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

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Core Ideas
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The purpose of these highlights is to give a concise summary that will be helpful in assessing the suitability of the manuscript for publication in the journal and for selecting appropriate reviewers. If the article is accepted the highlights may also be used for promoting and publicizing the research.

Core Idea 1: Cover crop effects on soil water storage at 14 cm depth varied by trial

Core Idea 2: Cover crops increased water held at field capacity in two of four trials

Core Idea 3: Cover crops did not affect water held at saturation or increase percentage of macropores

Core Idea 4: Proposed causal model shows cover crop root measurements may be a key measurement

Core Idea 5: CUST_CORE_IDEA_5 :No data available.

1   June 29 2021

2

3   To the Editorial Board of *Agrosystems Geosciences & Environment*:

4

5   On behalf of all co-authors, herewith I am submitting a manuscript entitled "Winter Cover Cropping
6   Effects on Soil Water Storage Vary by Site: Field Measurements and a Proposed Causal Model"
7   to be considered for publication in *Agrosystems Geosciences & Environment*.

8   This manuscript contains new information on the effects of winter cover cropping in maize and soybean
9   systems in Iowa USA, a state located in one of the most agriculturally productive regions in the world.
10   We performed this study to address a lack of data concerning the long-term effects of cover cropping on
11   soil water storage and to generate knowledge to support assessments and modelling of cover crop's
12   potential to increase productive capacity, adaptive abilities, and environmental sustainability. Our study
13   offers several innovative aspects:

14   Soil sampling from long-term (10+ years) cover crop experiments

15   Sampling from multiple sites across Iowa

16   Sampling at a 10-18 cm soil depth which may be more relevant than shallow sampling when considering
17   crop water needs

18   First graphical model of proposed causal links between cover crops and soil water storage

19   This unique dataset allowed us to demonstrate the large amount of variability in how soils respond to
20   winter cover cropping. Our analysis indicated that above-ground cover crop biomass is a poor predictor
21   for the magnitude of soil water storage changes with cover cropping. We propose measuring below-
22   ground biomass as an area of future focus, and support this with a graphical analysis of a causal
23   diagram.

24   Given the implications of soil water storage on agriculture and the environment we believe this
25   contribution is a very relevant to your journal.

26

27   Sincerely,

28

29   Virginia Nichols

30   PhD student, Department of Agronomy, Iowa State University

31   **Winter Cover Cropping Effects on Soil Water Storage Vary by Site: Field Measurements**

32   **and a Proposed Causal Model**

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38   **Abbreviations:**

39   CC, cover crop

40   USDA, United States Department of Agriculture

41

42   **Core ideas**

43   • Cover crop effects on soil water storage at 14 cm depth varied by trial

44   • Cover crops increased water held at field capacity in two of four trials

45   • Cover crops did not affect water held at saturation or increase percentage of macropores

46   • Proposed causal model shows cover crop root measurements may be a key measurement

47   **ABSTRACT**

48   Addition of an over-wintering cereal rye (*Secale cereal*) cover crop (CC) to Midwestern maize

49   (*Zea mays*)-based systems offers several environmental benefits, but the long-term effects on soil

50 hydrological properties are not well-understood. We utilized four long-term (10+ year) no-till

51 trials in Iowa, USA that included a replicated winter rye CC and no-cover treatment in systems

52 with a maize crop (grain or silage) rotated with soybean (*Glycine max*). At each trial, we took

53 intact 7.62 cm diameter soil samples from a 10-18 cm depth increment shortly after cash crop

54 planting in the spring of 2019. We measured the volumetric soil water content at saturation and

55 matric potentials of -3.8, -10, -25, -50, -100, -200 and -500 cmH2O. Additionally, we measured

56 organic matter, soil texture, and bulk densities of the samples. Pore-size distribution indices and

57 air-entry potentials were estimated from non-linear models fit to the soil water retention curves,

58 and percent macropores (>30 um) was estimated from the capillary rise equation. Water contents

59 at saturation and at field capacity (0 and -100 cmH_2O, respectively) were taken directly from the

60 data. Neither pore-size distribution nor air-entry potential (model parameters) were affected by

61 CCs. At the depth sampled, CCs did not meaningfully affect bulk density or water contents at

62 saturation at any trial, nor did CCs increase the percentage of macropores. At two trials, soil

63 water content at field capacity increased with CCs by 2.5% (SE: 1.2%) and 2.4% (SE:1.3%),

64 respectively. The presence or absence of a CC effect on field capacity was not related to CC

65 above-ground biomass production or soil texture at the trial sites. We propose a causal model

66 relating CCs to soil properties relevant to soil water that indicates root characteristics may be key

67 to understanding variable effects of CCs on soil water storage. Our results indicate more research

68 is needed on the exact mechanisms by which CCs can affect soil water storage, as well as when

69 and where potential benefits may be most easily realized.

70   **INTRODUCTION**

71 Addition of an over-wintering cereal rye (*Secale cereale*) cover crop (CC) to Midwestern maize (*Zea*

72 *mays*)-based systems potentially offers several environmental benefits including reduced soil erosion and

73   nutrient pollution (Strock et al., 2004; Kaspar et al., 2007; Kaspar and Singer, 2011; Kladivko et al.,

74   2014). On average, rye CCs have no effect on maize yields compared to winter fallow in the short term

75   (Marcillo and Miguez, 2017), but it is possible that long-term cover cropping could stabilize crop yields.

76   In Midwestern rain-fed systems, crops rely on stored soil water and often suffer from drought stress

77   (Campos et al., 2006). In these systems, CCs may induce changes in soil characteristics such as increased

78   organic matter, lower bulk densities, and more macro-pores (Haruna et al., 2020a). In theory, these

79   changes could result in more water storage capacity (Hudson, 1994; Minasny and McBratney, 2018; King

80   et al., 2020), and therefore buffer crop yields against drought stress (Williams et al., 2016; Kane et al.,

81   2021). Cover crops might also benefit crop-water relations by increasing water infiltration or reducing

82   evaporation through a mulching effect (Unger and Vigil, 1998; Leuthold et al., 2021). Two global meta-

83   analyses suggest CCs increase soil's capacity to store water and increase infiltration rates (Basche and

84   DeLonge, 2017, 2019). However, to our knowledge there are few studies supporting these findings in

85   Midwestern cover cropping contexts, and the few existing studies report contradicting results (Villamil et

86   al., 2006; Haruna and Nkongolo, 2015; Basche et al., 2016; Rorick and Kladivko, 2017; Irmak et al.,

87   2018). Region-specific studies are needed, as climatic and managerial constraints of maize-soybean

88   rotations can limit CC options and growth potential (Strock et al., 2004; Baker and Griffis, 2009; Nichols

89   et al., 2020b).

90   In addition to regional differences in CC effects, the duration of cover cropping may also influence

91   whether changes in soil are detected. Long-term studies on tillage have shown significant, but slow

92   changes to the soil after implementing no-till (Al-Kaisi et al., 2014; Cusser et al., 2020). Addition of CCs

93   might likewise require several years before improved soil hydrological properties can be detected,

94   necessitating data collection from long-term experiments. Furthermore, while shallow soil depths (0-

95   10cm) may be more responsive to CC effects e.g. (Atwood and Wood,; Kaspar et al., 2006; Moore et al.,

96   2014), deeper depths may be more important when considering the soil's contribution to the crop's water

97   supply (Williams et al., 2008; Asbjornsen et al., 2008; Rizzo et al., 2018).

98   Lastly, to our knowledge the causal relationships between CCs and soil water storage have not been

99   explicitly presented. Causal models can help identify data needs, and when sufficient data is available can

100   be used to construct structural equation models that estimate the relative strength of causal paths (Smith et

101   al., 2014). Casual modelling can also be used to frame hypotheses, resulting in more targeted research

102   questions that directly test the presence or absence of causal links. Therefore, a credible causal model can

103   greatly aid in advancing future research.

104   Given the need to quantify long-term benefits of cover cropping, the scarcity of Midwest-specific data,

105   and lack of a framework for organizing relevant knowledge, the objectives of our study were to (1)

106   determine what aspects of a soil's hydrological characteristics are affected by long-term cover cropping at

107   a depth relevant to crop production, and (2) use our findings to propose a causal model connecting CCs to

108   changes in soil properties to aid in targeting future research. We collected soil samples at a 10-18 cm

109   depth increment from four long-term (10+ years) no-till cover crop trials located in Iowa, USA. Two

110   trials were on-farm production fields, and two trials were part of a larger research experiment. We

111   assessed the effects of long-term cover cropping on soil water content at saturation, soil water content at

112   matric potentials approximating field capacity on the shallow water tables that characterize landscapes in

113   this region (-100 cm H_2O, Moore 2021), and pore-size distributions as estimated by the soil water

114   retention curve. To complement and contextualize these data, we also measured soil texture, soil organic

115   matter, and bulk densities of the soil samples. We used our results in combination with previous literature

116   to construct a proposed causal model (Pearl, 2010).

117   **MATERIALS AND METHODS**

118   *Site descriptions*

119   Three long-term sites were used for this study (**Figure 1**), with one site having two trials. Therefore, a

120   total of four trials were sampled (**Table 1**). Each trial consisted of two treatments that had been in place

121   for at least 10 years: (1) a maize/soybean rotation (either grain- or silage-based) with a winter rye CC

122   planted yearly in the fall following cash crop harvest and terminated in the spring, and (2) the same

123   rotation without a CC. Every trial was arranged in a randomized complete block design with four (West

124   and East) or five (Central) replicates. The plots within each trial were managed identically save for the

125   planting of the CC in the fall. The exact herbicide and nutrient programs varied by site, reflective of their

126   particular managers and contexts (**Supplementary Tables S1, S2, S3**). More detailed accounts of

127   agronomic management have been published elsewhere for the research and commercial farm sites

128   (Moore et al., 2014; Nichols et al., 2020a). All sites had sub-surface tile drainage and were managed

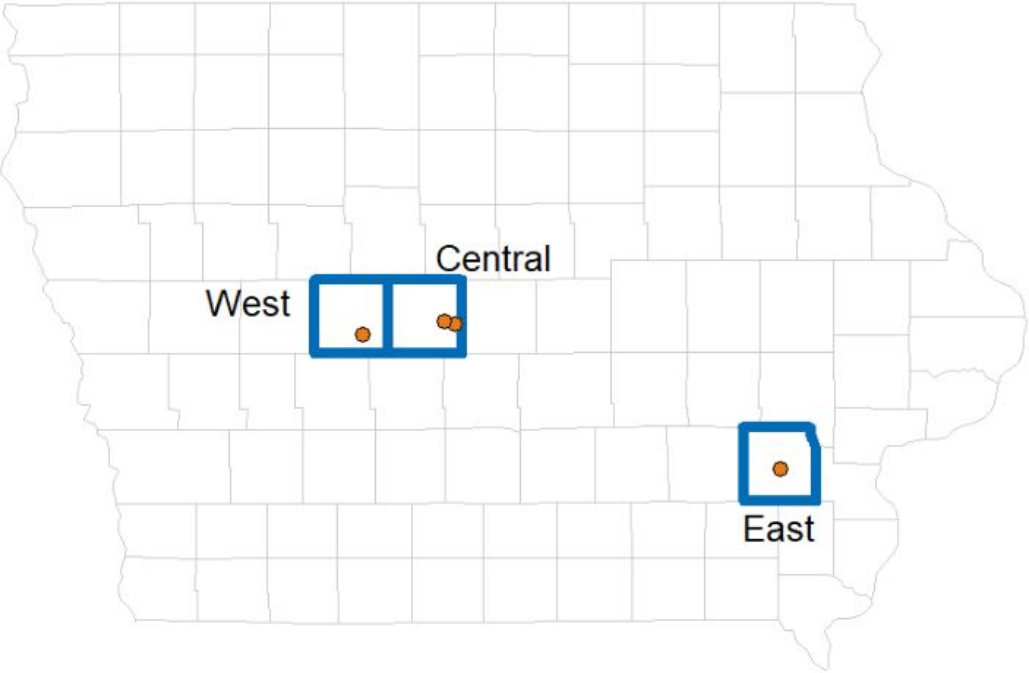129   without tillage since initiation of the trials.

Figure 1. Map of Iowa showing locations of the three experimental sites (West, Central, East), with the Central site containing two trials.

130

131

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

Plot Size and Average Slope[*]	Treatment Replications	Dominant Soil Types[*]	Average Depth to Water Table[*]	30-year Annual Mean		Mean Cover Crop Biomass		2018 Crop	2019 Sampling Date
				Air Temperature	Precipitation	5-year	10-year		
m			cm	^0C	mm	Mg ha^{-1}	Mg ha^{-1}		
West-grain (commercial farm), 41^{0}55'N 94^{0}36'W, initiated in 2008									
25 x 250 (1-3%)	4	Nicollet loam	67	9.5	880	0.24	0.45	Soybean	May 23
Central-silage (research plots); 42^{0}00'N 93^{0}48'W; initiated in 2002									
3.8 x 55 (1-3%)	5	Clarion loam	100	9.8	907	2.38	1.98	Maize	June 6
Central-grain (research plots); 42^{0}00'N 93^{0}48'W; initiated in 2009									
3.8 x 55 (1-3%)	5	Clarion loam	100	9.8	907	1.53	0.88	Maize	June 6
East-grain (commercial farm); 41^{0}18'N 92^{0}48'W; initiated in 2009									
25 x 275 (0-2%)	4	Taintor silty clay loam	0	10.2	947	1.73	1.32	Maize	June 10

133 ** From Web Soil Survey data using map unit area weighted estimates*

134   The West-grain and East-grain trials were production fields on commercial farms, and only one phase of

135   the maize/soybean rotation was present each year. The Central site was a larger research study managed

136   by the United States Department of Agriculture (USDA) and included both phases of each rotation

137   (Kaspar et al., 2007, 2012). For the present study, only the soybean phase of the USDA site was sampled

138   due to time constraints. Cover crop biomass sampling occurred each spring at every trial; details about

139   methodology are reported elsewhere (Nichols et al., 2020a) and historical values are available

140   (**Supplementary Table S4**).

141   *Soil Sampling*

142   An aluminum ring 7.62 cm in diameter and 7.62 cm tall was used to take intact soil samples. Sampling

143   occurred in May or June of 2019 after maize (West) or soybean (East, Central-grain, Central-silage)

144   emergence at each site. Sampling was conducted immediately following crop emergence to minimize the

145   effects of live roots in the samples, and a few days following a rain to ensure the soil was fully drained,

146   but wet enough to remain in the ring during sampling (Al-Shammary et al., 2018).

147   At all trials, samples were taken in the middle of the plots between planted rows. To get intact soil cores,

148   a hole 10 cm deep was dug, and soil was smoothed by hand to create a flat area approximately 30 cm

149   square. The ring was placed on the soil surface in the center of the flat area, a hollow metal cap was

150   placed on it, and a 15 kg weight was used to evenly drive the ring into the undisturbed soil. Once the ring

151   was fully inserted into the soil, a hole was dug around the ring. A flat sheet of metal was slid under the

152   ring to extract it, and a knife was used to remove soil from the top and bottom of the ring using a Z-

153   cutting motion. The ring was wrapped in aluminum foil with the soil orientation (top, bottom) marked.

154   The foil-wrapped ring was then placed in an individual plastic container and placed in a cooler. This

155   process was repeated for each plot. Samples remained in the cooler for no more than four hours before

156   being placed in a refrigerator.

Soil-water-retention curve

158 Analytical equipment could accommodate 12 samples at a time, so each trial's samples were run together

159 in a batch. Our interest was in comparing relative effects within a trial, so variation between runs was

160 statistically included in variation between trials. The samples were analyzed in the order they were

161 collected. A given trial's cores had cheesecloth taped to the bottom of each core and an additional ring

162 taped to the top. Each full batch of samples (eight for East and West, 10 for Central) was then placed in a

163 vacuum chamber for at least 12 hours in a solution of 0.01 M $CaCl_2$ filled to the top of the first ring,

164 allowing the samples to saturate with minimal air entrapment. The top ring was removed from the cores,

165 then the saturated cores were weighed, then transferred to a custom-built pressure cell apparatus (Ankeny

166 et al. 1992). Measurements were made according to the protocol described by Kool et al. (2019). Cores

167 were drained at atmospheric pressure for 12 hours to obtain a measurement for gravity-drained values (Ψ_m

168 = -3.8 cmH2O). Subsequent measurements were taken at matric potentials (Ψ_m) of -10, -25, -50, -100, -

169 200, and -500 cmH2O. The samples were then oven dried at 60 ^{o}C for at least 48 hours, then weighed.

170 Bulk densities were estimated by dividing the oven-dried weight of soil by the ring volume (347.5 cm^3;

171 Han et al. 2016). A water balance was constructed for each core individually as quality control, resulting

172 in the removal of one replicate from the no-cover treatment of the Central-silage trial, which had a large

173 visible hole in the center of the core upon destructive inspection, confirming its justified removal from the

174 dataset.

Soil Texture

176 The oven-dried soil was ground and passed through a 2 mm sieve. Two teaspoons of soil (~10 grams)

177 from each core were used for soil texture measurements. Soil texture was quantified using laser

178 diffractometry (Miller and Schaetzl, 2012) with a Malvern Mastersizer 3000 and a HydroEV attachment

179 (Malvern Panalytical Ltd, UK), producing estimates for the percentage of the soil that was sand (50-2000

180 μm), silt (6-50 μm), and clay (0.1-6 μm).

181   *Organic carbon*

182   Half of the remaining oven-dried soil cores were sent for organic matter analysis (Agsource, Ellsworth

183   Iowa, USA) using the loss-on-ignition method (Nelson and Sommers, 1983). While this method may not

184   produce reliable absolute estimates of organic matter (Hoogsteen et al., 2015), our interest was in pairwise

185   comparisons of treatments rather than in obtaining absolute estimates of organic matter.

186   ***Statistical analysis***

187   All data manipulation, figure creation, and model fitting was done using R version 4.0.3 (R Core Team,

188   2020) and the tidyverse meta-package (Wickham et al., 2019). Non-linear models were fit using the nlraa

189   (Miguez, 2021) package functionality, with specific equation fits from the HydroMe (Omuto et al., 2021)

190   and soilphysics (de Lima et al., 2021) packages. Linear models were fit and summarized using the lme4

191   (Bates et al., 2015) package, which fits mixed effects models, and the emmeans (Lenth et al., 2018)

192   package which estimates both marginal and conditional means and confidence intervals and performs

193   pairwise comparisons.

194   We fit the Gardner (Gardner, 1958) and van Genutchen (van Genuchten, 1980) models to describe the

195   relationship between soil moisture and soil water matric potential in our datasets. We found the models

196   produced similar Akaike's Information Criteria (AIC; (Bozdogan, 1987)) values, with the Gardner model

197   showing a slightly better fit. We chose to use the results from the Gardner model due to its simplicity and

198   biologically meaningful parameters. The Gardner equation is as follows:

199
$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{1 + a\psi^n}$$

200   where θ is the volumetric moisture content at a given soil water potential ψ; the remaining variables are

201   fitted parameters. θ_r and θ_s are the residual and saturated water contents, respectively, *a* is the inverse of

202   the air-entry potential, and *n* is an index for the pore size distribution, with higher values indicating a

203   broader distribution of pore sizes. We fit the Gardner model to each experimental unit, then analyzed the

204   air-entry and pore-size distribution parameters as response variables, described below.

205   Residual water contents (θ_r) are estimated by the model, but can also be experimentally measured at -

206   15,000 cmH2O, i.e. the permanent wilting point (SSSA, 2008). The highest presssure applied to samples

207   in this study was -500 cmH2O, which could lead to less stable model fits due to lack of an anchoring

208   value (Groenevelt and Grant, 2004). To determine whether the model produced reasonable estimates

209   without these anchoring values, we compared the model-estimated saturated water contents with the data,

210   as well as the pore-size distribution parameter estimate against values estimated using capillary rise

211   equations, which assumes the mean pore neck diameter (in cm) of drained pores at a given pressure is

212   equal to 0.3 divided by the head pressure (cmH2O). Pores with mean neck diameters greater than 30 µm

213   were considered macropores (Kirkham, 2014). The percent macropores was assessed as a response

214   variable, described below.

215   Volumetric water contents at saturation were extracted directly from the data. Volumetric water contents

216   at field capacity were estimated as the volumetric water content at a matric potential of -100 cmH2O

217   (Moore 2021). We used this approximation because the actual field capacity matric potential depends on

218   the depth to the water table, which can vary seasonally. The trials sampled all had artificial tile drainage

219   installed at ~1.2 meter depths and shallow water tables (Table 1), meaning field capacity will be at matric

220   potentials less negative than the commonly assumed value of -330 cmH2O (Bonfante et al., 2020).

221   Additionally, soil water retention curve data from Moore (2021), suggests that -100 cmH2O is a better

222   approximation for field capacity in mollic epipedons with shallow water tables.

223   The effects of trial, CC treatment, and their interaction on response variables (soil texture, organic matter,

224   water contents at saturation and field capacity, air-entry pressures, pore-size distribution index, percent

225   macropores) were assessed using mixed-effect models. Trial, CC treatment, and their interaction were

226   included as fixed effects. Percent sand was investigated as a covariate in appropriate models. Models

227   without a sand covariate had random intercept effects for replicates nested within location (East, Central,

228   West), and models that included a sand covariate had fixed effects only. Models were compared using

229   AIC. All results are available in **Supplementary Tables S5-S11**.

230   **RESULTS AND DISCUSSION**

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

232   All plots had textures within ranges classified as silty-clay-loams. Texture varied most strongly by trial,

233   with the East-grain trial having the lowest amount of sand and highest silt component. In the two

234   commerical field trials, the sample's texture also varied by CC treatment. The CC plots had a significantly

235   higher sand component, and significantly lower clay component than the no-cover plots in the West-grain

236   and East-grain trials (**Table 1**, **Figure 2**). While the plots in the production fields were randomly assigned

237   a CC treatment, the East-grain site's treatments were regularly alternating strips with blocks laid out

238   laterally, and the West-grain sites were close to regular alternations likewise laid out laterally. In fields

239   with a uniform texture gradient perpendicular to the blocking with only two treatments, this regularly

240   alternating pattern could result in one treatment having significantly different textures compared to the

241   other. The Central site had several treatments in small plots and the blocks were located in quadrants

242   within the field, which may have better randomized spatial patterns in the soil.
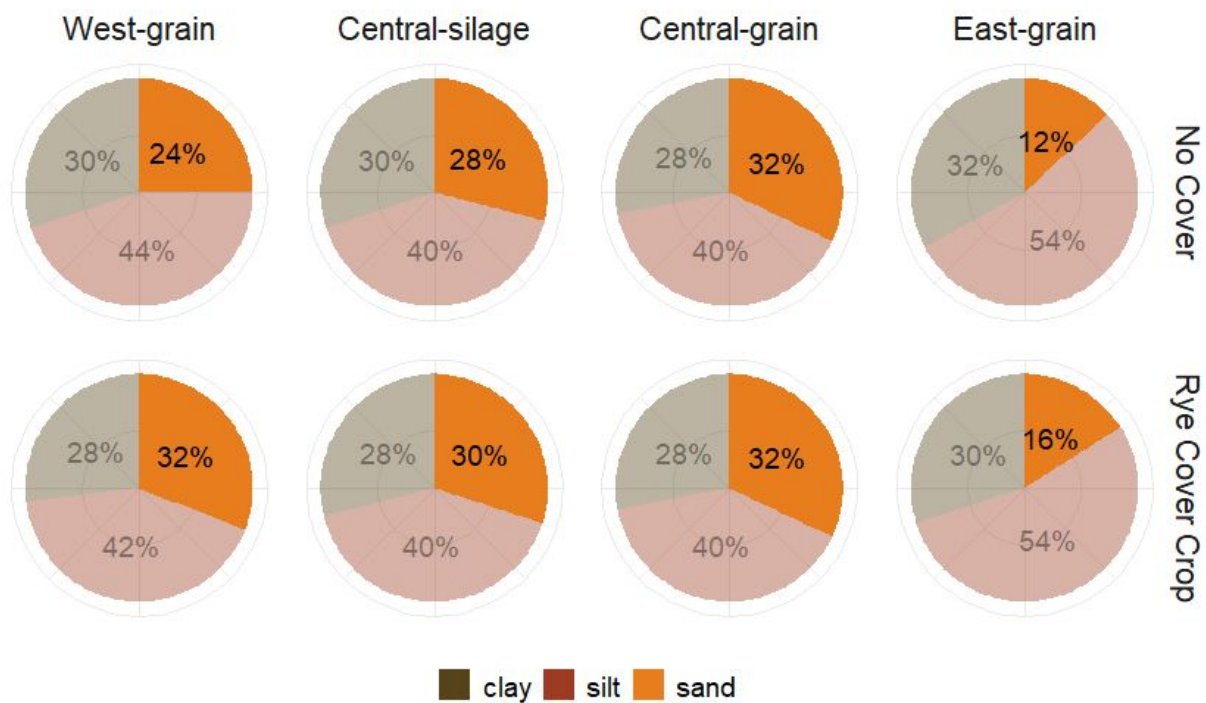
243

Figure 2. Soil texture components varied by trial and cover crop treatment, with the cover cropped plots having significantly more sand (bolded orange color) and significantly less clay at the West-grain and East-grain trials (both commercial production fields).

244

245   Based on these results, sand was investigated as a covariate in statistical models for response variables

246   thought to be affected by soil texture. Soil texture is the dominant factor determining soil water retention

247   (de Jong et al., 1983; Saxton and Rawls, 2006), particularly under wet conditions (i.e. saturation and field

248   capacity; Manns and Berg, 2014), so statistical comparisons of soil water at saturation and field capacity

249   are reported from models that include the sand co-variate.

250   Organic matter concentrations ranged from 1.8 to 4.6 g (g soil)$^{-1}$. The organic matter models were very

251   sensitive to inclusion of sand as a covariate. The two trials with significantly different sand components in

252   the cover crop and winter fallow treatments had lower organic matter in the cover crop treatments without

253   a sand-correction, but higher organic matter with a sand correction. We therefore choose not to report the

254   results from the organic matter analyses, but results are available (**Supplementary Table S7**).

255   Bulk densities varied from 1.2 g cm^{-3} to 1.7 g cm^{-3}. The large size of sand particles reduces packing

256   efficiencies compared with clay, meaning a sandy soil may have lower bulk densities simply due to

257   packing arrangements. However, regardless of the statistical model fit, all estimated CC effects were less

258   than measurement precision of the core method for measuring bulk density (±0.12 g cm^{-3}, (Han et al.,

259   2016), rendering their interpretation questionable. A recent summary of research on the effects of CCs on

260   bulk densities likewise found few studies where an overwintering rye CC grown in the US reduced bulk

261   densities more than typical measurement errors (Haruna et al., 2020b).

262   **Soil hydrological properties**

263   Due to the high amount of variability associated with soils, we assigned significance at p-values less than

264   0.10. With or without a sand correction, no trial exhibited a significant increase in water held at saturation

265   with the use of cover cropping (**Figure 3**). Water held at saturation is largely dependent on bulk density,

266   so these findings are consistent with the lack of meaningful effect of CCs on bulk densities in our study.
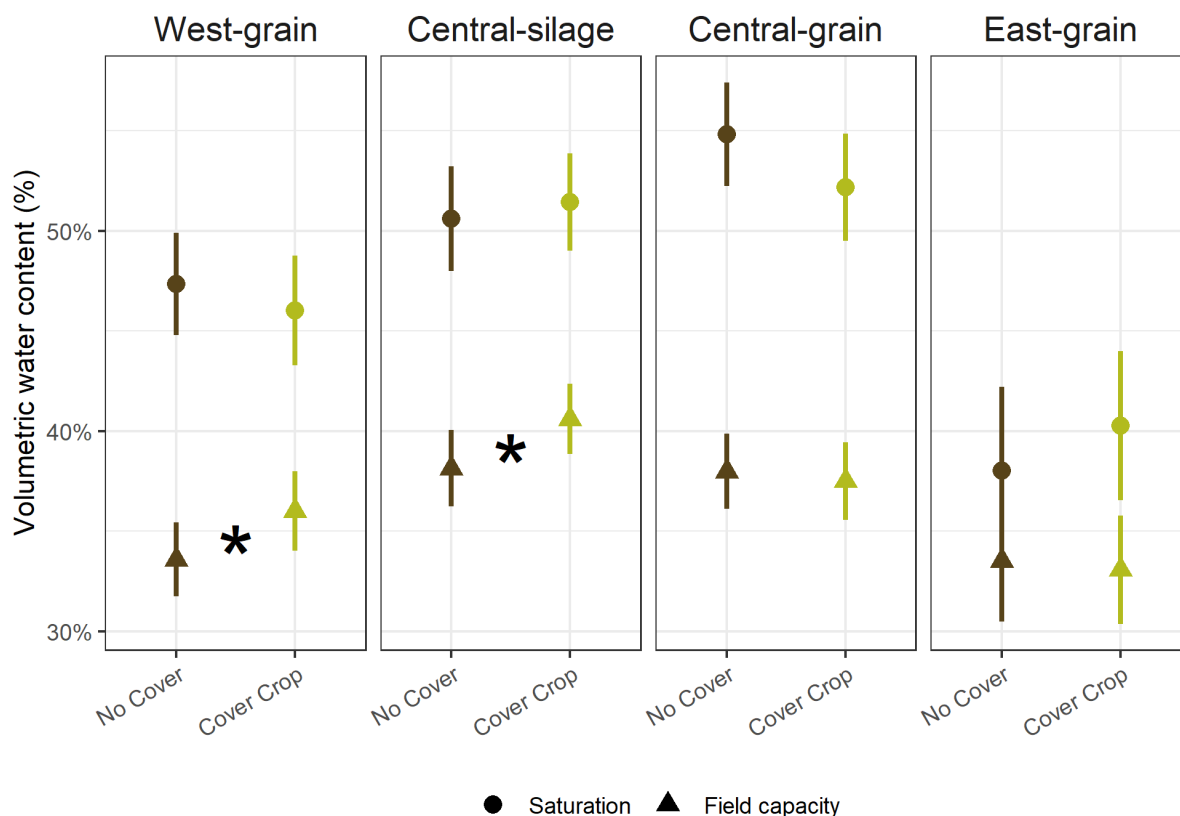
Figure 3. Soil volumetric water contents at saturation (circles) and field capacity (-100 cmH2O, triangles) with 10+ years of winter rye cover cropping (green) or winter fallow (brown) in a maize-soybean rotation at four trials. Points are estimated means, line ranges are the 95% confidence intervals around the mean. Stars indicate signficant differences at p<0.10 with the sand adjustment.

267

268   Field capacities were signifiantly higher in the cover cropped plots at both the West-grain (p = 0.07) and

269   Central-silage (p = 0.05) trials. At the West-grain trial, the soil water at field capacity was increased (after

270   sand correction) from 33.6 to 36.0 vol%, and at the Central-silage trial from 38.1 to 40.6 vol%,

271   respectively. The West-grain trial consistently produced the lowest above-ground CC biomasses, and the

272   Central-silage trial the highest (**Table 1**), indicating the changes in water held at field capacity could not

273   be predicted based on CC above-ground biomass production. Likewise, there was no pattern between soil

274   textural characteristitcs and presence or absence of a CC effect on water held at field capacity, meaning

275   that knowledge of a soil's texture did not help predict whether a CC would affect water held at field

276   capacity.

277   While the West-grain results were not significant without a sand correction, the trial exhibited the same

278   trend of increased water at field capacity with cover cropping regardless of whether the sand correction

279   was included or not. These results suggest CCs may have a larger impact on water at field capacity

280   compared to water held at saturation at the 10-18 cm soil depth increment. To our knowledge there are

281   limited studies examining the potential for CCs to reduce flood damage in the Midwest, but the few that

282   do account for only the increased evapo-transipiration with the use of CCs (Antolini et al., 2020). An

283   increase in the soil's ability to hold water after gravity drainage may also contribute to peak water flow

284   regulation. By increasing volumetric water content at field capacity by 2 vol%, CC fields could hold an

285   additional 200,000 L of water in each 100-cm hectare slice, which could reduce the amount of water

286   drained from a field after a saturating rain. Our study suggests considering how CC-induced increases to

287   the amount of water held in a soil at field capacity affect flood incidence and severity would be worth

288   investigating.

289   The Gardner equation fit converged for all experimental units (**Figure 4**), with *a* (inverse of air-entry

290   potential) ranging from 0.001 to 0.284, and *n* (pore-size distribution index) ranging from 0.45 to 1.49.

291   While the parameters did differ by trial, cover cropping did not significantly affect either parameter in any
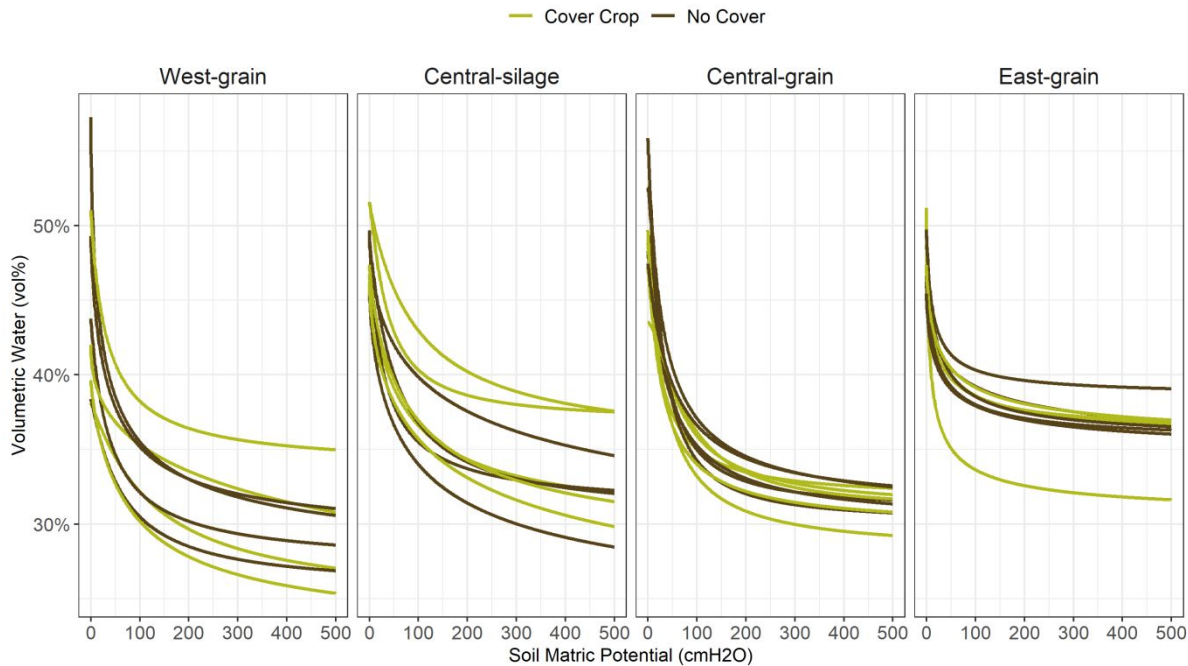
292   trial.

293

Figure 4. The Gardner equation was fit to each experimental unit, with four or five replicates for each cover crop treatment

294

295   Manual estimation of the pore-size distribution confirmed CCs did not increase the percentage of

296   macropores in any trial (**Figure 5**). In fact, in the West-grain trial the number of macropores significantly

297   decreased with cover croping, with 61% macropores in the control treatment compared with 48% in the

298   CC treatment. In a review of published studies, Haruna et al. (2020) found the effect of CCs on

299   macropore makeup of the soil highly variable, but with an overall average increase. The wide variation

300   may be partially due to varying cut-offs in pore sizes for macropore categorization (Luxmoore, 1981), but

301   the variability in combination with our results again demonstrates using literature averages to predict CC

302   impacts in Midwestern systems may be inappropriate.
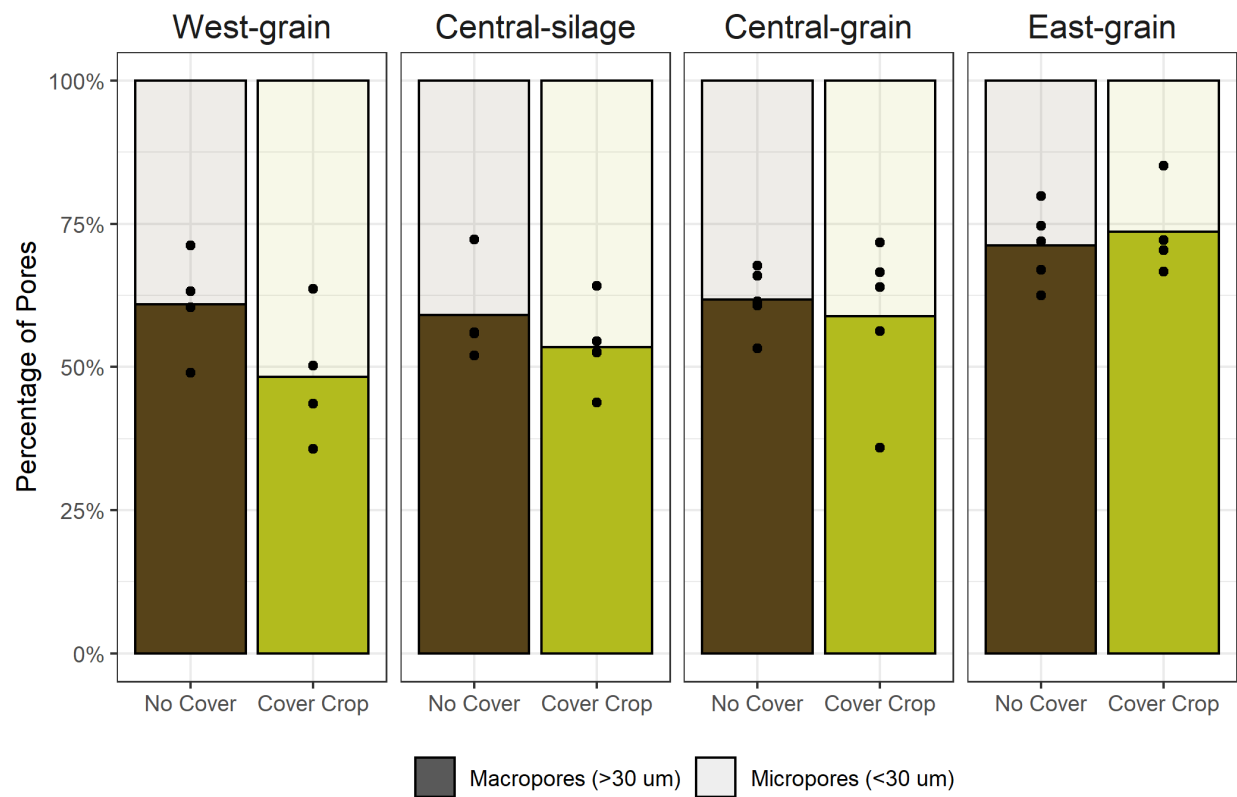
Figure 5. Replicate (point) and treatment mean (bars) percentage macropores (>30 μm) for each trial; percent macropores in the cover crop treatment was significantly lower (p=0.04) at the West-grain trial compared to the control treatment.

303

304 ***Causal model***

305 There are several pathways by which CCs might affect a soil's capacity to hold water (**Figure 6, Table**

306 **2**).
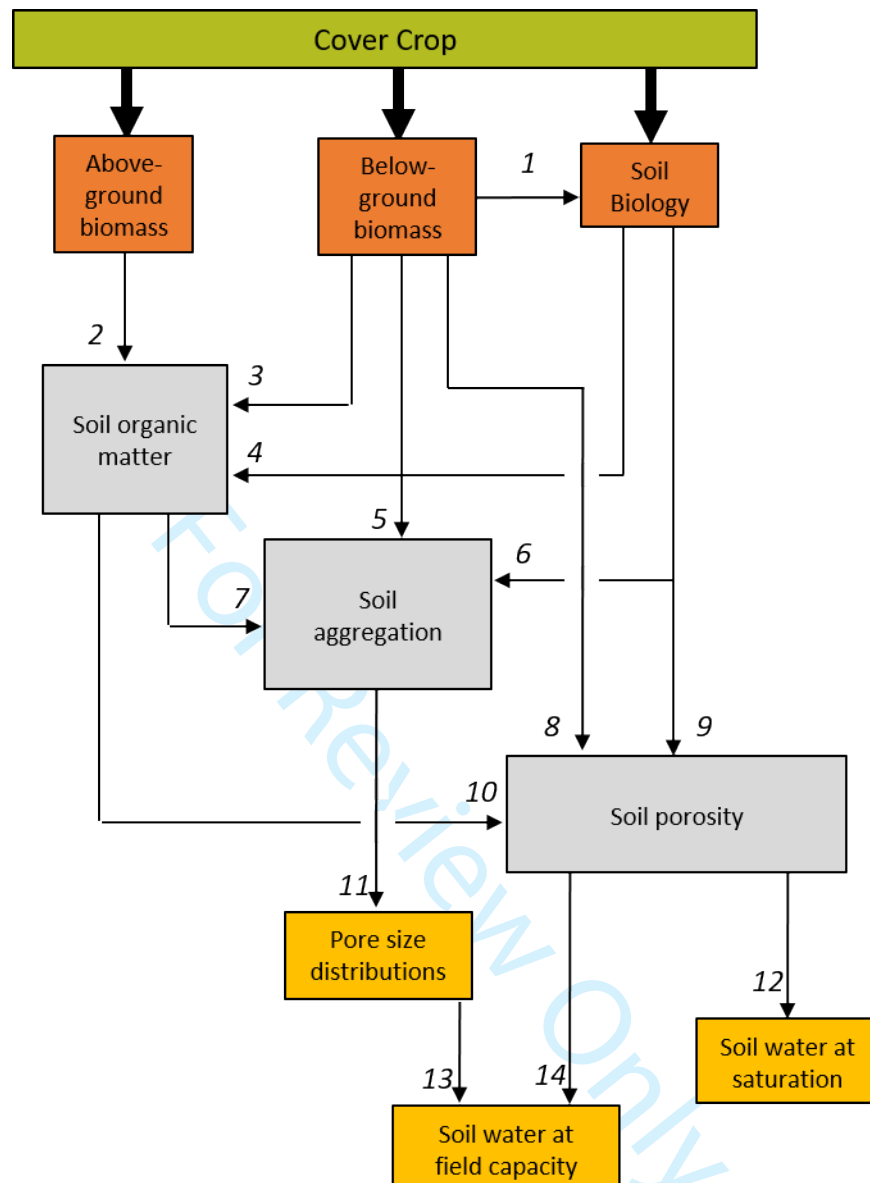
Figure 6. Pathways by which cover crops may affect the pore size distributions, the amount of water stored at field capacity, and the amount of water at saturation in no-till systems. The effects of soil erosion are not included. X→Y should be read as 'X affects Y'.

307

308   The causal model was built using literature relevant to Midwestern systems, and when applicable was

309   limited to evidence drawn from research conducted with a cereal rye cover crop (**Table 2**). The model is

310   simplified to exclude the effects of soil erosion, soil texture, tillage, and landscape position, which are all

311   factors that could potentially influence how soil responds to cover cropping (Moore 2021). Rather, we

312   present this simple casusal model to provide a base from which to build.

313   **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	

314

315   Causal diagrams such as **Figure 6** are the basis for constructing structural equation models,

316   which can greatly enhance researchers' ability to address complex research questions in

317   agriculture (Smith et al., 2014; Wade et al., 2020). For example, in our proposed causal diagram,

318   below-ground biomass measurements are necessary for estimating direct effects of cover

319   cropping on pore size distributions, field capacity, and saturation. This is further supported by

320   recent studies and reviews that identify CC roots as being a crucial component to understanding

321   CC effects on soil properties (Williams and Weil, 2004; Haruna et al., 2020b; Ogilvie et al.,

322   2021). While there is limited data available on both above- and below-ground biomass of CCs,

323   data collected over the period of five years in Iowa showed no relationship between above- and

324   below-ground rye biomass, with root-to-shoot ratios varying from 0.16-1.94 at similar levels of

325   aboveground biomass production (Martinez-Feria et al., 2016). Therefore, above-ground biomass

326   production cannot be used as a proxy for below-ground production with much confidence, and

327   studies that pair above- and below-ground CC biomass with soil measurements would be

328   advantageous in enhancing our understanding of CC effects on soil.

329   **CONCLUSIONS**

330   Context-specific effects of growing over-wintering CCs need to be explicitly

331   investigated, as the constraints of the Midwestern maize-soybean system may render the effects

332   smaller in magnitude compared to averages reported by global meta-analyses. In our study we

333   found CCs have a more pronounced effect on water held at field capacity compared to water

334   contents at saturation, suggesting changes in pore networks and sizes are stronger compared to

335   changes in bulk density. However, we found CCs increased water held at field capacity in only

336   two of the four trials, further demonstrating the need to understand causal mechanisms in order

337   to better predict where and when CCs might provide the most benefit.

338   **SUPPLEMENTAL MATERIAL**

339   Detailed management of trials (Tables S1-S3), historical cover crop biomass production

340   (Table S4), and statistical results (Tables S5-S11) are available as a PDF. The soil water

341   retention curve, bulk density, organic matter, and soil texture data are available as csvs.

342   **DATA AVAILABILITY**

343   All data is available in an R package (https://github.com/vanichols/PFIswhc) and code

344   repository (will be created once paper is accepted) available on github. Additionally, the data is

345   available as a downloadable csv file in supplementary material.

346   **CONFLICT OF INTEREST**

347   The authors declare no conflicts of interest.

348   **AUTHOR CONTIBUTIONS**

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

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362

363   **REFERENCES**

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559

Supplementary Material for 'Winter Cover Cropping Effects on Soil Water-Holding Capacity Vary by Site'

Nichols et al. 2021

6/15/2021

General Site Management Summary

Table 1: General Site Description

Site Description	General Location	Treatment Description	Year of Initiation	Crop Planted in 2019	Number of Treatment Replicates	Sampled in 2019
Central Grain	Boyd Farm, Boone, field 44	maize/soybean grain rotation, with and without rye cover crop	2009	maize	5	Y
	Boyd Farm, Boone, field 42	maize/soybean grain rotation, with and without rye cover crop	2009	soy	5	Y
Central Silage	Boyd Farm, Boone, field 44	maize silage/soybean grain rotation, with and without rye cover crop	2002	maize silage	5	Y
	Boyd Farm, Boone, field 42	maize silage/soybean grain rotation, with and without rye cover crop	2002	soy	5	N
West	Jefferson, IA	maize/soybean grain rotation, with and without rye cover crop	2008	maize	4	Y
East	Washington, IA	maize/soybean grain rotation, with and without rye cover crop	2009	soybeans	4	Y

2

Table 2: 2018-2019 Herbicide Use

Site Description	Herbicides Used in 2018 Growing Season	Herbicdes Used in Fall 2018	Herbicides Used in Spring 2019
Central Grain	glyphosate 1 week before soybean planting	none	glyphosate 1 week before maize planting; metalochlor, atrazine, and mesotrione at planting
Central Grain	glyphosate 1 week before maize planting; metalochlor, atrazine, and mesotrione at planting	none	glyphosate 1 week before soybean planting
Central Silage	glyphosate 1 week before soybean planting	none	glyphosate 1 week before maize planting; metalochlor, atrazine, and mesotrione at planting
Central Silage	glyphosate 1 week before maize planting; metalochlor, atrazine, and mesotrione at planting	none	glyphosate 1 week before soybean planting
West	glyphosate before planting; glyphosate and fluthiacet-methyl at planting	none	glyphosate before planting; glyphosate and fluthiacet-methyl at planting
East	glyphosate and acetochlor before planting (April 15), atrazine, acetochlor at planting (May 14); acetochlor and glyphosate after planting (June 15)	none	chlorimuron-ethyl, flumioxazin, pyroxasulfone, and glyphosate before planting, dicamba and acetochlor after planting

Table 3: General Management

Site Description	General Herbicide Regime	General Date of Cover Crop Termination	General Date of Crop Planting	Inorganic Fertilizer Used	Organic Fertilizer Used	Tillage Used
Central Grain	burndown, residual herbicide at maize planting	15-Apr	26-Apr	Y	NA	N
Central Grain	burndown, residual herbicide at maize planting	25-Apr	5-May	Y	NA	N
Central Silage	burndown, residual herbicide at maize planting	15-Apr	26-Apr	Y	NA	N
Central Silage	burndown, residual herbicide at maize planting	25-Apr	5-May	Y	NA	N
West	burndown, pre-emergent herbicide	1-May	10-May	Y	chicken or turkey manure	N
East	burndown, residual herbicide at planting, another application on maize at ~V6	1-May	5-May	Y	liquid swine, ~3000 gal/ac every other year to entire field	N

Cover crop biomass production over past 10 years of trials

Table 4: Historical cover crop biomass production (Mg/ha) by trial

trial	2010	2011	2012	2013	2014	2015	2016	2017	2019	2018
Central_grain	0.86	0.28	1.37	0.25	0.47	0.61	2.22	2.76	1.29	NA
Central_silage	1.59	1.72	3.32	1.26	0.91	1.76	4.23	2.21	2.05	NA
East_grain	2.11	1.46	0.00	0.92	0.00	0.36	0.51	7.30	0.30	0.19
West_grain	2.11	0.21	1.33	0.00	0.00	0.04	0.45	0.63	0.00	0.09

Statistical Results

Table 5: Statistical analysis of cover crop effect on clay

site_sys	respvar	cc	no	contrast	est_diff	diff_se	diff_pval
Central_grain	clay	27.740	28.000	cc - no	-0.260	0.186	0.164
Central_silage	clay	28.751	29.895	cc - no	-1.144	0.208	<0.001
East_grain	clay	31.730	34.606	cc - no	-2.876	0.208	<0.001
West_grain	clay	27.349	29.511	cc - no	-2.162	0.208	<0.001

Table 6: Statistical analysis of cover crop effect on sand

site_sys	respvar	cc	no	contrast	est_diff	diff_se	diff_pval
Central_grain	sand	32.486	31.600	cc - no	0.886	0.299	0.003
Central_silage	sand	29.811	29.233	cc - no	0.578	0.335	0.085
East_grain	sand	12.715	9.837	cc - no	2.877	0.335	<0.001
West_grain	sand	30.506	25.610	cc - no	4.896	0.335	<0.001

Table 7: Statistical analysis of cover crop effect on organic matter, with and without sand covariate

cov	site_sys	respvar	cc	no	contrast	est_diff	diff_se	diff_pval
none	Central_grain	om	2.360	2.480	cc - no	-0.120	0.051	0.02
none	Central_silage	om	2.640	2.416	cc - no	0.224	0.057	<0.001
none	East_grain	om	3.575	3.675	cc - no	-0.100	0.057	0.082
none	West_grain	om	2.750	2.975	cc - no	-0.225	0.057	<0.001
sand	Central_grain	om	3.034	3.066	cc - no	-0.032	0.082	0.696
sand	Central_silage	om	3.049	2.772	cc - no	0.278	0.088	0.002
sand	East_grain	om	2.290	2.105	cc - no	0.185	0.093	0.048
sand	West_grain	om	3.228	2.968	cc - no	0.260	0.096	0.007

Table 8: Mean bulk density (g/cm3) by trial

site_name	sys_trt	crop_trt	cc_trt	bulkden_mean	bulkden_sd
Central	grain	soy	cc	1.42	0.08
Central	grain	soy	no	1.37	0.07
Central	silage	soy	cc	1.46	0.06
Central	silage	soy	no	1.44	0.07
East	grain	soy	cc	1.44	0.05
East	grain	soy	no	1.49	0.04
West	grain	corn	cc	1.57	0.14
West	grain	corn	no	1.47	0.21

Table 9: Statistical analysis of cover crop effect on bulk density, with and without sand covariate

cov	site_sys	respvar	cc	no	contrast	est_diff	diff_se	diff_pval
none	Central_grain	bd	1.422	1.374	cc - no	0.048	0.010	<0.001
none	Central_silage	bd	1.464	1.436	cc - no	0.028	0.011	0.012
none	East_grain	bd	1.437	1.488	cc - no	-0.050	0.011	<0.001
none	West_grain	bd	1.573	1.472	cc - no	0.101	0.011	<0.001
sand	Central_grain	bd	1.309	1.275	cc - no	0.033	0.013	0.011
sand	Central_silage	bd	1.395	1.386	cc - no	0.010	0.014	0.483
sand	East_grain	bd	1.653	1.752	cc - no	-0.098	0.015	<0.001
sand	West_grain	bd	1.493	1.473	cc - no	0.020	0.015	0.188

Soil moisture (%vol) at saturation

Table 10: Statistical analysis of cover crop effect on soil water at saturation, with and without sand covariate

cov	site_sys	term	contrast	estimate	std.error	df	statistic	adj.p.value	param
sand	Central_grain	cc_trt	cc effect	-0.013	0.008	26.000	-1.688	0.103	saturation
sand	Central_silage	cc_trt	cc effect	0.004	0.008	26.000	0.510	0.614	saturation
sand	East_grain	cc_trt	cc effect	0.011	0.009	26.000	1.271	0.215	saturation
sand	West_grain	cc_trt	cc effect	-0.007	0.009	26.000	-0.729	0.473	saturation
none	Central_grain	cc_trt	cc effect	-0.016	0.008	13.050	-1.959	0.072	saturation
none	Central_silage	cc_trt	cc effect	0.002	0.009	14.068	0.246	0.809	saturation
none	East_grain	cc_trt	cc effect	0.002	0.009	13.050	0.228	0.823	saturation
none	West_grain	cc_trt	cc effect	-0.022	0.009	13.050	-2.430	0.030	saturation

Soil moisture (%vol) at field capacity (-100 cm water)

Table 11: Statistical analysis of cover crop effect on soil water at field capacity, with and without sand covariate

| cov	site_sys	term	contrast	estimate	std.error	df	statistic	adj.p.value	param
sand	Central_grain	cc_trt	cc effect	-0.002	0.006	26.000	-0.430	0.671	field capacity
sand	Central_silage	cc_trt	cc effect	0.012	0.006	26.000	2.041	0.052	field capacity
sand	East_grain	cc_trt	cc effect	-0.002	0.006	26.000	-0.353	0.727	field capacity
sand	West_grain	cc_trt	cc effect	0.012	0.007	26.000	1.835	0.078	field capacity
none	Central_grain	cc_trt	cc effect	-0.004	0.005	13.044	-0.800	0.438	field capacity
none	Central_silage	cc_trt	cc effect	0.012	0.006	14.005	2.242	0.042	field capacity
none	East_grain	cc_trt	cc effect	-0.007	0.006	13.044	-1.317	0.211	field capacity
none	West_grain	cc_trt	cc effect	0.003	0.006	13.044	0.597	0.561	field capacity
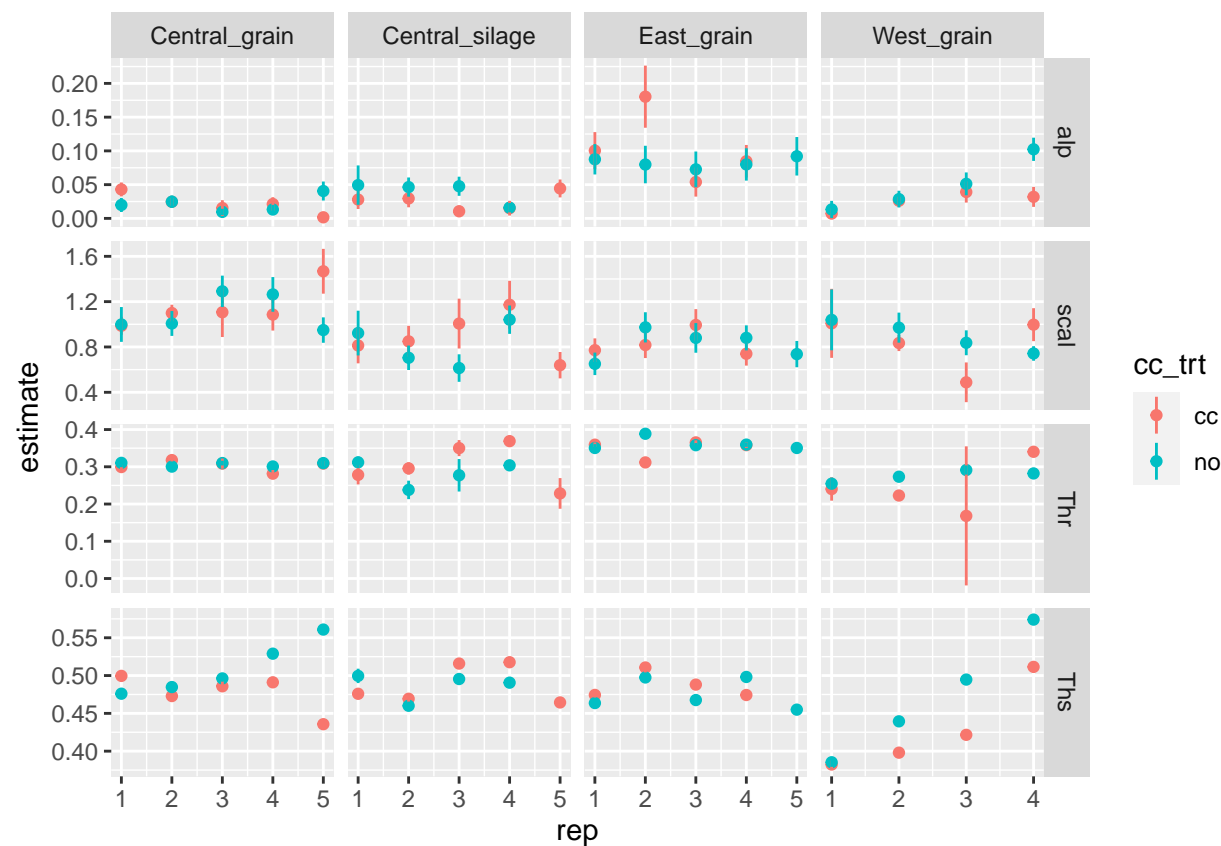
Figure 1: Non-linear model fitted parameters