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Soil water improvements with the long-term use of a winter rye cover crop

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ABSTRACT

The Midwestern United States, a region that produces one-third of maize and one-quarter of soybean grain globally, is projected to experience increasing rainfall variability. One approach to mitigate climate impacts is to utilize crop and soil management practices that enhance soil water storage and reduce the risks of flooding as well as drought-induced crop water stress. While some research indicates that a winter cover crop in maize-soybean rotations increases soil water availability, producers continue to be concerned that water use by cover crops will reduce water for a following cash crop. We analyzed continuous in-field soil water measurements from 2008 to 2014 at a Central Iowa research site that has included a winter rye cover crop in a maize-soybean rotation for thirteen years. This period of study included years in the top third of the wettest on record (2008, 2010, 2014) as well as drier years in the bottom third (2012, 2013). We found the cover crop treatment to have significantly higher soil water storage at the 0–30 cm depth from 2012 to 2014 when compared to the no cover crop treatment and in most years greater soil water content on individual days analyzed during the cash crop growing season. We further found that the cover crop significantly increased the field capacity water content by 10–11% and plant available water by 21–22%. Finally, in 2013 and 2014, we measured maize and soybean biomass every 2–3 weeks and did not see treatment differences in crop growth, leaf area or nitrogen uptake. Final crop yields were not statistically different between the cover and no cover crop treatment in any of the seven years of this analysis. This research indicates that the long-term use of a winter rye cover crop can improve soil water dynamics without sacrificing cash crop growth in maize-soybean crop rotations in the Midwestern United States.

1. Introduction

There is a need to maintain or improve soil productivity in the 21st century in light of climate change and increasing agricultural demands (Amundson et al., 2015; Lal et al., 2011). Currently, most of the Midwestern United States, where one-third of global maize (*Zea mays* L.) and one-quarter of global soybean (*Glycine max* (L.) Merr.) are grown, is usually not limited in water or soil resources and this, in part, contributes to its immense productivity (FAOSTAT, 2015; USDA-NASS, 2014). However, climate projections point to increased rainfall variability (Daniel, 2015; Winkler et al., 2012) beyond what has already been observed over the last several decades (Groisman et al., 2012; Mallakpour and Villarini, 2015) which threatens the soil and water resources currently available in the region. Further, these predicted climate changes are expected to reduce crop yields, especially for maize in the Midwestern Corn Belt, without changes to current management (Challinor et al., 2014; Walthall et al., 2013; Wang et al., 2015). However, other research indicates that the impacts of climate change can be reduced with conservation practices in this region (Basche et al., 2016; Panagopoulos et al., 2014; Van Liew et al., 2013).

Employing management practices that improve soil water dynamics (i.e. processes such as increased storage and enhanced infiltration) is one approach to mitigate the impacts of increased rainfall variability, on a field and landscape scale. Several alternative cropping systems have been tested to determine their impacts

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Table 1
Management dates and operation information during the seven years of this analysis.

Year	Cash Crop	Cover Crop Termination Date	Cash Crop Planting Date	Harvest Date	Cover Crop Planting Date	Total N applied kg ha^{-1}
2008	Maize	29-Apr	14-May	28-Oct	29-Oct	198
2009	Soybean	21-May	22-May	28-Sep	28-Sep	
2010	Maize	19-Apr	29-April	16-Sep	17-Sep	198
2011	Soybean	5-May	18-May	29-Sep	30-Sep	
2012	Maize	23-Apr	4-May	19-Sep	4-Sep[a]	197
2013	Soybean	13-May	23-May	20-Oct	4-Sep[a]	
2014	Maize	10-Apr	6-May	17-Oct	9-Sep[a]	196

[a] Winter rye cover crop was broadcast seeded before maize and soybean harvest. All other seasons cover crop was seeded with a drill post harvest.

on soil water dynamics in the Midwestern United States. Qi et al. (2011) found that a cereal rye (*Secale cereale* L.) cover crop increased soil water storage when added to a maize-soybean cropping system. Brye et al. (2000) found that a prairie ecosystem maintained higher soil water content deeper in the soil profile despite larger evapotranspiration and less drainage than a maize cropping system. Further, Daigh et al. (2014b) and Qi and Helmers (2010) found significantly lower cumulative drainage with a cover crop. There is also a body of evidence that supports the ability of cover crops to increase soil carbon or soil organic matter (Kaspar and Singer, 2011; McDaniel et al., 2014; Moore et al., 2014; Poeplau and Don, 2015) and to improve the soil physical properties which enhance soil water dynamics (Daigh et al., 2014a; Steele et al., 2012; Villamil et al., 2006). Further, there is a complex interaction of soil physical and chemical properties that contribute to soil water storage capacity, including soil organic matter concentration, aggregation and porosity (Emerson, 1995; Hudson, 1994; Kay, 1998). Growing an over winter cover crop between the harvest and planting of maize and soybeans does not take acres out of production and is one strategy for mitigating environmental impacts of Midwestern agriculture (EPA, 2008; INRS, 2012). However, survey data (SARE-CTIC, 2013, 2014) and leading practitioners (Carlson and Stockwell, 2013) indicate that producers are concerned that cover crops may reduce water availability for the following cash crop. Thus, even though cover crops provide many benefits, producers might be reluctant to adopt them if they perceive an increased risk of water stress for the cash crop.

Therefore to increase adoption of cover crops it is important to determine (and demonstrate in the long-term) whether cover crop water use reduces water availability for the following cash crop. It is also important to improve our understanding of how a cover crop alters water dynamics over wetter and drier seasons to evaluate their benefits in mitigating rainfall variability impacts. Our research questions were: How is soil water content affected by a winter rye cover crop? How is soil water storage affected by the cover crop? Which soil water retention properties are affected by the cover crop? Does the water use from the cover crop negatively impact maize and soybean growth? To answer these questions, we analyzed an extensive dataset from a long-term field site that included seven years of continuous soil water content measurements recorded over years with very different weather patterns and treatments with and without a cereal rye winter cover crop. We also collected crop growth data and soil hydraulic property measurements from the most recent two years of the experiment.

2. Materials and methods

2.1. Field site

The field site is located in Boone County, IA (42.05°N, 93.71°W) and was established in 1999. It is a randomized complete block design with four replications and includes different tillage, nitrogen management, and cover crop treatments within a maize-soybean cropping system, where maize is planted in the spring of the even-numbered years and soybeans in the spring of the odd-numbered years. This study evaluated the differences between a no-till winter rye cover crop treatment and a no-till control without a cover crop. The winter rye plots were first established within the maize-soybean rotation in fall 2000 and it represents a long-term record of winter rye impacts within the predominant cropping system found across the Midwest. The winter rye cover crop was established either by drilling after harvest of maize and soybeans in the fall (2007–2011) or by broadcast seeding before harvest in the late summer (2012–2014). Broadcast seeding was utilized in the more recent years of the experiment to examine the effect of earlier planting as well as to evaluate seeding methods that could be easier for farmers to implement. Further information on the site management can be found in Table 1, as well as in Kaspar et al. (2007) and Kaspar et al. (2012).

2.2. Soil water and soil physical properties analysis

Volumetric soil water content (θ) was estimated using an impedance soil moisture sensor Theta Probe (Model Type ML2x, Delta-T Devices, Cambridge, United Kingdom) hourly at depths of 5, 10 and 15 cm from 2008 to 2011 and at 5, 15 and 30 cm from 2012 to 2014. The depth of sensors was changed in the later experiment years to try to better differentiate cover crop differences at the three measurement depths and to extend the measurements deeper into the soil profile. Voltage measurements were converted to a dielectric constant then to volumetric water content, using the calibration equation for Des Moines Lobe soils based on the work of Kaleita et al. (2005). The Theta Probes were installed at two locations in three of the four experimental replications, vertically at 5 cm and horizontally at the lower depths. Sensors were removed only when necessary to accommodate field machinery operations and were replaced immediately following completion. Soil water storage was calculated by sectioning the available depths (0–5 cm, 5–10 cm, and 10–15 cm in 2008–2011; 0–5 cm, 5–15 cm and 15–30 cm in 2012–2014), assuming that the soil water content (θ) level was equal throughout that depth layer and multiplying the depth (mm) by corresponding volumetric soil water content level (mm^3 mm^{-3}). The cumulative soil water storage (SWS) values were derived by calculating the sum of the individual storage values for the three available depths.

We focused our analysis of soil water content on treatment differences on individual days during two key periods of the year when the cover crop might have important effects on soil water dynamics (Section 3.1). The first period was during the spring (between early April and mid-May) about ten days before the cover crop was terminated through about ten days after the cash crop was planted. These dates varied depending on whether maize or soybeans were the cash crop that year. The second period was during summer (mid-July through the end of August), when maize and soybeans enter reproductive growth and crop water demand is critical for optimizing yield (Claassen and Shaw, 1970a,b; NeSmith and Ritchie, 1992). We focused our analysis of treatment effects of soil water storage

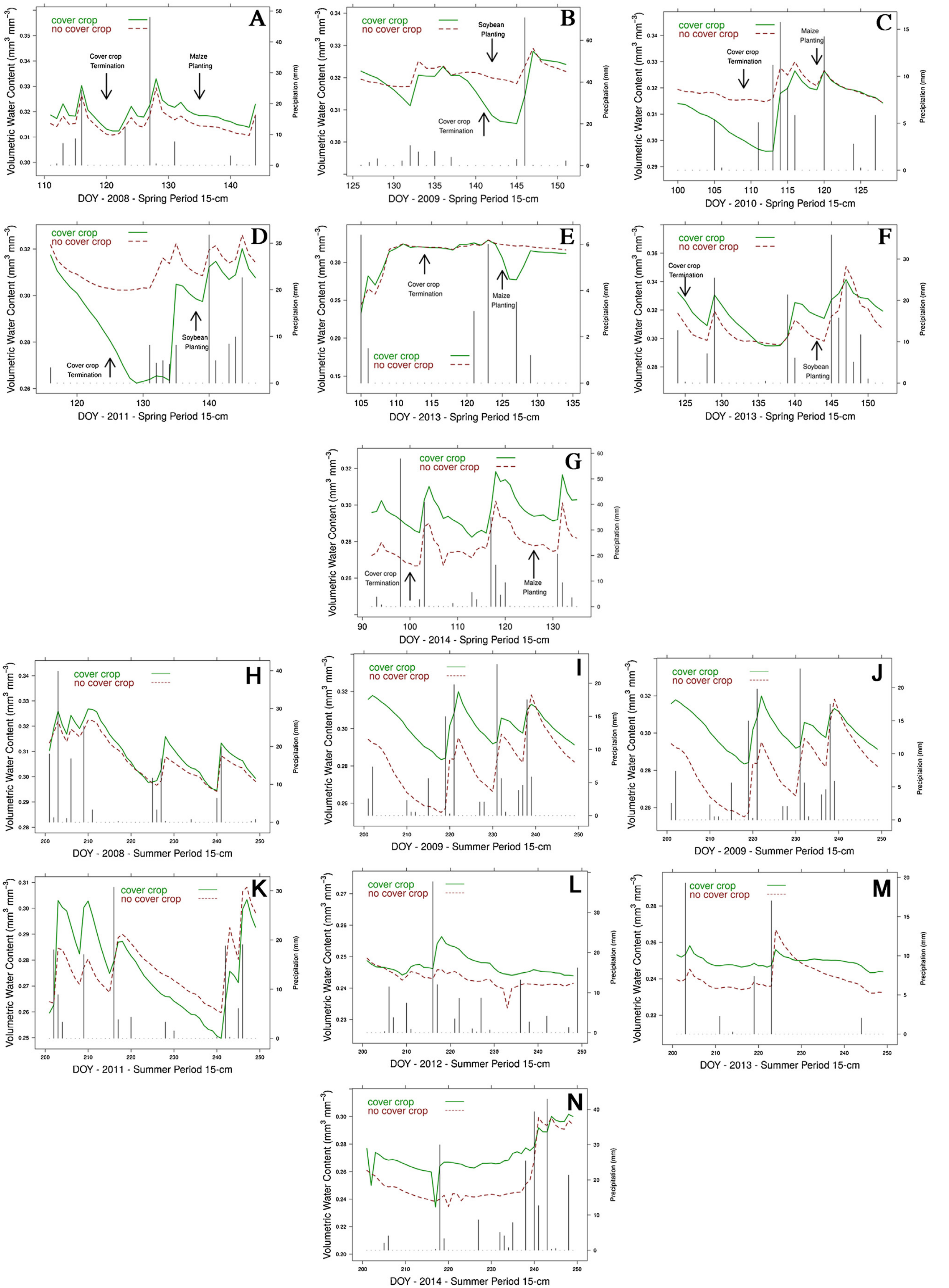

Fig. 1. Soil water content at 15 cm depth across the seven seasons (2008–2014) during the spring (a–g) and summer (h–n) periods. Horizontal lines represent soil water

over the entire growing season of April through October (Section 3.2).

Intact soil cores (7.6 cm by 7.6 cm) were sampled to approximately 4–11.6 cm and 21–28.6 cm depths in July 2013 when soybeans were in the V4 developmental stage. Two subsamples per plot were taken at each depth, with one subsample in a typically wheel trafficked interrow and the other in a typically non-wheel trafficked interrow to try to capture within plot variability and any differences resulting from wheel traffic compaction. For the purposes of this experiment, we define field capacity as the water retained in the soil at −33 kPa pressure, an approximation thought to represent the ability of the soil to retain water after internal drainage has ceased (Hillel, 1998), which we also considered the upper limit of plant available water (Veihmeyer and Hendrickson, 1950). We define the permanent wilting point as water retained at −1500 kPa, an approximation thought to represent the soil wetness at which point a plant cannot recover turgidity (Hillel, 1998) which we also considered to be the lower limit of plant available water (Veihmeyer and Hendrickson, 1950). Therefore, calculations for plant available water represented the difference between the water retained at field capacity and the permanent wilting point. Cores were analyzed at the Soil, Water and Plant Testing Laboratory at Colorado State University for water retention (water content) at field capacity (−33 kPa) with a pressure plate cell apparatus and at saturation (0 kPa) by wetting intact cores and weighing for percent water content (Klute, 1986). To detect treatment differences at the lower end of the water retention curve (−1500 kPa), in April 2015 we utilized soil samples from October 2014 at 0–15 cm and 15–30 cm using the Decagon WP4C Water Potential Meter (Decagon Devices, Inc, Pullman, WA). Water potential meters, such as the WP4C, convert sample readings of temperature and dew point to water activity (Campbell et al., 1973) and it is suggested that these types of instruments are best suited for measurement of very dry soils (Gee et al., 1992) when hydraulic conductivity is too low for water equilibration to occur in the soil sample (Gee et al., 2002). We mixed approximately a 30 g sample of air-dry soil with 6 mL of water according to suggested protocol to wet soils to a water content wetter than −1500 kPa. We then equilibrated the soil samples in closed vessels for several days at room temperature. Then we added a subsample of approximately 3.5 g of soil to the instrument's stainless steel sample cups, capped with a lid and allowed the samples to equilibrate for another 24 h. Matric potentials of the samples were measured in the WP4C chamber after which they were weighed, air-dried for a short period (20–40 min) and this procedure was repeated at least three times. This procedure allowed us to bracket the −1500 kPa water potential. Samples were then dried at 105 °C for 48 h and weighed to calculate water content at the corresponding matric potential readings. Values for the water content corresponding to −1500 kPa were interpolated using a regression line from the three sample readings (Campbell, 2007), taking the average of two subsamples per replication. Finally, the particle size analysis was performed on the soil samples using the pipette method (Gee and Or, 2002).

2.3. Crop growth and partitioning analysis

Two randomly selected 0.76 m^2 areas were used for sampling above ground plant material. We harvested by cutting at the ground level every 2–3 weeks during the growing season of the maize and soybean in each of the experimental replicates. Biomass sampling began about three weeks after planting. Green leaf area was determined using a bench-top leaf area meter (LI-3100 Area Meter, LI-COR Inc., Lincoln, NE) divided by the sampling area (i.e. 0.76 m^2). Samples were then dried at 60 °C until constant weight. Using a Thomas-Wiley mill (Model 4, Thomas Scientific, Swedesboro, NJ) dried samples were ground through a 1 mm sieve, a subsample taken, and the percentage nitrogen were determined by combustion at 950 °C in either a LECO (Model CHN-2000, LECO Co., St. Joseph, MI) or a VarioMax (Variomax CNS, Elementar, Hanau, Germany) C and N analyzer. Soybean samples were separated into leaves, stems and pods for dry weight and partitioning analysis. Maize samples were separated into leaves, stems, ears and husks for dry weight analysis and leaves, stems and kernels were ground separately for the partitioning analysis beginning at the R3 stage (Abendroth et al., 2011). Whole plant soybean samples were ground and analyzed, while after the second sampling date, maize samples were chopped into smaller pieces and subsampled before passing through the Wiley mill.

Table 2
Annual precipitation and spring precipitation over the seven years of this analysis (IEM, 2015).

Year	Annual Precipitation (mm)	April-May Precipitation (mm)
2008	1274	242
2009	946	216
2010	1287	178
2011	816	209
2012	637	35
2013	695	335
2014	1023	230
Average	954	206

2.4. Statistical analysis

Volumetric soil water content data has a number of characteristics: (1) The data has a high measurement frequency (sub-daily); (2) Measurements are highly correlated (i.e. one day of soil water content measurement is very similar to the previous day); (3) Measurements are highly influenced by precipitation events which cause sudden increases in values. To capture the pattern of this type of data we chose to use a smoothing splines approach. Splines are constructed from polynomial interpolation between knots (boundary points for the piecewise polynomials) that also need to be estimated (Silverman, 1985). Similar spline-fitting approaches have been used to describe the relationship of daily evapotranspiration over a season (Hankerson et al., 2012) and nitrogen fluxes in time (Cook et al., 2010; Dietzel, 2014). For simplicity, we conducted separate analyses for each year and depth, fitting individual equations for θ at each depth (5 cm, 10 cm, 15 cm, 30 cm) and each time period (spring and summer, Section 2.2) using a generalized linear

Table 3
Soil water storage effects over the April through October growing season period (Day of year 100–300) P values for treatment effect and spline*treatment interaction are displayed for each of the years in the analysis. Spline represents the curve fitting parameter (Section 2.4) which in our analysis is a proxy for time. In 2011 sensors were only functioning in one replication each treatment and variability could not be estimated.

Source	Year						
	2008 P-value	2009	2010	2011	2012	2013	2014
Treatment	0.264	0.968	0.478	–	0.101	0.015	0.039
Spline*Treatment	<0.0001	<0.0001	<0.0001	–	<0.0001	<0.0001	<0.0001

content in the two treatments (left axis) while vertical lines represent daily precipitation (right axis). Spring period days of year (DOY) varied by main crop period (earlier in spring for maize, later in spring for soybean) and dates for the cover crop termination and main crop planting are displayed with arrows. The summer period for each year is consistently displayed from mid-July through the end of August.

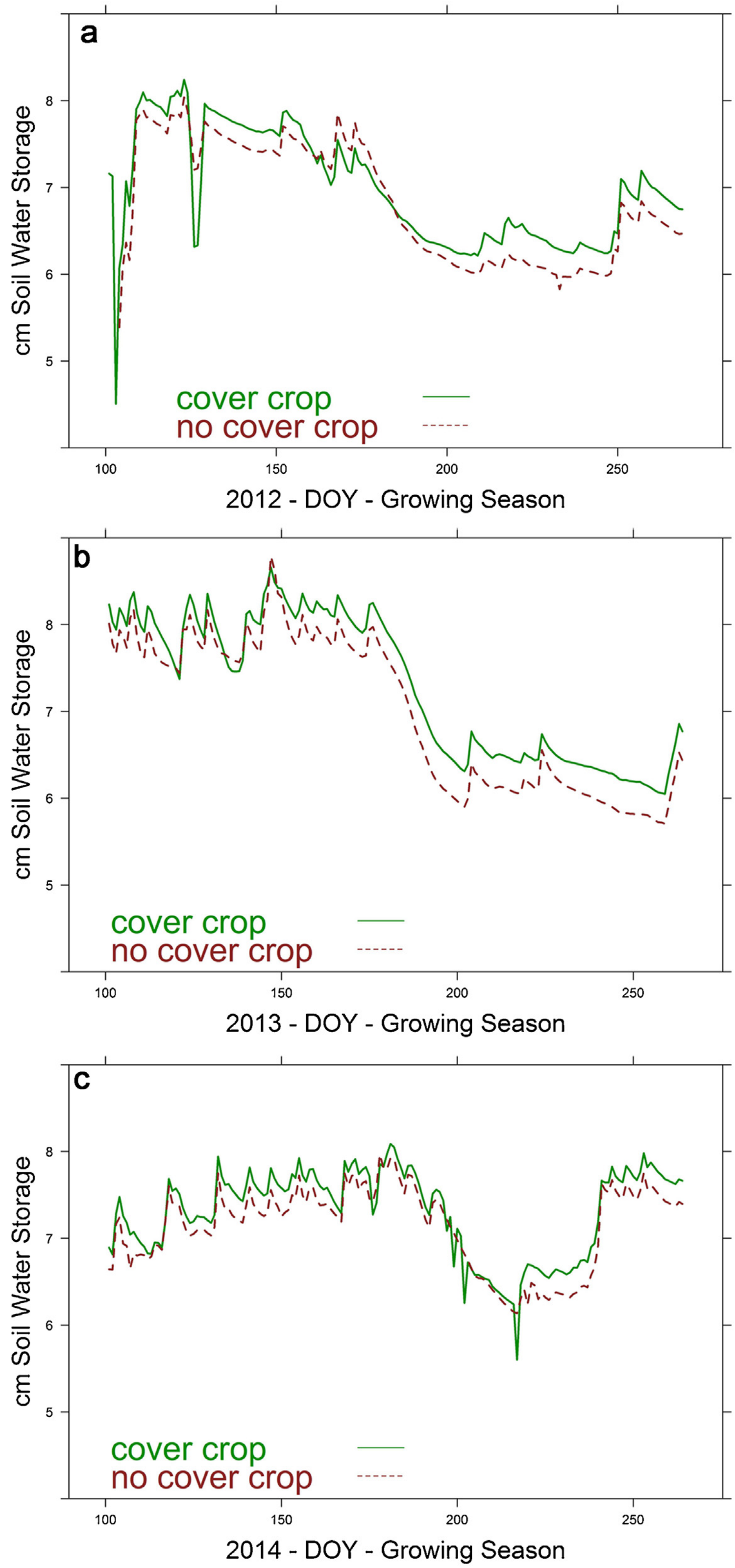

Fig. 2. Soil water storage (cm of water for the 0–30 cm depth) in 2012 (a), 2013 (b) and 2014 (c) from early April through late October (DOY—day of year 100 through 265) where the cover crop soil water storage was significantly different than the no cover crop treatment (see Table 3 for p values).

mixed model (PROC Glimmix procedure; SAS Institute, 2008) and linear combinations (i.e. estimate statements) for treatment effects on individual days. We accounted for the autocorrelation by fitting an autoregressive model to the residuals. To select the most appropriate statistical model we manually adjusted the number of splines in each time period and depth analysis, evaluated residual plots, and considered AIC (Akaike information criteria) and BIC (Bayesian information criteria) values. These criteria were also used to evalu-

Table 4
Soil texture, bulk density as well as the volumetric water content at saturation (SAT), field capacity (FC), permanent wilting point (PWP) and plant available water (PAW) for the treatments at two depths. Values with the same lowercase letters (by column) indicate no significant differences (treatment by depth difference at $p < 0.05$).

Depth	Treat-ment	Bulk Density g cm^{-3} (SE)	Sand% (SE)	Silt% (SE)	Clay% (SE)	SAT mm^3 mm^{-3} (SE)	FC mm^3 mm^{-3} (SE)	PWP mm^3 mm^{-3} (SE)	PAW mm^3 mm^{-3} (SE)
0–15 cm	Cover Crop	1.31 (0.04)^{a}	35.8 (4.8)^{a}	37.7 (2.9)^{a}	26.5 (2.0)^{ab}	0.571 (0.025)^{a}	0.347 (0.014)^{a}	0.175 (0.010)^{a}	0.172 (0.009)^{a}
0–15 cm	No Cover	1.30 (0.04)^{a}	33.8 (4.8)^{ab}	40.4 (2.9)^{b}	25.9 (2.0)^{a}	0.558 (0.025)^{a}	0.311 (0.014)^{b}	0.169 (0.010)^{a}	0.142 (0.009)^{b}
15–30 cm	Cover Crop	1.28 (0.04)^{ab}	35.6 (4.8)^{a}	36.9 (2.9)^{a}	27.5 (2.0)^{ab}	0.553 (0.025)^{a}	0.341 (0.014)^{ab}	0.174 (0.010)^{a}	0.167 (0.009)^{a}
15–30 cm	No Cover	1.20 (0.04)^{b}	32.0 (4.8)^{b}	40.2 (2.9)^{b}	27.8 (2.0)^{b}	0.574 (0.025)^{a}	0.310 (0.014)^{b}	0.174 (0.010)^{a}	0.137 (0.009)^{b}

Table 5
Maize (even-numbered years) and soybean (odd-numbered years) crop yields for the years included in this analysis. There were no significant differences between treatments in any of the years at the $p < 0.05$ level.

Year	Main crop yield cover crop Mg ha^{-1}	Main crop yield no cover crop Mg ha^{-1}	Least significant difference Mg ha^{-1}
2008	13.5	13.3	0.4
2009	2.4	2.4	0.2
2010	11.1	11.1	1.6
2011	3.6	3.6	0.2
2012	11.2	11.8	0.6
2013	3.0	3.0	0.2
2014	12.5	12.5	0.6
Average Maize	12.1	12.2	
Average Soybean	3.0	3.0	

ate the most appropriate variance-covariance matrix structure for the residuals. Treatment and time (day of year) were considered fixed effects. We evaluated specific days (i.e. cover crop termination date, cash crop planting date) of interest to detect treatment differences (cover crop versus no cover crop) in soil water content. For soil water storage we explored differences over the entire growing season (April through October) for each year in our dataset, summed over the depths available, with the same generalized linear mixed model where treatment and time (day of year) were considered fixed effects because we wanted to evaluate a seasonal effect. We assessed statistical significance at $p < 0.10$ for soil water content and soil water storage values given the large potential for variability between plots.

To assess treatment differences in soil texture, saturation, field capacity, permanent wilting point and plant available water, we used a mixed model where treatment and depth were fixed effects and block was considered random. For these factors we assessed significance at the $p < 0.05$ level. To assess treatment differences in plant growth and plant nitrogen uptake, we used a repeated measures analysis where sampling date was the repeated term and treatment nested in blocks was the sampling unit. We used an autoregressive variance-covariance structure that satisfied convergence criteria and produced smallest AIC and BIC values. For the plant analyses we assessed significance at the $p < 0.05$ level.

3. Results and discussion

3.1. Research question 1: how is soil water content affected by the cover crop?

We hypothesized that during the spring period we would see evidence that the growing cover crop depletes θ. We also hypothesized that if the cover crop had caused accumulated improvements in soil properties (i.e. surface residue cover, aggregation, soil organic matter, porosity) over time, there could be evidence of greater θ in later periods of the year. Several patterns emerged in separating differences in soil water content in the cover crop and no cover crop treatments. In comparing θ on individual days we found that during the spring periods (ten days before cover crop termination and ten days after cash crop planting) of 2009, 2010 and 2013 there were days that had significantly lower θ in the cover crop plots compared with the no cover crop plots (Table S1). In 2009, for example, it took five days for θ to return to the same levels in the two treatments at the 5 cm and 10 cm depths, where the cover crop plots were 0.03-0.04 mm^3 mm^{-3} (0.016 mm^3 mm^{-3} standard error), representing a 10–15% lower value than the no cover crop plots from May 22 to May 27 (DOY 142–147) at the 5 cm and 10 cm depths (Table S1). In spite of the lower spring soil water levels in the cover crop treatment plots, in five of the seven years θ was replenished to the statistically same level as the no cover crop treatment plots by the day that cash crop planting occurred. We conclude that the cover crop did use a measurable amount of water in the spring, but rainfall usually replenished soil water levels after cover crop termination, under both wetter and drier spring rainfall patterns (197 mm of rain in 2008 compared to 21 mm of rain in period in 2012 during the periods illustrated in Fig. 1). Cover crop water use in this region has been estimated to be between 20–60 mm by simulation models where soil evaporation is predicted to be reduced by a cover crop between 2 and 18% (Basche et al., 2016; Malone et al., 2007). Spring cover crop transpiration of 20–60 mm represents approximately 5% of the annual precipitation in Central Iowa or 10–30% of the historical average April-May rainfall, which is 194 mm (IEM, 2015). At our field site, this only reduced soil water levels to statistically different levels at maize and soybean planting in two of seven spring seasons, which could even be a benefit in wetter years because reduced soil water content might allow for earlier and more effective planting.

During the summer period, in six of the seven years (all but 2011), we found higher mean values of θ for individual days evaluated at lower depths in the soil profile (15 cm and 30 cm) in the cover crop plots (Fig. 1, Table S1). For example, during August and September of 2009, there was significantly higher θ

Table 6
Spring biomass of the winter rye cover crop.

Year	Cover crop biomass Kg ha^{-1} (standard error)
2008	1258 (40)
2009	498 (15)
2010	1728 (56)
2011	3523 (131)
2012	2517 (230)
2013	1079 (61)
2014	873 (52)
Average	1639

(0.02–0.03 $mm^3\ mm^{-3}$ with a standard error of 0.016 $mm^3\ mm^{-3}$, representing an increase of 8–12%) at the 15 cm depth for all of the days evaluated during a two week period. In 2009, total rainfall equaled 946 mm, above average for precipitation (815 mm is 100-year average for this location) (Fig. 1). We also detected about a two-week period in mid-August 2014 when θ at 15 cm was 0.02-0.03 $mm^3\ mm^{-3}$ higher (standard error of 0.013 $mm^3\ mm^{-3}$, or a 9–13% increase) in the cover crop treatment for the individual days evaluated. Because of measurement and experimental error, we found that the daily average θ needed to be different by approximately 0.02–0.03 $mm^3\ mm^{-3}$ between treatments to detect significant differences. These values for least significant differences are similar with those observed by other research in similar soils and cropping systems (Daigh et al., 2014a; Daigh et al., 2014b).

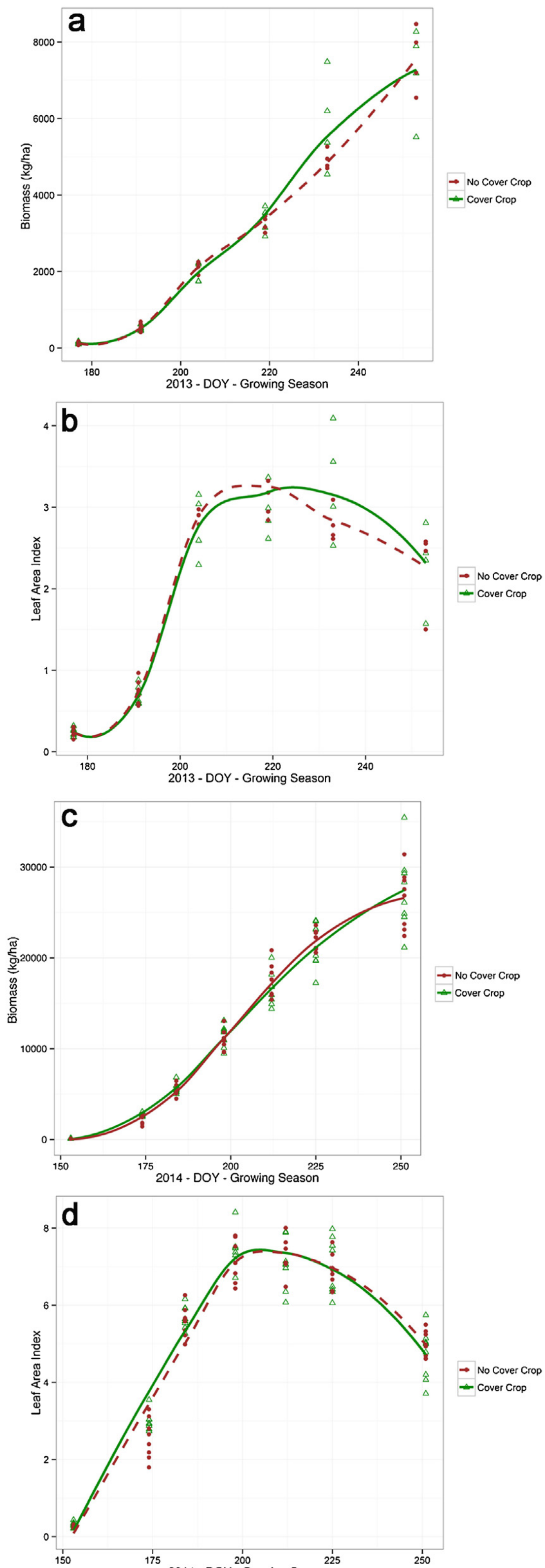

Fig. 3. Soybean biomass (a) and leaf area (b) for measurement days of year (DOY) during the growing season in 2013 and maize biomass (c) and leaf area (d) in 2014.

In general we found that the cover crop plots had higher daily θ at the 15 and 30 cm depths of the soil profile later in the summer period growing season (Fig. 1, Table S1). This could be evidence of reduced soil evaporation because of increased residue cover (Dabney, 1998; Unger and Vigil, 1998). It could also indicate that the long-term use of the cover crop increased porosity (Villamil et al., 2006), reduced soil bulk density (Steele et al., 2012; Villamil et al., 2006), increased hydraulic conductivity (Klik et al., 1998) or increased aggregate stability and aggregation (Liu et al., 2005; Rachman et al., 2003; Sainju et al., 2003; Villamil et al., 2006). This improvement in soil physical properties would increase infiltration, facilitate faster downward movement of water and enhance water storage capacity. Further, increases in soil carbon or soil organic matter also could also increase in soil water storage capacity (Hudson, 1994; Kay, 1998; McDaniel et al., 2014; Poeplau and Don, 2015).

It is important to note that the years included in our analysis were very different in their rainfall patterns. For example, 2012 was one of the driest (lowest 10%) and hottest years (one in 121 years for days above 21 °C, one in 121 years for warmest average temperature) in the historical record. In contrast, 2008 and 2010 were two of the top three wettest years in the 122-year historical record (IEM Climodat, 2015) (Table 2). In spite of these differences and the inherent soil variability, we were still able to detect the general pattern of increased soil water deeper in the soil profile later in the growing season, evidenced by greater average treatment differences at the lowest depth for which measurements were available (Table S1). We are also able to discern that early season water use by the cover crop was usually replenished by spring rains and soil water content was not lower than the control treatment at cash crop planting in the majority of years.

3.2. Research question 2: how is soil water storage affected by the cover crop?

We hypothesized that the calculated soil water storage (SWS) values over the growing season, based on the sum of the soil water content values multiplied by the measurement depth, would show evidence of higher level of stored water with the inclusion of the cover crop, given the potential for the cover crop to reduce soil water evaporation as well as to accrue soil changes (i.e. carbon content, porosity) that facilitate water storage. We found a significant effect of treatment for average SWS in the 0–30 cm soil layer during the entire growing season (DOY 100 through DOY 300) in 2012, 2013 and 2014 (Table 3), where soil water storage in the cover crop treatment was generally higher throughout the season (Fig. 2). These are the three years for which we had measurements to 30 cm as opposed to measurements from 2008 to 2011 that were only at the 0–15 cm depth. Thus, our results demonstrated higher SWS lower in the soil profile with a cover crop, similar to the pattern in θ. Similar to our study, Daigh et al. (2014a) used daily measurements of volumetric soil water content to calculate SWS values and also found that a rye cover crop led to an increase in soil water storage during the drought of 2012 at another central Iowa field site. Further, the cover crop treatment responded differently throughout the growing season of all the years analyzed relative to no cover crop and this is demonstrated by the significant interaction of spline and treatment (Table 3), indicating how the relative amount of water storage changed over time varied between the two treatments. A cover crop contributing to improved SWS increases could be a result of several soil physical changes reported to occur after long-term cover crop use, including increased porosity and enhanced aggregation (Liu et al., 2005; Rachman et al., 2003; Sainju et al., 2003; Villamil et al., 2006).

3.3. Research question 3: which soil water retention properties are affected by the cover crop?

There are a few reports of a cover crop increasing water retention at field capacity (Bilek, 2007; Lal et al., 1979; Patrick et al., 1957) or increasing plant available water content (Villamil et al., 2006). Because the cover crop treatment at our site had been established 13 years before we collected our soil, we had hypothesized that we might also see an increase in plant available water due to changes in water retention properties with the addition of the cover crop. This was confirmed, as we found that the cover crop treatment significantly increased the water content at field capacity by 10.9% and 10.0% relative to the no cover crop treatment at the 0–15 cm and 15–30 cm depths, respectively (Table 4). These differences in water could not have been due to the slight differences in soil texture between plots because the cover crop treatment plots had higher sand contents than the no cover treatment (Table 4), which would tend to lower water contents. We did not detect statistical differences in the permanent wilting point measurements between the two treatments. Therefore, mostly as a result of higher field capacity water content values in the cover crop treatment, we also found significant increases of 21.1% and 21.9% relative to the no cover crop treatment for plant available water at the 0–15 cm and 15–30 cm depths, respectively (Table 4).

The observed increases in water retention at field capacity are known to occur from both increases in soil organic matter as well as changes to soil aggregation. Emerson (1995) demonstrated the relationship of increasing carbon in the soil to increasing water held at −10 kPa matric potential. Hudson (1994) further demonstrated that an increase in plant available water, largely in the range of water potentials near field capacity, followed increasing levels of organic matter in the soil. Because treatment-driven changes in organic matter can be difficult to detect and require large numbers of samples, particularly in soils with naturally high levels of soil organic matter (Karlen et al., 1999; Kaspar et al., 2006), we did not measure organic matter extensively enough to detect treatment differences (Necpálová et al., 2014) in this experiment. However, in a nearby cover crop experiment that was initiated at the same time as this study, researchers did measure 15% more soil organic matter in the 0–5 cm soil layer after 10 years of a cereal rye cover crop (Moore et al., 2014).

In terms of soil aggregation, there is a known relationship between water retention and aggregate size distribution (Guber et al., 2004). In general, aggregation and a mixture of aggregate size classes increase the number of mesopores in the soil. Mesopores are thought to hold most of the water between 10 kPa and 1500 kPa, and can be influenced by management such as cover crops in no-till systems (Kay, 1998). The contribution of cover crop roots was found to be relatively more important for improvements to soil aggregate stability compared to incorporation of aboveground plant residues (Benoit et al., 1962). In a maize-soybean rotation in Illinois, Villamil et al. (2006) found that winter cover crops increased wet aggregate stability, soil organic matter and mesoporosity, which in turn increased plant available water. Dao (1993) attributed greater water availability at equivalent suction gradients to increased porosity when comparing no-till to a moldboard plow tilled soil. Thus, it seems reasonable that the increase in soil water content at field capacity in our study could be a result of cover crop shoots and roots increasing soil carbon, soil aggregation, and the accompanying water holding mesopores.

3.4. Research question 4: does the water use from the cover crop negatively impact maize and soybean growth?

We hypothesized that we would not see negative impacts of the cover crop on maize or soybean growth, particularly if the cover crop treatment showed increases in soil water availability during the main crop growing season. In general we found the growth and N accumulation patterns of soybeans in the cover crop and no cover crop treatments to be very similar. Over the soybean sampling period in 2013, we did not detect any notable differences in biomass or leaf area between the cover crop and no cover crop treatments (Fig. 3). However one sampling date (August 21, DOY 233) did show significantly higher biomass in the cover crop treatment. There were also no significant differences between treatments in total soybean plant N for any of the sampling dates (Table S2). Final soybean grain yields in 2013 were nearly identical in both treatments, equaling 2.99 Mg ha^{-1} in the cover crop treatment and 2.96 Mg ha^{-1} in the no cover crop treatment. It is important to note that 2013 was the second driest year of those included in this analysis (695 mm, Table 5), and the cover crop still did not have a negative impact on soybean yield. For maize in 2014, we similarly did not detect differences in biomass and leaf area between the cover crop and no cover crop treatments (Fig. 3). Further, in our analysis of plant nitrogen (Fig. 4), we found that there was significantly higher total nitrogen in the cover cropped maize plants on two sampling dates (DOY 174 June 23 V7 and DOY 198 July 17 VT). On the last sampling date of the season (DOY 251 Sept 8 R5) there was no significant difference in total plant nitrogen (leaves, stems and kernels combined) between the treatments, yet analyzed separately maize kernels showed a significantly higher nitrogen content (kg N ha^{-1}) for the cover crop treatment (Fig. 4). Similar to soybeans in 2013, final maize grain yields in 2014 were nearly identical in the two treatments, where the cover crop treatment yielded 12.4 Mg ha^{-1} and the no cover crop treatment 12.5 Mg ha^{-1}. Although we did not measure biomass throughout the growing seasons of 2008–2012, there were no significant differences (at the $p < 0.05$ level) between the cover crop and no cover crop treatments in final yields for maize or soybeans (Table 5) (Kaspar et al., 2012). In the drought year of 2012, the grain yield of the cover crop treatment was of 0.598 Mg ha^{-1} (9.56 bushels acre^{-1}) less than yield without a cover crop, which was close to the least significant difference of 0.602 Mg ha^{-1}, but there was no evidence to indicate this was a result of water stress (Fig. 1, Table S1), as soil water content levels were generally higher in the cover crop treatment during the summer period.

The strong relationship between cumulative plant biomass and cumulative transpiration is well documented for both irrigated and rainfed cropping systems (Stockle et al., 1994; Suyker and Verma, 2009; Tolk and Howell, 2009; Walker, 1986). We did not detect differences in aboveground maize and soybean biomass (Fig. 3), as well as final crop yields (Table 5), between the cover crop and no cover crop treatments suggesting similar transpiration patterns between the treatments. This further suggests that differences in soil water content between treatments during the summer period may not be attributable to differences in main crop plant transpiration, at least in the two seasons for which we have biomass measurements during the main crop growing season. Additionally, although cumulative drainage data is difficult to partition into specific time periods because of the lag time required for water to travel through soil to the drainage tiles, there were no years with significant differences in annual cumulative drainage from 2002 to 2012

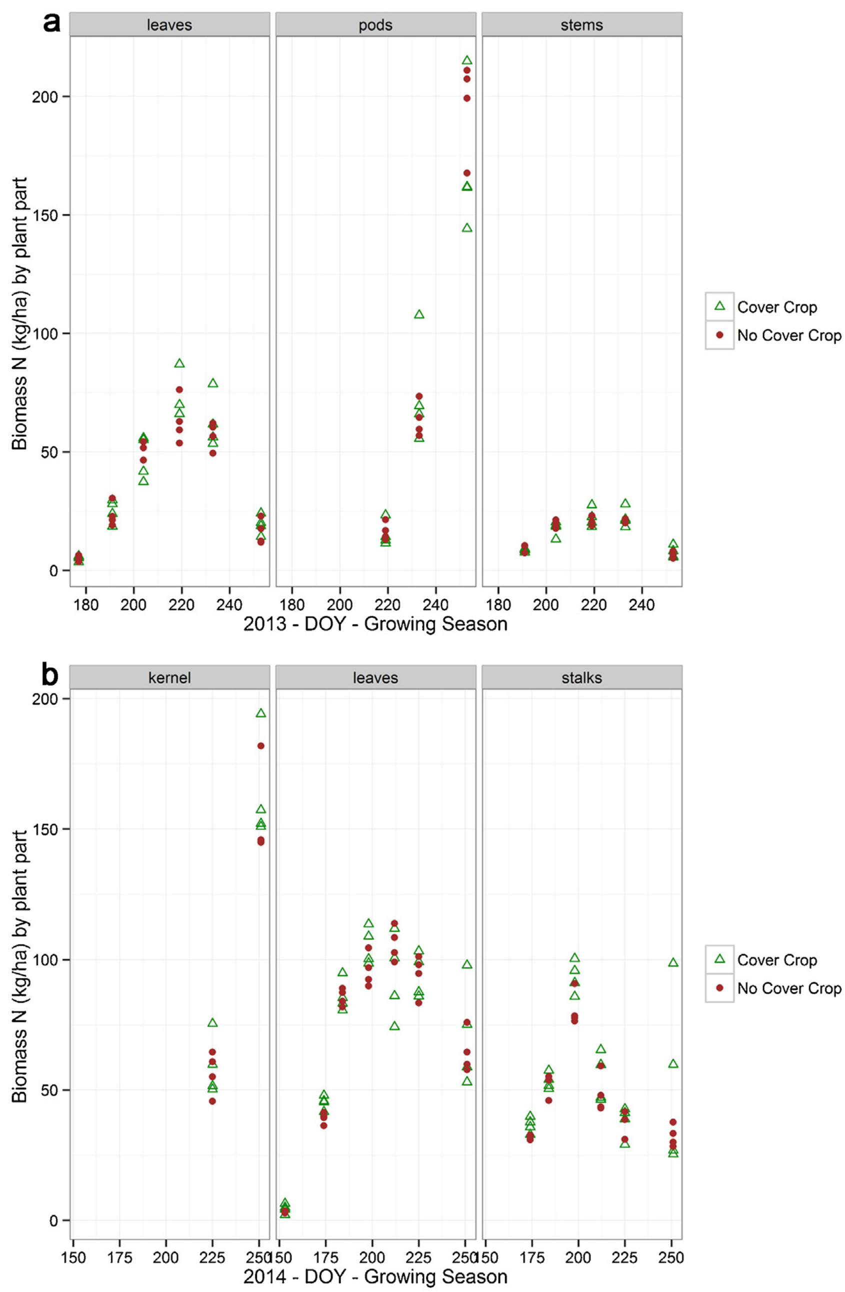

Fig. 4. Soybean biomass nitrogen by plant part for measurement days of year (DOY) during the growing season in 2013 (a) and maize biomass nitrogen by plant part in 2014 (b).

between treatments with and without cover crops (Kaspar et al., 2007; Kaspar et al., 2012). Therefore, if transpiration of main crop is unchanged and drainage is not increased, then this seems to support our other evidence that the higher soil water contents in the cover crop treatment during the summer period is due to a greater capacity for soil water storage at our research site.

While small maize yield decreases after cereal cover crops in the North Central region of the United States are not uncommon (Miguez and Bollero, 2005), our results do not suggest that the cover crop's water use in the spring negatively affected maize or soybean growth. The years of 2010, 2011, and 2012 experienced above average growth of the winter rye cover crop, ranging from 1700 kg ha^{-1} to 3500 kg ha^{-1} (Table 6). In those three years, water content during the summer period was lower in the cover crop treatment only in 2011 (Fig. 1) and soybean yields were still identical between the cover and no cover treatments (Table 5). This indicates that even in years when cover crop biomass was large for our location, these effects of spring water use did not persist into the summer period in a way that impacted cash crop yields. We recognize that our results are specific to years of this study and to a region that is generally not water-limited. However, understanding that cover crops both use water in the spring and over the long term increase water storage during summer, may allow us to manage cover crops so water is not limiting to the crops that follow. For example, Whish et al. (2009) found with model simulations for 31 locations in wheat producing regions of Australia that a millet cover crop ahead of wheat as opposed to fallow only negatively impacted wheat growth in 2% of the seasons, if the cover crop was planted early or removed after 50% cover was achieved. Joyce et al. (2002) found reduced runoff and increased water storage with a winter cover crop in the Sacramento Valley of California, but that to avoid impact to following cash crops, the cover crop must be terminated in early spring before excess water is lost by evapotranspiration from the cover cropped system. At our site we found evidence in two of seven years that spring precipitation did not replenish soil water content levels after the transpiration depletion from a growing cover crop before main crop planting. Thus, similar to drier regions, producers concerned about cover crop water use in the spring could effectively reduce risk by terminating cover crops earlier than normal, based upon criteria such as reaching a target level of cover crop biomass or if spring precipitation is measured to be below a target threshold. These are methods with proven success in other drier regions.

4. Conclusion

In this study we found that over a seven-year period, including years that were wetter, hotter and drier than normal, the consecutive use of a winter rye cover crop contributed to improved soil water content and soil water storage in a maize-soybean cropping system. We detected evidence of soil water use from a transpiring cover crop in the spring, but rainfall was able to replenish the soil to the same level in both the cover crop and no cover crop treatments by the time of maize and soybean planting in most springs. The cover crop increased the water retained in the soil at water potentials associated with field capacity (−33 kPa) by 10–11% as well as increasing plant available water by 21–22%. In the last two years of the experiment we further found that the winter rye cover crop did not have any negative effects on maize or soybean biomass, leaf area, and yield. Our analysis suggests that the long-term use of a winter rye cover crop, if managed appropriately, can improve soil water dynamics.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agwat.2016.04.006.

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