting	25-Apr	5-May	Y	NA	N
Central Silage	burndown, residual herbicide at maize planting	15-Apr	26-Apr	Y	NA	N
Central Silage	burndown, residual herbicide at maize planting	25-Apr	5-May	Y	NA	N
West	burndown, pre-emergent herbicide	1-May	10-May	Y	chicken or turkey manure	N
East	burndown, residual herbicide at planting, another application on maize at ~V6	1-May	5-May	Y	liquid swine, ~3000 gal/ac every other year to entire field	N

Cover crop biomass production over past 10 years of trials

Table 4: Historical cover crop biomass production (Mg/ha) by trial

trial	2010	2011	2012	2013	2014	2015	2016	2017	2019	2018
Central_grain	0.86	0.28	1.37	0.25	0.47	0.61	2.22	2.76	1.29	NA
Central_silage	1.59	1.72	3.32	1.26	0.91	1.76	4.23	2.21	2.05	NA
East_grain	2.11	1.46	0.00	0.92	0.00	0.36	0.51	7.30	0.30	0.19
West_grain	2.11	0.21	1.33	0.00	0.00	0.04	0.45	0.63	0.00	0.09

Supplemental material S3. Statistical summaries

Clay, silt, and sand components

Table 5: Statistical analysis of cover crop effect on clay

site_sys	respvar	cc	no	contrast	est_diff	diff_se	diff_pval
Central_grain	clay	27.740	28.000	cc - no	-0.260	0.186	0.164
Central_silage	clay	28.751	29.895	cc - no	-1.144	0.208	<0.001
East_grain	clay	31.730	34.606	cc - no	-2.876	0.208	<0.001
West_grain	clay	27.349	29.511	cc - no	-2.162	0.208	<0.001

Table 6: Statistical analysis of cover crop effect on silt

site_sys	respvar	cc	no	contrast	est_diff	diff_se	diff_pval
Central_grain	silt	39.772	40.399	cc - no	-0.627	0.206	0.003
Central_silage	silt	41.313	40.793	cc - no	0.520	0.230	0.025
East_grain	silt	55.552	55.557	cc - no	-0.005	0.230	0.983
West_grain	silt	41.896	44.728	cc - no	-2.831	0.230	<0.001

Table 7: Statistical analysis of cover crop effect on sand

site_sys	respvar	cc	no	contrast	est_diff	diff_se	diff_pval
Central_grain	sand	32.486	31.600	cc - no	0.886	0.299	0.003
Central_silage	sand	29.811	29.233	cc - no	0.578	0.335	0.085
East_grain	sand	12.715	9.837	cc - no	2.877	0.335	<0.001
West_grain	sand	30.506	25.610	cc - no	4.896	0.335	<0.001

Soil organic matter

Table 8: Statistical analysis of cover crop effect on organic matter, with and without sand covariate

cov	site_sys	respvar	cc	no	contrast	est_diff	diff_se	diff_pval
none	Central_grain	om	2.360	2.480	cc - no	-0.120	0.051	0.02
none	Central_silage	om	2.640	2.416	cc - no	0.224	0.057	<0.001
none	East_grain	om	3.575	3.675	cc - no	-0.100	0.057	0.082
	West_grain	om	2.750	2.975	cc - no	-0.225	0.057	<0.001
sand	Central_grain	om	3.034	3.066	cc - no	-0.032	0.082	0.696
sand	Central_silage	om	3.049	2.772	cc - no	0.278	0.088	0.002
sand	East_grain	om	2.290	2.105	cc - no	0.185	0.093	0.048
	West_grain	om	3.228	2.968	cc - no	0.260	0.096	0.007

Soil bulk density

Table 9: Mean bulk density (g/cm3) by trial

site_name	sys_trt	crop_trt	cc_trt	bulkden_mean	bulkden_sd
Central	grain	soy	cc	1.42	0.08
	grain	soy	no	1.37	0.07
	silage	soy	cc	1.46	0.06
	silage	soy	no	1.44	0.07
East	grain	soy	cc	1.44	0.05
	grain	soy	no	1.49	0.04
West	grain	corn	cc	1.57	0.14
	grain	corn	no	1.47	0.21

Table 10: Statistical analysis of cover crop effect on bulk density, with and without sand covariate

cov	site_sys	respvar	cc	no	contrast	est_diff	diff_se	diff_pval
none	Central_grain	bd	1.422	1.374	cc - no	0.048	0.010	<0.001
	Central_silage	bd	1.464	1.436	cc - no	0.028	0.011	0.012
	East_grain	bd	1.437	1.488	cc - no	-0.050	0.011	<0.001
	West_grain	bd	1.573	1.472	cc - no	0.101	0.011	<0.001
sand	Central_grain	bd	1.309	1.275	cc - no	0.033	0.013	0.011
	Central_silage	bd	1.395	1.386	cc - no	0.010	0.014	0.483
	East_grain	bd	1.653	1.752	cc - no	-0.098	0.015	<0.001
	West_grain	bd	1.493	1.473	cc - no	0.020	0.015	0.188

Soil moisture (%vol) at saturation

Table 11: Statistical analysis of cover crop effect on soil water at saturation, with and without sand covariate

cov	site_sys	term	contrast	estimate	std.error	df	statistic	adj.p.value	param
sand	Central_grain	cc_trt	cc effect	-0.013	0.008	26.000	-1.688	0.103	saturation
	Central_silage	cc_trt	cc effect	0.004	0.008	26.000	0.510	0.614	saturation
	East_grain	cc_trt	cc effect	0.011	0.009	26.000	1.271	0.215	saturation
	West_grain	cc_trt	cc effect	-0.007	0.009	26.000	-0.729	0.473	saturation
none	Central_grain	cc_trt	cc effect	-0.016	0.008	13.050	-1.959	0.072	saturation
	Central_silage	cc_trt	cc effect	0.002	0.009	14.068	0.246	0.809	saturation
	East_grain	cc_trt	cc effect	0.002	0.009	13.050	0.228	0.823	saturation
	West_grain	cc_trt	cc effect	-0.022	0.009	13.050	-2.430	0.030	saturation

Soil moisture (%vol) at field capacity (-100 cm water)

Table 12: Statistical analysis of cover crop effect on soil water at field capacity, with and without sand covariate

cov	site_sys	term	contrast	estimate	std.error	df	statistic	adj.p.value	param
sand	Central_grain	cc_trt	cc effect	-0.002	0.006	26.000	-0.430	0.671	field capacity
sand	Central_silage	cc_trt	cc effect	0.012	0.006	26.000	2.041	0.052	field capacity
sand	East_grain	cc_trt	cc effect	-0.002	0.006	26.000	-0.353	0.727	field capacity
	West_grain	cc_trt	cc effect	0.012	0.007	26.000	1.835	0.078	field capacity
none	Central_grain	cc_trt	cc effect	-0.004	0.005	13.044	-0.800	0.438	field capacity
none	Central_silage	cc_trt	cc effect	0.012	0.006	14.005	2.242	0.042	field capacity
none	East_grain	cc_trt	cc effect	-0.007	0.006	13.044	-1.317	0.211	field capacity
	West_grain	cc_trt	cc effect	0.003	0.006	13.044	0.597	0.561	field capacity

Fitted parameters a and n

Table 13: Table of 'a' Gardener parameter estimate

site_sys	cc_trt	rep	estimate	std.error
Central_grain	cc	1	0.043	0.010
		2	0.025	0.006
		3	0.015	0.012
		4	0.021	0.010
		5	0.002	0.001
	no	1	0.020	0.010
		2	0.025	0.009
		3	0.010	0.005
		4	0.013	0.007
		5	0.041	0.014
Central_silage	cc	1	0.028	0.014
		2	0.030	0.013
		3	0.011	0.008
		4	0.015	0.011
		5	0.044	0.013
	no	1	0.049	0.029
		2	0.046	0.014
		3	0.048	0.014
		4	0.016	0.007
East_grain	cc	1	0.100	0.027
		2	0.180	0.046
		3	0.054	0.022
		4	0.085	0.024
	no	1	0.088	0.022
		2	0.080	0.028
		3	0.073	0.026
		4	0.080	0.024
		5	0.092	0.029
West_grain	cc	1	0.007	0.008
		2	0.026	0.006
		3	0.039	0.016
		4	0.032	0.015
	no	1	0.013	0.013
		2	0.029	0.012
		3	0.051	0.017
		4	0.102	0.017

Table 14: Table of 'n' Gardener parameter estimate

site_sys	cc_trt	rep	estimate	std.error
Central_grain	cc	1	0.987	0.079
		2	1.099	0.073
		3	1.106	0.219
		4	1.086	0.141
		5	1.468	0.198
	no	1	0.999	0.154
		2	1.007	0.110
		3	1.291	0.139
		4	1.264	0.153
		5	0.949	0.112
Central_silage	cc	1	0.813	0.158
		2	0.850	0.137
		3	1.006	0.220
		4	1.173	0.212
		5	0.639	0.116
	no	1	0.923	0.197
		2	0.705	0.108
		3	0.614	0.121
		4	1.041	0.125
East_grain	cc	1	0.772	0.104
		2	0.817	0.115
		3	0.994	0.140
		4	0.740	0.105
	no	1	0.651	0.099
		2	0.973	0.133
		3	0.880	0.131
		4	0.880	0.110
		5	0.737	0.116
West_grain	cc	1	1.009	0.305
		2	0.834	0.071
		3	0.488	0.175
		4	0.997	0.145
	no	1	1.039	0.268
		2	0.970	0.133
		3	0.837	0.110
		4	0.743	0.064

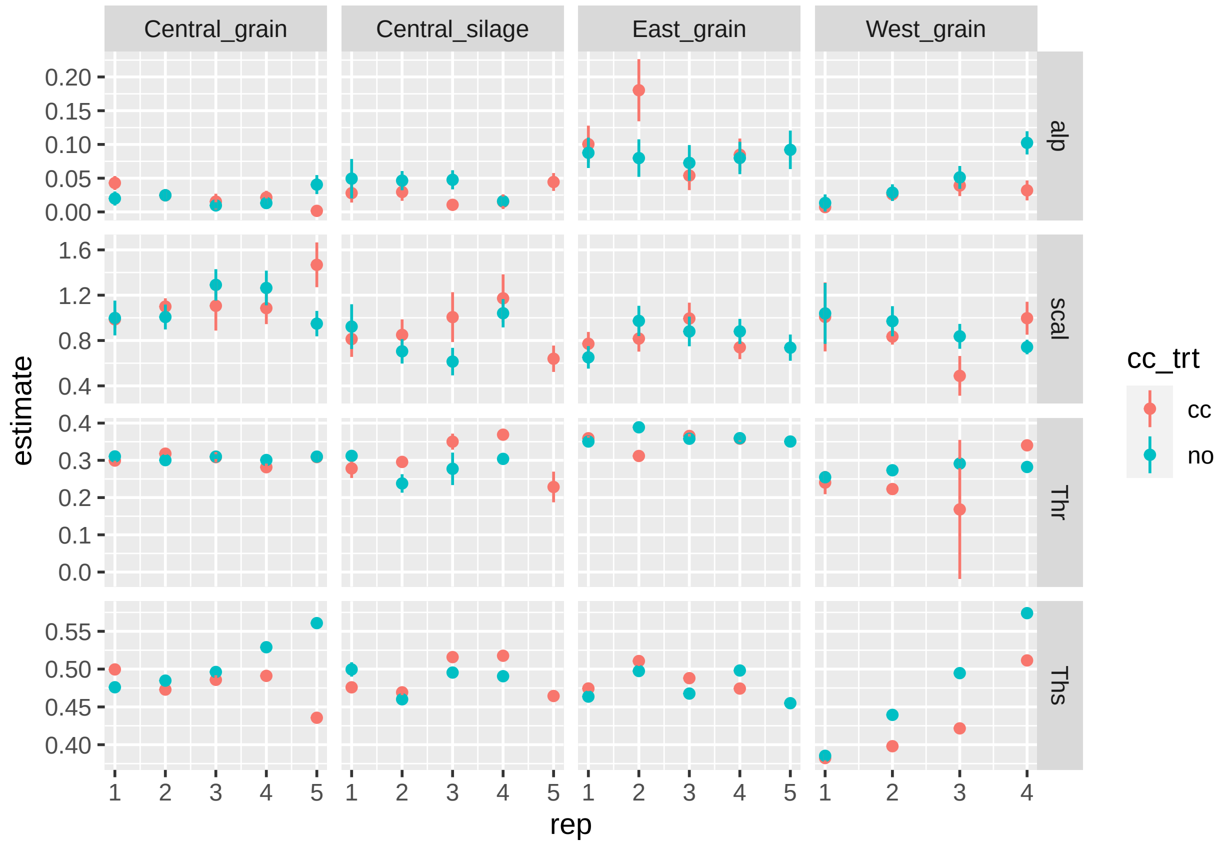

Figure 2: Non-linear model fitted parameters

Macro-pore percentages

Table 15: Table of macropores estimates and comparisons

site_sys	cc_trt	estimate	df	conf.low	conf.high	contrast	est_diff	pval_diff
Central-grain	cc	0.589	26.228	0.518	0.660	cc - no	-0.029	0.606
	no	0.618	26.228	0.547	0.689	cc - no		
Central-silage	cc	0.535	26.228	0.464	0.606	cc - no	-0.051	0.403
	no	0.586	26.989	0.506	0.665	cc - no		
East-grain	cc	0.731	26.989	0.651	0.811	cc - no	0.019	0.750
	no	0.712	26.228	0.641	0.783	cc - no		
West-grain	cc	0.478	26.989	0.399	0.558	cc - no	-0.127	0.053
	no	0.605	26.989	0.525	0.685	cc - no		

Supplemental material S4. Detailed soil texture results

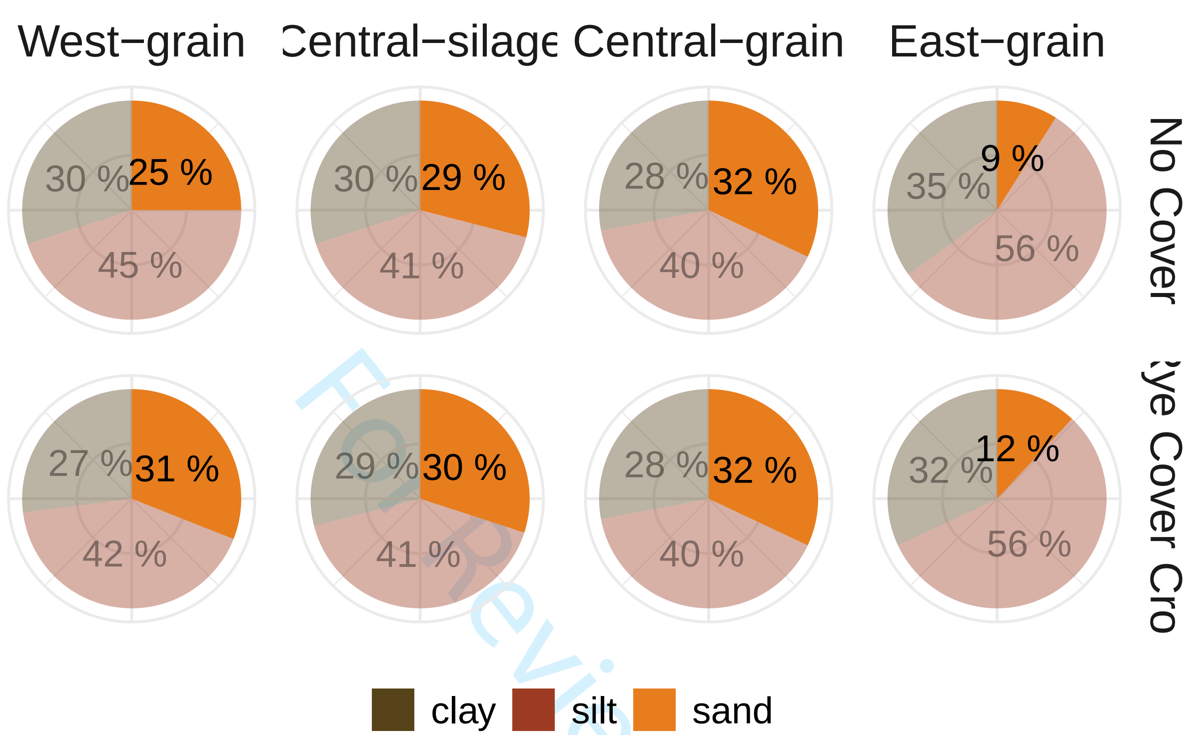

Figure 3: Soil texture components varied by trial and cover crop treatment, with the cover cropped plots having significantly more sand bolded orange color, and significantly less clay at the West-grain and East-grain trials both, commercial fields

Table with values:

Table 16: Table of values

site_sys	cc_trt	clay	sand	silt	tot	sig_sand_diff
Central-grain	cc	0.28	0.32	0.40	1	No
	no	0.28	0.32	0.40	1	
Central-silage	cc	0.29	0.30	0.41	1	
	no	0.30	0.29	0.41	1	
East-grain	cc	0.32	0.12	0.56	1	Yes
	no	0.35	0.09	0.56	1	
West-grain	cc	0.27	0.31	0.42	1	
	no	0.30	0.25	0.45	1	

Table 17: Table of sand statistics

site_sys	respvar	cc	no	contrast	est_diff	diff_se	pval
Central_grain	sand	32.486	31.600	cc - no	0.886	0.299	0.003
Central_silage	sand	29.811	29.233	cc - no	0.578	0.335	0.085
East_grain	sand	12.715	9.837	cc - no	2.877	0.335	<0.001
West_grain	sand	30.506	25.610	cc - no	4.896	0.335	<0.001