**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 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 experiments 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 experiments had been in place for at least 10 years and were managed without tillage. At each experiment, we took in-tact 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 -0.38, -2.5, -10, -25, -50, -100, and -500 cm water. Four hydrological parameters were used to compare the soils. 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. One of the experiments with increased field capacity also exhibited 1.2 times (SE:X) higher organic matter with cover cropping relative to no-cover; no significant difference observed in the other three experiments. 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 detectable 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. We propose a causal diagram relating cover crops to soil properties relevant to soil water holding capacities to aid in designing experiments to achieve these goals.

# 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 of this addition on soil hydrological properties is not well-understood.** Over-wintering cover crops help to perennialize rotations of summer annuals, which reduces soil erosion and nitrate leaching (CITE). Short term use of rye cover crops has, on average, a neutral effect on crop yields (Maricllo and Miguez XXXX), but long-term effects are less clear. Cover cropping benefits related to soil health such as increased soil carbon or microbial biomass have been reported (e.g. XX), which in theory should 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, 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. 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 et al. 2021), or buffering maize yields only at certain landscape positions (Leuthold et al. 2021). Additionally, the mulching effect of cover crop biomass may be equally as important as soil-related changes that allow for better infiltration and/or more soil water storage (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 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). 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.

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 10-18 cm depth from four long-term (10+ years) cover crop experiments located in Iowa, USA. Two experiments were on-farm, and two were research plots. 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.

# 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 and details about methodology are reported elsewhere (my weed paper, maybe somewhere else) with historical values 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 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 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 . 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).

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. 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 experiment 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 matric potentials of -50 and -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 experiments 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).

The effects of experiment, cover crop treatment, their interaction, and appropriate covariates 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 experiment, with the East-grain site having the lowest amount of sand and highest silt component. Within an experiment, the sample’s texture also varied by cover crop treatment, with the cover cropped plots having a significantly higher sand component than the no-cover plots in the West-grain and East-grain experiments (**Fig. 2**).

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| **Figure 2.** Soil texture components varied by experiment 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 experiments. |

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 clay as a covariate. Organic matter values ranged from 1.8 to 4.6%. Organic matter at the East-grain site was 1.2 (no clay adjustment) or 1.4 (clay 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 clay 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 experiment 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 experiment (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 experiment was the only experiment 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) experiments. At the West-grain experiment, the soil water at field capacity was increased from 35 to 37%, and at the Central-silage experiment 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) or winter fallow (brown) in a maize-soybean rotation at four experiments. Points are estimated means, line ranges are the standard errors of the estimate, and stars indicate significant differences at a p < 0.10. Note all estimates include an adjustment for the percent sand in the sample. |

### Soil water retention curves

The Gardener 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 Gardener 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). |

# Discussion

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

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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 relative contribution of path will likely depend on the context. For example, 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.

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), which can indirectly contribute to increasing soil water-holding capacities.

Cover crop roots can create pores directly (CITE), and roots may contribute disproportionate amounts of carbon to the soil organic matter pool (CITE). Additionally, belowground inputs may 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).

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). We found cover cropping increased the volumetric soil water at field capacity at two of the four experiments we sampled, each increasing it by 2 vol%. While we defined field capacity differently than the aforementioned study, XX

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 observations fall within that range. 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. The 20% relative 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 had significantly different soil textures. While the experimental site was flat (<X% slopes), 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. In addition to being the only site where cover cropping affected the soil organic matter, the East-grain experimental site was the only site to exhibit a change in bulk density with cover cropping. Furthermore, this difference in bulk density translated to an increased capacity to hold water at saturation. An increase in volumetric water contents at saturation from 41 to 44% translates to XX per hectare. While likely not meaningful on a field-scale, this increased ability of the soil to hold water at saturation could have implication for potential flood mitigation if translated to a landscape-scale. To our knowledge, this has not been investigated, and is an area that merits further research.

**Field capacity**

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 transpiration. At the East-grain experiment, the differences in bulk density and organic matter did not translate to increased soil water held at field capacity (**Figure X**). However, the West-grain and Central-silage experiments both exhibited 2% increases in volumetric soil water held at field capacity with the use of cover crops. Organic matter contents were not significantly different at these experiments, nor were bulk densities, indicating soil structures may be contributing to this difference. The pore-size distributions and air-entry potentials were not different at these experiments, 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.

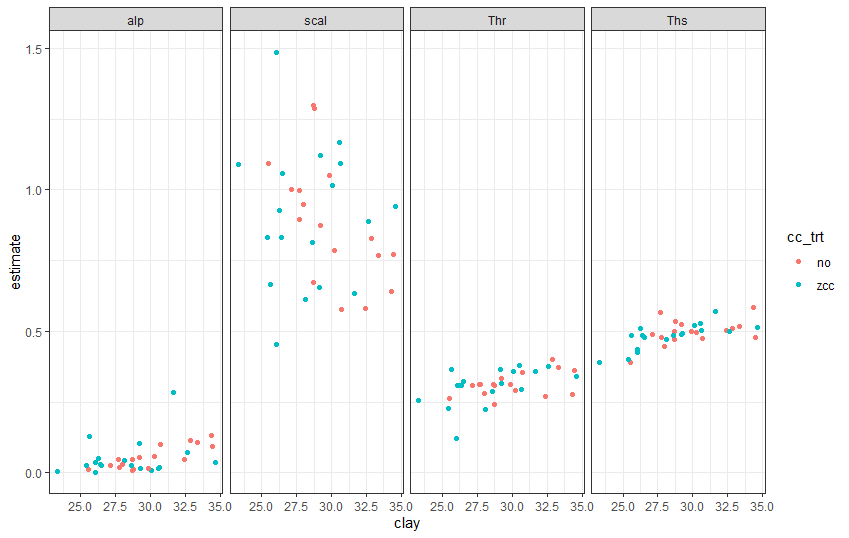
More direct measurements of soil pore size distributions may be necessary

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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).

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 |



# Citations

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