# Abstract

Including an over-wintering cereal rye (Secale cereal) cover crop in Midwestern maize-soybean systems offers several environmental benefits, but the effect on soil hydrological properties is not well-studied. Soil water retention curves can provide insight into cover crop-induced soil structural changes that may affect soil water. We took in-tact 7.6X diameter soil samples at 10-17cm depths from four long-term cover crop experiments in Iowa that included a winter cereal rye cover crop and no-cover treatment in no-till maize (Zea mays)-soybean (Glycine max) or maize silage/soybean systems. Samples were collected shortly after cash crop planting in May and June 2019. Organic matter, soil texture, and the volumetric soil water content at pressures ranging from -0.38 to -100 kPa (need to double check how to report these pressures) were measured. One of the four experiments exhibited a 20% (CIX-X) increase in organic matter with cover cropping, and three exhibited no change. Bulk densities, and therefore porosities, were not significantly affected by cover cropping at this sampling depth. Of the four hydrological parameters extracted from the soil water retention curves, three were unaffected by cover cropping. The volumetric water content at the highest pressure was significantly, but not biologically meaningfully higher (XX, CIX-X) with cover cropping. Our results support previous findings that suggest while some benefits may be less context-dependent, cover crop benefits to soil hydrological properties may vary widely. In Midwestern soils with high native amounts of organic matter, cover crop-induced increases in organic matter may not directly translate to improvements in soil water properties.

# Intro

Use of over-wintering cover crops such as cereal rye in Midwestern maize-based systems offer several well-studied environmental benefits, including reduced soil erosion and nitrate leaching (CITE). While cover cropping benefits related to soil health such as increased soil carbon have been reported (e.g. XX), the link between these improvements and crop yields is less clear. 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, 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. In a global meta-analysis, the authors found cover crops increase the amount of water stored at field capacity and 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). 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 with limited cover crop growing seasons (CITE). Additionally, many cover crop studies have focused on soil changes in shallow (0-10 cm) soil depths (Moore et al. 2014, Kaspar et al. 2006, XX), while deeper depths may be more important in contributing to the crop’s water supply (Asbjornsen et al 2008). A recent study found the soil benefits associated with switching to no-till may not be apparent for many years (Robertson paper). Likewise, the benefits of cover cropping to soil structure at deeper depths may take several years to manifest, requiring long-term experiments.

The water retention curve represents the relationship between soil water content and soil water potential. The curve can be used to predict the soil’s water-holding capacity, and the amount of water available for plant uptake, and provide insight into the soil’s structure such as pore-size distributions. The soil’s water holding capacity can be linked to crop drought resilience (CITE), and thus may provide a better link between cover crops and cash crop yield stability than other metrics.

The objectives of our study were to determine what aspects of the water retention curve are affected by long-term cover cropping at a depth relevant to crop production. To achieve our objective we collected soil samples at a 10-17 cm depth from four long-term (10+ years) cover crop experiments located in Iowa, USA.

# Methods and Materials

## Site descriptions

Three long-term sites were used for this study (**Figure 1**), with one site having two experiments. Therefore, a total of four experiments were used for this study (**Table 1**). Each experiment 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 experiment 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 at the Central site have been published elsewhere (Moore et al., 2014). All sites had sub-surface tile drainage and were managed without tillage since initiation of the trials.

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Longitude Latitude** | **Experiment Initiation** | **# of Reps.** | **Plot Size** | **30-year Annual Mean** | | **Mean Cover Crop Biomass (Mg ha-1)** | | **2018 Crop** | **2019 Sampling Date** |
| ***Air Temp (⁰C)*** | ***Precip (mm)*** | ***5-year*** | ***10-year*** |
| *West-grain (commercial farm)* | | | | | | | | | |
| 42⁰03’N  94⁰20’W | 2008 | 4 | 25 x 250 m | 9.5 | 880 | 0.24 | 0.45 | Soybean | May 23 |
| *Central-silage (research plots)* | | | | | | | | | |
| 42⁰00’N  94⁰12’W | 2002 | 5 | 3.8 x 55 m | 9.8 | 907 | 2.38 | 1.98 | Soybean | June 6 |
| *Central-grain (research plots)* | | | | | | | | | |
| 42⁰00’N  94⁰12’W | 2009 | 5 | 3.8 x 55 m | 9.8 | 907 | 1.53 | 0.88 | Soybean | June 6 |
| *East-grain (commercial farm)* | | | | | | | | | |
| 41⁰19’N  92⁰17’W | 2009 | 4 | 25 x 275 m | 10.2 | 947 | 1.73 | 1.32 | Maize | June 10 |

The West-grain and East-grain experiments 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, 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 experiment, details about methodology and yearly values are reported elsewhere (my paper, maybe somewhere else).

## Soil Sampling

An aluminum ring 7.62 cm in diameter and 7.62 cm tall was used to take in-tact 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 done immediately following crop emergence to minimize the effects of live roots in the samples.

At all locations, samples were taken in the middle of the plots between planted rows. 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, 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 before being taken to a refrigerator. This process was repeated for each plot.

## Measurements

### Soil-water-retention curve

## The equipment could accommodate 12 samples at a time, so each experiment’s samples were run together in a batch. Our interest was in comparing within a site, so variation between runs was included in variation between experiments. The samples were measured in the order they were sampled. A given experiment’s cores had cheesecloth taped to the bottom of each core and an additional ring taped to the top. The full batch of samples (8 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 = -3.8 cm H2O = −0.38 kPa XX Andrea calls this -33 kPa…Kool calls it -0.33, need to check on why this is). Subsequent measurements were taken at Ψ of -1, -2.5, -5, -10, -20, -50 kPa. 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 (XX).

### 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).

### 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).

## Statistical analysis

All model fitting and figures were done using R (CITE) and the tidyverse meta-package (CITE). Non-linear models were fit using nls (CITE) and nlraa (CITE) package functionality, with specific equation fits from the HydroMe (CITE) and soilphysics (CITE) packages. Linear models were fit and summarized using the lme4 (CITE) and emmeans (CITE) packages. The meta-analysis of individual plot’s fitted parameters was performed using the metaphor package (CITE).

### Texture and organic matter

The effects of experiment, cover crop treatment, and their interaction on soil texture components and organic matter were assessed using mixed-effect models. Experiment, cover crop, and their interaction were included as fixed effects, with a random intercept effect for replicates nested within site.

### Water retention curve

We fit the Gardener 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 Gardener model due to its simplicity and biologically meaningful parameters. The Gardener equation is as follows:

Where θ is the volumetric moisture content at a given soil water potential , 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).

Models were fit using both a fixed- and mixed-effect approach to account for differences between experiments. We found the two models produced similar fit statistics. The results from 2.4.1 indicated clay contents were higher in plots without a cover crop, and varied by site. Clay can influence soil water retention curves (CITE), so we controlled for the differences in clay by using it as a covariate. To facilitate this, we fit the Gardner equation to each experimental unit, then performed a meta-analysis on the parameters, weighting by their estimated uncertainties (CITE). For this analysis we included experiment as a random intercept, cover crop as a modifier, and percent clay as a covariate.

# Results

Organic matter values ranged from 1.8 to 4.6%. Cover cropping significantly increased the amount of organic matter in the sampled soil at the East-grain experiment from an estimated 3.30% in the no-cover plots to 4.03% in the cover-cropped plots, corresponding to a an estimated 22% increase from the no-cover control (p=0.01). Cover crops did not significantly affect soil organic matter at the other three experimets (Fig X). Bulk densities varied from 1.2 g cm-3 to 1.7 g cm-3, with no significant effect of experiment, cover crop treatment, or their interaction. Percent clay ranged from 23-34%, with a significant effect of cover crop treatment (p<0.01), but no experimental effect nor an interaction. Cover crop plots had an estimated 1.65% higher clay content than the no-cover plots. Likewise, the effect of cover crop treatment on sand was significant (p<0.01), with cover cropped plots having an esimated 2.56% less sand compared to the no-cover plots. Sand and clay were inversely related (Supplemental).

We included sand as a covariate in models assessing the significance of the effect of cover crops on the curve parameters (see Methods and Materials). The meta-analysis of curve parameters indicated the volumetric soil water content at HIGH kPa increased by 1.3% (CI: 0.5-2.0%), meaning cover-cropped soils retained more water at higher pressures than no-cover soils. As pressures increase, the remaining water represesnts water bound in small pores via adhesive and osmotic binding, which is less accessible to plants (CITE).

Potential vs water content. Capillary binding of water at potentials close to 0. As potentials become more and more negative water is bound in small pores (adhesive and osmotic binding).

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| Fig X. The soil water content (SWC) at plant wilting (this might not be right, need to double check the pressures as reference) was the only Gardner equation parameter significantly affected by cover cropping after correcting for soil texture differences. Points represent estimates of the mean value, line ranges the 95% confidence intervals for the mean. Values greater than zero indicate an increase in response to cover cropping. |

# Discussion

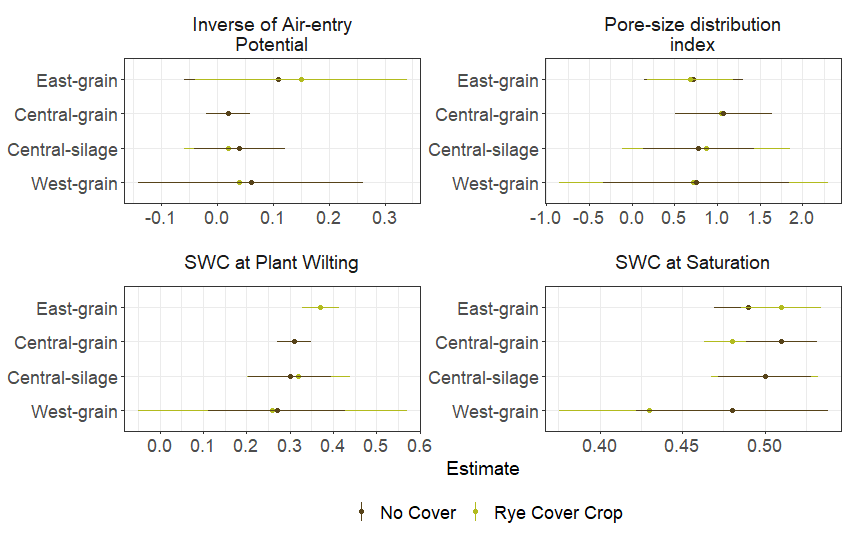
## Organic matter

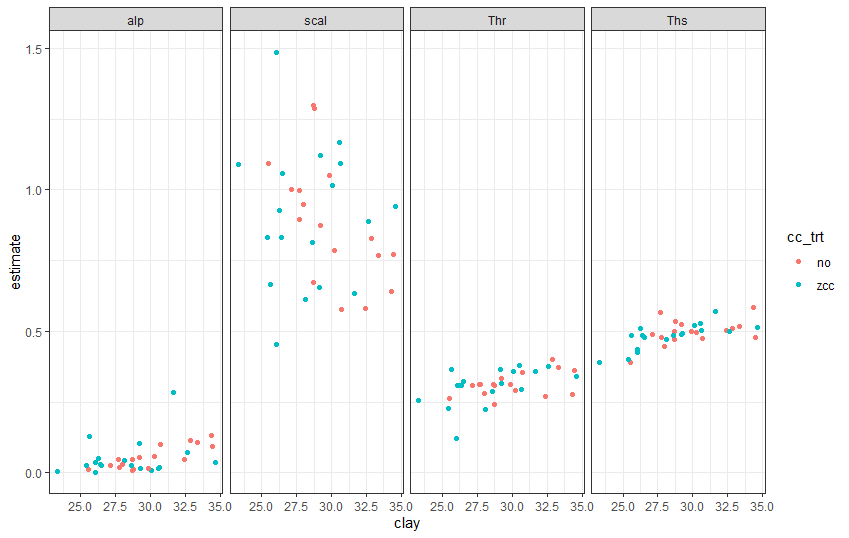
The effect of cover cropping on organic matter in Midwestern maize-based systems is inconsistent (<https://www.agevidence.org>). Our early spring sampling likely amplified differences in organic matter, due to the recently terminated cover crop residue and roots being less than a month old. The 20% increase at a 10-17cm depth observed at the East-grain experiment 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, a distinction that is likely important when understanding cover crop’s contribution to soil organic matter (Cotrufo et al. 2019, CITE). Although the East-grain site was the only experiment to exhibit a significant increase, the experiment’s 5- and 10-year average cover crop biomass production was moderate compared to the other experiments (Table 1), and the previous year’s cover crop biomass production was very low (0.3 Mg/ha; Supplemental). In addition to having higher organic matter, the cover cropped plots at the East-grain site had 3% higher clay contents (SE 0.80%, p < 0.01), indicating there may be confounding landscape factors present in the plots that may affect the organic matter results (Kaspar et al. 2006).

## Soil water

Several studies have compared the effect of cover crops on soil water relations (see Basche et al. XX, another), and on average have found cover crops improve soil’s storage capacities. However, to our knowledge, there is only one published study that compares soil water retention measurements in maize-based systems with and without winter cover cropping treatments (Basche et al. 2016). The authors found that in the 0-15 cm depths, cover cropping significantly increased the volumetric soil water at field capacity by 4 vol%, while having no effect on the soil water at -1500 kPa (plant wilting point). This difference translated to an increased amount of plant-availble-water. In contrast, we found cover cropping had no effect on soil water contents at saturation, and slightly increased the amount of water remaining in the soil at higher pressures. While we did not measure soil water contents at plant wilting, if the trend of increased water with cover cropping at high pressures was maintained it would have led to less plant-available water in the cover cropped plots.

Supplemental





1. Compare the soil’s porosity

Here, we measure the soil water retention curve

A X year field study in Pennsylvania found short-term use of cover crops did not change drought-induced yield penalties, suggesting improving soil hydrogical properties may require

Citations

Ankeny, M.D., Brown, H.J., Cruse, R.M., 1992. Means and method of soil water desorption. U.S. Patent 5,161,407.