Draft of a paper to be submitted to the Journal of Soil and Water Conservation (although I am open to suggestions on another journal)

**Root data key to unlocking variable cover crop effects on soil water holding capacity**

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# Abstract

Addition of an over-wintering cereal rye (*Secale cereal*) cover crop to Midwestern maize (*Zea mays*)-based systems offers several environmental benefits, but the long-term effects of this addition on soil hydrological properties is not well-understood. Soil water retention curves can provide insight into cover crop-induced soil changes that affect soil water dynamics. We utilized four long-term cover crop trials in Iowa, USA that included a winter rye cover crop and no-cover treatment in systems with a maize crop (grain or silage) rotated with soybean (Glycine max). All trials had been in place for at least 10 years and were managed without tillage. At each trial, we took intact 7.62 diameter soil samples from 10-18 cm depths shortly after cash crop planting in May and June 2019. We measured organic matter, soil texture, and the volumetric soil water content at matric potentials of -2.5, -10, -25, -50, -100, -200 and -500 cm water. Four hydrological parameters were used to compare the soils. Pore-size distribution indices and air-entry potentials were estimated from non-linear model fits to the soil water retention curves. Water contents at saturation and at field capacity (-100 cm water matric potentials) were taken directly from the data. Neither pore-size distribution nor air-entry potential (model parameters) were affected by cover cropping, but both had large amounts of uncertainty in their estimation. At this depth, cover-cropping did not meaningfully effect bulk density or water contents at saturation at any trial. At the trial with the highest 10-year mean cover crop biomass production (2.00 Mg ha-1), cover cropping increased organic matter contents by 0.2% (SE:0.05%) and soil water content at field capacity by 1.3% (SE: 0.5%). At the trial with the lowest 10-year mean production (0.45 Mg ha-1), cover cropping had no effect on organic matter but increased soil water at field capacity by 1.2% (SE:0.4%). Cover cropping had no effect on organic matter or soil water at field capacity in the two trials with intermediate 10-year cover crop biomass productions (1.32 Mg ha-1, 1.34 Mg ha-1). There was likewise no relationship between the effects and the previous year’s biomass production. The lack of relationship between the amount of above-ground biomass produced by the cover crop and the cover crop’s effects on field capacity indicates the two are not directly related. We propose a causal model relating cover crops to soil properties relevant to soil water holding capacities to aid in understanding these relationships. The casual model indicates measuring below-ground biomass of cover crops is a vital measurement for understanding how cover crops affect soil hydrology. While some cover crop benefits have been clearly linked to above-ground biomass production (e.g. reduced soil erosion and nitrate leaching), examining the role of roots in cover crop services merits further exploration. More research is needed on the exact mechanisms by which cover crops can improve soil water, as well as when and where those benefits may be most easily realized.

# Intro (note: JSWC doesn’t have an ‘intro section’, they want the first sentence to be a thesis statement.

**Addition of an over-wintering cereal rye (*Secale cereal*) cover crop to Midwestern maize (*Zea mays*)-based systems offers several environmental benefits, but the long-term effects on soil hydrological properties is not well-understood.** Cover cropping can significantly reduce soil erosion and nitrate leaching from annual crop based systems (CITE Kaspar et al. 2001, Kaspar et al. 2007). In some circumstances, cover crop may offer additional benefits by increasing soil carbon (Moore XX) or microbial biomass (McDaniel et. al 2014), which in theory could support more stable crop yields (cite Jordan’s paper?). For example, one of the main purported benefits of increased soil organic matter is the increased capacity for the soil to hold and supply water for the crop to use in the absence of rain or irrigation (Hatfield paper, Allyn Williams paper, Kane paper, other one). Whether cover crop-induced increases in soil carbon translate to improved soil hydrological properties, and thus more stable yields under drought conditions, is not well studied. Short term use of rye cover crops has, on average, a neutral effect on crop yields (Maricllo and Miguez XXXX), but the effects after long-term use, as well as in stress-years is less clear. Recent field studies have shown mixed results with respect to cover crops and drought, with cover crops exacerbating drought effects (Martinez-Feria et al. 2016), having no effect (Hunter et al. 2021), or buffering maize yields only in certain landscape positions (Leuthold et al. 2021). Additionally, the mulching effect of cover crop biomass may be equally as important as soil-related changes when considering drought (Leuthold et al. 2021, another). In a global meta-analysis, the authors found cover crops increase the amount of water stored at field capacity, as well as the porosity of the soil compared to no-cover controls (Basche and DeLonge 2017). However, that dataset included only one study from a winter cover crop in a Midwestern row crop system (Basche XX), and there are few additional studies from this region (Villa one, other?). As more Midwestern farmers consider including a cover crop in their maize-based rotations (CITE), more data is needed to understand how cover crops can improve soil hydrological properties specifically in these systems, as climate and management constraints can limit cover crop growth potential (Strock, maybe mine, the other guys). Additionally, while shallow soil depths (0-10cm) may be more responsive to cover crop effects (e.g. Moore et al. 2014, Kaspar et al. 2006, XX), deeper depths may be more important when considering the soil’s contribution to the crop’s water supply (Asbjornsen et al 2008, another). While cropping system and depth of sampling may influence soil responses to cover cropping, the duration of cover cropping may also be important. Long-term studies on tillage have shown significant, but slow changes to the soil after implementing no-till (Robertson paper, maybe an al-kaisi). Likewise, addition of cover crops may require several years before improved soil hydrological properties can be detected.

Given this lack of data, the objectives of our study were to determine what aspects of a soil’s hydrological profile are affected by long-term cover cropping at a depth relevant to crop production. We collected soil samples at a 10-18 cm depth from four long-term (10+ years) cover crop trials located in Iowa, USA. Two trials were on-farm production fields, and two trials were part of a research experiment. We assessed the effects of long-term cover cropping on (1) pore-size distributions as estimated by the soil water retention curve shape, (2) soil water content at saturation, and (3) soil water content at matric potentials approximating field capacity (100 cm H2O, Moore XX). To complement and contextualize these data, we also measured soil texture, soil organic matter, and bulk densities of the soil samples.

# Methods and Materials

## 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 cover crop planted yearly in the fall following cash crop harvest and terminated in the spring, and (2) the same rotation without a cover crop. Every trial was arranged in a randomized complete block design with four (West and East) or five (Central) replicates. The plots within each trial were managed identically save for the planting of the cover crop in the fall. The exact herbicide and nutrient programs varied by site, reflective of their particular managers and contexts (**supplementary material**). More detailed accounts of agronomic management has been published elsewhere for the Central site (Moore et al., 2014) and production sites (Nichols et al. 2020). All sites had sub-surface tile drainage and were managed without tillage since initiation.

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| **Plot Size and Average Slope\*** | **Treatment Replications** | **Dominant Soil Types\*** | **Average Depth to Water Table\* (cm)** | **30-year Annual Mean** | |  | **Mean Cover Crop Biomass (Mg ha-1)** | | **2018 Crop** | **2019 Sampling Date** |
| ***Air Temperature (⁰C)*** | ***Precipitation (mm)*** |  | ***5-year*** | ***10-year*** |
| *West-grain (commercial farm),* 41⁰55’N 94⁰36’W, initiated in 2008 | | | | | | | | | | |
| 25 x 250 m (1-3%) | 4 | Nicollet loam | 67 | 9.5 | 880 |  | 0.24 | 0.45 | Soybean | May 23 |
| *Central-silage (research plots);* 42⁰00’N 93⁰48’W; initiated in 2002 | | | | | | | | | | |
| 3.8 x 55 m  (1-3%) | 5 | Clarion loam | 100 | 9.8 | 907 |  | 2.38 | 1.98 | Soybean | June 6 |
| *Central-grain (research plots);* 42⁰00’N 93⁰48’W; initiated in 2009 | | | | | | | | | | |
| 3.8 x 55 m  (1-3%) | 5 | Clarion loam | 100 | 9.8 | 907 |  | 1.53 | 0.88 | Soybean | June 6 |
| *East-grain (commercial farm);* 41⁰18’N 92⁰48’W; initiated in 2009 | | | | | | | | | | |
| 25 x 275 m  (0-2%) | 4 | Taintor silty clay loam | 0 | 10.2 | 947 |  | 1.73 | 1.32 | Maize | June 10 |

*\* From Web Soil Survey data, see supplementary material for field maps*

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 and included both phases of each rotation (Kaspar et al., 2007, Kaspar et al. 2012). For this study, only the soybean phase of each rotation 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. 2020) and historical values are available in supplementary material.

## 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.

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, then 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.

## Measurements

### Soil-water-retention curve

## The 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 site, so variation between runs was experimentally included in variation between trials. The samples were measured in the order they were sampled. A given trial’s cores had cheesecloth taped to the bottom of each core and an additional ring taped to the top. The 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 CaCl2 filled to the top of the first ring, allowing the solution to move upward to saturate the soils 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. Briefly, the cores were drained at atmospheric pressure for 12 hours to obtain a measurement for gravity-drained values (Ψ = -2.5 cm water). Subsequent measurements were taken at matric potentials (Ψ) of -10, -25, -50, -100, -200, and -500 cm water. The samples were then oven dried at 60 deg 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 cm3).

### Texture

The oven-dried soil was ground and passed through a 2 mm sieve. Two teaspoons of soil from each core were used for soil texture measurements. Soil texture was measured using laser diffractometry (Miller and Schaetzel 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 micrometers), silt (6-50 micrometers), and clay (0.1-6 micrometers).

Organic carbon

Half of the remaining oven-dried soil cores were sent for organic matter analysis (Agsource, need to find the paper that explains their methods) using the loss-on-ignition method with the following conversions:

(LOI%) \* 0.89 = OM%

OM% \* 0.58 = C%

## Probably need to mention how flawed this method is..Statistical analysis

All model fitting and figures 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 (Da Silva and De Lima 2015) packages. Linear models were fit and summarized using the lme4 (Bates et al. 2015) and emmeans (Lenth 2021) packages. The meta-analysis of individual plot’s fitted parameters was performed using the metaphor package (Viechtbauer 2010).

### Texture, organic matter, water content at saturation and field capacity

The effects of trial, cover crop treatment, and their interaction on soil texture, organic matter, and water contents at saturation and field capacity were assessed using mixed-effect models. Trial, cover crop, and their interaction were included as fixed effects, with a random intercept effect for replicates nested within site. Appropriate covariates were added to models for water content at saturation and field capacity, based on results from soil texture models.

### Water retention curve

We fit the Gardner equation (CITE) and Van Genutchen models (the 1980 one) 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 values (CITE), with the Gardner model showing a slightly better fit, consistent with other studies (Too et al. 2014). We chose to use the results from the Gardner model due to its simplicity and biologically meaningful parameters. The Gardner equation is as follows:

Where θ is the volumetric moisture content at a given soil water potential . The remaining variables are fitted parameters. θr and θs 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 larger distribution (CITE). Residual water contents are measured at -15,000 cm water. The highest presssure we used in this study was -500 cm water, so…can I even use these equations?

Models were fit using both a fixed- and mixed-effect approach to account for differences between trials. We found the two models produced similar fit statistics. We chose to fit the Gardner equation to each experimental unit, then performed a meta-analysis on the parameters, weighting by their estimated uncertainties from the non-linear model fitting procedure (CITE). For the meta-analysis we included trial as a random intercept, cover crop as a modifier, and fit models both with and without percent sand as a covariate.

### Saturation and field capacity

Volumetric water contents at saturation were extracted directly from the data. Volumetric water contents at field capacity were estimated as the volumetric water content averaged over measurements taken at a matric potential of - -100 cm water (cite Britt’s dissertation). We used this approximation because the true field capacity matric potential will depend on the distance to the water table. The trials sampled all had artificial tile drainage installed at ~1.2 meter depths, suggesting shallow water tables are present and field capacity will be at matric potentials less than the commonly assumed -330 cm water (cite) (Bonfante et. al 2020).

The effects of trial, cover crop treatment, their interaction, and appropriate covariates on water contents at saturation and field capacity were assessed using mixed-effect models, with a random intercept effect for replicates nested within site and all other factors as fixed.

# Results

## Soil texture and organic matter

All plots had textures within ranges classified as silty-clay-loams. Texture varied most strongly by trial, with the East-grain site having the lowest amount of sand and highest silt component. Within an trial, the sample’s texture also varied by cover crop treatment, with the cover cropped plots having a significantly higher sand component, and significantly lower clay component than the no-cover plots in the West-grain and East-grain trials (**Fig. 2**).

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| **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. |

Based on these results, sand or clay was included as a covariate in statistical models for response variables thought to be affected by soil texture.

Clay soils can accrue organic matter more easily compared to sand, due to the high surface area and ionic charges associated with clays (Cite). Therefore, for the organic matter response variable, we report the results from statistical models that included sand as a covariate. Organic matter values ranged from 1.8 to 4.6%. Organic matter at the East-grain site was 1.2 (no sand adjustment) or 1.4 (sand adjustment) times higher in the cover crop plots compared to the no-cover plots (p=0.01 and p < 0.01, respectively). Cover cropping did not significantly affect soil organic matter at the other three experimets, regardless of sand adjustments (supplemental material).

Sand is denser than clay, so a sandy soils with the same pore space as a clay soil will have higher apparent bulk densities. Because we were interested in using bulk density as a proxy for pore space, we included sand as a covariate in the models evaluting the effects of cover cropping on bulk densities. Bulk densities varied from 1.2 g cm-3 to 1.7 g cm-3. The bulk densitiy of the cover cropped plots at the East-grain trial were significantly lower than the no-cover plots by 0.1 g cm-3 (SE=0.04, p = 0.02), after adjusting for sand contents. Cover cropping did not significantly affect bulk densities at any other trial (supplemental material).

## Soil hydrological properties

### Saturation and field capacity

Soil volumetric water at saturation is inversely related to bulk density, as it reflects the amount of pore space in a given volume of soil. Consistent with the bulk density results, the East-grain trial was the only trial where cover cropping significantly affected the amount of soil water at saturation (**Figure 3**), increasing it from an estimated 41% to 44% (p= 0.06) after correcting for sand contents. Inclusion of the sand covariate changed the magnitude of the difference at the East-grain, but not the direction. Field capacities were signifiantly higher in the cover cropped plots at both the West-grain (p = 0.06) and Central-silage (p = 0.01) trials. At the West-grain trial, the soil water at field capacity was increased from 35 to 37%, and at the Central-silage trial from 40 to 42%, respectively.

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| **Figure 3**. Soil volumetric water contents at saturation and field capacity with 10+ years of winter rye cover cropping (green triangles) or winter fallow (brown circles) in a maize-soybean rotation at four trials. Points are estimated means, line ranges are the standard errors of the estimate, and stars indicate significant differences at a p < 0.10. All estimates include an adjustment for the percent sand in the sample, and the y-axes have different scales for ease of viewing. |

### Soil water retention curves

The Gardner equation fit converged for all experimental units (**Figure 4**), with *a* ranging from 0.001 to 0.284, and *n* ranging from 0.45 to 1.49 (supplemental material). Cover cropping did not significantly affect either parameter.

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| **Figure 4.** The Gardner equation was fit to each experimental unit, with four (West-grain, East-grain) or five (Central-silage, Central-grain) replicates for each cover crop treatment (no cover and rye, brown and green, respectively). |

### Causal model

There are several pathways by which cover crops may affect soil hydrology (**Fig. 5**).

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| **Figure 5**. 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. Red arrows indicate an inverse relationship, while black arrows indicate positive relationships. Gray boxes indicate variables that were measured in this experiment. |

The causal model was built using literature (Table X).

Table X.

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| --- | --- |
| Causal arrow | Citation(s) |
| Cover crops increase soil biological activity |  |
| Above-ground and below-ground biomass reduces soil erosion independently of one another |  |
| Soil erosion reduces soil aggregation, soil porosity, soil organic matter, and soil structure |  |
| Above-ground and below-ground biomass contributions to soil organic matter may be independent |  |
| Soil organic matter increases soil structure, soil aggregation, and soil porosity |  |
| Soil aggregation increases soil strucutre independently of soil organic matter |  |
| Below-ground biomass (roots) increase soil porosity and stimulate soil biology |  |
| Soil biology (worms) increase soil porosity |  |
| Soil structure and bulk density affect soil water at field capacity |  |

Graphical analysis of the causal model identified belowground biomass as a necessary measured variable for assessing the strength of each path connecting the effect of cover crops on soil water at saturation and field capacity.

# Discussion

In addition to being the only site where cover cropping affected the soil organic matter, the East trial was the only one to exhibit a change in bulk density with cover cropping, with an associated increased capacity to hold water at saturation. An increase in volumetric water contents at saturation from 41 to 44% in an 8 cm slice of soil translates to XX L of water per hectare. While soil water at saturation is not meaningful for crop production, this increased ability of the soil to hold water at saturation, combined with increased infiltration rates observed with the use of cover crops (DeLong and Basche paper) could have potential implications for flood mitigation if translated to a landscape-scale. To our knowledge, this has not been investigated, and is an area that merits further research.

At the field-level, soil water at field capacity has more relevance for crop production, as it represents the amount of water available for plant uptake when the soil is sufficiently aerated to allow for plant growth. At the East trial, the differences in bulk density and organic matter did not translate to increased soil water held at field capacity (**Fig. 3**). The West and Central-silage trials both exhibited 2 vol% increases in soil water held at field capacity with the use of cover crops. Organic matter contents were not significantly different at these trials, nor were bulk densities, indicating soil structural changes driven by other paths may be more important for these differences (**Fig. 5**). The pore-size distributions and air-entry potentials were not different at these trials (**Fig. 4**), but both of these parameters were very sensitive and were not estimated with high certainty. Vilamma and collegues (XX) found cover cropping….pore size things. More direct measurements of soil pore size distributions may be necessary to detect these small changes.

The effect of long-term cover cropping on the three soil hydrological properties measured in this experiment was inconsistent between trials and was unrelated to the cover crop’s aboveground biomass production in the previous year or on a mean basis. The causal model provides a framework for assessing why the effect may vary between the trials, but also demonstrates that below-ground biomass is a necessary measurement for dissecting the contributions of different pathways. While there is limited data available on both above- and below-ground biomass, data collected over the period of five years in Iowa show no relationship between above- and below-ground rye biomass, with root-to-shoot ratios varying from 0.16-1.94 at similar aboveground biomass productions (Martinez-Feria et al. 2016). Therefore, above-ground biomass production cannot be used as a proxy for below-ground production with much confidence.

While there are few studies with which to compare our results, other authors have found cover cropping significantly increased the volumetric soil water at field capacity in the 0-15 cm depth range by 4 vol%, while having no effect on the soil water at -1500 kPa (plant wilting point; Basche et al. 2016). We found cover cropping increased the volumetric soil water at field capacity at two of the four trials we sampled, each by 2 vol% at 10-18 cm depths. Differences in defining field capacity matric potentials, as well as large site-to-site variability as demonstrated by the current study would contribute to the differences. Likewise, the effect of cover cropping on organic matter in Midwestern maize-based systems is inconsistent, ranging from 13% relative decreases to 35% relative increases ([Atwood](https://www.agevidence.org) and Wood 2020). Our early spring sampling may have amplified differences in organic matter, due to the recently terminated cover crop roots being less than a month old, but the 20% relative increase at a 10-17cm depth we observed at the East trial is within the range observed in other studies looking at 0-30 cm depths. Organic matter was not the focus of this study, and we did not distinguish between particulate and mineral-associated organic matter, which is likely important when understanding cover crop’s contribution to soil organic matter (Cotrufo et al. 2019, CITE). However, in addition to having higher organic matter, the cover cropped plots at East had significantly different soil textures. While the trial site was flat (<X% slopes, **Table 1**), there may have been confounding landscape factors indirectly impacting organic matter accrual (Kaspar et al. 2006), although effects to the 10 cm depth are less likely and may have simply been a reflection of normal variation.

# Conclusion

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*Ramblings*

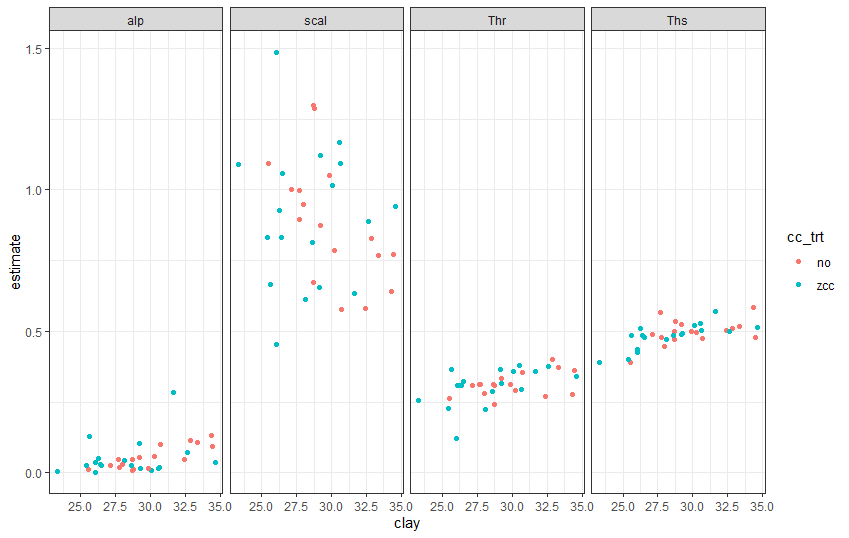
*Soil erosion removes top soil, leaving soil layers that are generally higher bulk densities and have less organic matter and soil structure (CITE). In fields with high erosion potentials, the strongest effect may be through cover crops’ prevention of soil degradation via erosion, rather than directly contributing to enhancing the soil’s capacity to hold water. In those contexts, the characteristics of the underlying soil layers will determine how cover crops affect (or rather maintain) soil hydrological characteristics. In the current experiment, all fields were relatively flat and were managed with no-till. Therefore, in this dataset, the path connecting cover crops to soil water status through soil erosion is likely not strong.*

*In the East trial, cover crops decreased the soil’s bulk density, increased soil organic matter, but only affected the soil water at saturation (no effect on soil water at field capacity). This indicates the arrow linking soil organic matter and soil structure is very weak in that system. There is a potential link between soil organic matter and bulk density (Saxton and Rawls 2006, King et al. 202x), but evidence from controlled experiments is lacking. Either roots or worms could have contributed to decreased bulk densities in the cover crop plots. The East site has milder weather relative to the other sites, so more worm activity in response to cover cropping at this trial is a plausible explanation, but is purely conjecture.*

*Neither the West nor Central-Silage trials exhibited changes in soil organic matter with cover cropping, but both had increased soil water contents at field capacity and no changes in bulk densities. These two trials produced the highest and lowest average cover crop biomass, again suggesting a weak link between above-ground carbon inputs, soil organic matter, and soil water field capacity.*

Supplemental

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| Supplementary figure X. The inverse of the air-entry potential (*a*) and pore-size distribution index (*n*) were not signficantly affected by inclusion of a winter rye cover crop |



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