**Effects of long-term cover cropping on soil hydrological properties**

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# Abstract

Addition of an over-wintering cereal rye (*Secale cereal*) cover crop in Midwestern maize (*Zea mays*)-based systems offers several environmental benefits, but the effect on soil hydrological properties is not well-understood. Soil water retention curves can provide insight into cover crop-induced soil changes that may affect soil water. We took in-tact 7.62 diameter soil samples at 10-17cm depths from four long-term cover crop experiments in Iowa 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 experiments had been in place for at least 10 years, and were managed without tillage. Soil samples were collected 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 -0.38, -2.5, -10, -25, -50, -100, and -500 cm water. One of the four experiments exhibited 1.2 times (SE:X) higher organic matter with cover cropping relative to no-cover, with no significant difference observed in the other three. Four hydrological parameters were used to compare the systems. Pore-size distribution index 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 (average of values at -50 and -100 cm water matric potential, respectively) were taken directly from the data. Neither pore-size distribution nor air-entry potentials were affected by cover cropping, but both had large amounts of uncertainty in their estimation. Cover-cropping increased soil water contents at saturation by 2% (SE:0.9%) in one experiment, increased field capacity by 1% (SE:0.4%) in two other experiments, and had no effect on either parameter in the fourth. While some cover crop benefits are consistent across environments and contexts, benefits to soil hydrological properties at depths relevant for crop production may be less consistent. Additionally, 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. 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

Use of over-wintering cover crops such as cereal rye (*Secale cereal*) in Midwestern maize (*Zea mays*)-based systems offers 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 or microbial biomass 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), among other functions (cite Alison King’s paper). 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. Recent field studies have shown mixed results with respect to cover crops and drought, with cover crops exacerbating drought effects (Martinez-Feria XX), having no effect (Hunter XX), or buffering maize yields at certain landscape positions (Leuthold et al. 2021). Additionally, the mulching effect of cover crop biomass in water conservation may be equally important as soil-related changes that allow for better infiltration and/or more soil water storage (Leuthold et al. 2021). 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 (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 with limited cover crop growing seasons (CITE). Additionally, while shallower 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 in contributing to the crop’s water supply (Asbjornsen et al 2008, another). In addition to limited data on depths relevant to crop production, there are few studies looking at long-term changes in soils from cover cropping. 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 data from long-term experiments.

There are several pathways by which cover crops may affect soil hydrology (Fig. 2), and the relative importance of each may depend on context. Soil erosion removes top soil, leaving layers with less organic matter and soil structure (CITE). In some instances cover crops may be simply preventing soil degradation via erosion, rather than directly contributing to enhancing the soil’s capacity to hold water.

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| Timeline  Description automatically generated |
| Figure 2. Pathways by which cover crops may affect the amount of water stored at field capacity and at saturation in no-till systems. |

The direct role of soil organic matter in water retention is unclear (that one, King et al. 2020), but soil organic matter is required for soil aggregation (CITE), which builds soil structure (CITE). Cover crop roots can create pores directly (CITE), and are roots are an important source of carbon that goes into organic matter (CITE) and contributes particulate organic carbon that promomtes soil aggregation (CITE). Additionally, belowground inputs promote biological activity that helps foment soil aggregation (CITE) and creation of pores (CITE).

The water retention curve represents the relationship between soil water content and soil water potential. The curve can be used to provide insight into the soil’s structure such as pore-size distributions. Additionally, the soil water status at saturation and field capacity provide information about porosity and the amount of water the soil can provide for a crop. These metrics may provide a more direct link between cover crops and cash crop yield stability than other soil health measurements, whose effects may have additional mediators (King et al. 2020, others).

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. To achieve our objectives 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 sampled (**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 experiment 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.

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| **Longitude Latitude** | **Initiation Year** | **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, 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 experiment, details about methodology are reported elsewhere (my weed paper, maybe somewhere else), 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 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, and a few days following a rain to ensure the soil was fully drained, but wet enough to remain in the ring during sampling (CITE?).

At all locations, samples were taken in the middle of the plots between planted rows. To get in-tact 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 experiment’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 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 (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 = -3.8 cm water). Subsequent measurements were taken at matric potentials (Ψ) of -2.5, -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 (XX 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 (X microns-Xmicrons), silt (X), and clay (X).

### 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 version 4.0.3 (R Core Team, 2020) and the tidyverse meta-package (Wickham et al. 2019). Non-linear models were fit using 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 experiment, 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. Experiment, 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 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 or sand 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 1.7% 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. 6% less sand compared to the no-cover plots. Sand and clay were inversely related (Supplemental material).

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).

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

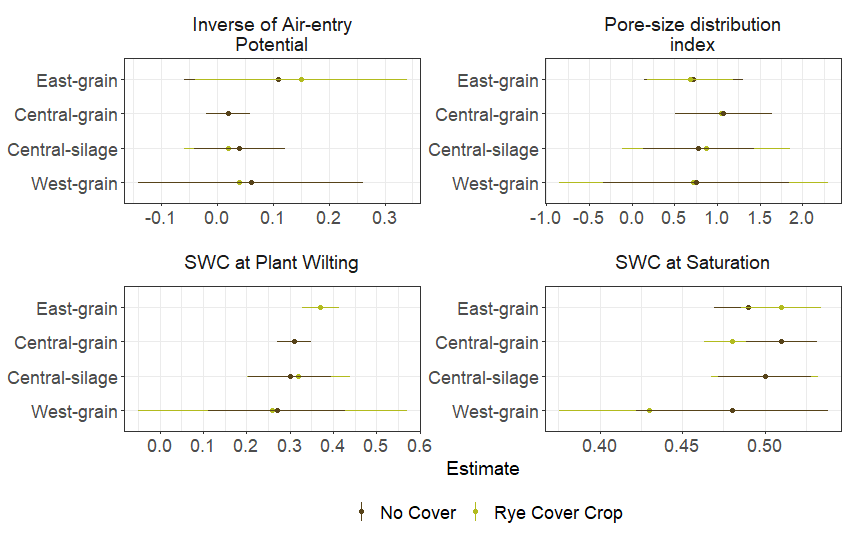
## Organic matter

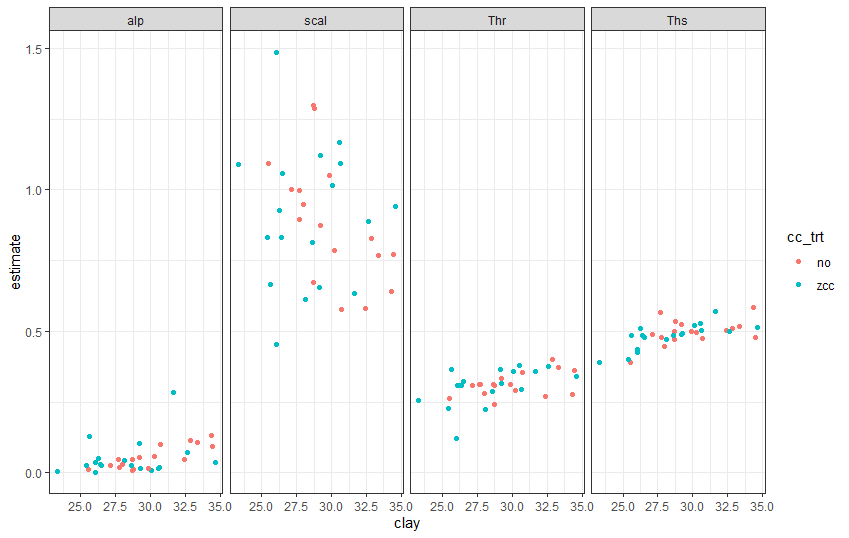
The effect of cover cropping on organic matter in Midwestern maize-based systems is inconsistent ([Atwood](https://www.agevidence.org) and Wood 2020). Our early spring sampling likely amplified differences in organic matter, due to the recently terminated cover crop residue and roots being less than 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.

Lesley W. Atwood and Stephen A. Wood. 2020. [AgEvidence: Agro-environmental responses of conservation agricultural practices in the US Midwest published from 1980 to 2020.](https://knb.ecoinformatics.org/view/doi%3A10.5063%2FZ31X15" \t "_blank)Knowledge Network for Biocomplexity. [doi:10.5063/Z31X15](https://doi.org/10.5063/Z31X15).

Douglas Bates, Martin Maechler, Ben Bolker, Steve Walker (2015). Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48. doi:10.18637/jss.v067.i01.

Da Silva, A.R.; De Lima, R.P. (2015) soilphysics: an R package to determine soil pre-consolidation pressure. Computers and Geosciences, 84: 54-60.

Miguez, Fernando (2021). nlraa: Nonlinear Regression for Agricultural Applications. R package version 0.83.

Omuto, Christian Thine; Martin Maechler and Vitalis Too (2021). HydroMe: Estimating Water Retention and Infiltration Model Parameters using Experimental Data. R package version 2.0-1. https://CRAN.R-project.org/package=HydroMe

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.

Russell V. Lenth (2021). emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.5.4. https://CRAN.R-project.org/package=emmeans

Wickham et al., (2019). Welcome to the tidyverse. Journal of Open Source Software, 4(43), 1686, <https://doi.org/10.21105/joss.01686>

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. Journal of Statistical Software, 36(3), 1-48. URL: https://www.jstatsoft.org/v36/i03/