

**Winter Cover Cropping Effects on Soil Water Storage Vary
by Site: Field Measurements and a Proposed Causal Model**

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Manuscripts

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 14 cm depth varied by trial

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: Proposed causal model shows cover crop root measurements may be a key measurement

Core Idea 5: CUST_CORE_IDEA_5 :No data available.

June 29 2021

To the Editorial Board of *Agrosystems Geosciences & Environment*:

On behalf of all co-authors, herewith I am submitting a manuscript entitled "Winter Cover Cropping Effects on Soil Water Storage Vary by Site: Field Measurements and a Proposed Causal Model" to be considered for publication in *Agrosystems Geosciences & Environment*.

This manuscript contains new information on the effects of winter cover cropping in maize and soybean systems in Iowa USA, a state located in one of the most agriculturally productive regions in the world. We performed this study to address a lack of data concerning the long-term effects of cover cropping on soil water storage and to generate knowledge to support assessments and modelling of cover crop's potential to increase productive capacity, adaptive abilities, and environmental sustainability. Our study offers several innovative aspects:

Soil sampling from long-term (10+ years) cover crop experiments

Sampling from multiple sites across Iowa

Sampling at a 10-18 cm soil depth which may be more relevant than shallow sampling when considering crop water needs

First graphical model of proposed causal links between cover crops and soil water storage

This unique dataset allowed us to demonstrate the large amount of variability in how soils respond to winter cover cropping. Our analysis indicated that above-ground cover crop biomass is a poor predictor for the magnitude of soil water storage changes with cover cropping. We propose measuring below-ground biomass as an area of future focus, and support this with a graphical analysis of a causal diagram.

Given the implications of soil water storage on agriculture and the environment we believe this contribution is a very relevant to your journal.

Sincerely,



Virginia Nichols

PhD student, Department of Agronomy, Iowa State University

**Winter Cover Cropping Effects on Soil Water Storage Vary by Site: Field Measurements
and a Proposed Causal Model**

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Abbreviations:

CC, cover crop

USDA, United States Department of Agriculture

Core ideas

- Cover crop effects on soil water storage at 14 cm depth varied by trial
- 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
- Proposed causal model shows cover crop root measurements may be a key measurement

ABSTRACT

Addition of an over-wintering cereal rye (~~*Secale cereal*~~) cover crop (CC) to Midwestern maize (*Zea mays*)-based systems offers several environmental benefits, but the long-term effects on soil

hydrological properties are not well-understood. We utilized four long-term (10+ year) no-till trials in Iowa, USA that included a replicated winter rye CC and no-cover treatment in systems with a maize crop (grain or silage) rotated with soybean (*Glycine max*). At each trial, we took intact 7.62 cm diameter soil samples from a 10-18 cm depth increment shortly after cash crop planting in the spring of 2019. We measured the volumetric soil water content at saturation and matric potentials of -3.8, -10, -25, -50, -100, -200 and -500 cmH₂O. Additionally, we measured organic matter, soil texture, and bulk densities of the samples. Pore-size distribution indices and air-entry potentials were estimated from non-linear models fit to the soil water retention curves, and percent macropores (>30 μ m) was estimated from the capillary rise equation. Water contents at saturation and at field capacity (0 and -100 cmH₂O, respectively) were taken directly from the data. Neither pore-size distribution nor air-entry potential (model parameters) were affected by CCs. At the depth sampled, CCs did not meaningfully affect bulk density or water contents at saturation at any trial, nor did CCs increase the percentage of macropores. At two trials, soil water content at field capacity increased with CCs by 2.5% (SE: 1.2%) and 2.4% (SE:1.3%), respectively. The presence or absence of a CC effect on field capacity was not related to CC above-ground biomass production or soil texture at the trial sites. We propose a causal model relating CCs to soil properties relevant to soil water that indicates root characteristics may be key to understanding variable effects of CCs on soil water storage. Our results indicate more research is needed on the exact mechanisms by which CCs can affect soil water storage, as well as when and where potential benefits may be most easily realized.

INTRODUCTION

Addition of an over-wintering cereal rye (*Secale cereale*) cover crop (CC) to Midwestern maize (*Zea mays*)-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; Kladvko 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 that long-term cover cropping could stabilize crop yields. In Midwestern rain-fed systems, crops rely on stored soil water and often suffer from drought stress (Campos et al., 2006). In these systems, CCs may induce changes in soil characteristics such as increased organic matter, lower bulk densities, and more macro-pores (Haruna et al., 2020a). 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 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 contradicting results (Villamil et al., 2006; Haruna and Nkongolo, 2015; Basche et al., 2016; Rorick and Kladvko, 2017; Irmak et al., 2018). Region-specific studies are needed, as climatic and managerial constraints of maize-soybean rotations can limit CC options and growth potential (Strock et al., 2004; Baker and Griffis, 2009; Nichols et al., 2020b).

In addition to regional differences in CC effects, the duration of cover cropping may also influence whether changes in soil are detected. Long-term studies on tillage 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 improved soil hydrological properties can be detected, necessitating data collection from long-term experiments. Furthermore, while shallow soil depths (0-10cm) may be more responsive to CC effects e.g. (Atwood and Wood, 2006; Moore et al., 2014), deeper depths may be more important when considering the soil's contribution to the crop's water supply (Williams et al., 2008; Asbjornsen et al., 2008; Rizzo et al., 2018).

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

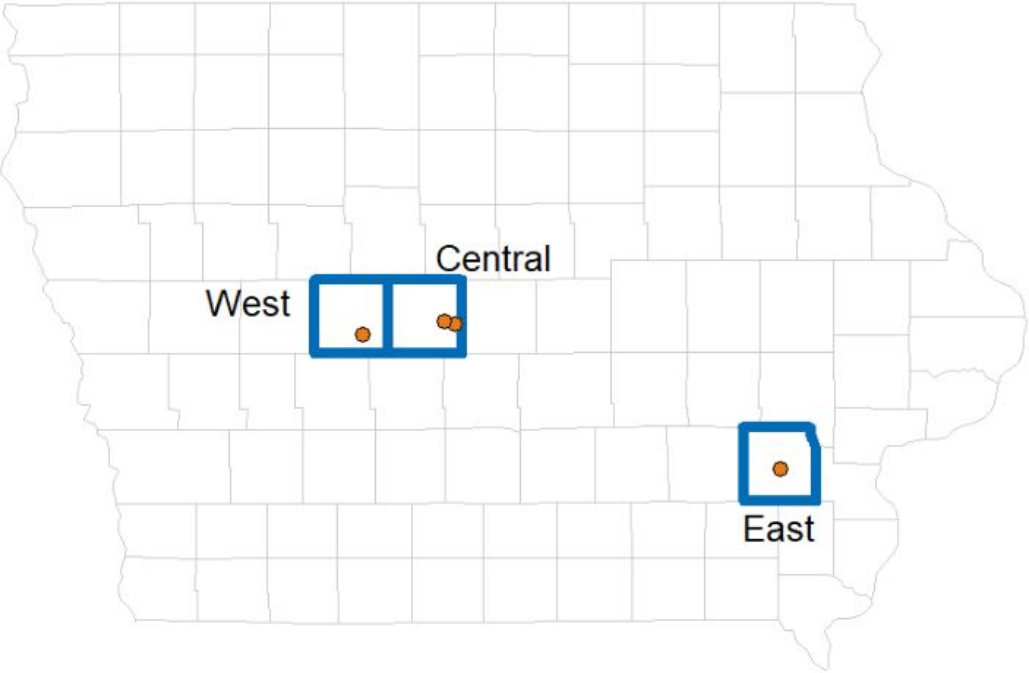
Given the need to quantify long-term benefits of cover cropping, the scarcity of Midwest-specific data, and lack of a framework for organizing relevant knowledge, the objectives of our study were to (1) determine what aspects of a soil's hydrological characteristics are affected by long-term cover cropping at a depth relevant to crop production, and (2) use our findings to propose a causal model connecting CCs to changes in soil properties to aid in targeting future research. 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-farm production fields, and two trials were part of a larger 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 on the shallow water tables that characterize landscapes in this region (~100 cm H₂O, Moore 2021), and pore-size distributions as estimated by 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 (Pearl, 2010).

MATERIALS AND METHODS

Site descriptions

Three long-term sites were used for this study (**Figure 1**), 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

122 planted yearly in the fall following cash crop harvest and terminated in the spring, and (2) the same
123 rotation without a CC. Every trial was arranged in a randomized complete block design with four (West
124 and East) or five (Central) replicates. The plots within each trial were managed identically save for the
125 planting of the CC in the fall. The exact herbicide and nutrient programs varied by site, reflective of their
126 particular managers and contexts (**Supplementary Tables S1, S2, S3**). More detailed accounts of
127 agronomic management have been published elsewhere for the research and commercial farm sites
128 (Moore et al., 2014; Nichols et al., 2020a). All sites had sub-surface tile drainage and were managed
129 without tillage since initiation of the trials.



130 **Figure 1.** Map of Iowa showing locations of the three experimental sites (West, Central, East), with the Central site containing two trials.

131

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

| Plot Size and Average Slope* | Treatment Replications | Dominant Soil Types* | Average Depth to Water Table* | 30-year Annual Mean | | Mean Cover Crop Biomass | | 2018 Crop | 2019 Sampling Date |
|--|---------------------------|-------------------------------|----------------------------------|---------------------|---------------|----------------------------|---------------------------|-----------|--------------------------|
| | | | | Air Temperature | Precipitation | 5-year | 10-year | | |
| <i>m</i> | | | <i>cm</i> | <i>°C</i> | <i>mm</i> | <i>Mg ha⁻¹</i> | <i>Mg ha⁻¹</i> | | |
| <i>West-grain (commercial farm); 41°55'N 94°36'W; initiated in 2008</i> | | | | | | | | | |
| 25 x 250 (1-3%) | 4 | Nicollet loam | 67 | 9.5 | 880 | 0.24 | 0.45 | Soybean | May 23 |
| <i>Central-silage (research plots); 42°00'N 93°48'W; initiated in 2002</i> | | | | | | | | | |
| 3.8 x 55 (1-3%) | 5 | Clarion loam | 100 | 9.8 | 907 | 2.38 | 1.98 | Maize | June 6 |
| <i>Central-grain (research plots); 42°00'N 93°48'W; initiated in 2009</i> | | | | | | | | | |
| 3.8 x 55 (1-3%) | 5 | Clarion loam | 100 | 9.8 | 907 | 1.53 | 0.88 | Maize | June 6 |
| <i>East-grain (commercial farm); 41°18'N 92°48'W; initiated in 2009</i> | | | | | | | | | |
| 25 x 275 (0-2%) | 4 | Taintor silty clay loam | 0 | 10.2 | 947 | 1.73 | 1.32 | Maize | June 10 |

133 * From Web Soil Survey data using map unit area weighted estimates

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 United States Department of Agriculture (USDA) and included both phases of each rotation (Kaspar et al., 2007, 2012). For the present study, only the soybean phase of the USDA site was sampled due to time constraints. Cover crop biomass sampling occurred each spring at every trial; details about methodology are reported elsewhere (Nichols et al., 2020a) and historical values are available (Supplementary Table S4).

Soil Sampling

An aluminum ring 7.62 cm in diameter and 7.62 cm tall was used to take intact soil samples. Sampling occurred in May or June of 2019 after maize (West) or soybean (East, 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 a few 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, samples were taken in the middle of the plots between planted rows. To get intact soil cores, 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 using a Z-cutting motion. 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 and placed in a cooler. This process was repeated for each plot. 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. Our interest was in comparing relative effects within a trial, so variation between runs was statistically included 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. Each full batch of samples (eight for East and West, 10 for Central) 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. The top ring was removed from the cores, then the saturated 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 values ($\Psi_m = -3.8 \text{ cmH}_2\text{O}$). Subsequent measurements were taken at matric potentials (Ψ_m) of -10, -25, -50, -100, -200, and -500 cmH_2O . The samples were then oven dried at 60°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 ; Han et al. 2016). 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 visible hole in the center of the core upon destructive inspection, confirming its justified removal from the dataset.

Soil Texture

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).

Organic carbon

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, 1983). 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 manipulation, figure creation, and model fitting was 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 Genuchten (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. We chose to use the results from the Gardner model due to its simplicity and biologically meaningful parameters. 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 is the inverse of the air-entry potential, 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, but can also be experimentally measured at -15,000 cmH₂O, i.e. the permanent wilting point (SSSA, 2008). The highest pressure applied to samples in this study was -500 cmH₂O, 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 the model-estimated saturated water contents with the data, as well as 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 (cmH₂O). Pores with mean neck diameters greater than 30 μ m 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 data. Volumetric water contents at field capacity were estimated as the volumetric water content at a matric potential of -100 cmH₂O (Moore 2021). We used this approximation because the actual field capacity matric potential depends on the depth to the water table, which can vary seasonally. The trials sampled all had artificial tile drainage installed at ~1.2 meter depths and shallow water tables (Table 1), meaning field capacity will be at matric potentials less negative than the commonly assumed value of -330 cmH₂O (Bonfante et al., 2020). Additionally, soil water retention curve data from Moore (2021), suggests that -100 cmH₂O is a better approximation for field capacity in mollic epipedons with shallow water tables.

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. 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 results are available in **Supplementary Tables S5-S11**.

RESULTS AND DISCUSSION

Soil texture, organic matter, and bulk density

All plots had textures within ranges classified as silty-clay-loams. Texture varied most strongly by trial, with the East-grain trial having the lowest amount of sand and highest silt component. In the two commercial field trials, the sample's texture also varied by CC treatment. The CC plots had a significantly higher sand component, and significantly lower clay component than the no-cover plots in the West-grain and East-grain trials (**Table 1, Figure 2**). While the plots in the production fields were randomly assigned a CC treatment, the East-grain site's treatments were regularly alternating strips with blocks laid out laterally, and the West-grain sites were close to regular alternations likewise laid out laterally. In fields with a uniform texture gradient perpendicular to the blocking with only two treatments, this regularly alternating pattern could result in one treatment having significantly different textures compared to the other. The Central site had several treatments in small plots and the blocks were located in quadrants within the field, which may have better randomized spatial patterns in the soil.

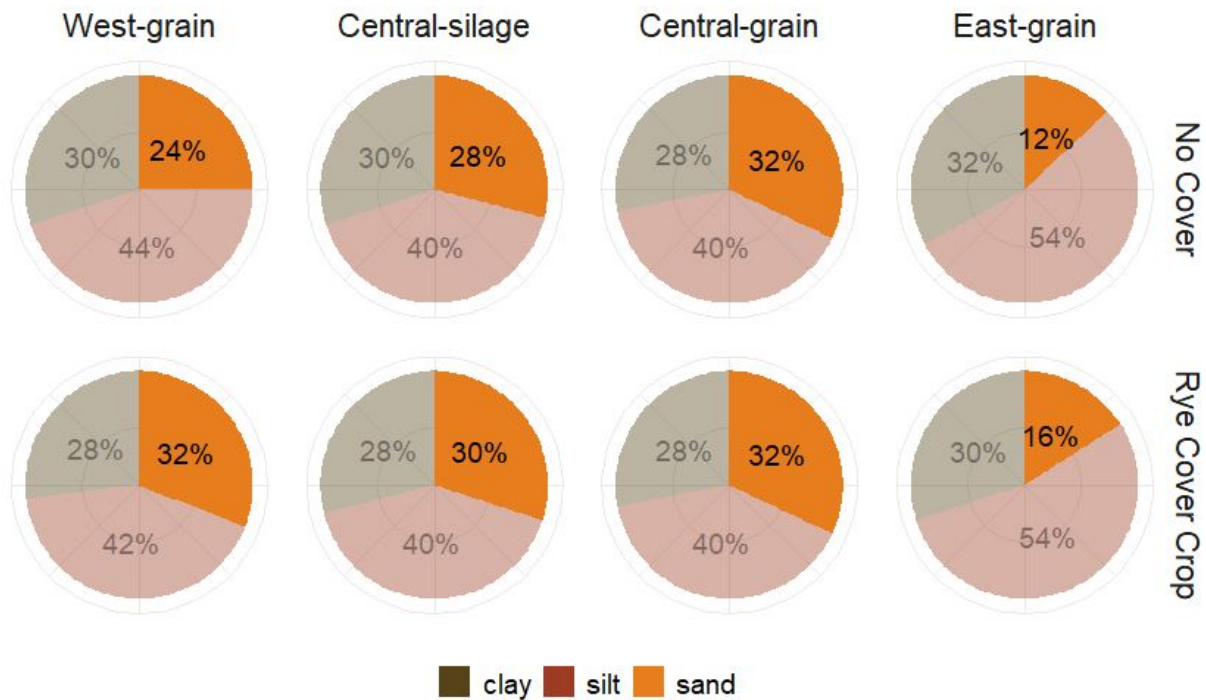


Figure 2. Soil texture components varied by trial and cover crop treatment, with the cover cropped plots having significantly more sand (bolded orange color) and significantly less clay at the West-grain and East-grain trials (both commercial production fields).

Based on these results, sand was investigated as a covariate in statistical models for response variables thought to be affected by soil texture. 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), so statistical comparisons of soil water at saturation and field capacity are reported from models that include the sand co-variate.

Organic matter concentrations ranged from 1.8 to 4.6 g (g soil)⁻¹. The organic matter models were very sensitive to inclusion of sand as a covariate. The two trials with significantly different sand components in the cover crop and winter fallow treatments had lower organic matter in the cover crop treatments without

a sand-correction, but higher organic matter with a sand correction. We therefore choose not to report the results from the organic matter analyses, but results are available (**Supplementary Table S7**).

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., 2020b).

Soil hydrological properties

Due to the high amount of variability associated with soils, we assigned significance at p-values less than 0.10. With or without a sand correction, no trial exhibited a significant increase in water held at saturation with the use of cover cropping (**Figure 3**). 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.

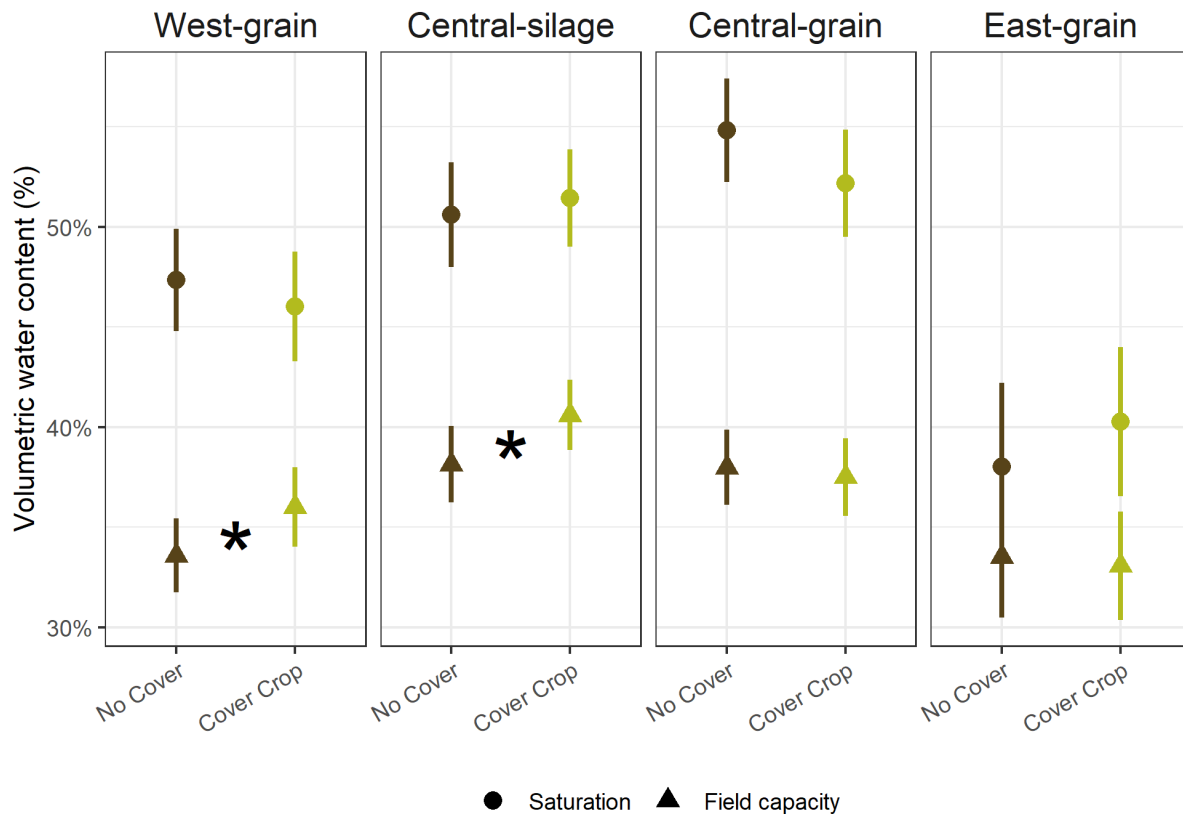


Figure 3. Soil volumetric water contents at saturation (circles) and field capacity ($-100 \text{ cmH}_2\text{O}$, triangles) with 10+ years of winter rye cover cropping (green) or winter fallow (brown) in a maize-soybean rotation at four trials. Points are estimated means, line ranges are the 95% confidence intervals around the mean. Stars indicate significant differences at $p < 0.10$ with the sand adjustment.

267

268 Field capacities were significantly higher in the cover cropped plots at both the West-grain ($p = 0.07$) and
 269 Central-silage ($p = 0.05$) trials. At the West-grain trial, the soil water at field capacity was increased (after
 270 sand correction) from 33.6 to 36.0 vol%, and at the Central-silage trial from 38.1 to 40.6 vol%,
 271 respectively. The West-grain trial consistently produced the lowest above-ground CC biomasses, and the
 272 Central-silage trial the highest (**Table 1**), indicating the changes in water held at field capacity could not
 273 be predicted based on CC above-ground biomass production. Likewise, there was no pattern between soil
 274 textural characteristics and presence or absence of a CC effect on water held at field capacity, meaning

275 that knowledge of a soil's texture did not help predict whether a CC would affect water held at field
276 capacity.

277 While the West-grain results were not significant without a sand correction, the trial exhibited the same
278 trend of increased water at field capacity with cover cropping regardless of whether the sand correction
279 was included or not. These results suggest CCs may have a larger impact on water at field capacity
280 compared to water held at saturation at the 10-18 cm soil depth increment. To our knowledge there are
281 limited studies examining the potential for CCs to reduce flood damage in the Midwest, but the few that
282 do account for only the increased evapo-transpiration with the use of CCs (Antolini et al., 2020). An
283 increase in the soil's ability to hold water after gravity drainage may also contribute to peak water flow
284 regulation. By increasing volumetric water content at field capacity by 2 vol%, CC fields could hold an
285 additional 200,000 L of water in each 100-cm hectare slice, which could reduce the amount of water
286 drained from a field after a saturating rain. Our study suggests considering how CC-induced increases to
287 the amount of water held in a soil at field capacity affect flood incidence and severity would be worth
288 investigating.

289 The Gardner equation fit converged for all experimental units (**Figure 4**), with a (inverse of air-entry
290 potential) ranging from 0.001 to 0.284, and n (pore-size distribution index) ranging from 0.45 to 1.49.
291 While the parameters did differ by trial, cover cropping did not significantly affect either parameter in any
292 trial.

293

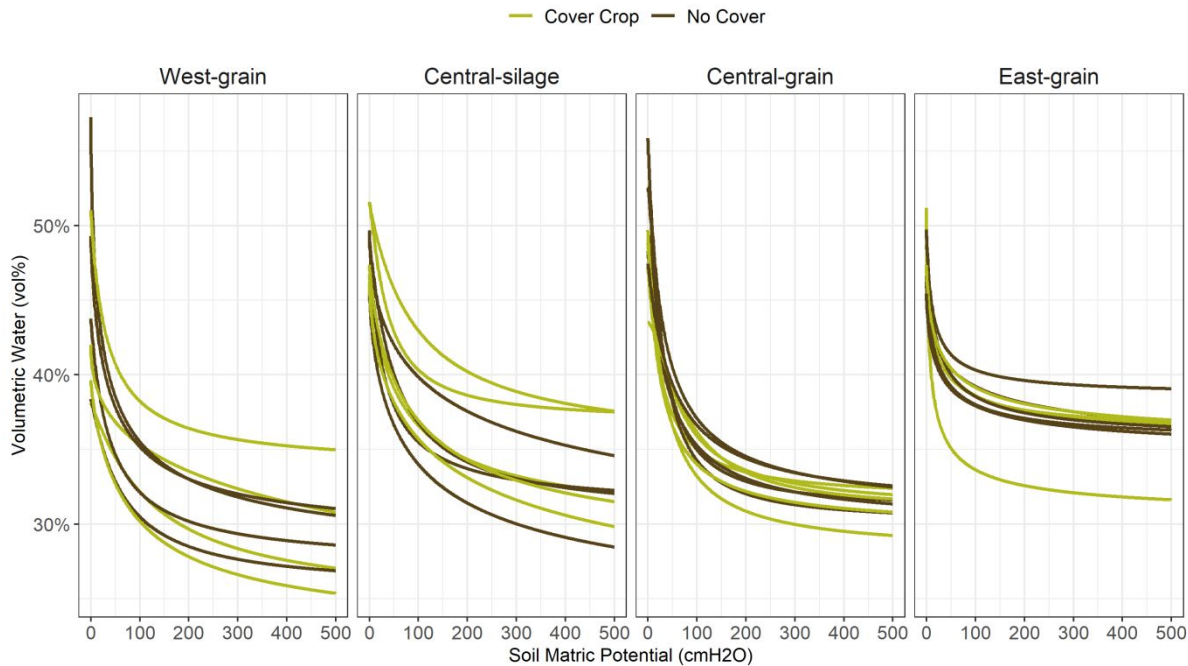


Figure 4. The Gardner equation was fit to each experimental unit, with four or five replicates for each cover crop treatment

Manual estimation of the pore-size distribution confirmed CCs did not increase the percentage of macropores in any trial (**Figure 5**). In fact, in the West-grain trial the number of macropores significantly decreased with cover cropping, with 61% macropores in the control treatment compared with 48% in the CC treatment. 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.

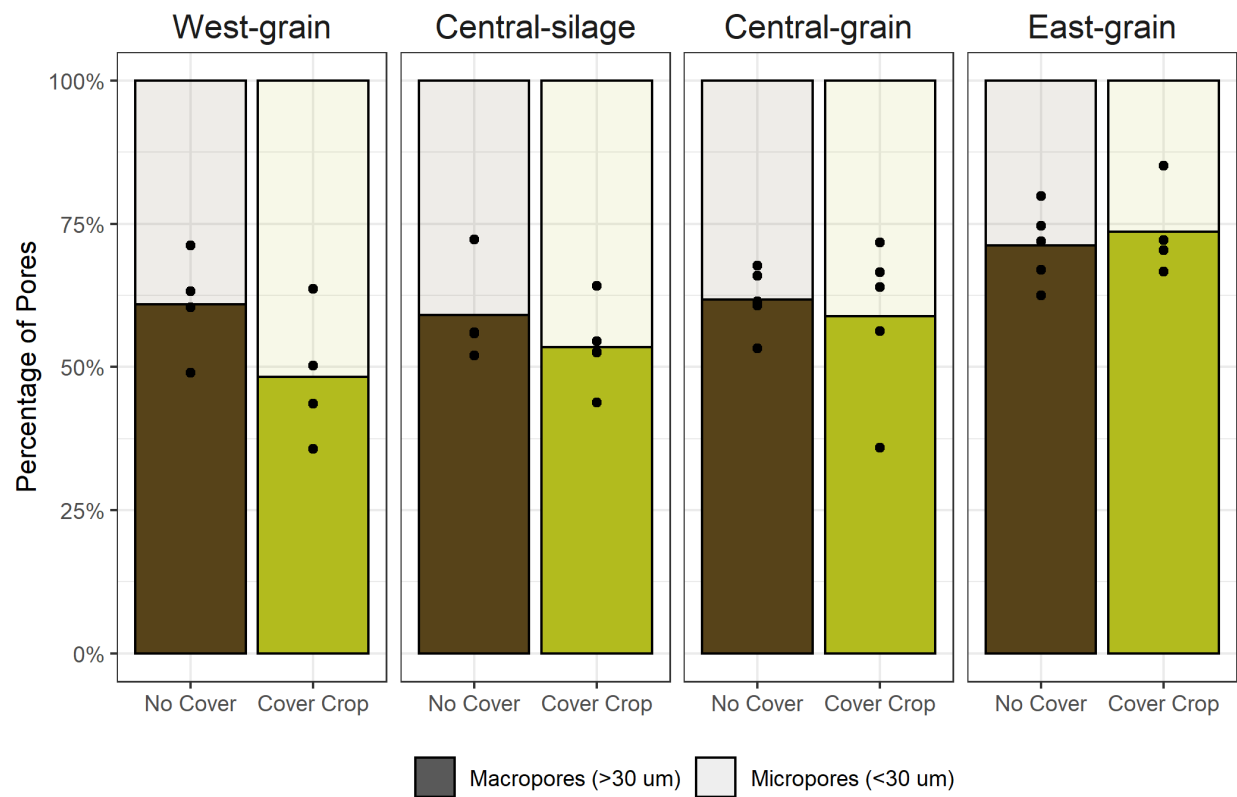


Figure 5. Replicate (point) and treatment mean (bars) percentage macropores (>30 μm) for each trial; percent macropores in the cover crop treatment was significantly lower (p=0.04) at the West-grain trial compared to the control treatment.

Causal model

There are several pathways by which CCs might affect a soil’s capacity to hold water (Figure 6, Table 2).

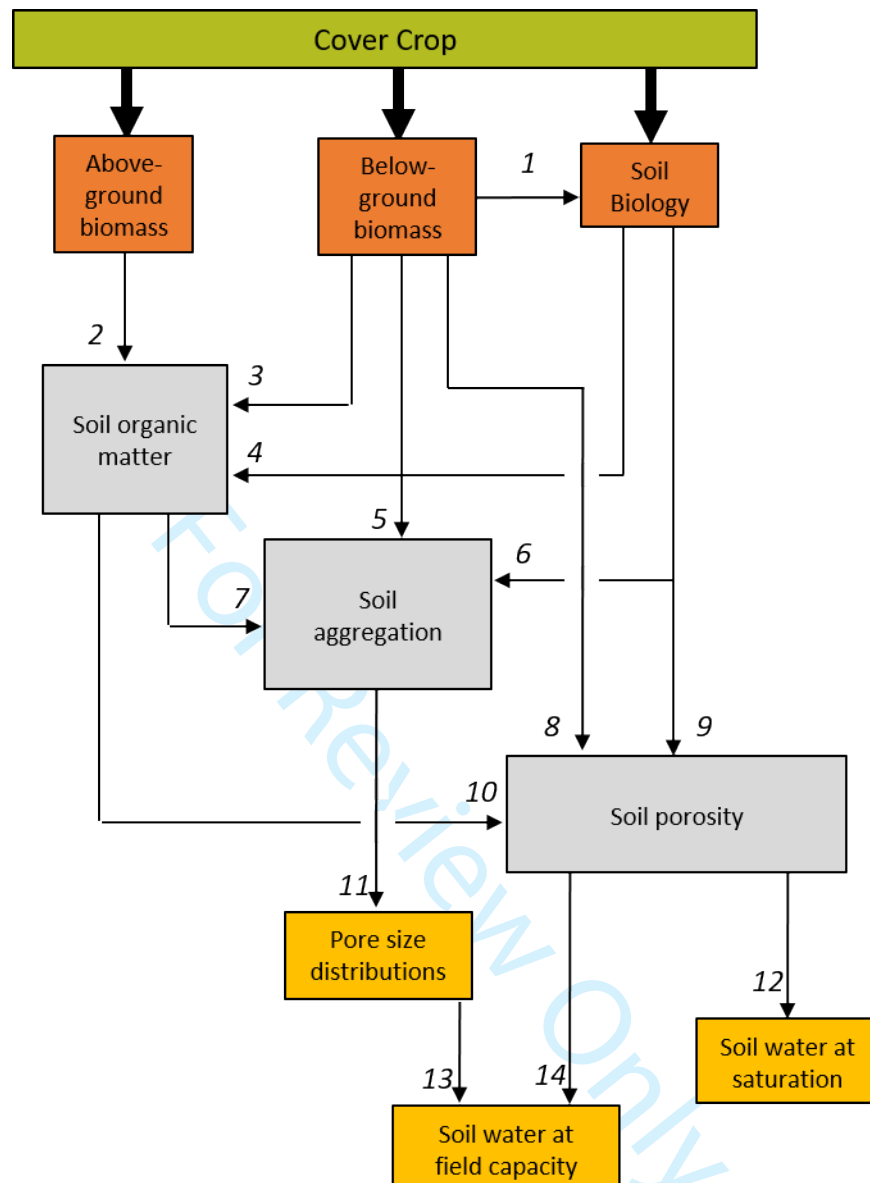


Figure 6. Pathways by which cover crops may affect the pore size distributions, the amount of water stored at field capacity, and the amount of water at saturation in no-till systems. The effects of soil erosion are not included. X→Y should be read as ‘X affects Y’.

307

308 The causal model was built using literature relevant to Midwestern systems, and when applicable was

309 limited to evidence drawn from research conducted with a cereal rye cover crop (**Table 2**). The model is

310 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.

Table 2. Support for inclusion of causal relationships presented in Figure 6.

| Casual Arrow | Causal relationship | Citation(s) |
|--------------|--|---|
| 1 | CC below-ground biomass affects soil biology | (Leslie et al., 2017; Kim et al., 2020) |
| 2 | CC above-ground biomass affects soil organic matter | (Austin et al., 2017) |
| 3 | CC below-ground biomass affects soil organic matter, more strongly than above-ground biomass | (Austin et al., 2017) |
| 4 | Soil biology affects soil organic matter cycling | (Cotrufo et al., 2013) |
| 5 | CC below-ground biomass (root exudates) affect soil aggregation | (Cotrufo et al., 2013; Austin et al., 2017) |
| 6 | Soil biology affects soil aggregation | (Cotrufo et al., 2013) |
| 7 | Soil organic matter affects soil aggregation | (Boyle et al., 1989; Kay et al., 1997; Abiven et al., 2009) |
| 8 | Root channels affect soil porosity | (Williams and Weil, 2004; Ogilvie et al., 2021) |
| 9 | Soil biology (e.g. worm activity) affects soil porosity | (Edwards et al., 1988) |
| 10 | Soil organic matter affects bulk density, which affects soil porosity | (Ruehlmann and Körschens, 2009) |
| 11 | Soil aggregation affects pore sizes | (Boyle et al., 1989) |
| 12 | Soil water at saturation is affected by soil porosity | |
| 13 | Pore size distributions affect capillary forces, which affect soil water at field capacity | |
| 14 | Soil porosity affects space available for water which affects soil water at field capacity | |

Causal diagrams such as **Figure 6** 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., 2020b; Ogilvie et al., 2021). While there is limited data available on both above- and below-ground biomass of CCs, data collected over the period of five years in Iowa 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

Context-specific effects of growing over-wintering CCs need to be explicitly investigated, as the constraints of the Midwestern maize-soybean system may render the effects smaller in magnitude compared to averages reported by global meta-analyses. In our study we found CCs have a more pronounced effect on water held at field capacity compared to water contents at saturation, suggesting changes in pore networks and sizes are stronger compared to changes in bulk density. However, we found CCs increased water held at field capacity in only two of the four trials, further demonstrating the need to understand causal mechanisms in order to better predict where and when CCs might provide the most benefit.

SUPPLEMENTAL MATERIAL

Detailed management of trials (Tables S1-S3), historical cover crop biomass production (Table S4), and statistical results (Tables S5-S11) are available as a PDF. The soil water retention curve, bulk density, organic matter, and soil texture data are available as csvs.

DATA AVAILABILITY

All data is available in an R package (<https://github.com/vanichols/PFIswhc>) and code repository (**will be created once paper is accepted**) available on github. Additionally, the data is available as a downloadable csv file in supplementary material.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

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

For Review Only

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/soybean 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/soybean 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/soybean 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 | Herbicides 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 Ter- mination | 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 |

For Review Only

Statistical Results

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 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 |

Table 7: 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 |
| none | 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 |
| sand | West_grain | om | 3.228 | 2.968 | cc - no | 0.260 | 0.096 | 0.007 |

Table 8: 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 |
| Central | grain | soy | no | 1.37 | 0.07 |
| Central | silage | soy | cc | 1.46 | 0.06 |
| Central | silage | soy | no | 1.44 | 0.07 |
| East | grain | soy | cc | 1.44 | 0.05 |
| East | grain | soy | no | 1.49 | 0.04 |
| West | grain | corn | cc | 1.57 | 0.14 |
| West | grain | corn | no | 1.47 | 0.21 |

Table 9: 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 |
| none | Central_silage | bd | 1.464 | 1.436 | cc - no | 0.028 | 0.011 | 0.012 |
| none | East_grain | bd | 1.437 | 1.488 | cc - no | -0.050 | 0.011 | <0.001 |
| none | 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 |
| sand | Central_silage | bd | 1.395 | 1.386 | cc - no | 0.010 | 0.014 | 0.483 |
| sand | East_grain | bd | 1.653 | 1.752 | cc - no | -0.098 | 0.015 | <0.001 |
| sand | West_grain | bd | 1.493 | 1.473 | cc - no | 0.020 | 0.015 | 0.188 |

Soil moisture (%vol) at saturation

Table 10: 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 |
| sand | Central_silage | cc_trt | cc effect | 0.004 | 0.008 | 26.000 | 0.510 | 0.614 | saturation |
| sand | East_grain | cc_trt | cc effect | 0.011 | 0.009 | 26.000 | 1.271 | 0.215 | saturation |
| sand | 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 |
| none | Central_silage | cc_trt | cc effect | 0.002 | 0.009 | 14.068 | 0.246 | 0.809 | saturation |
| none | East_grain | cc_trt | cc effect | 0.002 | 0.009 | 13.050 | 0.228 | 0.823 | saturation |
| none | 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 11: 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 |
| sand | 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 |
| none | West_grain | cc_trt | cc effect | 0.003 | 0.006 | 13.044 | 0.597 | 0.561 | field capacity |

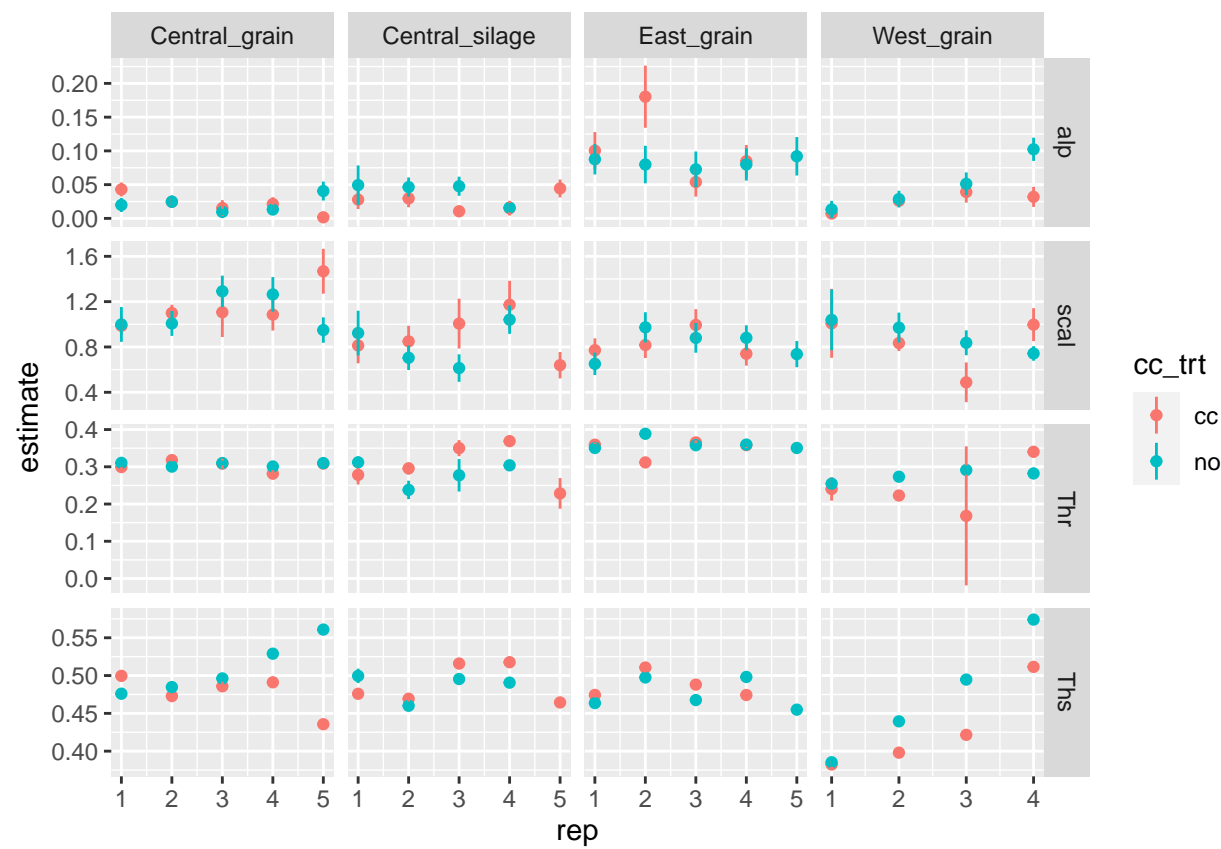


Figure 1: Non-linear model fitted parameters