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

V.A. Nichols1\*, E. B. Moore2, S Gailans3, M Liebman1

**Affiliations:**

1Department of Agronomy, 716 Farmhouse Lane, Iowa State University, Ames IA, 50011

2Department of Environmental Sciences, 601 S. College Road, University of North Carolina Wilmington, Wilmington NC, 28403

3Practical Farmers of Iowa, 1615 Golden Aspen Dr, Ames IA 50010

\*corresponding author

**Abbreviations:**

CC, cover crop

USDA, United States Department of Agriculture

**Core ideas**

* Cover crop effects on soil water storage at 10-18 cm soil cm depth varied by trial
* Cover crops increased water held at field capacity in two of four trials
* Cover crops did not affect water held at saturation or increase percentage of macropores
* Proposed causal model shows cover crop root measurements may be a key measurement

Abstract

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

Introduction

Addition of an over-wintering cereal rye (*Secale cereale* L.) cover crop (CC) to Midwestern maize (*Zea mays* L.)-based systems potentially offers several environmental benefits including reduced soil erosion and nutrient pollution (Strock et al., 2004; Kaspar et al., 2007; Kaspar and Singer, 2011; Kladivko et al., 2014). On average, rye CCs have no effect on maize yields compared to winter fallow in the short term (Marcillo and Miguez, 2017), but it is possible that long-term cover cropping could stabilize crop yields. In Midwestern rain-fed systems, crops rely on stored soil water and often suffer from drought stress (Campos et al., 2006). Using CCs may induce changes in soil characteristics such as increased organic matter, lower bulk densities, and more macro-pores (Haruna et al., 2020a). In theory, these changes could result in more water storage capacity (Hudson, 1994; Minasny and McBratney, 2018; King et al., 2020), and therefore buffer crop yields against drought stress (Williams et al., 2016; Kane et al., 2021). Cover crops might also benefit crop-water relations by increasing water infiltration or reducing evaporation through a mulching effect (Unger and Vigil, 1998; Leuthold et al., 2021). Two global meta-analyses suggest CCs increase soil’s capacity to store water and increase infiltration rates (Basche and DeLonge, 2017, 2019). However, to our knowledge there are few studies supporting these findings in Midwestern cover cropping contexts, and the few existing studies report contradicting results (Villamil et al., 2006; Haruna and Nkongolo, 2015; Basche et al., 2016; Rorick and Kladivko, 2017; Irmak et al., 2018). Region-specific studies are needed, as climatic and management constraints of maize-soybean rotations can limit CC options and growth potential (Strock et al., 2004; Baker and Griffis, 2009; Nichols et al., 2020a).

In addition to regional differences in CC effects, the duration of cover cropping may also influence whether changes in soil are detected. Long-term studies on tillage have shown significant, but slow changes to the soil after implementing no-till (Al-Kaisi et al., 2014; Cusser et al., 2020). Addition of CCs might likewise require several years before changes in soil hydrological properties can be detected, necessitating data collection from long-term experiments. Furthermore, while shallow soil depths (0-10cm) may be more responsive to CC effects e.g. (Atwood and Wood, 2021; Kaspar et al., 2006; Moore et al., 2014), deeper depths may be more important when considering the soil’s contribution to the crop’s water supply (Williams et al., 2008; Asbjornsen et al., 2008; Rizzo et al., 2018).

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

Given the need to quantify long-term benefits of cover cropping, the scarcity of Midwest-specific data at depths relevant to crop water-use, and lack of a framework for organizing relevant knowledge, the objectives of our study were to:

(1) Determine what aspects of a soil’s hydrological characteristics are affected by long-term cover cropping at a depth relevant to crop production, and whether those effects are consistent across sites.

(2) Use our findings to propose a causal model connecting CCs to changes in soil properties to aid in targeting future research.

We collected soil samples at a 10-18 cm depth increment from four long-term (10+ years) no-till cover crop trials located in Iowa, USA. Two trials were on-farm production fields, and two trials were part of a larger research experiment. We assessed the effects of long-term cover cropping on soil water content at saturation, soil water content at matric potentials approximating field capacity on the shallow water tables that characterize landscapes in this region (-100 cm H2O, Moore 2021), and pore-size distributions as estimated by the soil water retention curve. To complement and contextualize these data, we also measured soil texture, soil organic matter, and bulk densities of the soil samples. We used our results in combination with previous literature to construct a proposed causal model (Pearl, 2010).

Materials and Methods

## *Site descriptions*

Three long-term sites were used for this study (**Supplementary Figure S1**), with one site having two trials. Therefore, a total of four trials were sampled (**Table 1**). Each trial consisted of two treatments that had been in place for at least 10 years: (1) a maize/soybean rotation (either grain- or silage-based) with a winter rye CC planted yearly in the fall following cash crop harvest and terminated in the spring, and (2) the same rotation without a CC. 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 except for the planting of the CC in the fall. The exact herbicide and nutrient programs varied by site, reflective of their managers and contexts (**Supplementary Tables S1, S2, S3**). More detailed accounts of agronomic management have been published elsewhere for the research and commercial farm sites (Moore et al., 2014; Nichols et al., 2020b). All sites had sub-surface tile drainage at approximately 1.2 m and were managed without tillage since initiation of the trials.

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

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Plot Size and Average Slope\*** | **Treatment Replications** | **Dominant Soil Types\***  **Sand/Silt/Clay\*\*** | **Average Depth to Water Table\*** | **30-year Annual Mean** | |  | **Mean Cover Crop Biomass** | | **2018 Crop** | **2019 Sample Date** |
| ***Air Temperature*** | ***Precipitation*** |  | ***5-year*** | ***10-year*** |
| *m* |  | *%* | *cm* | *⁰C* | *mm* |  | *Mg ha-1* | *Mg ha-1* |  |  |
| *West-grain (commercial farm),*  41⁰55’N 94⁰36’W, initiated in 2008 | | | | | | | | | | |
| 25 x 250  (1-3%) | 4 | Nicollet loam; 29/43/28 | 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  (1-3%) | 5 | Clarion loam;  30/41/29 | 100 | 9.8 | 907 |  | 2.38 | 1.98 | Maize | June 6 |
| *Central-grain (research plots),*  42⁰00’N 93⁰48’W, initiated in 2009 | | | | | | | | | | |
| 3.8 x 55  (1-3%) | 5 | Clarion loam;  32/40/28 | 100 | 9.8 | 907 |  | 1.53 | 0.88 | Maize | June 6 |
| *East-grain (commercial farm),*  41⁰18’N 92⁰48’W, initiated in 2009 | | | | | | | | | | |
| 25 x 275  (0-2%) | 4 | Taintor silty clay loam;  11/56/33 | 0 | 10.2 | 947 |  | 1.73 | 1.32 | Maize | June 10 |
| *\* From Web Soil Survey data using map unit area weighted estimates*  *\*\* Measured, see Materials and Methods* | | | | | | | | | | |

The West-grain and East-grain trials were production fields on commercial farms, and only one phase of the maize/soybean rotation was present each year. The Central site was a larger research study managed by the United States Department of Agriculture (USDA) and included both phases of each rotation (Kaspar et al., 2007, 2012). For the present study, only the soybean phase of the USDA site was sampled due to time constraints. Cover crop biomass sampling occurred each spring at every trial by removing two or four aboveground biomass from an area of 0.25-0.36 m2 from each plot, depending on the trial; details about methodology are reported elsewhere (Nichols et al., 2020b) and historical values are available in both supplementary material as in a published dataset (Nichols et al. 2020c). Maize and soybean grain yields were measured yearly. Results from the commercial fields showed the effect of cover cropping on grain yields varied by trial and by year (Practical Farmers of Iowa, 2018). Yields from the research plots have been published for 2005-2010 (Kaspar et al., 2012), and likewise show the effects of cover cropping on grain yields depended on the year. Understanding how cover crops affect grain crop yields in the long-term is a valuable topic of research, but is not the focus of the present study.

## *Soil Sampling*

An aluminum ring 7.62 cm in diameter and 7.62 cm in length was used to extract 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 two to four days following a rain to ensure the soil was fully drained, but wet enough to remain in the ring during sampling (Al-Shammary et al., 2018).

At all trials, samples were taken in the middle of the plots between planted rows. To get intact soil cores from a 10-18 cm depth increment, a hole 10 cm deep was dug, and soil was smoothed by hand to create a flat area approximately 30 cm square. The ring was placed on the soil surface in the center of the flat area, a hollow metal cap was placed on it, and a 15 kg weight was used to evenly drive the ring into the undisturbed soil. Once the ring was fully inserted into the soil, a hole was dug around the ring. A flat sheet of metal was slid under the ring to extract it, and a knife was used to remove soil from the top and bottom of the ring using a Z-cutting motion. The ring was wrapped in aluminum foil with the soil orientation (top, bottom) marked. The foil-wrapped ring was then placed in an individual plastic container and placed in a cooler. This process was repeated for each plot. Samples remained in the cooler for no more than four hours before being placed in a refrigerator.

### *Soil-water-retention curve*

## Analytical equipment could accommodate 12 samples at a time, so each trial’s samples were run together in a batch for a total of four batches (e.g., the eight samples from the West-grain trial were run together in one batch). Our interest was in comparing relative effects within a trial, so variation between runs was statistically included in variation between trials. The samples were analyzed in the order they were collected. A given trial’s cores had cheesecloth taped to the bottom of each core and an additional ring taped to the top. Each full batch of samples (eight samples 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 samples to saturate with minimal air entrapment. The top ring was removed from the cores, then the saturated cores were weighed, then transferred to a custom-built pressure cell apparatus (Ankeny et al. 1992). Measurements were made according to the protocol described by Kool et al. (2019). Cores were drained at atmospheric pressure for 12 hours to obtain a measurement for gravity-drained values (Ψm = -3.8 cmH2O). Subsequent measurements were taken at matric potentials (Ψm) of -10, -25, -50, -100, -200, and -500 cmH2O. The samples were then oven dried at 60 ⁰C 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; Grossman et al., 2002). A water balance was constructed for each core individually as quality control, resulting in the removal of one replicate from the no-cover treatment of the Central-silage trial, which had a large visible hole in the center of the core upon destructive inspection, confirming its justified removal from the dataset.

### *Soil texture and organic carbon*

The oven-dried soil was ground and passed through a 2 mm sieve. Two teaspoons of soil (~10 grams) from each core were used for soil texture measurements. Soil texture was quantified using laser diffractometry (Miller and Schaetzl, 2012) with a Malvern Mastersizer 3000 and a HydroEV attachment (Malvern Panalytical Ltd, UK), producing estimates for the percentage of the soil that was sand (50-2000 µm), silt (6-50 µm), and clay (0.1-6 µm). Half of the remaining oven-dried soil cores were sent for organic matter analysis (Agsource, Ellsworth Iowa, USA) using the loss-on-ignition method (Nelson and Sommers, 1983). While this method may not produce reliable absolute estimates of organic matter (Hoogsteen et al., 2015), our interest was in pairwise comparisons of treatments rather than in obtaining absolute estimates of organic matter.

## *Statistical analysis*

All data analysis, figure creation, and model fitting 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* (de Lima et al., 2021) packages. Linear models were fit and summarized using the *lme4* (Bates et al., 2015) package, which fits mixed effects models, and the *emmeans* (Lenth et al., 2018) package which estimates both marginal and conditional means and confidence intervals and performs pairwise comparisons.

We fit the Gardner (Gardner, 1958) and van Genutchen (van Genuchten, 1980) models to describe the relationship between soil moisture and soil water matric potential in our datasets. We found the models produced similar Akaike’s Information Criteria (AIC; Bozdogan, 1987) values, with the Gardner model showing a slightly better fit. 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 broader distribution of pore sizes. We fit the Gardner model to each experimental unit, then analyzed the air-entry and pore-size distribution parameters as response variables, described below.

Residual water contents (θr) are estimated by the model, but can also be experimentally measured at -15,000 cmH2O (SSSA, 2008). The highest presssure applied to samples in this study was -500 cmH2O, which could lead to less stable model fits due to lack of an anchoring value (Groenevelt and Grant, 2004). To determine whether the model produced reasonable estimates without these anchoring values, we compared (1) the model-estimated saturated water contents with the data, and (2) the pore-size distribution parameter estimate against values estimated using capillary rise equations, which assumes the mean pore neck diameter (in cm) of drained pores at a given pressure is equal to 0.3 divided by the head pressure (cmH2O). Pores with mean neck diameters greater than 30 µm were considered macropores (Kirkham, 2014). The percent macropores was assessed as a response variable, described below.

Volumetric water contents at saturation were extracted directly from the data. Volumetric water contents at field capacity were estimated as the volumetric water content at a matric potential of -100 cmH2O (Moore 2021). We used this approximation because the matric potential that respresents field capacity depends on the depth to the water table. The trials sampled all had artificial tile drainage installed at ~1.2 meter depths and shallow water tables (Table 1), meaning field capacity will be at matric potentials less negative than the commonly assumed value of -330 cmH2O (Bonfante et al., 2020). Soil water retention curve data from Moore (2021), suggests that -100 cmH2O is a better approximation for field capacity in mollic epipedons with shallow water tables, such as those sampled in the present study.

The effects of trial, CC treatment, and their interaction on response variables (soil texture, organic matter, water contents at saturation and field capacity, air-entry pressures, pore-size distribution index, percent macropores) were assessed using mixed-effect models. Trial, CC treatment, and their interaction were included as fixed effects. Percent sand was investigated as a covariate in appropriate models because texture is the dominant driver of water retention curve parameters (de Jong et al., 1983; Saxton and Rawls, 2006). Models without a sand covariate had random intercept effects for replicates nested within location (East, Central, West), and models that included a sand covariate had fixed effects only. Models were compared using AIC. All results are available in **Supplementary Tables S5-S11**.

Results and Discussion

## *Soil texture, organic matter, and bulk density*

All plots had textures within ranges classified as silty-clay-loams. Texture varied most strongly by trial, with the East-grain trial having the lowest amount of sand and highest silt component. In the two commerical farm field trials, the sample’s texture also varied by CC treatment. The CC plots had a significantly higher sand component, and significantly lower clay component than the no-cover plots in the West-grain and East-grain trials (**Table 1**, **Supplemental Figure S2**). While the plots in the commercial farm fields were randomly assigned a CC treatment, the East-grain site’s treatments were regularly alternating strips with blocks laid out laterally, and the West-grain sites were close to regular alternations likewise laid out laterally. In fields with a uniform texture gradient perpendicular to the blocking with only two treatments, this regularly alternating pattern could result in one treatment having significantly different textures compared to the other. The Central site had several treatments in small plots and the field was divided into four quadrats to create the four blocks with each treatment being randomly assigned within the block; this arrangement may have better randomized treatments with respect to natural patterns of soil texture variability spatially within the site.

Based on these results, sand was investigated as a covariate in statistical models for response variables thought to be affected by soil texture. Soil texture is the dominant factor determining soil water retention (de Jong et al., 1983; Saxton and Rawls, 2006), particularly under wet conditions (i.e. saturation and field capacity; Manns and Berg, 2014), so statistical comparisons of soil water at saturation and field capacity are reported from models that include the sand co-variate.

Organic matter concentrations ranged from 1.8 to 4.6%. The organic matter models were very sensitive to inclusion of sand as a covariate. The two trials with significantly different sand components in the cover crop and winter fallow treatments had lower organic matter in the cover crop treatments without a sand-correction, but higher organic matter with a sand correction. We therefore choose not to report the results from the organic matter analyses, but results are available (**Supplementary Table S7**).

Bulk densities varied from 1.2 g cm-3 to 1.7 g cm-3. The large size of sand particles reduces packing efficiencies compared with clay, meaning a sandy soil may have lower bulk densities simply due to packing arrangements. However, regardless of the statistical model fit, all estimated CC effects were less than measurement precision of the core method for measuring bulk density (±0.12 g cm-3, (Han et al., 2016), rendering their interpretation questionable. A recent summary of research on the effects of CCs on bulk densities likewise found few studies where an overwintering rye CC grown in the US reduced bulk densities more than typical measurement errors (Haruna et al., 2020b).

## Soil hydrological properties

The Gardner equation fit converged for all experimental units (**Figure 1**), with *a* (inverse of air-entry potential) ranging from 0.001 to 0.284, and *n* (pore-size distribution index) ranging from 0.45 to 1.49. While the parameters did differ by trial, cover cropping did not significantly affect either parameter in any trial.

|  |
| --- |
|  |
| **Figure 1.** The Gardner equation was fit to each experimental unit (dotted lines); mean values (solid lines) for each trial and cover crop treatment are presented to aid in interpretation. |

Due to the high amount of variability associated with soils, we assigned significance at p-values less than 0.10. With or without a sand correction, no trial exhibited a significant increase in water held at saturation with the use of cover cropping (**Figure 2**). Water held at saturation is largely dependent on bulk density, so these findings are consistent with the lack of meaningful effect of CCs on bulk densities in our study.

|  |
| --- |
|  |
| **Figure 2**. Soil volumetric water contents at saturation and field capacity (-100 cmH2O) with 10+ years of winter rye cover cropping (green) or winter fallow (brown) in a maize-soybean rotation at four trials. Bars show estimated means, line ranges are the 95% confidence intervals around the mean. Text presents the estimated effect of cover cropping on volumetric water content in instances of a significant effect. |

Field capacities were signifiantly higher in the cover cropped plots at both the West-grain (p = 0.07) and Central-silage (p = 0.05) trials. At the West-grain trial, the soil water at field capacity was increased (after sand correction) from 33.6 to 36.0 vol%, and at the Central-silage trial from 38.1 to 40.6 vol%, respectively. The West-grain trial consistently produced the lowest above-ground CC biomasses, and the Central-silage trial the highest (**Table 1**), indicating the changes in water held at field capacity could not be predicted based on CC above-ground biomass production. Likewise, there was no pattern between soil textural characteristitcs and presence or absence of a CC effect on water held at field capacity, meaning that knowledge of a soil’s texture did not help predict whether a CC would affect water held at field capacity. We explore potential causes for our variable results and identify additional measurements in a later section.

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

Manual estimation of the pore-size distribution confirmed CCs did not increase the percentage of macropores in any trial (**Supplemental Figure S3**). In fact, in the West-grain trial the number of macropores significantly decreased with cover croping, with 61% macropores in the control treatment compared with 48% in the CC treatment. In a review of published studies, Haruna et al. (2020) found the effect of CCs on macropore makeup of the soil highly variable, but with an overall average increase. The wide variation may be partially due to varying cut-offs in pore sizes for macropore categorization (Luxmoore, 1981), but the variability in combination with our results again demonstrates using literature averages to predict CC impacts in Midwestern systems may be inappropriate.

## *Causal model*

There are several pathways by which CCs might affect a soil’s capacity to hold water (**Figure 3, Table 2**).

|  |
| --- |
|  |
| **Figure 3**. Pathways by which cover crops may affect the pore size distributions, the amount of water stored at field capacity, and the amount of water at saturation in no-till systems. The effects of soil erosion are not included. X→Y should be read as ‘X affects Y’. |

The causal model was built using literature relevant to Midwestern systems, and when applicable was limited to evidence drawn from research conducted with a cereal rye cover crop (**Table 2**). The model is simplified to exclude the effects of soil erosion, soil texture, tillage, and landscape position, which are all factors that could potentially influence how soil responds to cover cropping (Moore 2021). Rather, we present this simple casusal model to provide a base from which to build.

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

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

Causal diagrams such as **Figure 6** are the basis for constructing structural equation models, which can greatly enhance researchers’ ability to address complex research questions in agriculture (Smith et al., 2014; Wade et al., 2020). For example, in our proposed causal diagram, below-ground biomass measurements are necessary for estimating direct effects of cover cropping on pore size distributions, field capacity, and saturation. This is further supported by recent studies and reviews that identify CC roots as being a crucial component to understanding CC effects on soil properties (Williams and Weil, 2004; Haruna et al., 2020b; Ogilvie et al., 2021). While there is limited data available on both above- and below-ground biomass of CCs, data collected over the period of five years in Iowa showed no relationship between above- and below-ground rye biomass, with root-to-shoot ratios varying from 0.16-1.94 at similar levels of aboveground biomass production (Martinez-Feria et al., 2016). Therefore, above-ground biomass production cannot be used as a proxy for below-ground production with much confidence, and studies that pair above- and below-ground CC biomass with soil measurements would be advantageous in enhancing our understanding of CC effects on soil.

Conclusions

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

Supplemental Material

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

Data availability

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

Conflict of interest

The authors declare no conflicts of interest.

Author contibutions

VN contributed to conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, writing of original draft, and review/editing. ML contributed to funding acquisition, project administration, supervision, and review/editing of draft. SG contributed to project administration, resources, and review/editing. EM contributed to methodology, resources, and review/editing.

Acknowledgments

We would like to acknowledge Dr. Robert Horton for generously allowing us to use his lab space and equipment for this project. We also thank the two farmers and Keith Kohler for allowing us to collect data in their long-term plots, and Wyatt Westfall for his help collecting and preparing samples. We also thank the Practical Farmers of Iowa staff and members for their support throughout this project. This material is based upon work supported in part by the National Science Foundation (Grant No. DGE-1828942), the North Central Region Sustainable Research and Education Program (Grant No. 2017-38640-26916), and endowment funds for the Henry A. Wallace Chair for Sustainable Agriculture at Iowa State University.

References

Abiven, S., S. Menasseri, and C. Chenu. 2009. The effects of organic inputs over time on soil aggregate stability - A literature analysis. Soil Biology and Biochemistry 41(1): 1–12. doi: 10.1016/j.soilbio.2008.09.015.

Al-Kaisi, M.M., A. Douelle, and D. Kwaw-Mensah. 2014. Soil microaggregate and macroaggregate decay over time and soil carbon change as influenced by different tillage systems. Journal of Soil and Water Conservation 69(6). doi: 10.2489/jswc.69.6.574.

Al-Shammary, A.A.G., A.Z. Kouzani, A. Kaynak, S.Y. Khoo, M. Norton, et al. 2018. Soil Bulk Density Estimation Methods: A Review. Pedosphere 28(4): 581–596. doi: 10.1016/S1002-0160(18)60034-7.

Antolini, F., E. Tate, B. Dalzell, N. Young, K. Johnson, et al. 2020. Flood Risk Reduction from Agricultural Best Management Practices. Journal of the American Water Resources Association 56(1): 161–179. doi: 10.1111/1752-1688.12812.

Asbjornsen, H., G. Shepherd, M. Helmers, and G. Mora. 2008. Seasonal patterns in depth of water uptake under contrasting annual and perennial systems in the Corn Belt Region of the Midwestern U.S. Plant and Soil 308(1–2): 69–92. doi: 10.1007/s11104-008-9607-3.

Atwood, L.W., and S.A. Wood. AgEvidence: Agro-environmental responses of conservation agricultural practices in the US Midwest published from 1980 to 2017. Knowledge Network for Biocomplexity.

Austin, E.E., K. Wickings, M.D. McDaniel, G.P. Robertson, and A.S. Grandy. 2017. Cover crop root contributions to soil carbon in a no-till corn bioenergy cropping system. GCB Bioenergy 9(7): 1252–1263. doi: 10.1111/gcbb.12428.

Baker, J.M., and T.J. Griffis. 2009. Evaluating the potential use of winter cover crops in corn-soybean systems for sustainable co-production of food and fuel. Agricultural and Forest Meteorology 149(12): 2120–2132. doi: 10.1016/j.agrformet.2009.05.017.

Basche, A., and M. DeLonge. 2017. The Impact of Continuous Living Cover on Soil Hydrologic Properties: A Meta-Analysis. Soil Science Society of America Journal 81(5): 1179–1190. doi: 10.2136/sssaj2017.03.0077.

Basche, A.D., and M.S. DeLonge. 2019. Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis. PLoS ONE 14(9): 1–22. doi: 10.1371/journal.pone.0215702.

Basche, A.D., T.C. Kaspar, S. v. Archontoulis, D.B. Jaynes, T.J. Sauer, et al. 2016. Soil water improvements with the long-term use of a winter rye cover crop. Agricultural Water Management 172: 40–50. doi: 10.1016/j.agwat.2016.04.006.

Bates, D., M. Mächler, B. Bolker, and S. Walker. 2015. Fitting Linear Mixed-Effects Models using lme4. Journal of Statistical Software 67(1): 1–48. doi: 10.18637/jss.v067.i01.

Bonfante, A., A. Basile, and J. Bouma. 2020. Exploring the effect of varying soil organic matter contents on current and future moisture supply capacities of six Italian soils. Geoderma 361: 114079. doi: 10.1016/j.geoderma.2019.114079.

Boyle, M., W.T. Frankenberger, and L.H. Stolzy. 1989. The Influence of Organic Matter on Soil Aggregation and Water Infiltration. Journal of Production Agriculture 2(4): 290–299. doi: 10.2134/jpa1989.0290.

Bozdogan, H. 1987. Model selection and Akaike’s Information Criterion (AIC): The general theory and its analytical extensions. Psychometrika 52(3): 345–370. doi: 10.1007/BF02294361.

Campos, H., M. Cooper, O. Edmeades, C. Loffler, J.R. Schussler, et al. 2006. Changes in drought tolerance in maize associated with fifty years of breeding for yield in the US corn belt. . Maydica 51(2).

Cotrufo, M.F., M.D. Wallenstein, C.M. Boot, K. Denef, and E. Paul. 2013. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? Global Change Biology 19(4): 988–995. doi: 10.1111/gcb.12113.

Cusser, S., C. Bahlai, S.M. Swinton, G.P. Robertson, and N.M. Haddad. 2020. Long‐term research avoids spurious and misleading trends in sustainability attributes of no‐till. Global Change Biology 26(6). doi: 10.1111/gcb.15080.

Edwards, W.M., L.D. Norton, and C.E. Redmond. 1988. Characterizing Macropores that Affect Infiltration into Nontilled Soil. Soil Science Society of America Journal 52(2): 483–487. doi: 10.2136/sssaj1988.03615995005200020033x.

Gardner, W.R. 1958. Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Science 85(4): 228–232. doi: 10.1097/00010694-195804000-00006.

van Genuchten, M.Th. 1980. A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. Soil Science Society of America Journal 44(5): 892–898. doi: 10.2136/sssaj1980.03615995004400050002x.

Groenevelt, P.H., and C.D. Grant. 2004. A new model for the soil-water retention curve that solves the problem of residual water contents. European Journal of Soil Science 55(3): 479–485. doi: 10.1111/j.1365-2389.2004.00617.x.

Grossman, R.B., and T.G. Reinsch. 2002. Bulk density and linear extensibility. In J. H. Dane & G. C. Topp (Eds.), Methods of soil analysis: Part 4, physical methods (pp. 201–228). SSSA. https://doi.org/10.2136/sssabookser5.4.c9

Han, Y., J. Zhang, K.G. Mattson, W. Zhang, and T.A. Weber. 2016. Sample Sizes to Control Error Estimates in Determining Soil Bulk Density in California Forest Soils. Soil Science Society of America Journal 80(3): 756–764. doi: 10.2136/sssaj2015.12.0422.

Haruna, S.I., S.H. Anderson, R.P. Udawatta, C.J. Gantzer, N.C. Phillips, et al. 2020a. Improving soil physical properties through the use of cover crops: A review. Agrosystems, Geosciences & Environment 3(1). doi: 10.1002/agg2.20105.

Haruna, S.I., S.H. Anderson, R.P. Udawatta, C.J. Gantzer, N.C. Phillips, et al. 2020b. Improving soil physical properties through the use of cover crops: A review. Agrosystems, Geosciences & Environment 3(1). doi: 10.1002/agg2.20105.

Haruna, S.I., and N. v. Nkongolo. 2015. Cover Crop Management Effects on Soil Physical and Biological Properties. Procedia Environmental Sciences 29: 13–14. doi: 10.1016/j.proenv.2015.07.130.

Hoogsteen, M.J.J., E.A. Lantinga, E.J. Bakker, J.C.J. Groot, and P.A. Tittonell. 2015. Estimating soil organic carbon through loss on ignition: Effects of ignition conditions and structural water loss. European Journal of Soil Science 66(2): 320–328. doi: 10.1111/ejss.12224.

Hudson, B.D. 1994. Available water capacity and soil organic matter. Journal of Soil and Water Conservation 49(2): 189–194. doi: 10.1081/E-ESS-120018496.

Irmak, S., V. Sharma, A.T. Mohammed, and K. Djaman. 2018. Impacts of Cover Crops on Soil Physical Properties: Field Capacity, Permanent Wilting Point, Soil-Water Holding Capacity, Bulk Density, Hydraulic Conductivity, and Infiltration. Transactions of the ASABE 61(4). doi: 10.13031/trans.12700.

de Jong, R., C.A. Campbell, and W. Nicholaichuk. 1983. Water retention equations and their relationship to soil organic matter and particle size distribution for disturbed samples. Canadian Journal of Soil Science 63(2): 291–302. doi: 10.4141/cjss83-029.

Kane, D.A., M.A. Bradford, E. Fuller, E.E. Oldfield, and S.A. Wood. 2021. Soil organic matter protects US maize yields and lowers crop insurance payouts under drought. Environmental Research Letters 16(4). doi: 10.1088/1748-9326/abe492.

Kaspar, T.C., D.B. Jaynes, T.B. Parkin, and T.B. Moorman. 2007. Rye cover crop and gamagrass strip effects on NO3 concentration and load in tile drainage. Journal of environmental quality 36(5): 1503–1511. doi: 10.2134/jeq2006.0468.

Kaspar, T.C., D.B. Jaynes, T.B. Parkin, T.B. Moorman, and J.W. Singer. 2012. Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. Agricultural Water Management 110(3): 25–33. doi: 10.1016/j.agwat.2012.03.010.

Kaspar, T.C., T.B. Parkin, D.B. Jaynes, C.A. Cambardella, D.W. Meek, et al. 2006. Examining Changes in Soil Organic Carbon with Oat and Rye Cover Crops Using Terrain Covariates. Soil Science Society of America Journal 70(4): 1168–1177. doi: 10.2136/sssaj2005.0095.

Kaspar, T., and J. Singer. 2011. The Use of Cover Crops to Manage Soil. Publications from the USDA-ARS/UNL Faculty. p. 1382

Kay, B.D., A.P. da Silva, J.A. Baldock, D. Silva, A.P. And Baldock, et al. 1997. Sensitivity of soil structure to changes in organic carbon content: Predictions using pedotransfer functions. Canadian Journal of Soil Science 77(4): 655–667.

Kim, N., M.C. Zabaloy, K. Guan, and M.B. Villamil. 2020. Do cover crops benefit soil microbiome? A meta-analysis of current research. Soil Biology and Biochemistry 142: 107701. doi: 10.1016/j.soilbio.2019.107701.

King, A.E., G.A. Ali, A.W. Gillespie, and C. Wagner-Riddle. 2020. Soil Organic Matter as Catalyst of Crop Resource Capture. Frontiers in Environmental Science 8. doi: 10.3389/fenvs.2020.00050.

Kirkham, M.B. 2014. Principles of soil and plant water relations, 2nd Edition. Elsevier Inc.

Kladivko, E.J., T.C. Kaspar, D.B. Jaynes, R.W. Malone, J. Singer, et al. 2014. Cover crops in the upper midwestern United States: Potential adoption and reduction of nitrate leaching in the Mississippi River Basin. Journal of Soil and Water Conservation 69(4): 279–291. doi: 10.2489/jswc.69.4.279.

Kool, D., B. Tong, Z. Tian, J.L. Heitman, T.J. Sauer, et al. 2019. Soil water retention and hydraulic conductivity dynamics following tillage. Soil and Tillage Research 193: 95–100. doi: 10.1016/j.still.2019.05.020.

Lenth, R., H. Singmann, and J. Love. 2018. Emmeans: Estimated maringal means, aka least-squares means.

Leslie, A.W., K.H. Wang, S.L.F. Meyer, S. Marahatta, and C.R.R. Hooks. 2017. Influence of cover crops on arthropods, free-living nematodes, and yield in a succeeding no-till soybean crop. Applied Soil Ecology 117–118: 21–31. doi: 10.1016/j.apsoil.2017.04.003.

Leuthold, S.J., M. Salmerón, O. Wendroth, and H. Poffenbarger. 2021. Cover crops decrease maize yield variability in sloping landscapes through increased water during reproductive stages. Field Crops Research 265. doi: 10.1016/j.fcr.2021.108111.

de Lima, R.P., A.R. da Silva, and Á.P. da Silva. 2021. soilphysics: An R package for simulation of soil compaction induced by agricultural field traffic. Soil and Tillage Research 206: 104824. doi: 10.1016/j.still.2020.104824.

Luxmoore, R.J. 1981. Micro-, Meso-, and Macroporosity of Soil. Soil Science Society of America Journal 45(3): 671–672. doi: 10.2136/sssaj1981.03615995004500030051x.

Manns, H.R., and A.A. Berg. 2014. Importance of soil organic carbon on surface soil water content variability among agricultural fields. Journal of Hydrology 516: 297–303. doi: 10.1016/j.jhydrol.2013.11.018.

Marcillo, G.S.S., and F.E.E. Miguez. 2017. Corn yield response to winter cover crops: An updated meta-analysis. Journal of Soil and Water Conservation 72(3): 226–239. doi: 10.2489/jswc.72.3.226.

Martinez-Feria, R.A., R. Dietzel, M. Liebman, M.J. Helmers, and S. v Archontoulis. 2016. Rye cover crop effects on maize: A system-level analysis. Field Crops Research 196: 145–159. doi: 10.1016/j.fcr.2016.06.016.

Miguez, F. 2021. nlraa: Nonlinear Regression for Agricultural Applications.

Miller, B.A., and R.J. Schaetzl. 2012. Precision of Soil Particle Size Analysis using Laser Diffractometry. Soil Science Society of America Journal 76(5): 1719. doi: 10.2136/sssaj2011.0303.

Minasny, B., and A.B. McBratney. 2018. Limited effect of organic matter on soil available water capacity. European Journal of Soil Science 69(1): 39–47. doi: 10.1111/ejss.12475.

Moore, E.B., M.H. Wiedenhoeft, T.C. Kaspar, and C.A. Cambardella. 2014. Rye Cover Crop Effects on Soil Quality in No-Till Corn Silage-Soybean Cropping Systems. Soil Science Society of America Journal 78(3): 968–976. doi: 10.2136/sssaj2013.09.0401.

Nelson, D.W., and L.E. Sommers. 1983. Total Carbon, Organic Carbon, and Organic Matter. John Wiley & Sons, Ltd. p. 539–579

Nichols, V., R. Martinez‐Feria, D. Weisberger, S. Carlson, B. Basso, et al. 2020a. Cover crops and weed suppression in the U.S. Midwest: A meta‐analysis and modeling study. Agricultural & Environmental Letters 5(1). doi: 10.1002/ael2.20022.

Nichols, V., L. English, S. Carlson, S. Gailans, and M. Liebman. 2020b. Effects of Long-Term Cover Cropping on Weed Seedbanks. Frontiers in Agronomy 2: 591091. doi: 10.3389/fagro.2020.591091.

Nichols, V., English, L. E., and Liebman, M. (2020c). Long Term Cover Cropping Effects on Weed Seedbanks [Dataset]. Iowa State University. doi: 10.25380/iastate.12762011.v1

Ogilvie, C.M., W. Ashiq, H.B. Vasava, and A. Biswas. 2021. Quantifying root-soil interactions in cover crop systems: A review. Agriculture (Switzerland) 11(3). doi: 10.3390/agriculture11030218.

Omuto, C.T., M. Maechler, and V. Too. 2021. HydroMe: Estimating Water Retention and Infiltration Model  Parameters using Experimental Data.

Pearl, J. 2010. An introduction to causal inference. International Journal of Biostatistics 6(2). doi: 10.2202/1557-4679.1203.

Practical Farmers of Iowa. 2018. Winter cereal rye cover crop effect on cash crop yield Year 10. Available online (Accessed September 2021): https://www.iowalearningfarms.org/files/page/files/winter\_rye\_effect\_on\_yield\_year\_10\_1.pdf

Rizzo, G., J.I.R. Edreira, S. v. Archontoulis, H.S. Yang, and P. Grassini. 2018. Do shallow water tables contribute to high and stable maize yields in the US Corn Belt? Global Food Security 18: 27–34. doi: 10.1016/J.GFS.2018.07.002.

Rorick, J.D., and E.J. Kladivko. 2017. Cereal rye cover crop effects on soil carbon and physical properties in southeastern Indiana. Journal of Soil and Water Conservation 72(3). doi: 10.2489/jswc.72.3.260.

Ruehlmann, J., and M. Körschens. 2009. Calculating the Effect of Soil Organic Matter Concentration on Soil Bulk Density. Soil Science Society of America Journal 73(3): 876–885. doi: 10.2136/sssaj2007.0149.

Saxton, K.E., and W.J. Rawls. 2006. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. Soil Science Society of America Journal 70(5): 1569–1578. doi: 10.2136/sssaj2005.0117.

Smith, R.G., A.S. Davis, N.R. Jordan, L.W. Atwood, A.B. Daly, et al. 2014. Structural equation modeling facilitates transdisciplinary research on agriculture and climate change. Crop Science 54(2): 475–483. doi: 10.2135/cropsci2013.07.0474.

SSSA. 2008. Glossary of Soil Science Terms 2008. American Society of Agronomy and Soil Science Society of America, Madison, WI, USA.

Strock, S.J., P.M. Porter, and M.P. Russelle. 2004. Cover cropping to reduce nitrate loss through subsurface drainage in the northern U.S. corn belt. Journal of environmental quality 33(3): 1010–1016. doi: 10.2134/jeq2004.1010.

Unger, P.W., and M.F. Vigil. 1998. Cover crop effects on soil water relationships. Journal of Soil and Water Conservation 53(3): 200–207.

Villamil, M.B., G.A. Bollero, R.G. Darmody, F.W. Simmons, and D.G. Bullock. 2006. No-Till Corn/Soybean Systems Including Winter Cover Crops. Soil Science Society of America Journal 70(6): 1936–1944. doi: 10.2136/sssaj2005.0350.

Wade, J., S.W. Culman, J.A.R. Logan, H. Poffenbarger, M.S. Demyan, et al. 2020. Improved soil biological health increases corn grain yield in N fertilized systems across the Corn Belt. Scientific Reports 10(1): 3917. doi: 10.1038/s41598-020-60987-3.

Wickham, H., M. Averick, J. Bryan, W. Chang, L. McGowan, et al. 2019. Welcome to the Tidyverse. Journal of Open Source Software 4(43): 1686. doi: 10.21105/joss.01686.

Williams, A., M.C. Hunter, M. Kammerer, D.A. Kane, N.R. Jordan, et al. 2016. Soil water holding capacity mitigates downside risk and volatility in US rainfed maize: Time to invest in soil organic matter? PLoS ONE 11(8): 1–11. doi: 10.1371/journal.pone.0160974.

Williams, C.L., M. Liebman, J.W. Edwards, D.E. James, J.W. Singer, et al. 2008. Patterns of regional yield stability in association with regional environmental characteristics. Crop Science 48(4): 1545–1559. doi: 10.2135/cropsci2006.12.0837.

Williams, S.M., and R.R. Weil. 2004. Crop Cover Root Channels May Alleviate Soil Compaction Effects on Soybean Crop. Soil Science Society of America Journal 68(4): 1403–1409. doi: 10.2136/sssaj2004.1403.