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Cereal rye cover crop effects on soil physical and chemical properties in southeastern Indiana

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CEREAL RYE COVER CROP EFFECTS ON SOIL PHYSICAL AND CHEMICAL PROPERTIES IN SOUTHEASTERN INDIANA

A Thesis

Submitted to the Faculty

of

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by

Joseph D. Rorick

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of

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ABSTRACT

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Major Professor: Eileen J. Kladivko.

Cover crops are growing in popularity in the Midwest, although questions remain about how to include them most effectively in a corn-soybean (*Zea mays* L. - *Glycine max* L.) rotation. This study was conducted to determine the effects of cereal rye (*Secale cereale* L.) on soil bulk density and water retention, soil organic carbon, soil nitrogen, and water stable aggregate mean weight diameter after four years of cover crop growth and the effects on soil moisture over a five year period. The study was conducted at the Southeast Purdue Agricultural Center (SEPAC) on silt loam soils. A 14 hectare field was laid out in a split plot design with four blocks of four treatments in each block for a total of sixteen plots. Treatments were corn with cereal rye, corn with no cover, soybean with cereal rye, and soybean with no cover, all four treatments every year, with the corn and soybeans alternating yearly. The field site was established in the spring of 2011 and baseline samples were taken in the summer of that year before the first establishment of the cover crop in fall 2011. Measurements were taken at 0-10, 10-20, 20-40, and 40-60 cm depth intervals in 2011 and 2015 for bulk density, water retention, soil organic carbon, total soil nitrogen, and aggregate stability. Soil moisture and temperature were measured at five minute intervals from 2011-2016 at 10, 20, 40, 60, and 100 cm depths.

After four years of a cereal rye cover crop, wet soil aggregate mean weight diameter increased 55% when compared to the no cover control in the 0 to 10 cm depth and 29% in the 10 to 20 cm depth. Bulk density, water retention, soil organic carbon, and total soil nitrogen showed no change between cover crop treatments. Differences in soil moisture were detected throughout the year but further analysis is needed to fully quantify the effects of the cover crop as results were mixed throughout the time periods analyzed. Overall, in the early spring before cash crop planting, cereal rye either had significantly lower soil moisture or had no effect on soil moisture compared to no cover, while during the cash crop growing season in the 40 and 60 cm depths five of eight plot pairs showed relatively higher soil moisture and three of eight plot pairs showed lower soil moisture with cereal rye than with no cover. Cereal rye can be an effective soil conservation tool, protecting the soil surface from erosive forces, taking up excess nutrients at the end of a growing season, and helping feed soil microbes during a typically fallow period, but some of the improvements it has been reported to make may require a longer time period to change than the years included in this study.

CHAPTER 1. INTRODUCTION

One of the largest questions facing agriculture today is how to increase production while maintaining or decreasing the current agricultural footprint and doing it all in a more sustainable manner. In a world of increasingly variable weather patterns, how can we make our cropping systems more resilient to these increasing and variable climate stresses? Cover crops have been identified as one possible management practice to increase soil carbon storage, take up and hold nutrients, cover and protect the soil from erosion and loss, improve soil structure to increase water infiltration and air exchange, and many other benefits consistent with the concept of resiliency. Cereal rye is a popular cover crop because it has a wide window of efficacy for use as a winter cover, it can be planted later in the fall than many other cover crops, achieve reasonable amounts of growth, overwinter, and begin growing early in the spring taking up excess nutrients and protecting the soil during the early spring when much of the excess rainfall in the Midwest is received.

In 2011, a multi-state transdisciplinary project was begun to identify ways to increase the productivity and long term sustainability of corn based cropping systems. This thesis work is part of that large regional project supported by the USDA-NIFA, Award No. 2011-68002-30190, “Cropping Systems Coordinated Agricultural Project:

Climate Change, Mitigation, and Adaptation in Corn-based Cropping Systems." Thirty-five field sites were established across nine states in the Corn Belt researching many different field management techniques from extended crop rotations to different tillage practices and cover crops. This thesis includes results from one of these sites that was begun to investigate cover crops in a no-till corn-soybean rotation.

The objectives of this work were to determine the effects of a cereal rye cover crop on: 1) soil bulk density, soil water retention, soil organic carbon, total soil nitrogen, and wet soil aggregate mean weight diameter after four years of cover crop growth, 2) soil moisture in different seasons and at different depths over five years.

The analysis of these selected soil physical and chemical properties on a field site after four years of a cover crop is covered in chapter two. This chapter has been accepted for publication in the Journal of Soil and Water Conservation (accepted November 1, 2016). An initial analysis and observations of soil moisture over a five year period are discussed in chapter three. Chapter four contains discussion of the major findings of this work and includes thoughts on direction for future analyses as well as a synopsis of some of the challenges associated with conducting longer term field scale research.

CHAPTER 2. CEREAL RYE COVER CROP EFFECTS ON SOIL CARBON AND PHYSICAL PROPERTIES IN SOUTHEASTERN INDIANA

2.1 Abstract

Cover crops can be a management practice used to improve soil health and increase resilience to extreme climate events in a typical Midwestern corn-soybean (*Zea mays* L. - *Glycine max* L.) rotation. This study was conducted as part of a large regional project with a goal of studying how to make corn based cropping systems more resilient to climate stresses. A field site was established in Southeastern Indiana to study the effects of a cereal rye (*Secale cereale* L.) cover crop on soil physical and chemical properties in a no till corn and soybean rotation. Soil measurements included water stable soil aggregates using the wet sieving method, bulk density and water retention using intact cores, and soil organic carbon and total nitrogen. After four years of a cereal rye cover crop, wet soil aggregate mean weight diameter increased 55% when compared to the no cover control in the 0 to 10 cm depth and 29% in the 10 to 20 cm depth. Bulk density, water retention, soil organic carbon, and total soil nitrogen showed no change between cover crop treatments. This research shows that a cereal rye cover crop can increase water stable aggregation in a relatively short time, but changes in other physical and chemical properties are more difficult to detect.

2.2 Introduction

In the Midwest, corn (*Zea mays* L.) is a dominant cash crop and is at least a part of almost every major cropping system, but questions have been raised about the sustainability and environmental impacts of corn based cropping systems. In 2011 the USDA NIFA funded Climate and Corn-based Cropping Systems Coordinated Agricultural Project (CSCAP), an eight state transdisciplinary five year project, was begun to "evaluate the social, economic, and environmental impacts of climate variability on corn-based cropping systems" (sustainablecorn.org). One of the goals of the project was to investigate agronomic management practices and their effects on increasing the sustainability and resilience of these systems. Cover crops have been identified as a possible way to protect and improve soil physical properties and water quality (Blanco-Canqui et al. 2011; Kladivko et al. 2014a), but research is still needed on how to integrate cover crops into corn based cropping systems and to quantify the potential benefits and drawbacks of doing so. Cereal rye (*Secale cereale* L.) was used as the cover crop in this regional project because it has good germination and establishment even when planted in late fall, exceptional winter hardiness, and early resumption of growth in the spring. These characteristics were likely to result in substantial biomass production across the broad range of field sites included in the larger study throughout the Midwest. Cereal rye as a cover crop has been shown to have many benefits including weed suppression (Barnes and Putnam 1983), improved soil aggregation and structure (Benoit et al. 1962; Villamil et al. 2006), decreased bulk density and compaction (Moore et al. 2014; Blanco-Canqui et al. 2011), and improved soil water retention characteristics (Villamil et al. 2006; Basche et al. 2016). Other studies have shown no change in soil physical properties other than water stable aggregation, when measured during the cash crop growing season (Steele et al. 2012). Soil organic matter and soil organic carbon (SOC) have been shown to increase under a cover crop (Kuo et al. 1997; Moore et al. 2014; Villamil et al. 2006) but many researchers have also documented no change (Eckert 1991; Jokela et al. 2009) indicating a need for more research. This study was conducted to test the hypothesis that after four years of a cereal rye cover crop, there would be differences in soil physical and chemical properties between cover crop and no cover crop treatments on a poorly structured silt loam soil in Indiana.

2.3 Materials and Methods

The field site was established at Purdue University's Southeast Purdue Agricultural Center (SEPAC) near Butlerville, Indiana (39° 1' 32.88" N, 85° 32' 24" W) in 2011. Previous to the study the field was in a conventionally tilled corn and soybean rotation with soybean being the 2010 cash crop. In spring 2011 the field was tilled with a disk to a depth of 10 cm and then with a field cultivator to a depth of ~5 cm prior to the overlay of the plots and treatments. Sixteen plots measuring 18 x 365 m were laid out in a 14 ha field in a split plot design with each plot having a no till corn and soybean rotation with or without a cereal rye cover crop. Treatments were corn with cereal rye, soybean with cereal rye, corn no cover, and soybean no cover replicated in each of four blocks. The cereal rye was drilled as soon as possible after cash crop harvest each year at a rate of 70 kg ha^{-1} and was chemically terminated in the spring with herbicide. In 2012, all treatments were terminated at the same time at least two weeks before corn planting. In the last three years of the study it was decided to maximize cover crop growth so the termination timeline changed slightly. In the last three years the plots going into corn (called “before corn”) were terminated at least two weeks before cash crop planting. The no cover plots going into soybean (called “before soybean”) were also sprayed at the same time as the before corn treatments to terminate any weeds present, so for three out of four treatments the termination timing is the same. The cereal rye in plots before soybean was allowed to grow until a few days before soybean planting in the last three years, in order to have greater biomass which might have greater impact on soil properties. Above-ground biomass amounts at the time of spring termination, averaged across the four years of treatments were 1,900 kg ha^{-1} for the cereal rye treatments and 545 kg ha^{-1} of weedy biomass for the no cover treatments. Crop and fertility management was performed in accordance with good agronomic practices and did not differ between cover crop treatments.

Soils at this field were mapped on site by Purdue pedologist Phillip Owens (personal communication, 2011). Soil types in the areas sampled were predominantly Nabb (fine-silty, mixed, active, mesic Aquic Fragiudalfs), Blocher (fine-silty, mixed, active, mesic Oxyaquic Hapludalfs), and Cincinnati (fine-silty, mixed, active, mesic, Oxyaquic Fragiudalfs) silt loams. This project was part of a larger regional project, and sampling protocols were standardized to ensure consistent methods across the regional network (Kladivko et al. 2014b). Soil measurements were taken within four weeks of planting the cash crop in odd years of the study (2011, 2013, and 2015) and sampling depths used were 0 to 10, 10 to 20, 20 to 40, and 40 to 60 cm. Samples were taken in the quarter-row position of the corn rows (~19 cm from the corn row) and midway between soybean drilled rows, avoiding any cereal rye plants if present. Wheel tracks were avoided where they were obvious, but due to different sizes and types of equipment used on the field, it was not always clear if a wheel track had been there or not.

Samples for aggregate stability were taken using a Giddings hydraulic probe 5.3 cm in diameter in 2011 and 2015. These samples were cut into four depth increments (0 to 10, 10 to 20, 20 to 40, 40 to 60 cm) and two cores of each depth increment were composited per subsample. Three subsamples were taken per plot, analyzed individually, and then averaged for each plot. Each subsample was pushed through an 8 mm sieve while still field moist and then air dried and sieved to remove the < 2 mm fraction. Two 25 g subsamples of each subsample were analyzed using the wet aggregate size distribution method (Nimmo and Perkins 2002), and an average mean weight diameter (MWD) was calculated for each depth.

Soil organic carbon and total soil nitrogen samples were collected with a hydraulic probe similar to the aggregation samples and split into the same four depths. Six 5.3 cm diameter cores were collected per plot, analyzed individually, and then averaged for each plot. Soil samples were air dried, hand ground to pass a 2 mm sieve, and stored for subsampling and testing. An ~10 g subsample from each core was further hand ground to pass a 150 µm sieve for SOC and total nitrogen analysis. These subsamples were analyzed at the Iowa State University Soil and Plant Analysis Laboratory (Ames, IA) using the dry combustion method, and evolved CO_2 was measured using a LECO TruSpec (LECO Corp., St. Joseph, MO). Inorganic C was negligible in this soil profile. In 2011 a subsample was taken from the < 2 mm stored samples and sent to A&L Great Lakes Laboratory (Fort Wayne, Indiana) to be analyzed for texture using the hydrometer method (Gee and Or 2002). Texture is unlikely to change over a 4-year period so it was determined only once on all plots at each depth (Kladivko et al. 2014b).

Bulk density was measured using the short core method as described by Grossman and Reinsch (2002) using a 6 cm tall core 5.4 cm in diameter with three repetitions per depth in each plot. Samples were taken from the approximate center of each depth interval sampled to represent that depth increment. In 2011 and 2015 all four depths were sampled and in 2013 only the 0 to 10 cm and 10 to 20 cm depths were sampled for water retention measurements and bulk density, due to the generally slow rate of change of these properties, especially in the lowest two depths.

Soil water retention was measured at five water potentials using sand tables and pressure pots according to the methods described by Dane and Hopmans (2002a, 2002b). The same cores used for bulk density measurements were used for water retention at saturation and -4.9, -9.8, and -33 kPa. A bulk sample air dried and crushed to < 2 mm was used for measurements at -1500 kPa. Cores were gradually soaked to reach saturation, weighed, then placed on sand tables, allowed to equilibrate, and weighed to measure -4.9 kPa and -9.8kPa water retention. Cores were then transferred to pressure pots to measure water retention at -33 kPa and then oven dried to obtain a dry mass for bulk density measurements. Aeration porosity was calculated as the difference between saturation and -4.9 kPa (Kohnke 1968). Water holding capacity (WHC) was calculated as the difference between -9.8 and -1500 kPa.

Statistical analyses for all measurements were performed using SAS Version 9.4 software (SAS Institute Inc., Cary, NC.). Summary statistics and graphical data analysis were used to check for errors in the data and to see if a transformation was required (Box et. al, 1978). The soil carbon data were square root transformed and aggregate stability data were log transformed prior to the analysis to make the data more normally distributed. Results are presented in back-transformed units. Each measure was analyzed as a split plot split block experimental design with cash crop used as the whole unit, cover crop as the split plot, and depth as the split block treatment. Error variances were dropped from the model where the majority of the variances were not significant at p=0.25. The MIXED procedure was used for the analysis of variance and an LSMeans separation test was performed on all significant effects ($p \leq 0.05$).

Standardized protocols agreed upon by the USDA NIFA funded Climate and Corn-based Cropping Systems Coordinated Agricultural Project (Kladivko et al., 2014) were followed; see paper for full explanation of methods. Research data and supporting metadata were uploaded to the team’s central database with review and quality control performed by database managers to ensure data integrity and adherence to standardization (Herzmann et al., 2014). The data will be published at the National Agricultural Library (NAL) Ag Data Commons in 2017 (*doi forthcoming*). Data regarding comparisons not significantly different are not presented in this paper, however the reader can access the data through the NAL.

2.4 Results and Discussion

In June 2011, prior to establishing cover crop treatments in fall 2011, there were no differences in MWD among plots, indicating that the baseline values for plots that would receive rye cover vs no cover were the same (figure 1; p>0.05). Aggregate size was greater in the upper soil depths than in the lower soil depths at the onset of the study and four years after treatments were instituted. After four years of a cereal rye cover crop wet soil aggregate MWD in the 0 to 10 cm depth was 55% larger with cover crop and 29% larger in the 10 to 20 cm depth when compared to the no cover treatments (figure 1, cover crop x depth $p \leq 0.05$). No difference between cover crop treatments occurred below 20 cm and no difference between cash crops occurred at any depth in any year. Many studies have reported increased aggregate size or stability with the use of cover crops and continuous field cover (Villamil et al. 2006, Sainju et al. 2003, Rachman et al. 2003). The increased aggregation may be short-lived, however, as found by Linsler et al. (2016) in a greenhouse/incubation study where several brassicas or legumes were grown in the greenhouse and then terminated by freezing. After a 12-week incubation in a microcosm room following the cover crop termination, there was no difference in large macroaggregate concentration and total macroaggregates, indicating that differences in aggregation caused by some cover crops may be relatively short term. Tisdall and Oades (1982) reference the importance of actively growing roots and fungal hyphae on the stability of soil aggregates, adding strength to the argument for growing winter cover crops during a typically fallow period in a corn soybean production system in order to help protect and improve the soil. The fibrous root system of cereal rye was likely one cause of the increased MWD (Benoit et al. 1962, Villamil et al. 2006), as well as fungal hyphae and the decaying organic matter from the dead roots (Tisdall and Oades 1982). Larger more stable soil aggregates are better able to withstand erosive forces, allow for better water infiltration, and help to prevent surface compaction and runoff (Blanco-Canqui et al. 2011).

Texture in the four depths ranged from silt loam in the 0 to 10 cm depth with 26% clay to silty clay loam in the 40 to 60 cm depth with 33% clay. This small difference in clay content indicates that the increased aggregate MWD at shallower depths compared with deeper depths is more likely due to the effects of the cash and cover crop roots on biological activity and soil organic matter concentration, rather than differences in clay content.

After four years of the cereal rye winter cover crop treatments, soil organic carbon was unaffected by crop rotation and cover crop treatment (table A-1). In 2015 the organic carbon concentration in the 0-10 cm depth, when averaged between cash crops, was 15.05 and 14.02 g C kg^{-1} for cover and no cover, respectively (p>0.05). Other researchers have found little effect of cereal rye cover crop on soil organic carbon over a similar time frame (Eckert 1991; Kaspar et al. 2006) although when measured after ten years, Moore et al. (2014) was able to detect a 15 percent greater average soil organic matter content in the cereal rye treatment when compared to the no cover treatment. Kuo et al. (1997) found a 1 g kg^{-1} higher SOC amount in a 0-15 cm depth after eight years of cereal rye when compared to a no cover treatment, but both Eckert in Ohio (1991) and Jokela et al. in Wisconsin (2009) recorded no difference in SOC or soil organic matter after four years of cereal rye cover. A regional power analysis of minimum detectable differences (MDD) for SOC found a mean MDD of 3.38 g C kg^{-1} for comparing two treatments with five replications at an α=0.05 and a ß=0.15 (Necpalova et al. 2014). With the SOC values being only about 1 g C kg^{-1} different between cover crop treatments in our study, it is not surprising that differences were not statistically significant due to the inherent variability of SOC. Organic carbon significantly decreased with depth (table 2-1), which is expected due to the predominance of roots in surface horizons and the deposition of cash crop and cover crop residues on the soil surface without incorporation from tillage.

The distribution of total soil nitrogen mirrors that of organic carbon (table 2-1) with the highest values at the surface and decreasing with depth in all years. Soils sampled in soybean had lower soil nitrogen than in corn; 0.94 g N kg^{-1} and 1.03 g N kg^{-1}, respectively in 2011 and 1.01 g N kg^{-1} and 1.13 g N kg^{-1}, respectively in 2015 ($p \leq 0.05$). No differences were found between cover crop treatments for soil nitrogen (table A-2), with values in 2015 in the 0-10cm depth of 1.64 g N kg^{-1} and 1.55 g N kg^{-1} ($p > 0.05$) for the cover crop and no cover crop treatments, respectively.

No differences in bulk density were found between cover crop treatments in any year (tables A-3 to A-6) and in the 0-10 cm depth in 2015 for both cover and no cover the values were 1.32 g cm^{-3}. In 2015, bulk density was slightly greater in corn (1.41 g cm^{-3}) than in soybean (1.38 g cm^{-3}) similar to what was found in Iowa (Moore et al. 2014). Bulk density increased with depth in both years consistent with the decrease in SOC with depth. Over time we would expect soil bulk density to decrease due to the presence of the fibrous root system of the cereal rye. However, even after 13 years of cereal rye growth in a study in Maryland, no differences in bulk density were measured during the cash crop growing season, although there were some differences observed during the cover crop winter season (Steele et al. 2012). In our study the samples were all taken at a similar time of year in all three years. Care was also taken to sample in similar row positions on all plots and to avoid wheel tracks, but it is still possible that some less obvious wheel tracks were sampled, adding variability and making it very difficult to detect smaller changes due to the cover crop. Kaspar et al. (1995) found that trafficked interrows had up to a 36% higher bulk density (1.36 Mg m^{-3}) when compared to untrafficked interrows (1.09 Mg m^{-3}) averaged across different tillage systems including chisel plow and no till, highlighting the need to plan sampling locations carefully.

Volumetric water content at saturation (0 kPa) had an inverse relationship with bulk density in 2011 and 2015 (table 2-2). Soils that are less dense have more total pore space that can be occupied by water at saturation. In both 2011 and 2015 the surface depth had significantly higher saturated water content than deeper depths consistent with a lower bulk density in the upper depths as previously discussed. Similarly, aeration porosity (the difference between 0 kPa and -4.9 kPa) did not differ with cover crop or cash crop although in 2011 and 2015, depth was a significant factor with the greatest values in the 0 to 10 cm depth (0.110 and 0.082, respectively) and the lowest values in the 40 to 60 cm depth (0.025 in both years). Water retention at every water potential measured did not differ between cover crops nor between cash crops (tables A-3 to A-6). Water retention of the 0 to 10 cm depth in 2011 and 2015 at -4.9, -9.8, and -33 kPa showed a significant difference when compared to the 40 to 60 cm depth except for -4.9 kPa in 2015. Volumetric water content at -1500 kPa in 2011 and 2015 showed significant differences between the top two depths and the bottom two depths. This may be due to a clay increase and the significant density increases with increasing depth resulting in more surface area for water retention at this approximation of wilting point. In the 0-10 cm depth, in 2015 the measured water potential values for the no cover treatment were all within 98-100% of the cover crop treatment ($p > 0.05$, data not shown), and WHC was 0.224 and 0.219 cm^3 cm^{-3} for the cover and no cover treatments, respectively. The WHC was not significantly different for cover crop or cash crop treatments in any year at

$p \leq 0.05$, but WHC was significantly greater in cover crop treatments compared to no cover treatments at $p \leq 0.10$ in 2015 across all depths (data not shown). In 2015 WHC in the 0 to 10 cm depth was greater than in the 40 to 60 cm depth (table 2-2). These findings contrast with a study on a Mollisol in Illinois over a similar time period where slight differences were found in aeration porosity and WHC between cover crop treatments (Villamil et al. 2006). Additionally, Basche et al. (2016) found that after thirteen years of cover crops, plant available water was 21% greater for the cover treatment compared to the no cover treatment in the 0 to 15 cm depth on a loam soil in Iowa.

2.5 Conclusion

The addition of cereal rye as a winter cover crop to a no-till corn and soybean rotation can increase soil health benefits and improve soil physical properties over time. Soil aggregate stability in the 0 to 10 cm depth was increased by 55% and in the 10 to 20 cm depth by 29% after four years of cereal rye cover crop as compared to the control, which can help to improve water infiltration as well as help to protect against erosion and surface crusting. Bulk density, water retention, and SOC were unchanged by cover crop growth during that four year period, however. Increasing the amount of cover crop biomass produced within any year and over a greater number of years could increase the likelihood of maintaining or increasing soil organic carbon which in turn could help to improve soil physical properties. Measuring changes in soil physical properties can be difficult due to the inherent spatial and temporal variation found in any soil, and differences may need to be large in order to be detectable within this natural variation.

2.6 Acknowledgements

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Table 2-1 Soil organic carbon (SOC) and total soil nitrogen (Tot N) with depth, averaged across cover crop and cash crop within each year. SOC shown in back-transformed units.

Year	Depth (cm)	SOC (g kg^{-1})	Tot N (g kg^{-1})
2011	0-10	14.25a	1.46a
	10-20	10.02b	1.22b
	20-40	5.06c	0.76c
	40-60	3.10d	0.51d
2013	0-10	13.00a	1.31a
	10-20	8.68b	1.00b
	20-40	4.16c	0.52c
	40-60	3.12d	0.36d
2015	0-10	14.54a	1.60a
	10-20	9.58b	1.25b
	20-40	5.01c	0.82c
	40-60	3.65d	0.62d

Note: Means followed by the same letter within a column and year are not significantly different at $p \leq 0.05$

Table 2-2 Bulk density (BD) and volumetric water content at five water potentials, and water holding capacity (WHC*) with depth averaged across cover crop and cash crop within year

			Volumetric Water Content (cm^3 cm^{-3})					
			water potential (kPa)					
Year	Depth (cm)	BD (g cm^{-3})	0	-4.9	-9.8	-33	-1500	WHC
2011	0-10	1.27a	0.459c	0.349a	0.330a	0.311a	0.123a	0.207a
	10-20	1.40b	0.414b	0.356a	0.340a	0.319ab	0.134a	0.206a
	20-40	1.44b	0.405ab	0.360ab	0.345a	0.330b	0.165b	0.180a
	40-60	1.48c	0.397a	0.372b	0.363b	0.355c	0.172b	0.192a
2013	0-10	1.36a	0.445b	0.365a	0.348a	0.325a	0.135a	0.213a
	10-20	1.39a	0.420a	0.355a	0.339a	0.318a	0.122a	0.217a
2015	0-10	1.32a	0.446d	0.364c	0.346b	0.321b	0.125a	0.221c
	10-20	1.36b	0.416c	0.352a	0.336a	0.313a	0.129a	0.208bc
	20-40	1.42c	0.406b	0.361bc	0.349bc	0.332c	0.158b	0.192a
	40-60	1.49d	0.395a	0.370cd	0.361d	0.350d	0.166b	0.196ab

Note: Means followed by the same letter within a column and year are not significantly different at $p \leq 0.05$
*WHC calculated between -9.8 and -1500 kPa

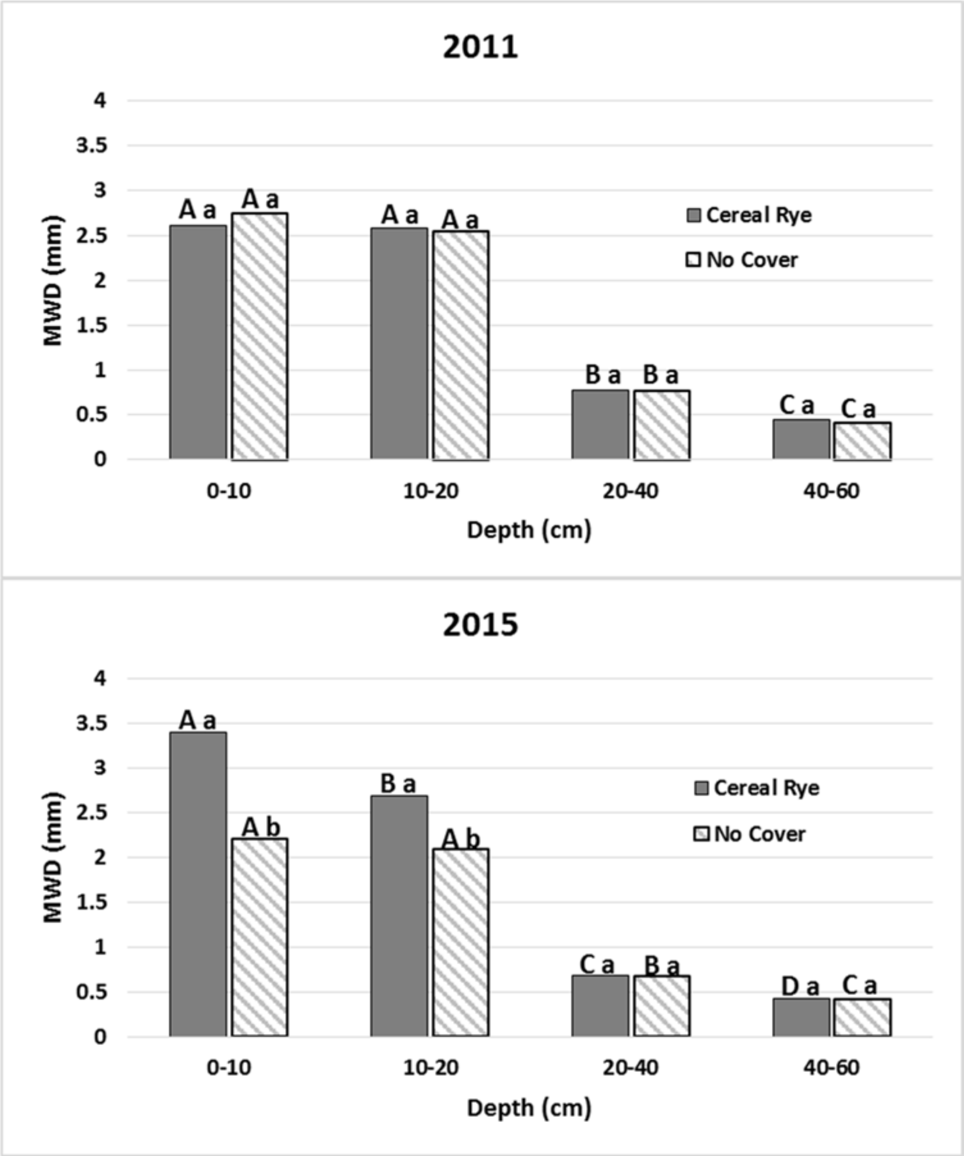

Figure 2-1 Effects of a cereal rye cover crop on water stable aggregate mean weight diameter (MWD) in 2011* and 2015, averaged across cash crop as affected by a cover crop by depth interaction. Shown in back-transformed units.

Note: Depths with the same uppercase letters within a cover crop treatment are not significantly different $p \leq 0.05$. Cover crop treatments with the same lowercase letters are not significantly different within a depth at the $p \leq 0.05$ level.
*2011 samples were taken in the spring after cash crop planting but before any cover crops had been established at the site.

CHAPTER 3. EFFECTS OF A CEREAL RYE COVER CROP ON SOIL MOISTURE IN A SILT LOAM SOIL IN SOUTHEASTERN INDIANA

3.1 Abstract

Cereal rye (*Secale cereale* L.) is a cover crop often used in the Midwest to improve soil health and protect soil during a typically fallow period in a corn-soybean (*Zea mays* L. - *Glycine max* L.) rotation, but questions remain about its effects on soil moisture. This study was conducted as part of a large regional project with a goal of studying how to make corn based cropping systems more resilient to climate stresses. A field site was established in Southeastern Indiana to study the effects of a cereal rye cover crop on soil physical and chemical properties in a no till corn and soybean rotation. Soil moisture is a very important physical condition, having a large effect on plant growth and development, crop productivity, and the ability to perform in-field management operations. Soil moisture and temperature were measured for five years (2011-2016) at five depths (10, 20, 40, 60, and 100cm) in two replicates of four treatments. Median soil moisture differences were calculated for four plot pairs as cover minus no cover for each of four periods of interest, and each plot pair moisture difference in each depth was compared back to the initial baseline period during the winter soil moisture recharge period. Overall, in the early spring before cash crop planting, cereal rye either had no effect on soil moisture or had significantly lower soil moisture than the no cover treatment when compared to the difference of the baseline period. During the summer growing season

cereal rye had mixed effects on soil moisture. Long term, high frequency sampling in real world field conditions presents many challenges and also creates large datasets that require careful thought, analysis, and interpretation.

3.2 Introduction

Cereal rye has been shown to provide many benefits to soil health and to increase the resiliency of corn based cropping systems but questions have been raised about its effects on soil moisture. Soil moisture is crucial for plant growth and development. The lack of adequate soil moisture during peak periods of the growing season reduced corn yields by as much as 90% (NeSmith and Ritchie, 1992) and grain yield was the factor affected more than any other plant characteristic by moisture stress in any growth stage (Denmead and Shaw, 1960). When cereal rye is growing it is also transpiring water pulled from the soil profile. This can be a concern in semi-arid regions where precipitation amounts may not be adequate to provide soil water recharge (McGuire et al., 1998). After the cover crop has been terminated, depending on the amount of biomass produced, there can be a mulch effect of the residue similar to that seen in conservation tillage systems that can increase soil moisture over what a bare soil counterpart would be. In a review of cover crop effects on soil water relationships, Unger and Vigil (1998) found that in humid and semi-humid regions, where precipitation is adequate for crop growth and the cover crop residues were left on the soil surface, there was little effect on the cash crop. Results are highly dependent on many factors including the timing and amount of rainfall received, the amount of cover crop biomass, and the tillage management of the study, although many studies showed little or no negative effects of the cover crop on soil moisture (Basche et al., 2016; Clark et al., 1997; Clark et al., 2007; Daigh et al., 2014; Qi and Helmers, 2009).

This research was conducted to test the hypothesis that cover crops will have an effect on soil moisture. During the early spring the cereal rye would be growing and transpiring water so the soil moisture would likely be lower under cereal rye when compared to a no cover treatment. Later in the spring after the cover crop has been terminated and into the cash crop growing season the residue can act as a mulch thereby conserving soil moisture so a cereal rye cover crop would have higher soil moisture than a no cover treatment.

3.3 Materials and Methods

The field site was established at Purdue University's Southeast Purdue Agricultural Center (SEPAC) near Butlerville, Indiana (39° 1' 32.88" N, 85° 32' 24" W) in 2011. Previous to the study the field was in a conventionally tilled corn and soybean rotation with soybean being the 2010 cash crop. In spring 2011 the field was tilled with a disk to a depth of 10 cm and then with a field cultivator to a depth of ~5 cm prior to the overlay of the plots and treatments. Sixteen plots measuring 18 x 365 m were laid out in a 14 ha field in a split plot design with each plot having a no till corn and soybean rotation with or without a cereal rye cover crop (figure 3-1). Treatments were corn with cereal rye, soybean with cereal rye, corn no cover, and soybean no cover replicated in each of four blocks. The cereal rye was drilled as soon as possible after cash crop harvest each year at a rate of 70 kg ha^{-1} and was chemically terminated in the spring with herbicide. In 2012, all treatments were terminated at the same time 28 days before corn planting. In the last three years of the study it was decided to maximize cover crop growth so the termination timeline differed dependent on the crop to be planted. In the last three years the plots going into corn (called “before corn”) were terminated at least two weeks before cash crop planting. The no cover plots going into soybean (called “before soybean”) were also sprayed at the same time as the before corn treatments to terminate any weeds present, so for three out of four treatments the termination timing is the same. The cereal rye in plots before soybean was allowed to grow until a few days before soybean planting in the last three years, in order to have greater biomass which might have greater impact on soil properties. Above-ground biomass amounts at the time of spring termination, averaged across the four years of treatments were 1,900 kg ha^{-1} for the cereal rye treatments and 545 kg ha^{-1} of weedy biomass for the no cover treatments. Crop and fertility management was performed in accordance with good agronomic practices and did not differ between cover crop treatments.

Standardized protocols agreed upon by the USDA NIFA funded Climate and Corn-based Cropping Systems Coordinated Agricultural Project (Kladivko et al., 2014) were followed; see paper for full explanation of methods. Research data and supporting metadata were uploaded to the team’s central database with review and quality control performed by database managers to ensure data integrity and adherence to standardization (Herzmann et al., 2014). The data will be published at the National Agricultural Library (NAL) Ag Data Commons in 2017 (*doi forthcoming*).Soils at this field were mapped on site by Purdue pedologist Phillip Owens (personal communication, 2011). Soil types in the areas sampled were predominantly Nabb (fine-silty, mixed, active, mesic Aquic Fragiudalfs), Blocher (fine-silty, mixed, active, mesic Oxyaquic Hapludalfs), and Cincinnati (fine-silty, mixed, active, mesic, Oxyaquic Fragiudalfs) silt loams. These soils exhibit fragic qualities at depth, so for the purposes of this analysis only the top 4 depths will be used, and the 100 cm depth will be ignored.

Soil moisture readings were required for cover crop sites (Kladivko et al., 2014) and an indirect method was desired so measuring dielectric permittivity was the method selected (Topp and Ferre, 2002). Soil temperature was measured using a surface mounted thermistor on the 5TM sensor (McInness, 2002). One Decagon Devices EM50 data logger and five 5TM soil moisture and temperature sensors were placed in 8 of the 16 plots and the middle 8 plots (plots 5-12) were chosen as the closest soil types and topography and were considered the most representative of the field. A bore hole was dug and sensors were placed horizontally into the side of the hole into the undisturbed soil profile at 10, 20, 40, and 60 cm. Sensors at 100 cm were placed vertically into the bottom of the bore hole and the hole was refilled by hand, approximating the same bulk density as the surrounding undisturbed profile in order to prevent preferential flow pathways. Loggers were set to read every 5 minutes to gather higher resolution data, but for the purposes of this analysis the data have been aggregated to a daily average. Data collection began in the summer of 2011, however, since there was not a cover crop planted until the fall of 2011, only data from January 2012 – the summer of 2016 will be reported here. Data were downloaded monthly and converted to a structured text file for upload to the main project database. Google Gadgets were used and a visualization and aggregation tool was created by the database team at Iowa State to ease the process of handling such a large dataset. Graphs created by this Gadget are shown below (figures 3-2 to 3-15) and data were downloaded as daily averages for statistical analysis.

The data were broken up into four initial time periods of interest in order to determine differential effects of the cover crop due to transpiration versus acting as a soil mulch (table 3-1). Period 1 is January 1st through the end of February (Feb. 28 or 29 in the leap years). This period is used as the baseline period because Indiana in the winter time typically receives enough precipitation to get full soil water recharge and the soils are approximately at a rough estimation of a “field capacity”, meaning that overall through the course of the period the free water has been drained by gravity and the remaining water is held by the soil matrix. Period 2 is March 1st through the day of termination of the cover crop (table 3-1). As stated previously, in the first year of the study the cover crop was terminated at the same time in the corn and soybean plots so the period in 2012 runs until March 25th. In the last 4 years of the study the cover crop before corn and the no cover crop plots before both corn and soybeans were terminated on the same date, this was April 14th in 2013 (table 3-1). The cereal rye before soybean was allowed to grow about two weeks longer, until April 29th in 2013 for example. Due to the complicated nature of the dataset, which will be explained in greater detail later, in order to simplify the analysis it was decided to analyze the data on a plot pair basis so that each pair had the same cash crop, either corn or soybeans every year. Analyzing the data on a cash crop basis required us to assign one beginning and one ending date to the pair of plots so it was decided to use the cover crop termination date for both the corn and soybean plots. The corn plots with and without rye are in fact, the same date, but for the soybean plots in the beginning of period 2 there are growing weeds in the no cover plots and growing cereal rye in the cover plots, then the weeds are terminated but the cover crop is allowed to remain alive. So for a portion of period 2, generally about two weeks, there is a cover crop growing and transpiring in the cover plots before soybean and nothing growing in the no cover plots that were terminated at the same time as the cover crop plots before corn. Period 3 is the day after termination of the cover crop through cash crop planting (table 3-1). For the before corn treatments this period is about two weeks long or longer, such as in 2016 when it was about six weeks, which is a time period of interest since there is concern in the Midwest about anything that may interfere with corn planting. For the before soybean treatments period 3 is only a few days at most and in 2016 is nonexistent (table 3-1). Period 4 ranges from the day after cash crop planting until August 31st for 2012 through 2015 which is nearing the end of the growing season for both corn and soybeans in Indiana. In 2016 the plots were split in half and two different N rates were applied so the treatments including corn run until the time of side-dress N application and the soybean treatments run until July 14th which are the last data available from the database.

Due to the large and complicated nature of the data, analysis began with a simple look at whether or not differences might exist between the cover and no cover treatments. Since the field is in a split plot design, two plots next to each other have the same cash crop in each year, but one plot received the cover treatment and the other plot in each pair was a no cover treatment. During period 1 (table 3-1) in Indiana there is typically enough precipitation to recharge soil moisture and it is expected that plots would all have a similar soil moisture approaching a “field capacity”, but as can be seen in figure 3-2, in January and February of 2012, the soil moisture values for each plot appear to behave similarly but they are not equal. These differences could be related to many different factors including localized variation or the plots being inherently different at the sensor locations, but they caused us to look at the relationships between plot pairs rather than use the actual values for soil moisture in each plot. A simple difference in soil moisture between adjacent plots was calculated by taking the values for the cereal rye plot minus the soil moisture values for the no cover plot for each plot pair. As mentioned previously, four time periods of interest were identified with time period one being considered the baseline time period to be compared against. Since the largest effect was suspected to be due to the growing cover crop rather than an effect compounding over time, it was decided to aggregate the five years together for an initial analysis. Combining the years in this manner allowed for comparisons to be made to test for effects of the cover crop when compared back to the baseline period. Since the plots are in a corn-soybean rotation and the time periods are assigned based on hard dates, cover crop termination, and cash crop planting, combining years still allows for each period in any year to have similar conditions (growing cover crop, terminated cover crop, growing cash crop, etc.) as the years before or after it because the period lengths are variable based on the cash crop to account for this. Matlab software (Natick, MA) was used for statistical analysis and a two sided Wilcoxon rank sum test was performed on 50% of the data selected at random in order to account for the autocorrelation contained in the dataset. Differences in the medians are considered significant at the $p \leq 0.05$ level.

3.4 Results and Discussion

Figures 3-2 through 3-15 are captures from the Google Gadget and are intended to provide graphic representation of what the daily average data look like. There are two graphs for each year, depth, and measurement combination, so for 2012, for example there are two figures (3-2 and 3-3) for soil moisture at the 10 centimeter depth, broken up into approximately 120 day time intervals (January to May and May to September) to condense the amount of data represented. The year 2014 actually has six figures, two for soil moisture at the 10 cm depth (figures 3-6 and 3-7), two for soil temperature at the 10 cm depth (figures 3-8 and 3-9) to highlight some issues with the data related to some observations in the moisture data, and two for soil moisture at the 20 cm depth (figures 3-10 and 3-11) to illustrate what the moisture at the lower depths of the soil profile looked like.

When reviewing the figures for soil moisture it can be observed that while most of the lines exhibit similar trends there is a fair amount of spread between the lines on any given day. We attribute most of this spread to localized variation within each plot but this indicates that there may be some other sources of variability that have been introduced in one or more of several possible ways. The first source of variability is that these sensors were not calibrated to this specific soil so there is about a ±0.03 cm^3 cm^{-3} volumetric water content accuracy and it can be seen that in many cases this could account for the greater portion of variation within the separation of the lines. The second source of variability is related to the installation of the sensors and data loggers. The very best job possible was done to ensure that each sensor location was as similar to the others as possible but the it could be that some sensor locations ended up in a locally high or low spot, a bore hole was filled in slightly differently or settled differently than the rest, or that there were inherent differences in the soils previous to the installation of the sensors. Yet another source of variation was introduced through the amount of time that this study covered. In the 5 years that these sensors and data loggers were in place, over time, various things happen and sensors and data loggers need to be replaced. In this case, for example, if a sensor was consistently reading at the upper end of the ±0.03 cm^3 cm^{-3} accuracy, and a new one was installed that was reading at the lower end of that accuracy range, there is automatically a quite large source of error that may have been introduced to even be able to collect data on a continuous basis.

Table 3-2 is a compilation of the median soil moisture value for each time period of interest within each depth and plot pair by cover crop treatment. Table 3-3 shows the results of the rank sum analysis, comparing each plot pair difference in any period and depth to the same plot pair depth combination in period 1. So for example, at the 10 cm depth for plot pair 5-6, the median soil moisture difference (cover minus no cover) was 0.022 cm^3 cm^{-3} for Period 1 and 0.020 cm^3 cm^{-3} for Period 4, meaning that the cover crop plot became relatively drier compared to no cover, and this change in relationship was significant at $p \leq 0.05$. Overall, in periods 2 and 3, for all four depths, cereal rye was evenly split between having either had no effect on soil moisture or having significantly reduced soil moisture compared to the no cover treatment, with only a few instances of increased soil moisture (table 3-3). These results fit closely with the original hypothesis that a growing cover crop would be transpiring water which would result in lower soil moisture in the early spring but contrasts with the hypothesis that the residue would act as a mulch in Period 3 and could increase soil moisture. This contrast could be due in part to how short Period 3 is (typically about two weeks) and the timing and amount of spring precipitation not being enough to overcome any previous deficit. Basche et al. (2016) found that, while cereal rye did lower soil moisture in the early spring, soil moisture was recharged by the time of cash crop planting in five out of seven years. It is interesting to note that at the 40 and 60 cm depths during the cash crop growing season (period 4) that every plot pair is significantly different when compared to period 1, suggesting that maybe there is some effect of the cereal rye roots at depth. In the 40 cm depth during period 4, half of the plot pairs showed significantly increased soil moisture with cereal rye and half showed significantly decreased soil moisture and in the 60 cm depth three plot pairs increased with cereal rye while one plot pair decreased. These findings are slightly different than hypothesized, as it was thought the cereal rye would act as a mulch and have higher soil moisture into the growing season but this was not always true. The difference in soil moisture in period 4 in the 10 cm depth is significantly different than in period 1 for both plots 5-6 and plot 9-10, with both having lower soil moisture. These plots are on the same corn soybean rotation schedule so it is possible that this may be due to an extra year of corn (three years of corn two years of soybean) or possibly due to an extra year of the different management of cereal rye before corn and soybean. There are several other instances of the plot pairs on the same cash crop rotation showing up as significant. In period 2 in the 20 cm depth, plot 5-6 and plot 9-10 are significant, as are plot 7-8 and plot 11-12 at the 60 cm depth. In period 3 at the 20 cm depth, plot 7-8 and plot 11-12 are both significantly different than period 1, and at the 40 cm depth plot 5-6 and plot 9-10 are significantly different also. Any future work should include trying to tease apart these apparent cash crop related differences.

3.5 Conclusion

Soil moisture is affected by a cereal rye cover crop as can be seen by the many significant differences in table 3-3. Long term high frequency soil moisture measurement presents many challenges and over long periods provided many opportunities for errors and gaps. Overall, in the early spring before cash crop planting, cereal rye either had significantly lower soil moisture or had no effect on soil moisture, while during the cash crop growing season in the 40 and 60 cm depths five out of eight plot pairs showed relatively higher soil moisture with cereal rye when compared to period 1, while three plot pairs showed the opposite. Future work on the data should include a more detailed analysis of the differences observed in this analysis in order to more fully understand the effects of a cereal rye cover crop on soil moisture. An analysis of individual years could more closely relate soil moisture to cover crop and cash crop growth, precipitation patterns, and may uncover some finer details that may have been missed in this larger scale analysis.

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Table 3-1 Soil moisture period of interest by year

Year	Cash Crop	Cover Crop	Plot	Period 1 (Baseline)		Period 2 March 1-Termination		Period 3 Termination-Crop Planting		Period 4 Crop Planting-End of Season	
2012	Corn	Rye	6	1/1	2/29	3/1	3/25	3/26	4/23	4/24	8/31
			9	1/1	2/29	3/1	3/25	3/26	4/23	4/24	8/31
	Corn	No Cover	5	1/1	2/29	3/1	3/25	3/26	4/23	4/24	8/31
			10	1/1	2/29	3/1	3/25	3/26	4/23	4/24	8/31
	Soybean	Rye	7	1/1	2/29	3/1	3/25	3/26	4/23	4/24	8/31
			12	1/1	2/29	3/1	3/25	3/26	4/23	4/24	8/31
	Soybean	No Cover	8	1/1	2/29	3/1	3/25	3/26	4/23	4/24	8/31
			11	1/1	2/29	3/1	3/25	3/26	4/23	4/24	8/31
2013	Corn	Rye	7	1/1	2/28	3/1	4/14	4/15	5/1	5/2	8/31
			12	1/1	2/28	3/1	4/14	4/15	5/1	5/2	8/31
	Corn	No Cover	8	1/1	2/28	3/1	4/14	4/15	5/1	5/2	8/31
			11	1/1	2/28	3/1	4/14	4/15	5/1	5/2	8/31
	Soybean	Rye	6	1/1	2/28	3/1	4/29	4/30	5/1	5/2	8/31
			9	1/1	2/28	3/1	4/29	4/30	5/1	5/2	8/31
	Soybean	No Cover	5	1/1	2/28	3/1	4/29	4/30	5/1	5/2	8/31
			10	1/1	2/28	3/1	4/29	4/30	5/1	5/2	8/31
2014	Corn	Rye	6	1/1	2/28	3/1	4/17	4/18	5/5	5/6	8/31
			9	1/1	2/28	3/1	4/17	4/18	5/5	5/6	8/31
	Corn	No Cover	5	1/1	2/28	3/1	4/17	4/18	5/5	5/6	8/31
			10	1/1	2/28	3/1	4/17	4/18	5/5	5/6	8/31
	Soybean	Rye	7	1/1	2/28	3/1	5/1	5/2	5/5	5/6	8/31
			12	1/1	2/28	3/1	5/1	5/2	5/5	5/6	8/31
	Soybean	No Cover	8	1/1	2/28	3/1	5/1	5/2	5/5	5/6	8/31
			11	1/1	2/28	3/1	5/1	5/2	5/5	5/6	8/31

Table 3-1 Continued

2015	Corn	Rye	7	1/1	2/28	3/1	4/16	4/17	5/5	5/6	8/31
			12	1/1	2/28	3/1	4/16	4/17	5/5	5/6	8/31
	Corn	No Cover	8	1/1	2/28	3/1	4/16	4/17	5/5	5/6	8/31
			11	1/1	2/28	3/1	4/16	4/17	5/5	5/6	8/31
	Soybean	Rye	6	1/1	2/28	3/1	5/3	5/4	5/4	5/5	8/31
			9	1/1	2/28	3/1	5/3	5/4	5/4	5/5	8/31
	Soybean	No Cover	5	1/1	2/28	3/1	5/3	5/4	5/4	5/5	8/31
			10	1/1	2/28	3/1	5/3	5/4	5/4	5/5	8/31
2016	Corn	Rye	6	1/1	2/29	3/1	4/14	4/15	5/24	5/25	6/8
			9	1/1	2/29	3/1	4/14	4/15	5/24	5/25	6/8
	Corn	No Cover	5	1/1	2/29	3/1	4/14	4/15	5/24	5/25	6/8
			10	1/1	2/29	3/1	4/14	4/15	5/24	5/25	6/8
	Soybean	Rye	7	1/1	2/29	3/1	5/24	N/A	N/A	5/25	7/14
			12	1/1	2/29	3/1	5/24	N/A	N/A	5/25	7/14
	Soybean	No Cover	8	1/1	2/29	3/1	5/24	N/A	N/A	5/25	7/14
			11	1/1	2/29	3/1	5/24	N/A	N/A	5/25	7/14

Table 3-2 Median volumetric water content ($cm^3 cm^{-3}$) by period of interest, depth, and plot pair for cover and no cover plots, at the SEPAC cover crop site averaged over five years

		Period of Interest							
		1		2		3		4	
Depth (cm)	Plot Pair	Cereal Rye	No Cover	Cereal Rye	No Cover	Cereal Rye	No Cover	Cereal Rye	No Cover
10	5-6	0.285	0.261	0.299	0.274	0.305	0.272	0.257	0.236
	7-8	0.288	0.253	0.301	0.258	0.277	0.245	0.266	0.216
	9-10	0.284	0.280	0.284	0.291	0.284	0.290	0.245	0.235
	11-12	0.279	0.276	0.286	0.286	0.292	0.264	0.249	0.245
20	5-6	0.286	0.269	0.294	0.280	0.293	0.284	0.258	0.243
	7-8	0.301	0.257	0.308	0.262	0.301	0.260	0.283	0.225
	9-10	0.281	0.290	0.279	0.298	0.281	0.298	0.266	0.251
	11-12	0.319	0.290	0.328	0.294	0.314	0.284	0.278	0.249
40	5-6	0.280	0.283	0.285	0.294	0.286	0.300	0.277	0.261
	7-8	0.304	0.282	0.320	0.291	0.318	0.295	0.313	0.277
	9-10	0.292	0.302	0.295	0.309	0.298	0.313	0.271	0.283
	11-12	0.281	0.293	0.294	0.294	0.289	0.303	0.254	0.274
60	5-6	0.271	0.284	0.279	0.292	0.283	0.302	0.262	0.275
	7-8	0.281	0.260	0.288	0.270	0.292	0.268	0.290	0.258
	9-10	0.265	0.272	0.275	0.278	0.278	0.284	0.259	0.263
	11-12	0.288	0.259	0.304	0.269	0.298	0.268	0.291	0.265

Table 3-3 Significance of the ranksum test using median difference in volumetric water content ($cm^3\ cm^{-3}$), with difference calculated as cover minus no cover, for cash crop pairs averaged over five years by depth within a period. Each period is compared to period 1.

		Period of Interest			
Depth (cm)	Plot Pair	1	2	3	4
10	5-6	0.022	0.023ns	0.023ns	0.020*
	7-8	0.028	0.018ns	0.020***	0.016ns
	9-10	-0.001	-0.006***	0.000ns	-0.002**
	11-12	0.037	0.006*	0.023ns	0.006ns
20	5-6	0.015	0.013**	0.001***	0.016ns
	7-8	0.052	0.050ns	0.056*	0.069***
	9-10	-0.015	-0.022***	-0.017ns	0.000***
	11-12	0.045	0.029***	0.026***	0.021***
40	5-6	-0.004	-0.009ns	-0.022***	0.007*
	7-8	0.024	0.026**	0.027ns	0.050***
	9-10	-0.012	-0.014ns	-0.020***	-0.017***
	11-12	-0.012	-0.004ns	-0.023*	-0.024***
60	5-6	-0.017	-0.005*	-0.021***	-0.001*
	7-8	0.021	0.020*	0.024***	0.034***
	9-10	-0.007	-0.007ns	-0.007ns	-0.009***
	11-12	0.030	0.023***	0.031ns	0.035***

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level

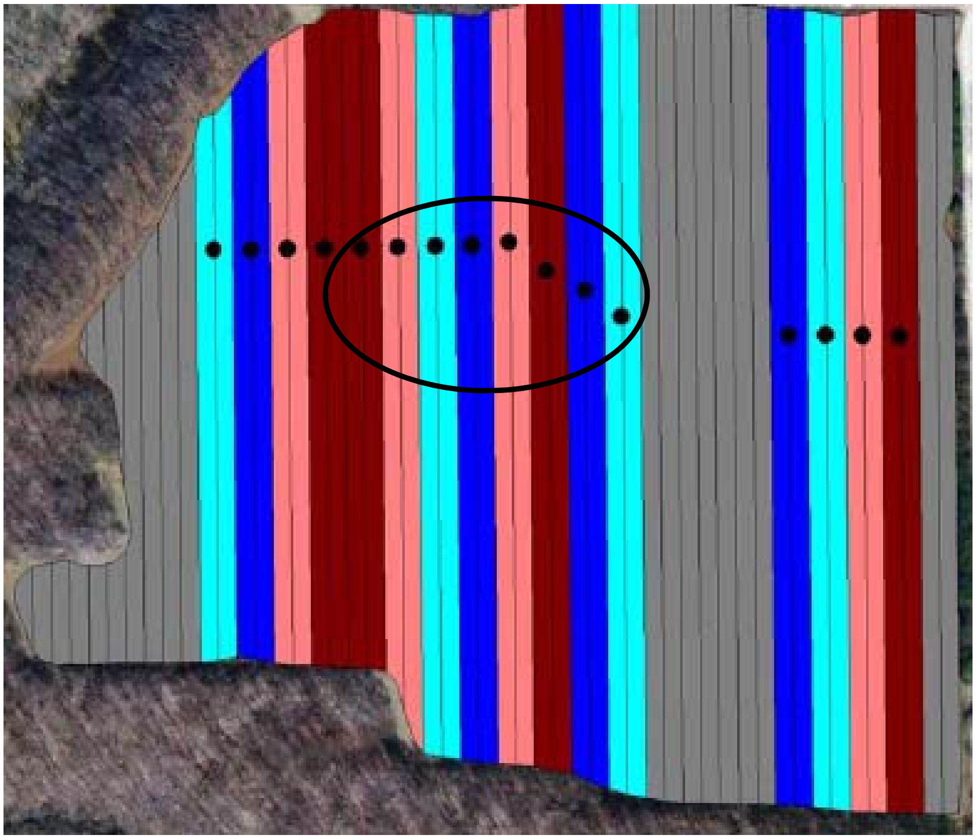

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Figure 3-1 SEPAC field layout. Each color represents one of the four treatments and each group of four plots is a block. The black dots are the approximate sampling locations within the field. The circled 8 plots (plots 5-12) are the locations of the Decagon soil moisture and temperature sensors.

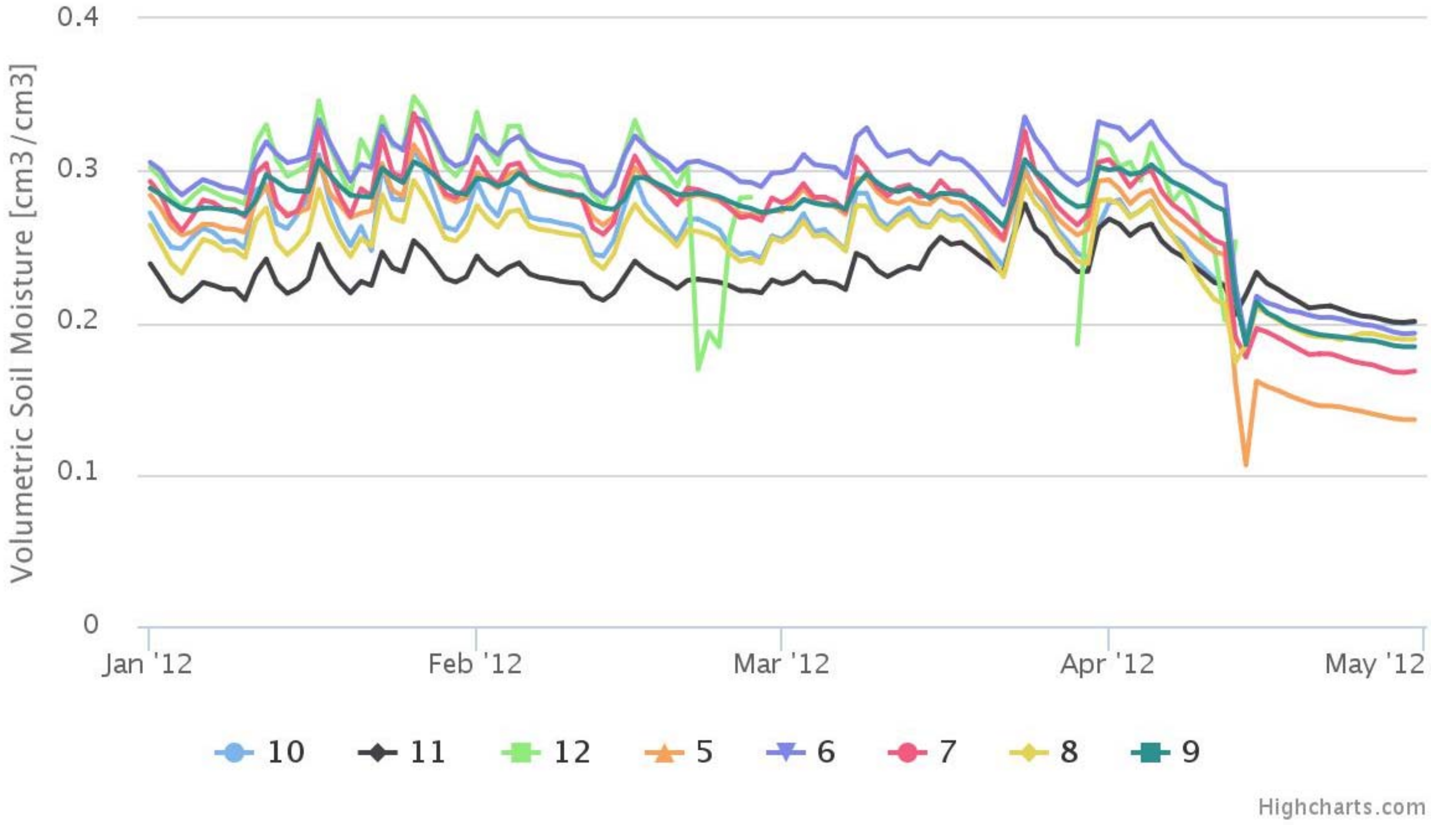

Figure 3-2 10 cm daily average soil moisture January 2012-May 2012 for plots 5-12 at the SEPAC cover crop site

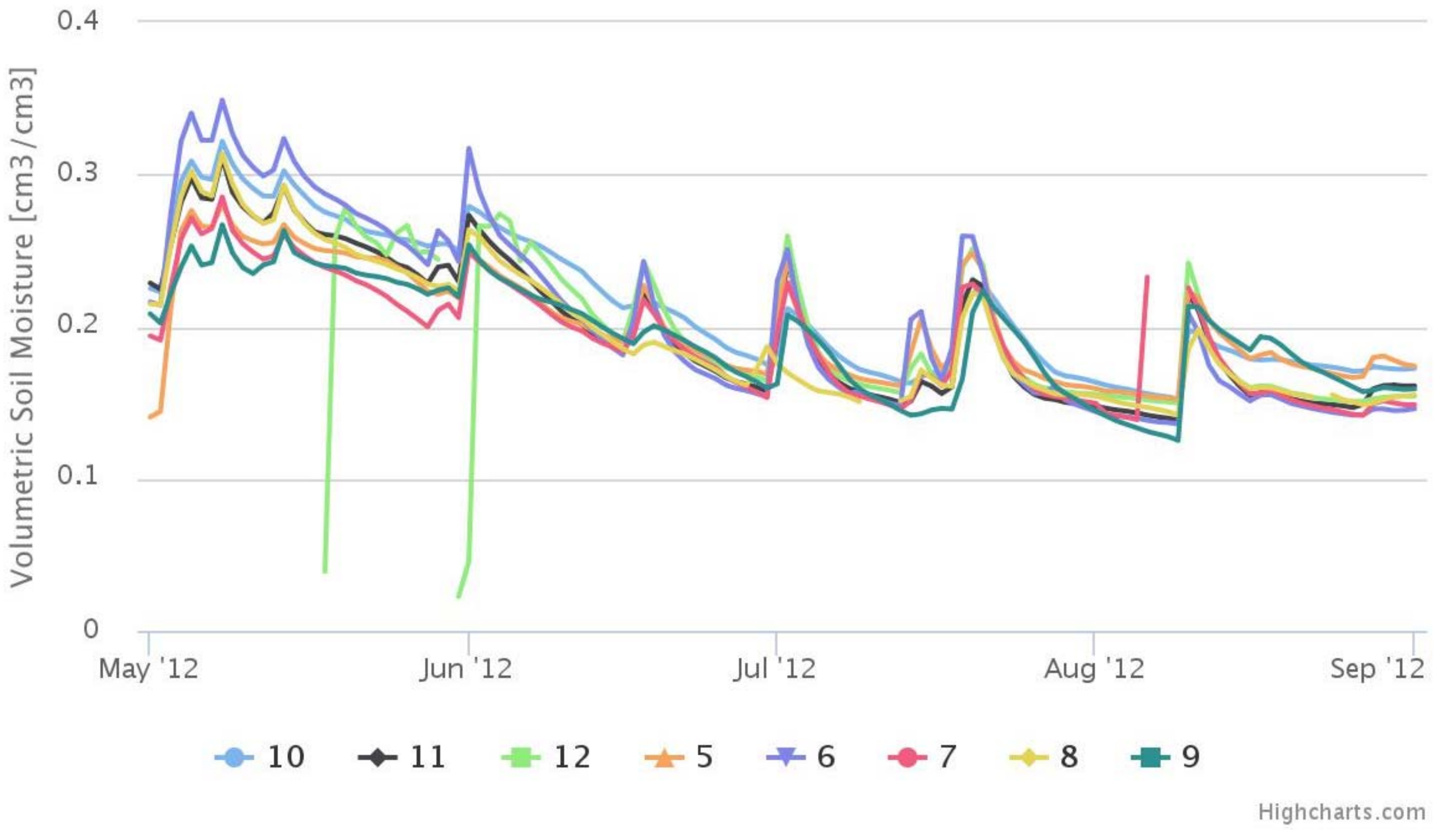

Figure 3-3 10 cm daily average soil moisture May 2012-September 2012 for plots 5-12 at the SEPAC cover crop site

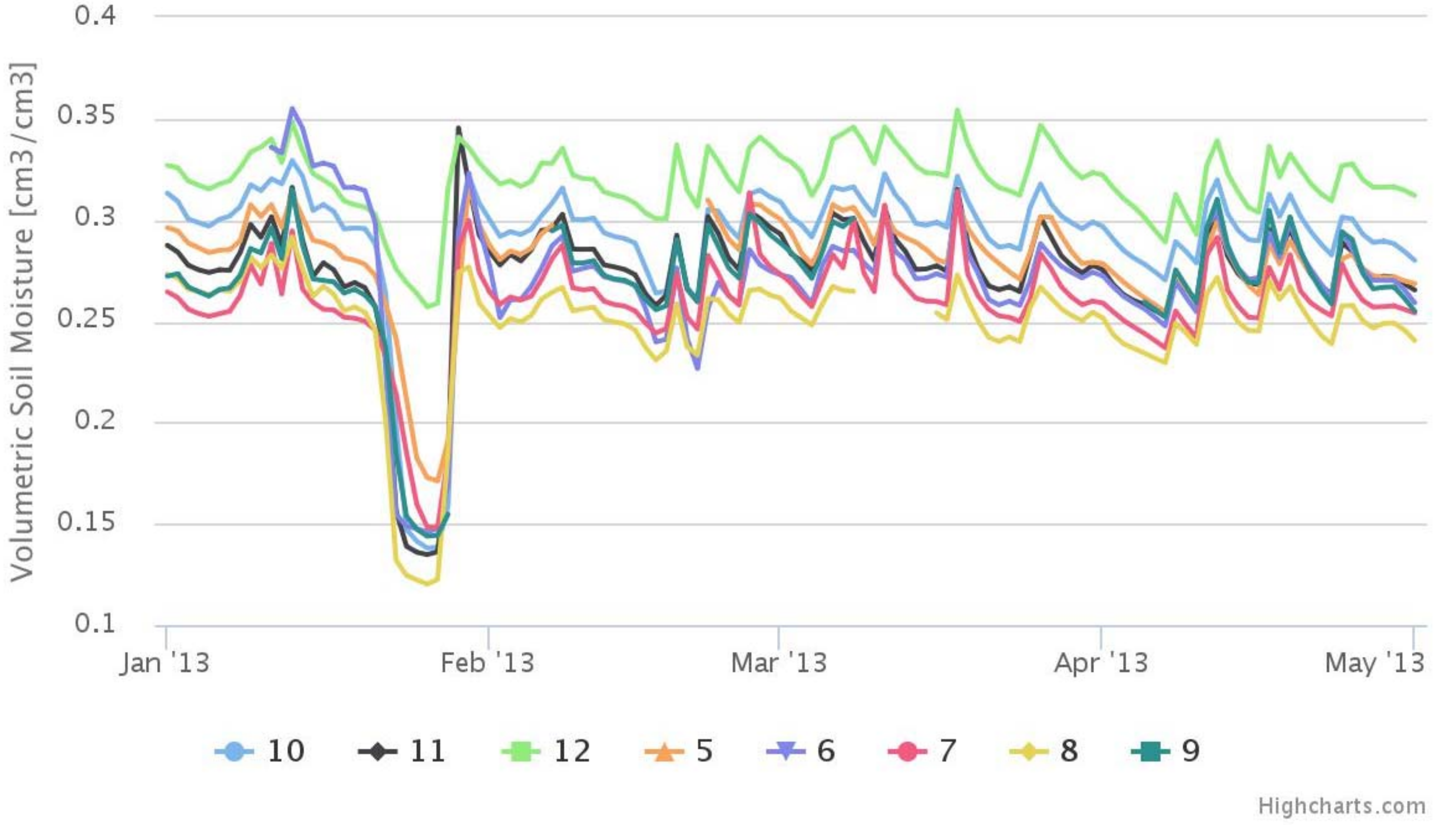

Figure 3-4 10 cm daily average soil moisture January 2013-May 2013 for plots 5-12 at the SEPAC cover crop site

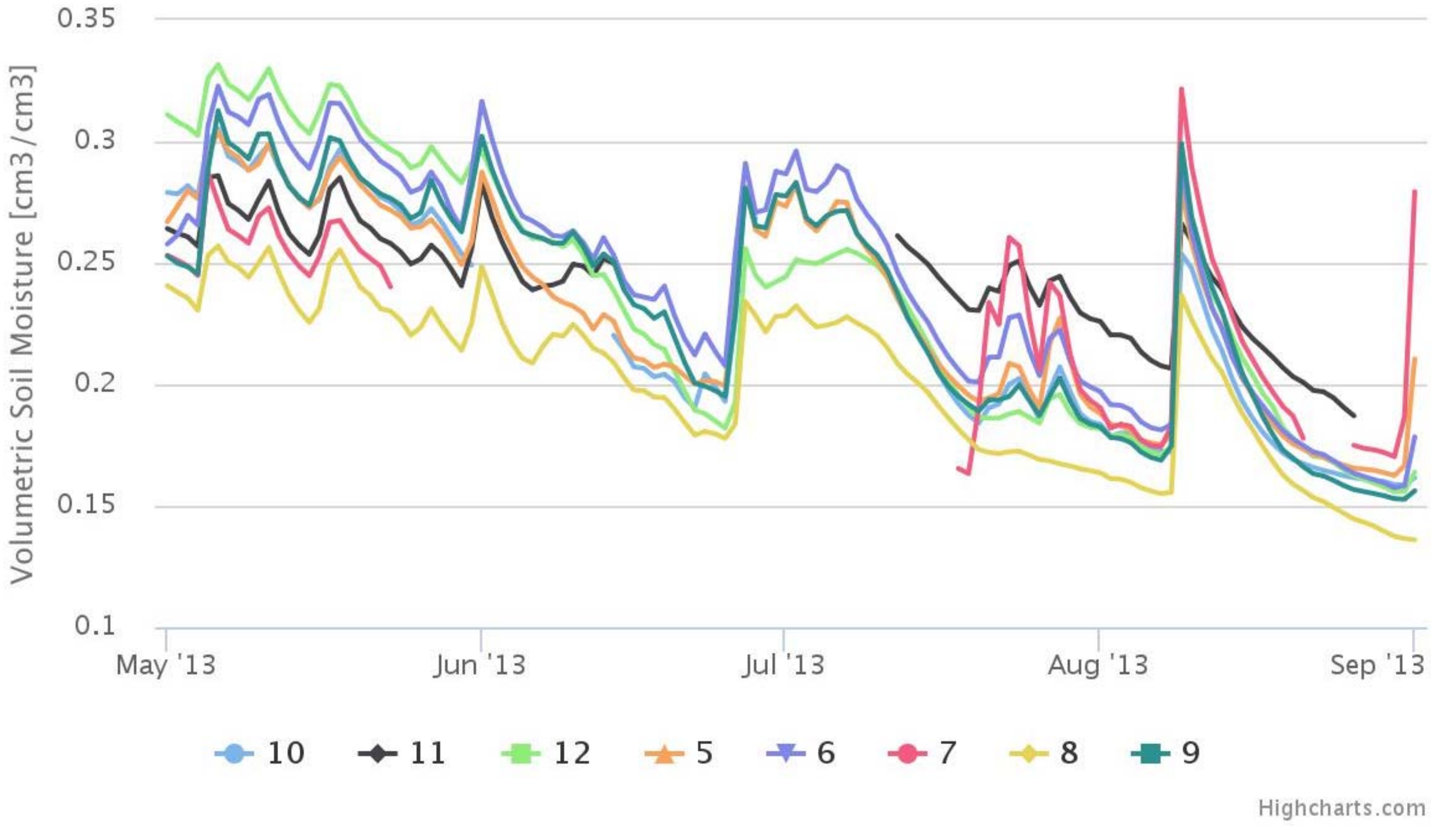

Figure 3-5 10 cm daily average soil moisture May 2013-September 2013 for plots 5-12 at the SEPAC cover crop site

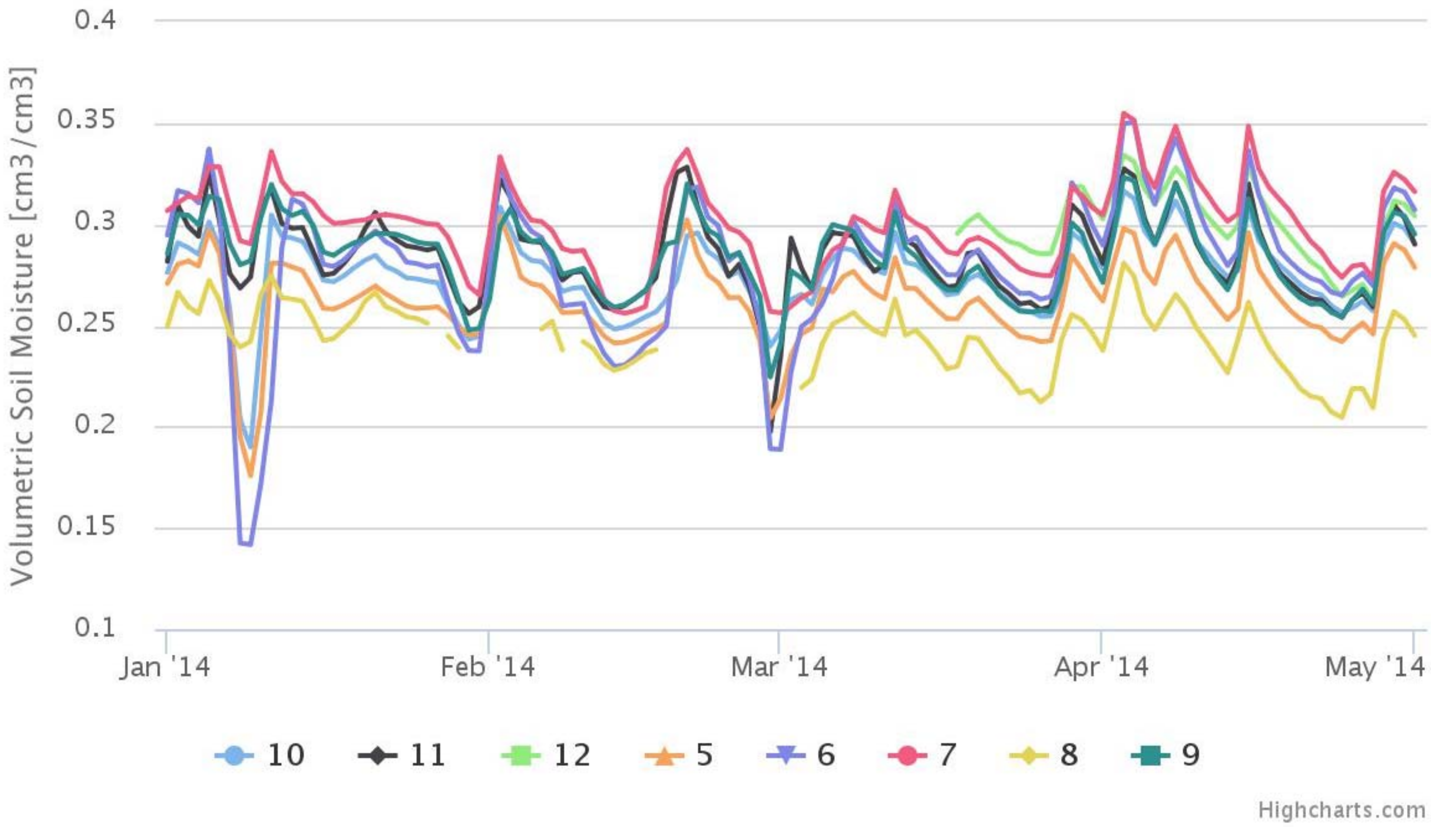

Figure 3-6 10 cm daily average soil moisture January 2014-May 2014 for plots 5-12 at the SEPAC cover crop site

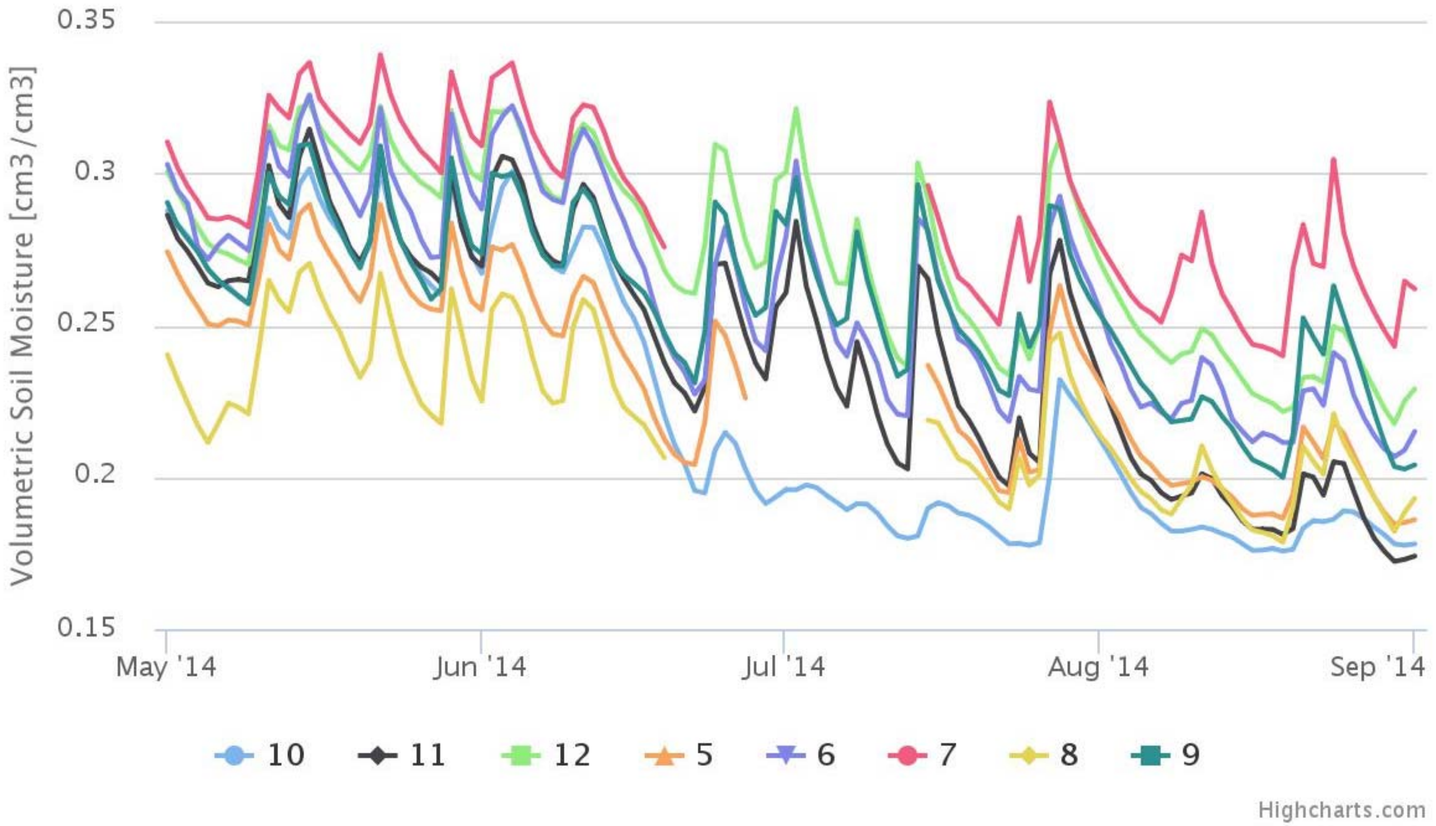

Figure 3-7 10 cm daily average soil moisture May 2014-September 2014 for plots 5-12 at the SEPAC cover crop site

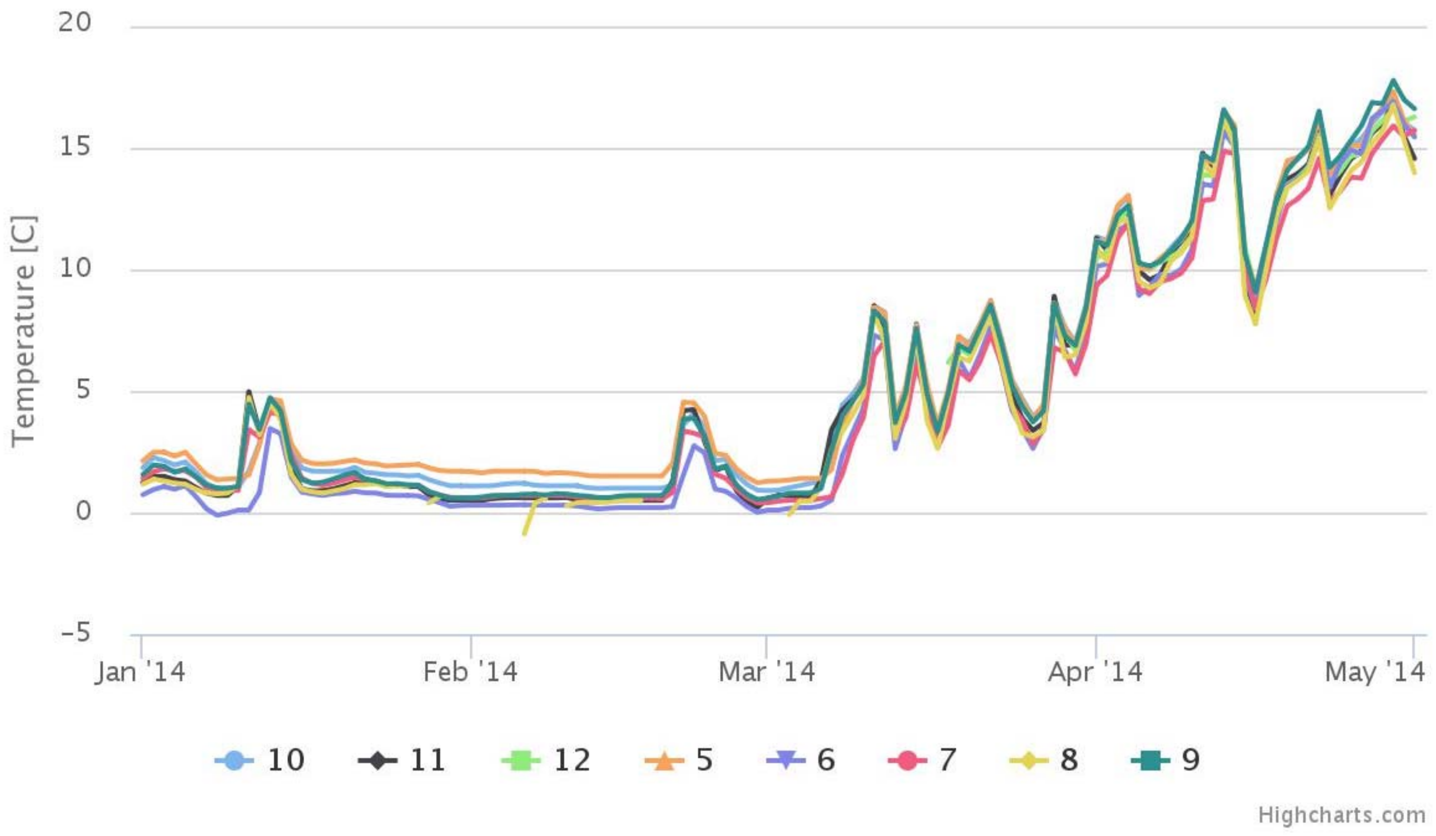

Figure 3-8 10 cm daily average soil temperature January 2014-May 2014 for plots 5-12 at the SEPAC cover crop site

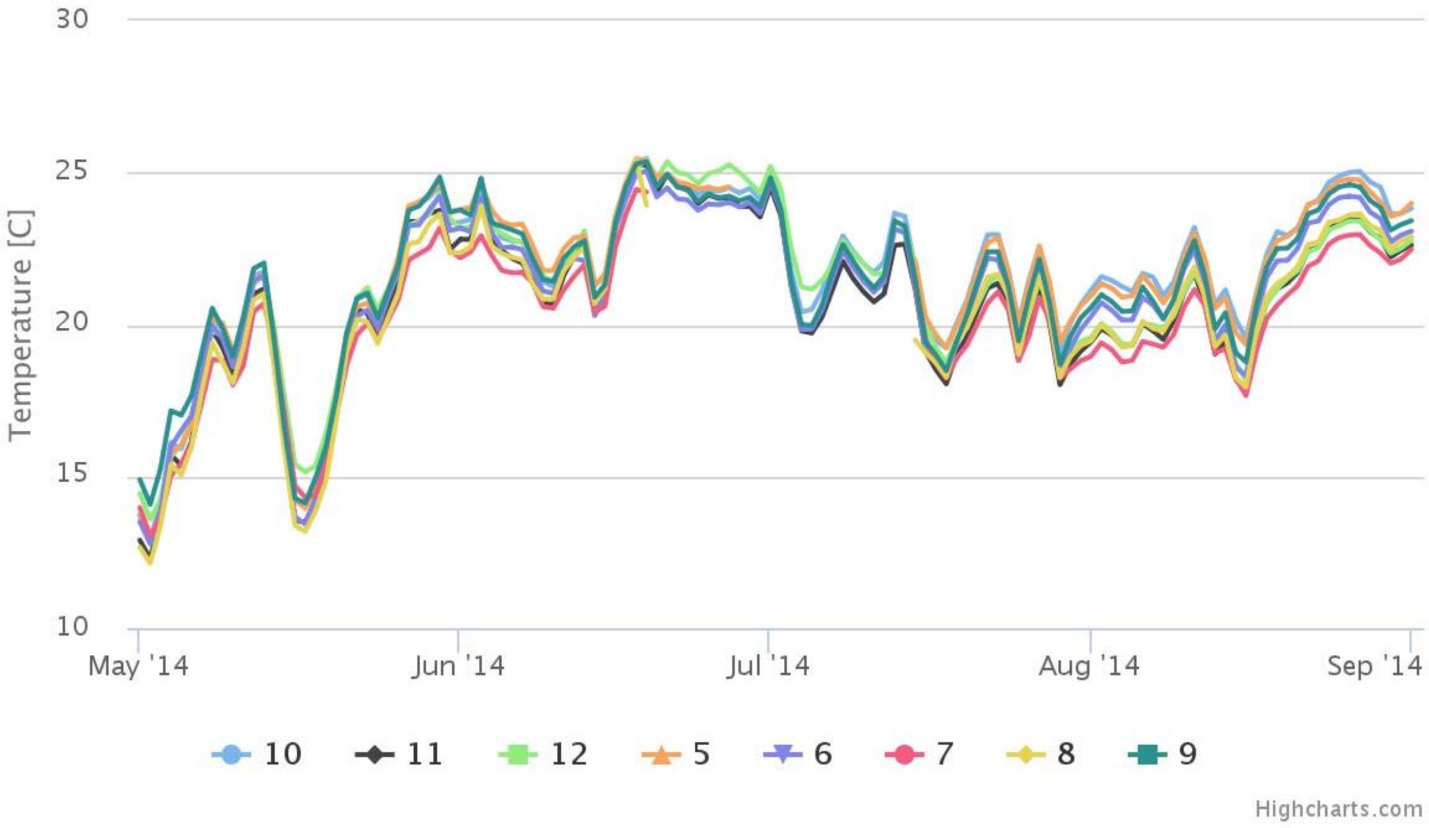

Figure 3-9 10 cm daily average soil temperature May 2014-September 2014 for plots 5-12 at the SEPAC cover crop site

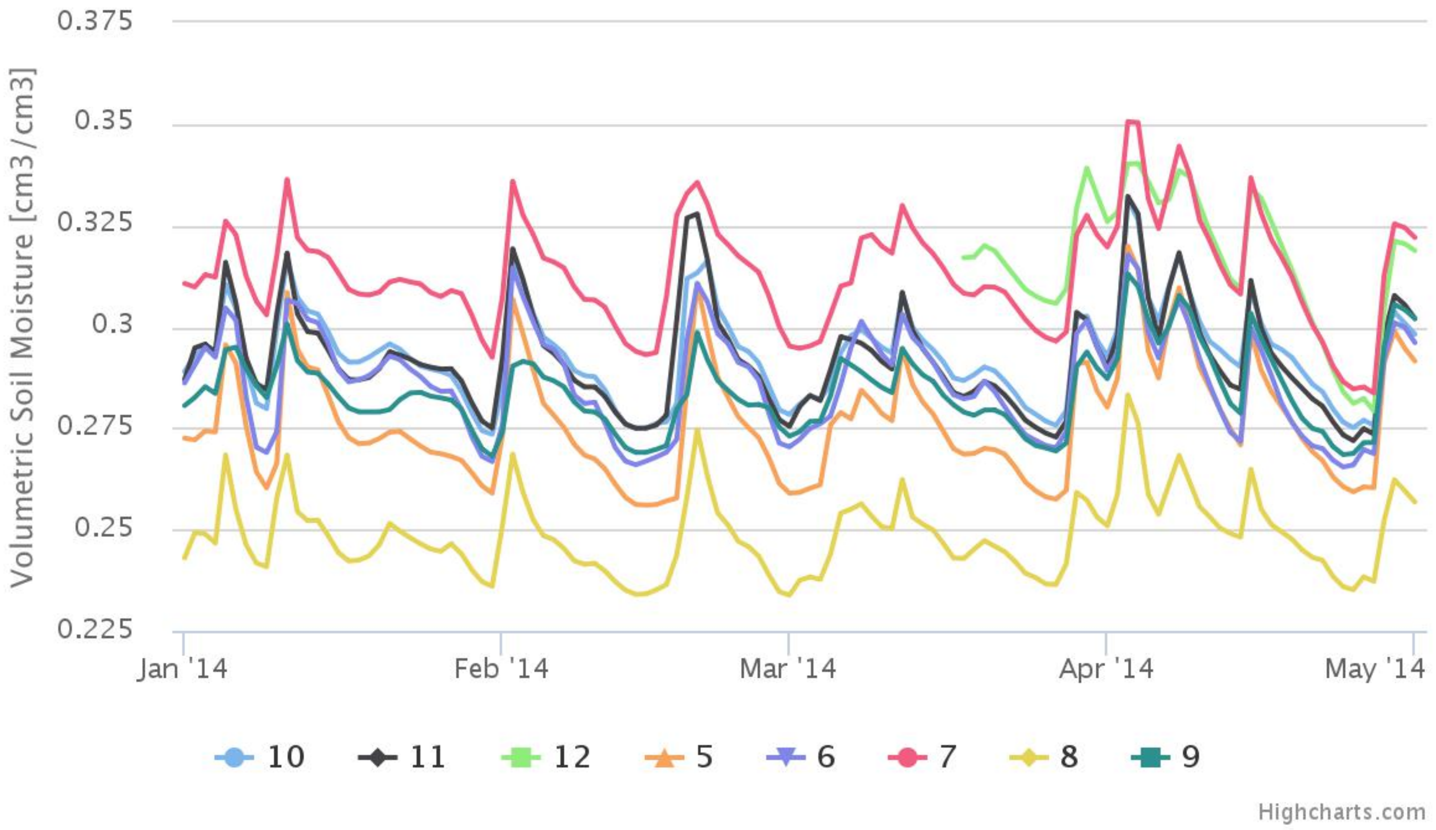

Figure 3-10 20 cm daily average soil moisture January 2014-May 2014 for plots 5-12 at the SEPAC cover crop site

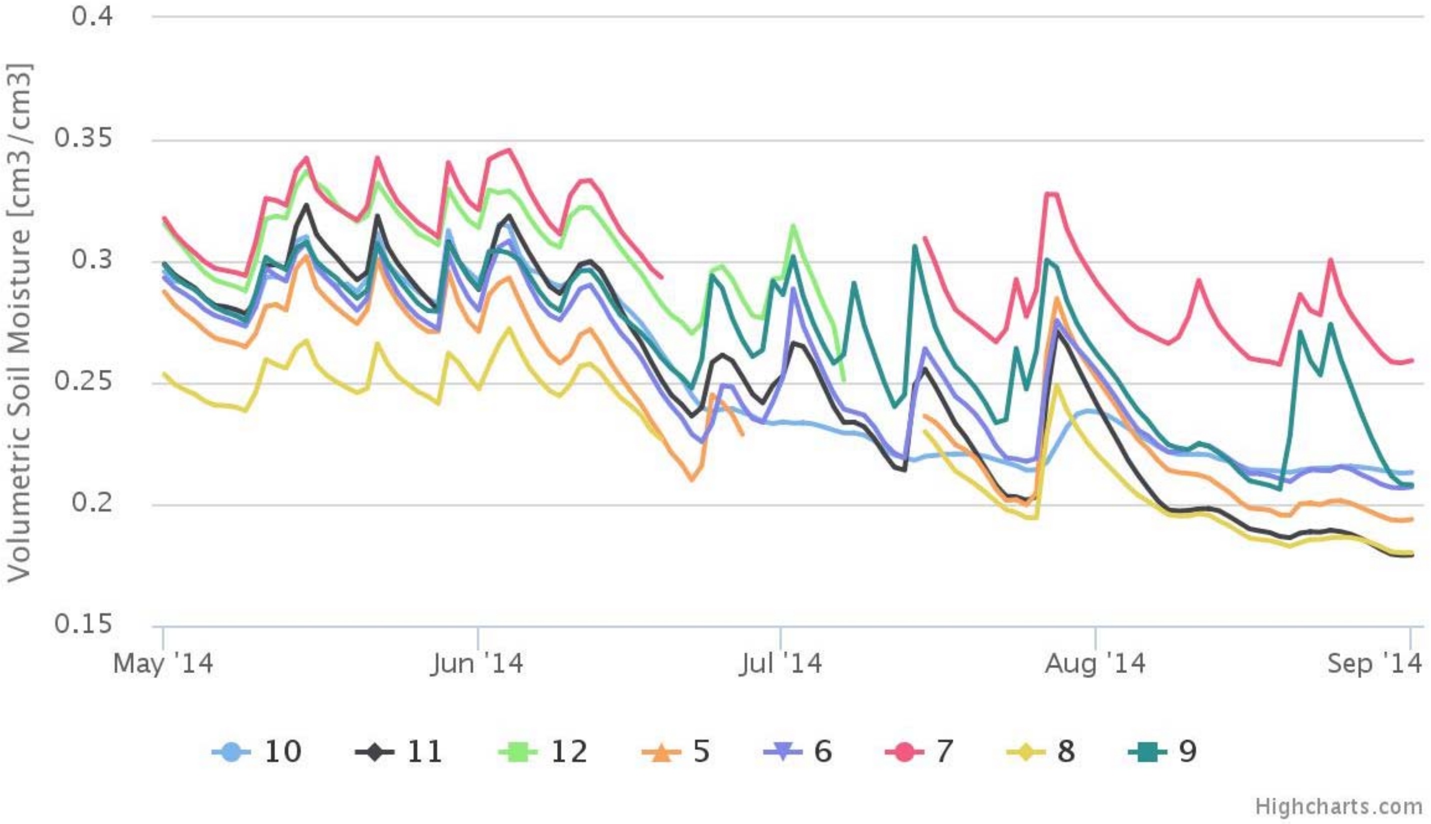

Figure 3-11 20 cm daily average soil moisture May 2014-September 2014 for plots 5-12 at the SEPAC cover crop site

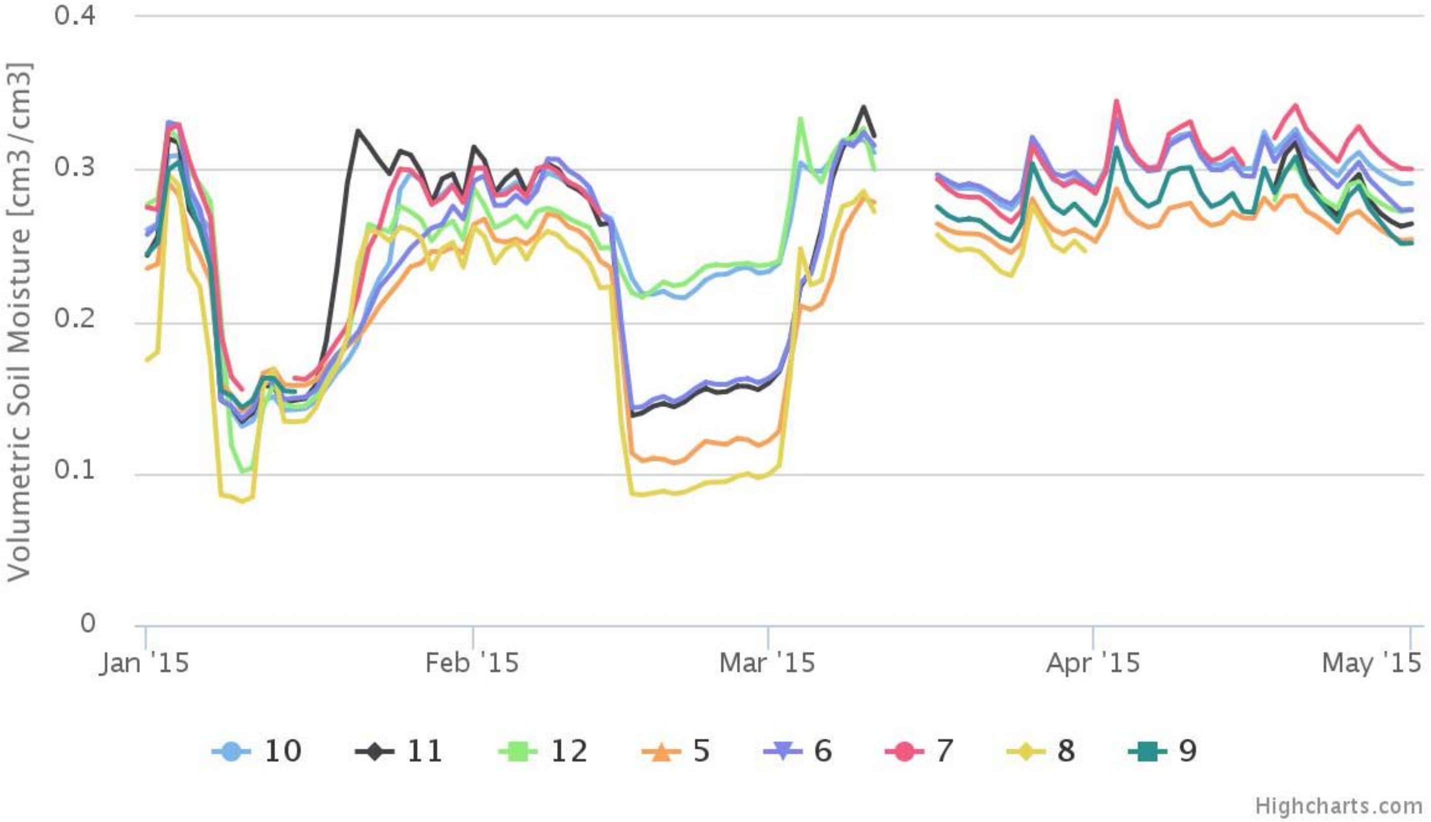

Figure 3-12 10 cm daily average soil moisture January 2015-May 2015 for plots 5-12 at the SEPAC cover crop site

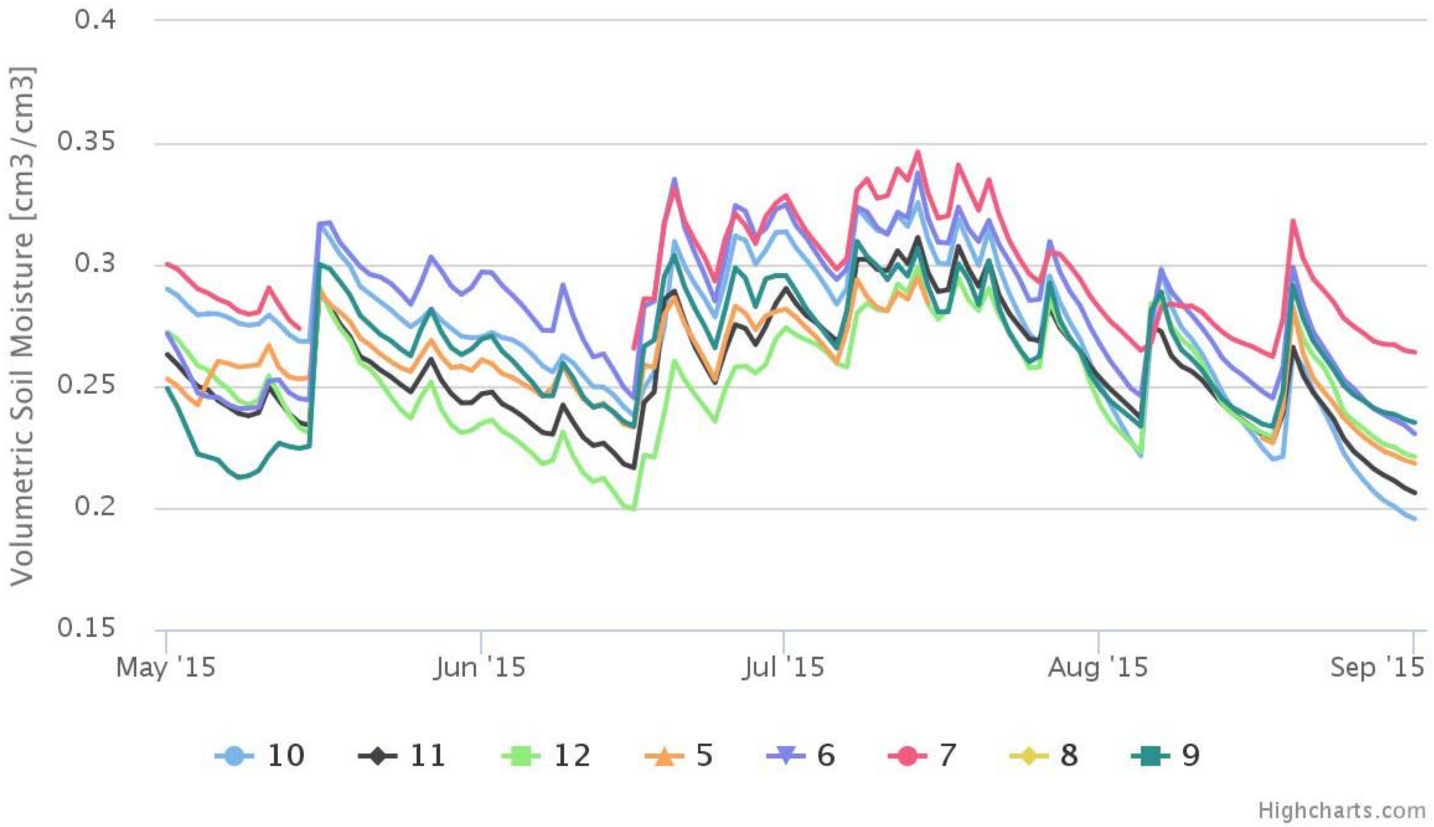

Figure 3-13 10 cm daily average soil moisture May 2015-September 2015 for plots 5-12 at the SEPAC cover crop site

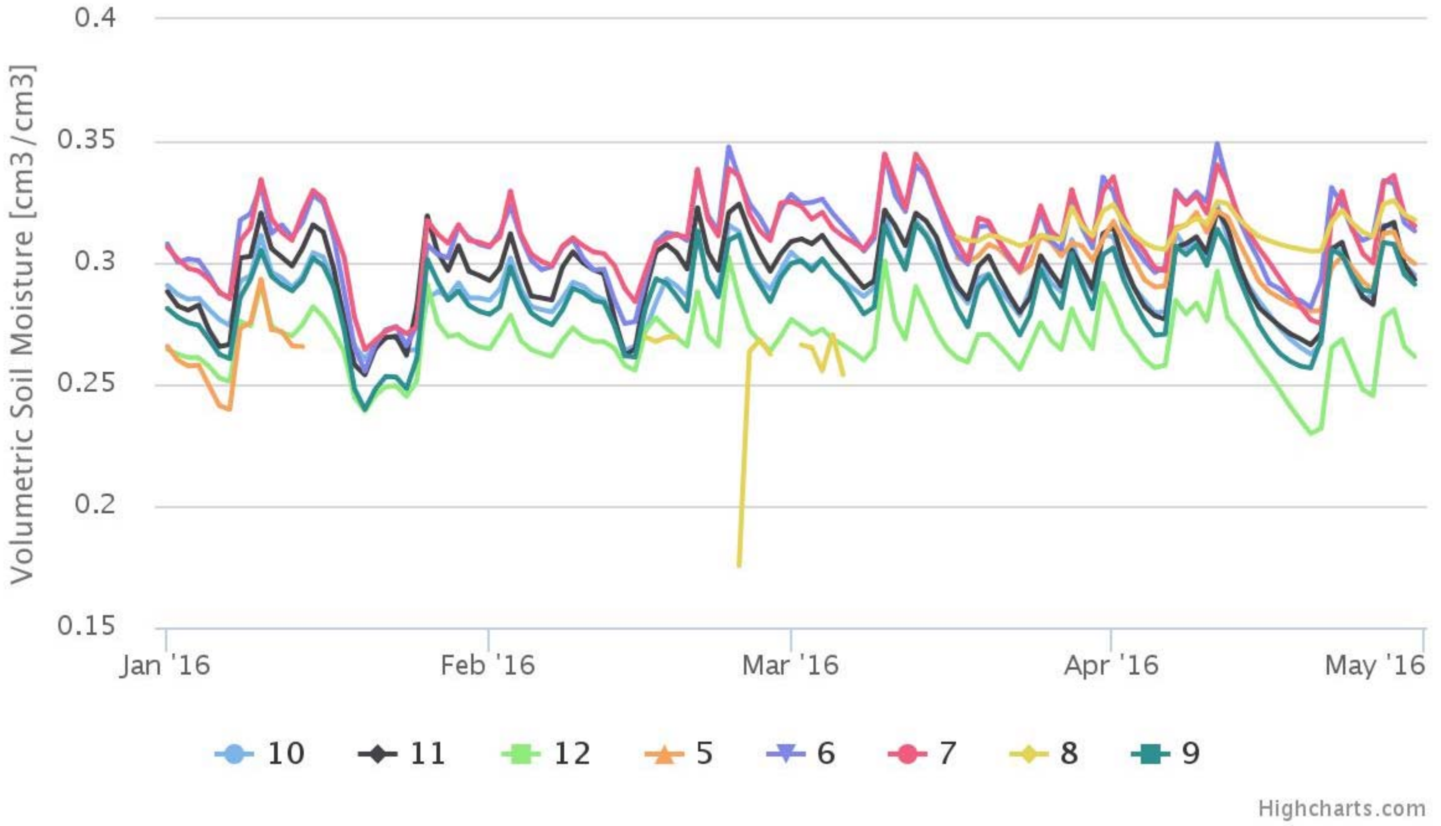

Figure 3-14 10 cm daily average soil moisture January 2016-May 2016 for plots 5-12 at the SEPAC cover crop site

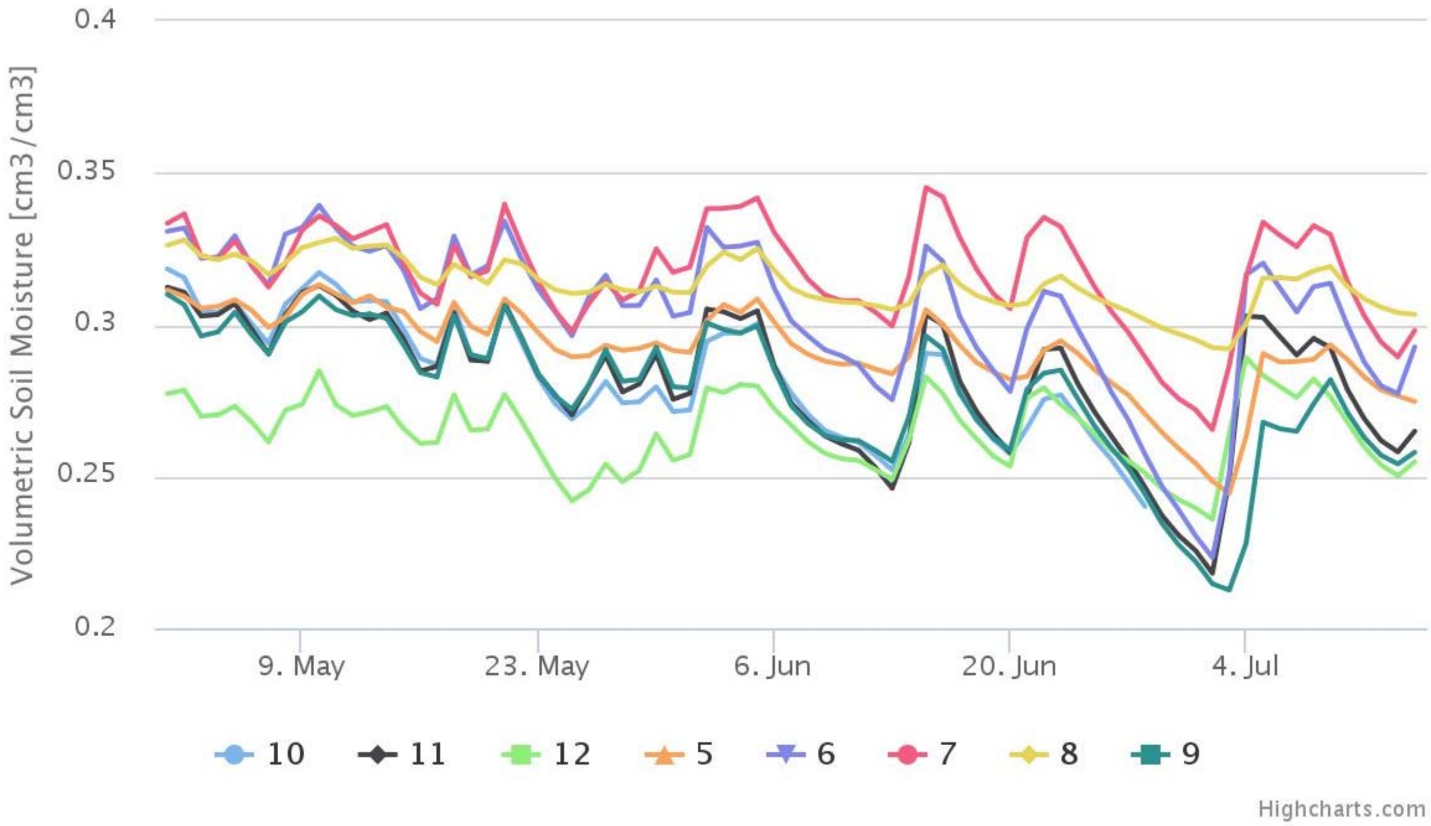

Figure 3-15 10 cm daily average soil moisture May 2016-September 2016 for plots 5-12 at the SEPAC cover crop site

CHAPTER 4. SUMMARY, CONCLUSIONS, AND FUTURE WORK

This research highlights the difficulties of doing large plot research on soil properties that are slow to change and often difficult to measure against a background of inherent soil variability. Cereal rye can serve well as a winter cover crop during a period in a typical corn-soybean system where the ground would normally be fallow. Its effects on soil physical and chemical properties are not always fast and large although there were some important changes noted in this study indicating that there may be a trend towards change occurring.

After four years of a cereal rye cover crop, soil aggregate mean weight diameter was 1.2 mm greater with cereal rye in the 0-10 cm depth and 0.6 mm greater in the 10-20 cm depth when compared to the no cover treatments. This is an important measure for a poorly structured silt loam soil such as the one at this field site. With increased aggregation water infiltration can increase, as structure improves the soil is better able to resist erosion from wind and water, and over longer periods there can be more protection and an increase of soil carbon and water holding capacity. Soil bulk density, water retention at saturation, -4.9, -9.8, -33, and -1500 kPa, water holding capacity between -9.8 and -1500 kPa, aeration porosity at -4.9 kPa, soil organic carbon, and total soil nitrogen were unchanged by the cover crop.

With more years of growth and with more growth within each of those years it is anticipated that many of these measures will improve although further study is warranted. Increasing the sample size of each measure may also help to decrease the signal to noise ratio and improve the chances of observing differences and overcoming the challenge of detecting small changes in these properties. A strong effort was made to take samples according to the standardized protocols however with a project of this magnitude, sampling over the course of multiple years with different crews, yearly weather variations, taking, transporting, storing, processing, and analyzing these samples, and a multitude of other factors, it is possible that even though the error introduced by each of these factors by itself may be very small, the accumulated error over such a large sampling regime over this long of a period may have had an effect on results.

There is clearly an effect of the cover crop on soil moisture but the results of this analysis show that sometimes cereal rye can increase soil moisture, while sometimes it can decrease it. Overall, in the early spring before cash crop planting, cereal rye has either no effect on soil moisture or has significantly lower soil moisture compared to no cover. During the summer cash crop growing season, in the 40 and 60 cm depths, five of eight plot pairs showed increased soil moisture in the cereal rye compared to the no cover, while three of eight plot pairs showed the opposite. The dataset is large and without question warrants further, more detailed analysis. There are many complications associated with taking high frequency data over long periods of time. Over time sensors and data loggers simply stop working and need to be replaced, increasing the chances for increased variability by disturbing the sensor locations. A semi-permanent structure in an open field is an inviting thing for wild creatures such as mice that chew on the exposed wiring, ants that cause corrosion in the circuit board of the data loggers, and wasps that require very careful attention to detail from the folks going to the field and downloading the data from the data loggers. Technological issues arise such as the computer used to download data inexplicably cuts out data from the dataset irrecoverably. A balance between the shortest necessary and the longest possible download interval must be achieved. The data were downloaded approximately monthly. This was determined to be a reasonable compromise between an efficient use of time and good data collection. The data loggers have a memory storage capability of approximately two months so this allowed for some flex if weather conditions delayed a download or if other farm or sampling tasks took priority; it also allowed for a larger dataset to be processed at one time versus a two week download interval, for example. At the same time, this also allowed a full month to pass between checking on the equipment and processing the data to detect errors. If there was a problem with a sensor there could be a long period of time with missing data and if a data logger stopped working then there could be no data for that plot entirely for some time. This issue combined with other field studies and research conflicting with time spent processing and checking data created some gaps in the data. Even when the data were processed in a timely manner the distance to the field site, replacement equipment availability, and the weather did not always permit rapid correction of problems. Data loggers that transmit wirelessly to a database could be another option to collect data in a timely manner.

Analysis of the soil moisture data proved to be difficult as the dataset is very large and a more complicated analysis is beyond the scope of this thesis. The data are strongly autocorrelated and any analysis must account for this. Based on the findings of this study there are several follow up analyses that should be conducted. Precipitation can be highly variable from year to year and this has a huge effect on soil moisture amounts so analyzing the data on a yearly basis and including that year's precipitation within the periods may help to provide some more conclusive and applicable answers. The periods could be more finely tuned to really home in on critical, although short, time periods throughout the year that may be getting lost in the larger time windows used here. A few examples of short but important time windows are the time around corn tasseling and pollination where soil moisture levels can have a critical effect on yield, an individual rain event to look at rates of infiltration or wetting fronts within the soil, and the time around cash crop planting to determine the effects on soil moisture and germination rates. Different statistical analyses may use some different assumptions and prove to be a better fit for this dataset depending on the hypothesis being tested. The dataset contains very high frequency measurements that have gone almost entirely unused for this analysis so once shorter time periods of interest have been identified it could be very interesting to look at an effect of cover on wetting fronts following a rainfall event for example. Some sort of gap filling procedure may have to be conducted if a more detailed analysis is to be performed as there are some gaps and holes in the data but there is a very large amount of information that still could be very useful.

Cover crops can be a useful management tool to increase the resilience of corn based cropping systems in the Midwest. Cereal rye can be used to increase soil aggregation to protect the soil from erosive forces during a time of the year that fields are typically fallow and exposed to excess rainfall. After four years of a cover crop soil bulk density and water retention remain unchanged, although from the literature these measures often prove slow to change and difficult to measure.

APPENDIX

APPENDIX

Table A-1 Soil organic carbon (SOC) treatment means by year at SEPAC

Depth (cm)	Treatment	SOC (g kg^{-1})		
		2011	2013	2015
0-10	Corn with no cover	14.18	12.43	13.88
	Soybean with no cover	14.72	12.75	14.12
	Corn with cereal rye	13.65	12.86	15.02
	Soybean with cereal rye	14.33	13.88	15.06
10-20	Corn with no cover	9.97	8.63	9.71
	Soybean with no cover	9.99	8.63	9.49
	Corn with cereal rye	9.76	8.39	9.39
	Soybean with cereal rye	10.24	9.00	9.69
20-40	Corn with no cover	5.23	4.10	5.37
	Soybean with no cover	5.05	4.24	5.08
	Corn with cereal rye	4.28	4.01	4.56
	Soybean with cereal rye	5.46	4.21	4.86
40-60	Corn with no cover	3.25	3.28	3.89
	Soybean with no cover	3.07	2.98	3.57
	Corn with cereal rye	2.96	2.75	3.63
	Soybean with cereal rye	3.08	3.39	3.44

Table A-2 Total soil nitrogen (TN) treatment means by year at SEPAC

Depth (cm)	Treatment	TN ($g\ kg^{-1}$)		
		2011	2013	2015
0-10	Corn with no cover	1.45	1.29	1.53
	Soybean with no cover	1.49	1.31	1.57
	Corn with cereal rye	1.39	1.23	1.55
	Soybean with cereal rye	1.51	1.39	1.73
10-20	Corn with no cover	1.21	1.01	1.20
	Soybean with no cover	1.21	1.03	1.30
	Corn with cereal rye	1.15	0.90	1.15
	Soybean with cereal rye	1.29	1.04	1.35
20-40	Corn with no cover	0.74	0.55	0.85
	Soybean with no cover	0.80	0.56	0.85
	Corn with cereal rye	0.64	0.41	0.67
	Soybean with cereal rye	0.87	0.54	0.90
40-60	Corn with no cover	0.49	0.38	0.63
	Soybean with no cover	0.54	0.37	0.62
	Corn with cereal rye	0.46	0.29	0.52
	Soybean with cereal rye	0.54	0.41	0.68

Table A-3 Bulk density (BD) and volumetric water content at five water potentials, and water holding capacity (WHC*) with depth for corn with no cover treatment at SEPAC

			Volumetric Water Content (cm^3 cm^{-3})					
			water potential (kPa)					
Year	Depth (cm)	BD (g cm^{-3})	0	-4.9	-9.8	-33	-1500	WHC
2011	0-10	1.28	0.455	0.349	0.330	0.312	0.119	0.212
	10-20	1.41	0.410	0.352	0.336	0.317	0.134	0.203
	20-40	1.45	0.403	0.357	0.343	0.330	0.167	0.176
	40-60	1.48	0.394	0.365	0.357	0.348	0.166	0.191
2013	0-10	1.37	0.442	0.369	0.349	0.323	0.133	0.217
	10-20	1.40	0.415	0.354	0.338	0.317	0.123	0.215
2015	0-10	1.33	0.445	0.362	0.342	0.317	0.125	0.217
	10-20	1.35	0.414	0.347	0.330	0.307	0.130	0.201
	20-40	1.46	0.396	0.363	0.352	0.340	0.165	0.187
	40-60	1.49	0.395	0.365	0.356	0.346	0.164	0.192

*WHC calculated between -9.8 and -1500 kPa

Table A-4 Bulk density (BD) and volumetric water content at five water potentials, and water holding capacity (WHC*) with depth for corn with cereal rye treatment at SEPAC

			Volumetric Water Content ($cm^3 cm^{-3}$)					
			water potential (kPa)					
Year	Depth (cm)	BD ($g cm^{-3}$)	0	-4.9	-9.8	-33	-1500	WHC
2011	0-10	1.27	0.459	0.345	0.327	0.310	0.123	0.204
	10-20	1.40	0.415	0.359	0.341	0.320	0.130	0.212
	20-40	1.42	0.410	0.361	0.343	0.328	0.168	0.175
	40-60	1.49	0.397	0.372	0.363	0.355	0.167	0.196
2013	0-10	1.37	0.442	0.363	0.348	0.327	0.132	0.216
	10-20	1.39	0.425	0.358	0.341	0.318	0.125	0.216
2015	0-10	1.34	0.444	0.363	0.346	0.323	0.122	0.224
	10-20	1.38	0.417	0.357	0.342	0.320	0.124	0.218
	20-40	1.43	0.407	0.364	0.353	0.338	0.159	0.194
	40-60	1.52	0.388	0.365	0.358	0.348	0.164	0.194

*WHC calculated between -9.8 and -1500 kPa

Table A-5 Bulk density (BD) and volumetric water content at five water potentials, and water holding capacity (WHC*) with depth for soybean with no cover treatment at SEPAC

			Volumetric Water Content ($cm^3\ cm^{-3}$)					
			water potential (kPa)					
Year	Depth (cm)	BD (g cm^{-3})	0	-4.9	-9.8	-33	-1500	WHC
2011	0-10	1.28	0.455	0.350	0.331	0.312	0.119	0.212
	10-20	1.40	0.415	0.357	0.341	0.321	0.127	0.214
	20-40	1.45	0.398	0.361	0.346	0.331	0.156	0.191
	40-60	1.47	0.404	0.376	0.366	0.357	0.169	0.197
2013	0-10	1.34	0.455	0.366	0.348	0.323	0.135	0.213
	10-20	1.37	0.428	0.354	0.337	0.315	0.116	0.221
2015	0-10	1.30	0.443	0.360	0.343	0.320	0.123	0.220
	10-20	1.37	0.413	0.351	0.336	0.315	0.130	0.206
	20-40	1.40	0.410	0.358	0.345	0.328	0.157	0.188
	40-60	1.47	0.400	0.378	0.369	0.358	0.168	0.201

*WHC calculated between -9.8 and -1500 kPa

Table A-6 Bulk density (BD) and volumetric water content at five water potentials, and water holding capacity (WHC*) with depth for soybean with cereal rye treatment at SEPAC

			Volumetric Water Content ($cm^3 cm^{-3}$)					
			water potential (kPa)					
Year	Depth (cm)	BD ($g cm^{-3}$)	0	-4.9	-9.8	-33	-1500	WHC
2011	0-10	1.25	0.465	0.349	0.330	0.309	0.129	0.200
	10-20	1.39	0.415	0.354	0.340	0.319	0.145	0.194
	20-40	1.42	0.408	0.361	0.346	0.331	0.170	0.177
	40-60	1.49	0.394	0.375	0.366	0.359	0.185	0.181
2013	0-10	1.38	0.440	0.364	0.346	0.328	0.141	0.205
	10-20	1.42	0.412	0.354	0.339	0.323	0.122	0.216
2015	0-10	1.29	0.453	0.369	0.351	0.325	0.127	0.223
	10-20	1.35	0.420	0.353	0.335	0.310	0.128	0.208
	20-40	1.39	0.410	0.359	0.344	0.323	0.148	0.197
	40-60	1.48	0.398	0.371	0.361	0.349	0.165	0.196

*WHC calculated between -9.8 and -1500 kPa