Soil quality and corn-soybean yields

as affected by winter rye at three sites in the U.S. Corn Belt

Thesis

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ABSTRACT

This study investigated soil quality under corn (Zea mays L.) - soybean (Glycine max L.) rotation as affected by cereal rye (Secale cereal L.) cover crop in the U.S. Corn Belt. The objectives were to 1) examine the affect of cereal rye cover cropping on various physiochemical soil quality indicators, including bulk density and total porosity, plant available water content, soil organic carbon concentration and stock, total nitrogen concentrations and stock, pH, cation exchange capacity, and clay activity ratios to a depth of 60 cm; 2) integrate several of these soil surface (0-10 cm depth) quantitative parameters into a unit less soil quality index (SQI); and 3) examine the affect of cereal rye cover cropping on corn and soybean yields. The hypotheses for the first two objectives were that cover crops would be associated with enhanced soil quality indicators, thus overall soil quality. The hypothesis for the third objective was that corn grain yields would be neither improved nor penalized, while soybean grain yields would be improved when following a cereal rye cover crop.

To test these hypotheses three case studies were investigated with soil samples taken in 2011 and crop yields over four growing seasons. These case studies were on a Mollisol (Nicollet series: Fine-loamy, mixed, superactive, mesic Aquic Hapludoll) in northwestern Iowa, an Alfisol (Nabb series: Fine-silty, mixed, active, mesic Aquic
Fragiudalf) in southeastern Indiana, and an Alfisol (Capac series: Fine-loamy, mixed active, mesic Aquic Glossudalf) in central Michigan.

There was an insignificant, yet observable trend, of decreased $\rho_b$ values in the CC treatments within all depths studied at the Iowa site. In the sandy loam soils at the Michigan site, where the NC treatment surface $\rho_b$ values were slightly higher, there was evidence of a plow pan in the 10-20 cm depth. Within this depth there was a slightly lower mean $\rho_b$ for the CC treatment, suggesting that rye cover crop rooting may be ameliorating the plow pan.

When the $\rho_b$ values were converted to SQ scores there was no indication that cover cropping was enhancing soil quality through improvements in the 0-10 cm layer. However, this result was limited to the surface layer and if summed throughout the entire profile, or at least through 20 cm, where the Michigan plow pan was detected, there may be evidence otherwise.

Available water content was significantly reduced (~31%) in the surface layer at the Iowa site. No treatment effect on AWC was detected at the Michigan site. When the AWC was converted to SQ scores there was no indication that cover crops were enhancing soil quality in the surface layer.

The Iowa site SOC, C stock, TN, and N stock values followed similar trends as to what was observed in $\rho_b$, only inverted, with slightly higher values observed in the CC treatments. When the SOC concentrations were converted to SQ scores there was evidence that cover crops had led to higher soil quality through enhancing the C pool at
the Michigan site. Though the Michigan site scored relatively low in both CC and NC treatments (CC = 0.35 NC = 0.27), there was an approximate 30% increase in SOC SQ score attributable to the addition of winter rye to the rotation.

The soil quality indices calculated by the Soil Management Assessment Framework (SMAF) with $\rho_b$, AWC, pH, and SOC included as indicators in the minimum data set were 82.41 and 84.81 for CC and NC at the Iowa site, respectively. This suggests that these soils are inherently high in quality and the addition of cover crops has led to no change in overall soil quality. Conversely, there was a significant increase in soil quality on the sandy loam soils at the Michigan site attributable to winter rye cover crop. The SQI at this site were reported as 77.63 for the CC treatment and 74.39 for the NC treatment. This increase in SQI is most likely due to the increased soil organic matter as the only individual indicator that contributed to this increase was that of SOC.

There were significant differences between sites in three of the four years observed during this study for both corn and soybean yields under CC and NC treatments. However, only one site-treatment difference was observed in any year (Iowa 2014 corn yields for CC = 7.85 Mg ha$^{-1}$ NC = 6.74 Mg ha$^{-1}$ p = 0.056).

The hypothesized affect of cereal rye on corn yields was confirmed in ten of eleven site-year combinations. There was not a significant reduction in corn grain yields associated with rye cover cropping. The hypothesized affect of cereal rye on subsequent soybean yields was not observed in any of the site-year combinations of this study. However, arguably more importantly, the soybean yields were not decreased
either. Based on these results and the numerous environmental benefits associated with cereal rye cover cropping it should be recommended to farmers in the U.S. Corn Belt to include cereal rye into their rotations preceding soybean.
DEDICATION

I would like to dedicate this work to my wife Marcie, my son Zachary, my daughter Sophia, my mom and dad Tina and LeRoy, and my mother-in-law, Monica.
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CHAPTER 1: INTRODUCTION

1.1 Challenges of 21st century agriculture

Agriculture in the 21st century has become, overall, more vulnerable to changes in climate and though the magnitude of and specifics regarding regional vulnerabilities are unique, there are certain overarching threats that all of society must prepare for (Lal, 2007; Vermeulen et al., 2012a; Melillo et al., 2014). Conventional cropping systems and cultivars are based on historical temperature and precipitation patterns that are not likely to remain throughout the coming century (Cubasch et al., 2013; Melillo et al., 2014). These expected spatial and temporal changes present in the form of shifting mean temperatures and precipitation totals, weed and pest pressures, as well as through increases in the intensity, frequency, and duration of extreme weather events, such as storms, droughts, heat waves, and cold spells (Cubasch et al., 2013).

With the threat of variable weather patterns and the concomitant changes in disease and pest pressures, it has become increasingly apparent that building resiliency into our cropping systems should be of the highest social priority (Vermeulen et al., 2012b; Lobell et al., 2014). However, the necessary understanding and implementation of the best management practices (BMPs) required to foster this needed resiliency
Is lacking and further research is required. To this end, in 2011 the United States Department of Agriculture (USDA) National Institute of Food and Agriculture (NIFA) funded three 5-year regional coordinated agricultural projects (CAPs) (Eigenbrode et al., 2014). The CAPs were initiated in the Northwestern, Southeastern, and Midwestern regions of the United States, to investigate the impacts of climate change on, as well as, the carbon, nitrogen, and water footprints of, soft white wheat (*Triticum aestivum* L.), loblolly pine (*Pinus taeda* L.), and corn (*Zea mays* L.) production, respectively.

1.2 Sustainable Corn CAP overview

The Cropping Systems CAP (CS-CAP) is a partnership of ten U.S. universities (many of which are land-grant universities), the USDA Agriculture Research Service (ARS) – Columbus, OH, and USDA-NIFA, assessing the environmental, economic, and social impacts of long-term climate variability on corn-based cropping systems. In 2012 the United States accounted for approximately 31% of global corn production (Ranum et al., 2014) 66% of which was generated within the Corn Belt states included in the CS-CAP (USDA NASS, 2014), thus the region is an optimal location for this integrated research project.

The CS-CAP, in the broadest sense, is focusing on ways to encourage resilient decision making, maintain yields, and reduce the environmental impact of corn production (Morton, 2014). Additionally, the project has the stated goal of working towards reducing the greenhouse gas (GHG) emissions of corn production and increasing soil carbon sequestration in corn based systems by 10 and 15%, respectively,
by 2030. To address this, the project has 35 field sites throughout eight Corn Belt states with experiments investigating multiple management practices (including tillage, cover crops, extended rotations, drainage water management, nitrogen sensing technology, and organic systems) all using conventionally tilled corn-soybean (Glycine max) rotation as the control system (Figure 1.1).

Objective 1 of CS-CAP was to create a standardized protocol for the soil, agronomic, and GHG monitoring methodologies to ensure that the results observed across the study could be compared and synthesized properly and to establish baseline

Figure 1.1: CS-CAP field site map. Figure credit [http://www.sustainablecorn.org](http://www.sustainablecorn.org)
measurements where experiments have not yet started (Kladivko et al., 2014).

Objective 2 was to initiate the field experiments investigating the crop management practices mentioned above, as well as utilize some on-going long-term experiments. These field observations have been and continue to be uploaded to a team wide internal website (that will be accessible to the public at the end of the project) where they have been utilized by the team members pursing Objective 3. This third objective is to use physical models and synthesized results to predict responses to various climate and economic scenarios (see Gonzalez-Ramirez et al. 2012; Jha and Gassman, 2013; Herzmann et al. 2014). The social, economic, and environmental acceptability of the cropping systems and management practices being examined by the first three biophysical objectives are the focus of Objective 4 (see Arbuckle et al. 2013; Wilke and Morton, 2015). CS-CAP Objective 5 team members area of expertise is in integrating the social and natural science work being conducted by the members of the other objective teams and are using this knowledge in extension and outreach efforts (Figure 1.2).

With the anticipated variability of our future climate this type of large-scale transdisciplinary approach, of bridging biophysical and social sciences, to agricultural research will be required to address the goal of building resiliency into our cropping systems. This is especially true if we are to put equal weights of priority on maintaining or enhancing the production of commodities, productive ecosystem services, and human wellbeing (Basche et al. 2014).
1.3 Cover Crop Overview

In 1799, Richard Parkinson said, “... it is seen how earnest my wish is that the surface of the ground should at all times, winter and summer, be well covered, whenever it possibly can be accomplished” (Pietrs, 1927). Cover crops, clearly not a novel concept, are in essence, short-term rotational crops that are grown on a piece of
land, between cash crops, in a time when the land would have otherwise been left fallow. These crops can be used for various purposes such as a winter surface cover, green manure, weed suppression, habitat for beneficial arthropods, as supplemental forage, or as a catch crop. Historically, the primary purpose of sowing cover crops has been to protect the soil surface from the erosional forces of wind and water (Lal et al. 1991, Reeves, 1994), however, it has been realized that the integration of cover crops into annual rotations is an opportunity to increase other ecosystem services from agricultural systems (Schipanski et al., 2014). These additional ecosystem services that cover crops may provide include improving nutrient cycling, soil and water quality, pest regulation, and crop productivity (Russelle and Hargrove, 1989; Lal et al., 1991; Tonitto et al., 2006; Dabney et al., 2010).

Though once a common component of many U.S. row-cropping systems their prominence began to decline with the rise of synthetic fertilizers at the end of WWII (Bullied et al., 2002; Dinnes et al., 2002). A national trend towards the decoupling of crop and livestock operations was also associated with the increase of commercially available fertilizers as manure was no longer required as a nutrient source, and meadow legumes were no longer needed on farms that began to specialize on short corn-soybean rotations (Dinnes et al., 2002: Drinkwater and Snapp, 2005). However, due to concerns regarding nutrient movement from agricultural nonpoint sources and their contributions to degrading water resources there is a current trend to reincorporate cover crops into many agroecosystems as exemplified by the USDA Natural Resource
Conservation Service (NRCS) Environmental Quality Incentives Program (EQIP) which is a cost sharing program to help offset the economic burden of cover cropping placed on farmers.

Cover crops are often classified as either winter or summer annuals or perennials, with winter annuals being the most often utilized in the U.S. Corn Belt. This is due to the fact that the sowing of summer cover crops would require a farmer to forgo a season of cash crop production (not a likely scenario), though this is occasionally done on severely degraded lands as a reclamation technique (Delgado et al., 2007). Further classification is taxonomically based, with most cover crops being nitrogen fixing legumes (Fabaceae family), grasses (Poaceae family), or brassicas (Brassicaceae family).

Commonly used nitrogen fixing legumes currently in use throughout the U.S. Corn Belt include crimson (Trifolium incarnatum L.) and red (Trifolium pratense L.) clover, hairy vetch (Vicia villosa L.), and field pea (Pisum sativum subsp. Arvense).

Commonly used non-leguminous cover crops include cereal rye (Secale cereale L.), annual rye (Lolium multiflorum L.), forage radish (Raphanus sativus L.), canola (Brassica rapa L.), wheat (Triticum aestivium L.) and oat (Avena sativa L.). The CS-CAP project focus is on the use of cereal rye as it is one of the most winter hardy species and is relatively easy to establish in the USDA hardiness zones (5a, 5b, and 6a) where this regional study is on-going.
1.3.1 Cover Crops and Erosion

Erosion is a three-stage process, including the detachment of particles from the soil mass, transportation of the detached particles downhill by floating, rolling, dragging, and splashing, and the subsequent deposition of soil particles somewhere at lower elevation (Flanagan, 2006). Left unprotected the soil surface can become extremely susceptible to soil erosion (Figure 1.3). Cover crops can limit erosion by mitigating the first two stages of this process by both intercepting raindrops and absorbing the kinetic energy that detaches particles from surface aggregates and by reducing the velocity of sediment filled runoff (Lal et al., 1991; Dabney et al., 2001). Furthermore, the fine-roots of cover crops contribute to reduction of erosion by promoting soil aggregation (Hermawan and Bomke, 1997) and enhancing infiltration into the soil profile (Lal et al., 1991; Dabney, 2001).

1.3.2 Nitrogen scavenging and recycling

Current estimates suggest that human activities have doubled the global fluxes of biologically active N, with agricultural sources accounting for ~75% of anthropogenic N forcings (Tonitto et al., 2006). Nitrogen is essential for growth and reproduction of all life; in particular common corn-based systems in the U.S. Corn Belt (often short rotational and tile-drained) require relatively high levels of N to produce desired yields. However, nitrogen use efficiency (NUE) for corn production is estimated to be only 37%
(Cassman et al., 2002) with the remaining N that is not taken up in harvested biomass, contained in recycled crop residue or incorporated into the soil organic matter and inorganic N pool being either, leached as nitrate (NO$_3$-N), eroded, or released as nitrous oxide (N$_2$O) gas (a GHG ~300 times more potent than CO$_2$). The fate of this lost N, no matter the mechanism, contributes to environmental degradation through the decline of surface and groundwater quality as well as through the exacerbation of anthropogenic climate change (Tonitto et al., 2006).

Figure 1.3. Accelerated erosion. Credit USDA. (http://archive.larouchepac.com/node/26879)
It is well documented that NO$_3$-N is the dominant form of N found in soil water (Dinnes et al., 2002; Snapp et al., 2005) and can be derived from both organic and inorganic sources. Both the over application of and poorly timed application of animal manure or synthetic fertilizers can lead to excessive amounts of plant-available N leading to subsequent losses into the hydrosphere and atmosphere. This residual N can be “scavenged” by cover crops and recycled to the subsequent cash crop (Dabney et al., 2001) thus reducing the amount of N that cascades into the surrounding biosphere.

Mitsch et al. (2001) and many others, have stated that simplified rotations of corn-soybean in the U.S. Corn Belt, largely made possible by the availability of synthetic fertilizers, has resulted in the preferential removal of winter annuals thereby leading to an increase in extended periods of fallow. This dependence on N fertilizer has resulted in a decrease in the duration of living plant cover, which in turn, reduces C-fixation and N-assimilation (Tonitto et al., 2006). Filling this winter niche with cover crops is a tool that can be easily applied to increase retention of post-harvest surplus inorganic N, thus reducing N losses (Drinkwater and Snapp, 2005). Ultimately, successful management of N via cover cropping is dependent upon synchronizing the degradation of cover crops, and release of N, so that it is available during periods of active uptake of the subsequent cash crop (Kaspar and Singer, 2011).

1.3.3 Soil moisture and temperature

Possibly the greatest impact that cover crops have on soil characteristics is in the affect that they have on soil moisture, both through increases in infiltration rates and...
soil water holding capacity. When the plant is alive it reduces soil moisture through increasing transpiration and after it is terminated, if left on the surface, it can help maintain soil moisture throughout the summer growing season (Dabney, 1998) providing a benefit for the subsequent cash crop.

Due to this temporal variability of cover crop impacts on soil moisture, it may also be one of the more challenging aspects of cover crop management. In an attempt to maximize soil moisture conservation benefits some farmers utilize the cover crops ability to dry out extensively wet soils from heavy spring rains by planting a soybean crop directly into a standing rye cover. By chemically terminating the cover at this point they create standing mulch that helps maintain soil moisture by regulating soil temperature and lowering evaporation rates (Kaspar and Singer, 2011). Conversely, during dry spring seasons, such as 2012 in the U.S. Corn Belt, cover crops may have a deleterious effect on soil moisture by transpiring the limited water supply and leaving little antecedent moisture for the following cash crop seed (Daigh et al., 2014).

Dabney et al. (2001) suggest that if incorporated into the soil through tillage, cover crops have little impact on soil temperature. However, standing cover crops and cover mulch can significantly affect soil temperature. Organic mulches reduce daily maximum soil temperature, which can be detrimental in cooler regions where crop growth is temperature limited and positive in warmer regions (Drury et al., 1999; Dabney et al., 2001).
1.4 Soil Quality Overview

1.4.1 Soil quality defined

Soil quality has been defined by many people in many, often conflicting ways. However, it can be defined as “the capacity of a soil to function” (Larson and Pierce, 1991; Doran and Parkin, 1994; Karlen et al., 1997). Within this definition, the term 'function' refers to the many ecosystem services that soils provide. These ecosystem services include sustaining biological activity, diversity, and productivity, regulating and filtering the water supply, degrading and detoxifying organic and inorganic materials from industrial and municipal by-products, cycling nutrients, such as C and N, and regulating important gas fluxes between the subsurface and the atmosphere (Andrews et al., 2004). Thus, the generally accepted definition implies that the quality of a particular soil varies with the function that one is expecting the soil to provide (i.e. a high quality soil for one function may be of low quality for another). Building upon this definition NRCS Soil Quality Institute defined soil quality as, “The capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation” (Mausbach and Tugel, 1995).

Letey et al. (2003) take issue with the definitions that focus on the term “function”, suggesting that the emphasis should rather be on the “use” of the soil. Function, they argue, implies a responsibility assigned to the soil, whereas when one substitutes for the term “use”, the responsibility of soil quality maintenance is placed on
the user and the concept distinctly shifts to quality management. Furthermore, the
definition proposed by Letey et al. (2003) follows as “The chemical, physical, and
biological properties of soil that affect its use.” Within this definition, it is imperative
that the intended use of the soil be clearly defined. This definition and its requirement
of clearly defining the intended use connect the concept of quality to the land manager
and their intended outcome.

Another related term, “soil health” is often used synonymously with soil quality,
however the choice of which term to use is often determined by the background of the
user. Farmers, land managers, extension agents, and other practicing professionals tend
to say “health”, whereas soil scientists and ecologist tend to prefer “quality” (Lal, 2011).

1.4.2 Properties of soil quality

Overall, soil quality is made up of two general classes of soil properties. Inherent
properties (sometimes referred to as the genoform) are those that are generally
controlled by Jenny’s (1941) soil forming factors of climate, parent material, landscape
position, soil organisms, and time. Dynamic soil properties (sometimes referred to as
phenoform) are those that are subject to accelerated change often due to the
anthropogenic forces of land management (Karlen et al., 2003). Though Jenny does
include “organisms” in the soil forming factors, and humans are indeed organisms, it
seems as if Jenny, at the time, did not consider humans to fall into this category as a
component of soil formation.

With the distinction between inherent and dynamic soil properties it seems that
traditional soil taxonomy and classification is decided mostly by a soils inherent
properties and considering the entire profile (3 m depth), whereas, the more recent
interest in soil quality is focused more on the dynamic properties of the soil surface
layer (Karlen et al., 2001). These dynamic properties are highly influenced by and often
limited by the underlying inherent properties (i.e. SOC is a dynamic soil property,
however, the potential for changes in SOC stock in a Mollisol are much greater than that
of an Ultisol). Due to these differences in inherent soil properties, there is no single
measurement that will always be useful for evaluating soil quality (Warkentin and
Fletcher, 1977). Therefore, soil quality research is not intended to replace soil
taxonomy, rather to build upon it by investigating the dynamic soil properties and a soils
ability to reach it’s full functional potential (Karlen, 2001).

1.4.3 Monitoring soil quality

In their classic soil science textbook Brady and Weil (2008) state, “soil in the
scale of human lifetimes cannot be considered a renewable resource, however, if
managed properly, they can be a reusable resource.” Furthermore, Larson and Pierce
(1991) state in their seminal soil quality paper that the use of a dynamic assessment for
evaluating soil quality in which the management of a system is assessed in terms of its
actual performance as opposed to a comparison of other systems should be favored.
Their hypothesis was that a management system could only be described as sustainable
when soil quality is maintained or improved; therefore, a quantitative assessment of
changes in soil quality provides a measure of sustainable management.
Figure 1.4 represents possible temporal trends in soil quality that may result from various soil management practices. This simple figure effectively captures the idea that monitoring soil quality, as affected by human use over time, is essential for assessing the impacts of management on the soil resource. By monitoring the effect of management on soil quality the trends represented in Figure 1.4 can be revealed and adaptive management of the resource is made possible (Karlen et al., 2001). If we are to ensure that the soil is in fact a reusable resource, it is critical that tools for evaluating the rate and direction of trends in soil quality, as related to soil management, be developed and utilized (Weinhold et al., 2005).

Critics of soil quality assessment often point to the value-laden interpretation of indicators, regional and taxonomic biases, and the fact that there is no such thing as a “pure soil” on which to base quality as shortcomings of the approach (Sojka and Upchuch, 1999; Sojka et al., 2003; Letey et al., 2003). First, the reservations regarding the value-laden interpretations of indicators are refuted with the acknowledgment that we live in a society that has values and that all decisions are value-laden and dominated by personal experiences and expectations (Keeney and Raiffa, 1976). Secondly, the regional and taxonomic biases are addressed in some indexing approaches through non-linear scoring curves that allow for regional (climatic) and taxonomic differences.

1.4.4 Soil quality indexing

With regard to indexing soil quality, the most important fact is that since both inherent and dynamic soil properties are involved, there are no, as Karlen et al. (2001)
put it, “magic” scores or perfect ratings. Soil quality is always relative and never absolute. Lal (2001) states, “important challenges of modern times are developing objective methods of quantification of soil quality and identifying those indices which scientists can quantify but farmers and land managers can understand and relate to.”

The primary purpose of developing a soil quality index is to simply help landowners and land operators visualize the integrated effects that land-use decisions are having on the soil, physical, chemical, and biological properties or processes (Karlen et al., 2001).

Figure 1.4. Possible temporal trends in soil quality (Figured adapted from Karlen et al. 2003)
Many methods for monitoring soil quality exist (Andrews, 1998; Hussain et al., 1999; Jaenicke and Lengnick, 1999; Shukla et al., 2006; Mukherjee and Lal, 2014). Understanding that soil quality indexing is a continual process and not a strict formula is an important concept for the development and improvements of current indexing methods. Another important concept to keep in mind is that in assessing the efficacy of any indexing method, it is necessary to define the management goals and the soil functions that are related to these goals. Andrews et al. (2004), with the development of the Soil Management Assessment Framework (SMAF), categorized three potential end-point management goals, including maximizing productivity, waste recycling, and environmental protection with each being associated with multiple supporting soil functions, including nutrient cycling, water relations, physical stability and support, filtering and buffering, resistance and resilience, and biodiversity and habitat.

1.5 Objectives and Hypotheses of the Current Study

The objectives of the present study are to 1) examine the affect of cereal rye cover cropping on various physiochemical soil quality indicators, including bulk density and total porosity, plant available water content, soil organic carbon concentration and stock, total nitrogen concentrations and stock, pH, cation exchange capacity, and clay activity ratios to a depth of 60 cm; 2) integrate several of these soil surface (0-10 cm depth) quantitative parameters into a unit less soil quality index via SMAF; and 3) examine the affect of cereal rye cover cropping on corn and soybean yields. The hypotheses for the first two objectives were that cover crops would be associated with
enhanced soil quality indicators, thus overall soil quality. The hypotheses for the third objective was that corn grain yields would be neither improved nor penalized, while soybean grain yields would be improved when following a cereal rye cover crop.

To test these hypotheses three case studies were investigated with soil samples taken in 2011 and crop yields over four growing seasons. These case studies were on a Mollisol (Nicollet series: Fine-loamy, mixed, superactive, mesic Aquic Hapludoll) in northwestern Iowa, an Alfisol (Nabb series: Fine-silty, mixed, active, mesic Aquic Fragiudalf) in southeastern Indiana, and an Alfisol (Capac series: Fine-loamy, mixed active, mesic Aquic Glossudalf) in central Michigan.
References


Chapter 2: SOIL QUALITY INDIATORS AS AFFECTED BY CEREAL RYE COVER CROP

2.1 ABSTRACT

This study analyzed agricultural soil under corn (Zea mays L.) - soybean (Glycine max L.) rotation [with cereal rye (Secale cereal L.) cover crop (CC) and without (NC)] at three sites in the U.S. Corn Belt (a Mollisol in northwest Iowa and Alfisols in central Michigan and southeast Indiana) with the primary objectives of 1) examining the affect of cereal rye cover crop on various soil physiochemical properties, including bulk density and total porosity, plant available water content, soil organic carbon concentration and stock, total nitrogen concentration and stock, pH, cation exchange capacity, and clay activity ratios to a depth of 60cm and 2) integrating several of these surface (0 – 10cm) physicochemical properties into unit less soil quality indices (SQI) using the Soil Management Assessment Framework (SMAF).

Statistically significant differences between the CC and NC treatments were found for plant available water content in the surface layer, with CC resulting in ~31% reduction at the Iowa site (p = 0.041). The CC plots at both the Michigan and Iowa sites showed increasing trends of soil organic carbon (SOC) in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths with statistically significant increases of 56 and 43% within the 10 - 20 and 20 - 40 cm depths at the Michigan site, respectively (10 - 20 cm p = 2.02e-05, 20 – 40 cm p = 0.028). Throughout the 60 cm profiles the carbon stock in the CC treatments
were 170 and 2.4 Mg C ha$^{-1}$ for the Iowa and Michigan site, respectively. These carbon stocks represent a 1.7% increase in the Gilmore site and an increase of 27% at the Michigan site when compared to the NC treatments.

Bulk density, plant available water capacity, pH, and SOC concentrations were the indicators selected for the SMAF scoring curves and integrated in total soil quality indices. The Gilmore site showed no differences in the total soil quality index or in any individual indicator between treatments. However, a significant increase in SQI was found at the Mason site (CC SQI = 77.63, NC SQI = 74.39, p = 0.076) and was driven by increases in SOC accounted to the CC treatment.

2.2 INTRODUCTION

It is not feasible to measure every aspect of a soil to quantify overall soil quality. Therefore, subsets of soil parameters must be selected and monitored to address the impacts that soil management practices have on soil quality over time, or to compare management practices against each other. These “indicators” of soil quality can give insight into which best management practices (BMPs) should be recommended on specific soil types, in specific regions, and for specific management goals.

The Soil Management Assessment Framework (SMAF) is a tool designed to help land managers select which indicators are appropriate to meet their end goals and to monitor the affect of management practices, either over time or through comparative assessments (Andrews and Carroll, 2001; Andrews et al. 2004). The SMAF is intended to
help land managers identify trends in soil quality to help make scientifically informed land management decisions.

Cover crops are an important BMP that can be easily utilized throughout the U.S. Corn Belt to enhance soil quality (Delgado et al. 2007). Many of the benefits of incorporating cover crops into cropping systems are due to the direct effects that cover crops have on soil physical and chemical properties. Furthermore, the enhancement of physicochemical indicators of soil quality has indirect effects on soil biological communities (Brady and Weil, 2008).

Annual crop plants, such as corn and soybean, only provide sufficient canopy cover for 4-6 months; leaving the soil surface unprotected and susceptible to erosion for the remainder of the year (Kaspar and Singer, 2011). When cover crops are included within the rotation, the time that the soil surface is protected by living plant canopy is significantly extended. This additional time of ground cover can reduce erosion and runoff. For example, Wendt and Burwell (1985) reported that winter rye (Secale cereale L.) following no-till corn for silage reduced annual soil loss from 22 Mg ha\(^{-1}\) to 0.9 Mg ha\(^{-1}\) in Missouri. Furthermore, they reported that annual runoff was reduced 50% (from 245 mm to 122 mm) when winter rye was included. Kaspar et al. (2001), in a 3-year rainfall simulation experiment in Iowa, overseeded winter rye into no-till soybean and showed reductions of interrill and rill erosion of 56 and 90%, respectively, when compared to no-till without rye. Both experiments concluded that the benefits of erosion and runoff reduction where attributed to cover crop induced enhancement of soil structure.
Soil structure is the physical relationship between the solid, liquid, and gaseous phases of soil. The arrangement of soil separates (sand, silt, and clay), as well as, soil organic matter, into aggregates determines the relative size, shape, and interconnectedness of soil pore space (Lal and Shukla, 2004). This arrangement has direct consequences to soil bulk density ($\rho_b$), total porosity ($f_t$), and soil water holding capacity. Soil structure impacts plants by either allowing or limiting root growth and altering gas and water movement. Conversely, plants alter soil structure through root development impacts on aggregation and porosity, as well as through the input of root and shoot biomass (Kaspar and Singer, 2011). The additional inputs of root and shoot biomass from cover crops can contribute to increases in soil organic carbon (SOC).

SOC is a central component of many of the ecosystem services facilitated by the soil (Lal, 2007); therefore it is a key indicator of overall soil quality. The SOC stocks in agricultural soils can be increased by BMPs that result in the amount of C entering the soil exceeding C lost to the atmosphere by oxidation or through leaching of the dissolved portion (Follett 2001). Cover crops are one of the BMPs that can lead to increases in soil C stock. Lal et al. (1998) estimated that the inclusion of winter cover crops into corn-based rotations in the U.S. could increase SOC sequestration rates between 5 and 15 MMT C yr\(^{-1}\).

Another soil chemical indicator that is highly correlated with SOC is the total nitrogen (TN) concentration. N is the most abundant element in the atmosphere and usually the most limiting crop nutrient. The ratio of C to N in agricultural soils of the U.S. Corn Belt range from 8:1 – 15:1, with the median being near 12:1 (Brady and Weil,
Knowledge of the soil C:N ratio allows for estimation of the amount of N that can potentially be mineralized in the soil and made plant available. Thus, the determination of soil C:N ratio is necessary for making plant fertility management decisions. The addition of plant biomass to soil can alter the C:N ratio depending on the C:N ratio of the biomass being added. Rye cover crops average C:N ratios of 26:1, while leguminous cover crops, such as hairy vetch average 12:1 (Clark, 2007) when in the vegetative state. This lower C:N ratio of leguminous cover crops leads to faster decomposition and mineralization of N.

Another key soil quality indicator related to SOC is that of plant available water content (AWC). SOC influences soil water holding capacity by increasing the moisture content at field capacity (FC), however having little to no influence on the permanent wilting point (PWP) (Lal and Shukla, 2004). Additionally, AWC, along with $\rho_b$ and a known rooting depth are required for calculation of the total available water holding capacity. This calculation has management implications, especially in the western reaches of the U.S. Corn Belt where irrigation is common.

SOC also has influence on the soil cation exchange capacity (CEC). The CEC is the total capacity of a soil to hold exchangeable cations ($Ca^{2+}$, $Mg^{2+}$, $K^+$, $Na^+$, $H^+$, and $Al^{3+}$). It influences the soils ability to hold onto essential nutrients and provides a buffer against soil acidification. CEC is also highly correlated with the clay content and type and can be used to categorize the activity of clay (Lal and Shukla, 2004). Cover crops are not expected to directly alter the CEC, as it is most highly associated with soil texture,
however cover crops may indirectly influence CEC through biomass inputs to the soil organic matter pool.

The objectives of this chapter are to 1) examine the affect of cereal rye cover cropping on various physiochemical soil quality indicators, including bulk density and total porosity, plant available water content, soil organic carbon concentration and stock, total nitrogen concentration and stock, pH, cation exchange capacity, and clay activity ratios to a depth of 60 cm and 2) integrate several of these soil surface (0 - 10 cm depth) quantitative parameters into a unit less soil quality index using SMAF. The hypotheses were that cover crops would be associated with enhanced soil quality indicators, thus overall soil quality.

To test these hypotheses three case studies were investigated with soil samples taken in 2011. These case studies are a Mollisol (Nicollet series: Fine-loamy, mixed, superactive, mesic Aquic Hapludoll) in northwestern Iowa, an Alfisol (Nabb series: Fine-silty, mixed, active, mesic Aquic Fragiuudalf) in southeastern Indiana, and an Alfisol (Capac series: Fine-loamy, mixed active, mesic Aquic Glossudalf) in eastern Michigan.

2.3 METHODS AND MATERIALS

Three corn-soybean (with [CC] and without [NC] rye cover crop) rotations located in northwest Iowa [Iowa State University Agriculture Drainage Water Quality-Research and Demonstration Site (Gilmore) near Gilmore City, IA (42°74’ N, 94°49’ W)], southeast Indiana [Southeast Purdue Agriculture Center (SEPAC) near Butlerville, IN (39°02’ N, 85°54’ W’)], and central Michigan [Michigan State University Agronomy Farm:
Mason Research Farm (Mason) near East Lansing, MI (42°62’ N, 84°43’ W) were selected for this study (Table 2.1).

Soil sampling took place during the spring (April 2011 for the Gilmore site and May 2011 for the SEPAC and Mason sites) to assure that the soils were moist and that the clays were fully hydrated (Kladivko et al. 2014). Soil cores were taken from the quarter row position to 60 cm depth with increments of 0 – 10, 10 – 20, 20 – 40, and 40 – 60 cm. Bulk soil was also sampled at the same increments and taken to the lab for chemical analysis.

2.3.1 Gilmore site

The corn-soybean rotation at the Gilmore site was established in 1989 with winter rye cover crop incorporated in the mid 1990s. The study is on a Nicollet (Fine-loamy, mixed, superactive, mesic Aquic Hapludoll) soil series with an historic land use of prairie grass and wetlands. The Nicollet series consists of very deep, somewhat poorly drained soils that formed in calcareous loamy glacial till on till plains and moraines. Slopes range from 0 to 5 percent. Mean annual temperature and precipitation is 9°C and 660 mm, respectively (USDA Soil Survey).

The experimental design is a completely randomized block design with conventional till (CT) and no-till (NT) having both phases (corn/soybean) represented. Additionally, there are winter rye cover crop plots (present/absent) in NT with both phases represented, for a total of six treatments replicated four times. However, the focus of this study is on the affect of cover crops, not tillage, therefore only the eight NT
replicates were investigated.

2.3.2 Mason site

The Mason site has been under row cropping since the late 1800s while the plots used for this study were established in the mid-1990s. The study is on a Capac (Fine-loamy, mixed active, mesic Aquic Glossudalf) soil series with an historic land use of forest. The Capac series consists of very deep, somewhat poorly drained soils formed in loam or clay loam till. These soils are on moraines and till plains. Slope ranges from 0 to 6 percent. Mean annual temperature and precipitation are 8.3°C and 813 mm, respectively (USDA Soil Survey).

The experiment is a split-plot design with phase (corn/soybean) as a whole plot factor and cover crop (present/absent) as a subplot factor. There are a two blocks replicated six times.

2.3.3 SEPAC site

The SEPAC site had been under light disc tillage and corn-soybean rotation since the mid-1990s. Cover crops were included into the rotation in the fall of 2011 and the plots were converted to NT in 2012. The study is on a Nabb (Fine-silty, mixed, active, mesic Aquic Fragiudalf) soil series with an historic land use of forest. The Nabb series consists of very deep, moderately well drained soils that formed in Loess and the underlying Paleosol in till. They are moderately deep to a fragipan and are on till plains.
Slope ranges from 0 to 6 percent. Mean annual temperature and precipitation is 12°C and 1092 mm, respectively (USDA Soil Survey).

The experimental design is a completely randomized block design with both phases (corn/soybean) represented, as well CC and NC treatments. This combinations makes for a total of four treatments replicated four times.

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil Series (order)</th>
<th>Drainage class</th>
<th>Texture Classification</th>
<th>Slope %</th>
<th>Mean Temperature (°C)</th>
<th>Mean Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gilmore (IA)</td>
<td>Nicollett (Mollisol)</td>
<td>somewhat poorly</td>
<td>clay loam</td>
<td>0 - 5</td>
<td>9.0</td>
<td>660</td>
</tr>
<tr>
<td>SEPAC (IN)</td>
<td>Nabb (Alfisol)</td>
<td>moderately well</td>
<td>silty clay loam</td>
<td>0 – 6</td>
<td>12.0</td>
<td>1092</td>
</tr>
<tr>
<td>Mason (MI)</td>
<td>Capac (Alfisol)</td>
<td>somewhat poorly</td>
<td>sandy loam</td>
<td>0 - 6</td>
<td>8.3</td>
<td>813</td>
</tr>
</tbody>
</table>

Table 2.1: Site description

2.3.4 Soil Physical Property Analysis

All data was collected from the SC-CAP team internal website. Following is a truncated description of the methods used for soil physical property analysis. For detailed description of the methods see cited references.
2.3.4.1 Bulk density

Soil bulk density \((\rho_b)\) was determined using the core method described by Grossman and Reinsch (2002). Briefly, soil cores 7.5 cm in diameter and 7.5 cm in height were inserted into the surface 0-10 and 10-20 cm layer with hand samplers. Hydraulic probes were used for the 20-40 and 40-60 cm layers. With the cores height being 7.5 cm, in the deeper layers the samples were taken near the midpoint of the range and assumed to be representative of the desired layer. The two surface layers were replicated three times per plot with the means being used for analysis. The two deeper layers were only sampled once per plot as spatial variability of \(\rho_b\) decreases with depth (Grossman and Reinsch, 2002). Each core was taken at or near field capacity water content and coated in plastic wrap in the field and brought to the lab for moisture analysis. The top and bottom of each core was neatly trimmed and subsamples were weighed and oven dried at 105\(^\circ\) C to determine gravimetric moisture content \((\omega)\) at time of sampling. After the top and bottoms of each sample were trimmed the cores were weighed to determine the mass of soil inside the known volume. Moisture corrections were used to convert the sampled field moist bulk densities \(\rho'_b\) to the reported dry \(\rho_b\) values.

\(\rho'_b\) was determined as the mass of the field moist soil divided by the volume of the soil core.

The reported \(\rho_b\) was determined by the following equation

\[
\rho_b = \frac{\rho'_b}{1+\omega} \quad [\text{Eq.1}]
\]
2.3.4.2 Total porosity

Total porosity ($f_t$) was derived from the calculated $\rho_b$ values and the standard assumption that the particle density ($\rho_s$) of mineral soils is 2.65 g cm$^{-3}$ (Brady and Weil, 2008) using the following equation

$$f_t = 1 - \frac{\rho_b}{\rho_s}$$  \hspace{1cm} [Eq. 2]

This derived value was then validated against the saturated volumetric water content $\theta_S$ using the following relationship

$$f_t = \theta_S$$  \hspace{1cm} [Eq. 3]

2.3.4.3 Available water content

The intact soil cores were stored in plastic wrap at field moisture content, after weighing for $\rho_b$. Cheesecloth was used to secure the bottom of the cores. To prepare for moisture retention analysis, the cores were pre-wetted by capillarity for 24h. Soil moisture characteristics were determined at 0 and -5 kPa with a tension table and at -10, -30, and -1500 kPa with pressure plate extractors following the methods described by Dane and Hopmans (2002). The $\omega$ was converted to $\theta$ by multiplying with the dry $\rho_b$. Available water content (AWC) was calculated by subtracting the $\theta$ at the permanent wilting point (PWP: -1500 kPa) from the $\theta$ at the field capacity (FC: -300 kPa). The water contents required for full moisture characteristics release curves were calculated, however only the FC, PWP, and AWC values are presented and discussed in the results of this study.
2.3.5 Soil Chemical Property Analysis

Following is a truncated description of the methods used for soil chemical property analysis. For detailed description of the methods see cited references.

2.3.5.1 Soil organic carbon and total nitrogen analysis

SOC and TN analysis were determined using a dry combustion method described by Nelson and Sommers (1996) for carbon and by Bremner (1996) for nitrogen. The pH of the soils at the Mason and SEPAC sites ranged from 5.7 to 7.1, thus it was assumed that any inorganic carbonates were negligible therefore disregarded and included in the SOC totals. However, the Gilmore site pH values ranged from 7.4 to 8.0, indicating consequential levels of inorganic carbonates, therefore these samples were pretreated with 5% sulfurous acid (H₂SO₃) as described by Nelson and Sommers (1996).

2.3.5.2 Soil C and N stock

The soil carbon pool was calculated as suggested by Lal et al. (1998) using the measured SOC%, ρb, and the depth of the individual soil layer by the following equation:

\[
\text{Soil C/N stock} = \text{SOC}/\text{TN}\% \times \rho_b \times \text{depth} \quad \text{[Eq. 4]}
\]

2.3.5.3 pH

Soil solution pH was determined using a standard pH - EC meter and a 1:1 soil:water ratio. The solution was made following the method described by Thomas (1996).
2.3.5.4 Cation exchange capacity and clay activity ratio

Cation exchange capacity (CEC) and the percentage of cation base saturation were measured using 1 M ammonium acetate extraction of exchangeable cations (Helmke and Sparks 1996). The clay activity ratio (CAR) was calculated by the following equation

\[
CAR = \frac{CEC}{\%\,\text{clay fraction}}
\]  

[Eq. 5]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density</td>
<td>Core</td>
<td>Grossman and Reinsch (2002)</td>
</tr>
<tr>
<td>Total porosity</td>
<td>Synthesized from bulk density</td>
<td>Lal and Shukla (2004)</td>
</tr>
<tr>
<td>Particle size</td>
<td>Hydrometer</td>
<td>Gee and Or (2002)</td>
</tr>
<tr>
<td>Available water content</td>
<td>Pressure plates and tension table</td>
<td>Dane and Hopmans (2002)</td>
</tr>
<tr>
<td>Total nitrogen</td>
<td>Dry combustion</td>
<td>Bremner (1996)</td>
</tr>
<tr>
<td>Cation exchange capacity</td>
<td>Ammonium acetate</td>
<td>Sumner and Miller (1996)</td>
</tr>
</tbody>
</table>

Table 2.2: Methods used for soil physiochemical analysis.
2.3.6 Soil Quality Assessment

The method used for determining the soil quality in this study is known as the Soil Quality Assessment Framework (SMAF) and was first developed in the late 1990’s. It has been subsequently further developed to add scoring algorithms for other soil quality indicators (Andrews and Carroll, 2001; Andrews et al. 2004).

2.3.6.1 Indicator Selection

Indicator selection for the SQI was driven by both the SC-CAP protocol (Kladivko et al. 2014) and the availability of previously determined scoring algorithms in SMAF (Andrews et al 2004). There were four observed soil quality indicators included within the SC-CAP database that have also had scoring algorithms developed within SMAF. These indicators include $\rho_b$, AWC, pH, and SOC and were therefore selected to represent the MDS for this approach to generating soil quality index (SQI). Only the surface (0-10cm) depth was used in the soil quality assessment.

2.3.6.2 Indictor Scoring

Scoring algorithms were used to transform the observed data into unit less values. The entire suite of scoring algorithms used by SMAF to determine SQI scores are discussed in detail by Andrews et al. (2004) and hereafter briefly, however, only for the indicators selected to represent the MDS ($\rho_b$, AWC, pH, and SOC) used for this study.
Bulk Density

IF texture >35% clay, THEN $y = a - b \exp(-c \cdot \rho)$, \[ Eq. 5 \]
ELSE $y = a - b \exp(-c \cdot \rho)$ \[ Eq. 6 \]

Where $a = 0.994$, is a fixed parameter and $b$, $c$, and $d = f(\text{texture})$

AWC

IF region = arid THEN $y = \frac{a + b \cdot c \cdot \text{AWC}^d}{b + \text{AWC}^d}$ \[ Eq. 7 \]
ELSE $y = a + b \cdot \cos(c \cdot \text{AWC} + d)$ \[ Eq. 8 \]

Where $a = 0.477; b = 0.527; c = 6.878$ are fixed parameters and $d = f(\text{texture})$

For the current study all sites are considered humid regions therefore are scored via the “ELSE” function.

pH

$y = a \exp \left[ -\frac{(pH-b)^2}{2+c^2} \right]$ \[ Eq. 9 \]

Where $a = 1.0$, is a fixed parameter and $b$ and $c = f(\text{crop})$

SOC

$y = \frac{a}{1+b\exp(-c\cdot\text{SOC})}$ \[ Eq. 10 \]

Where $a = 1; b = 50.1$, are fixed parameters and $c = f(\text{iOM, texture, climate})$
2.3.6.3 Scoring Integration

The final step in quantifying soil quality using the chosen method is to combine the individual soil quality scores derived above for each indicator \( S_i \) by the following equation:

\[
SQI = \left( \frac{\sum_{i=1}^{n} S_i}{n} \right) \times 100
\]

[Eq. 11]

2.3.6 Statistical Analysis

Results of the physiochemical indicators were first analyzed using two-way analysis of variance (ANOVA) testing the effect of treatment and the interactions of treatments and depth using the *agricolae* package (de Mendibru, 2014) within the R statistical software (R Core Team, 2014). There were no significant interactions between treatment and depth and the significance between depths was not of interest in this study. It was decided to reanalyze the data using one-way ANOVA for each individual depth. Mean values from one-way ANOVA were then tested for differences using Tukey’s Honest Significant Differences (HSD) test, at the \( \alpha = 0.05 \) level and \( \alpha = 0.1 \) level in some tests. Which \( \alpha \) used is clearly identified throughout the text.

2.4 RESULTS AND DISCUSSION

2.4.1 Bulk density and Total Porosity

Bulk density \( (\rho_b) \) is a basic soil property needed to understand soil quality, water flow, aeration, root development, and many other processes. It is also needed to
convert C and N values measured as concentrations to a volume basis for calculating C and N stocks in the soil profile (Klavidko et al. 2014).

Though there was a noticeable trend of lower \( \rho_b \) in the CC treatments relative to NC in all depths at the Gilmore site, these differences were not statistically significant at any observed depth. The measured \( \rho_b \) in the CC treatment was 1.12, 1.35, 1.40, and 1.52 g cm\(^{-3}\) and 1.14, 1.37, 1.42, and 1.53 g cm\(^{-3}\) for NC in the 0-10, 10-20, 20-40, and 40-60 cm depths, respectively (Figure 2.1). These \( \rho_b \) values are low enough, from an agronomic perspective, as to not restrict water movement or root penetration. Rye has an effective rooting depth between 75-230 cm (Wyland et al. 1996; Kutschera 1960). Therefore the roots would likely be distributed throughout the entire profile investigated in this study. The trend of lower \( \rho_b \) in the CC plots may not be statistically significant at any individual depth, however, given that the trend was noticed in all depths, the speculation that deep rooting system of the rye grass may be slowly contributing to a decrease in \( \rho_b \) may be valid. The mechanism behind this contribution to \( \rho_b \) is likely through enhanced soil structure. Low (1972) studied the time required to improve soil physical conditions with conversion of old arable lands to grass and concluded that it may take as many as 50 years in some clay soils to see improvements. This suggests that this improvement may be happening, but at a fairly slow pace in this clay loam soil.

The total porosity (\( f_t \)) of the CC treatments at the Gilmore site was 58, 50, 47, and 43\% in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively (Figure 2.2). The \( f_t \) in the corresponding depths of the NC treatment was calculated as 57, 49, 46, and
42%. As \( f_t \) was directly calculated from \( \rho_b \) the same insignificant trend of slightly more pore space within all layers of the CC treatment was observed. These slight differences in \( f_t \) may not be providing a functional difference with regard to water and air movement, however the distribution of pore size does affect soil water characteristics, specifically soil field capacity (FC). Pore sizes between 10 - 500 μm are characterized as gravitational, or transmission, pores and are those that are drained freely by the force of gravity (Greenland, 1977; Luxmoore, 1981).

Figure 2.1: Gilmore soil bulk density values by depth for CC and NC treatments. Same letters within depth indicate no significance between treatments.
The mean $\rho_b$ of the sandy loam soils at the Mason site was measured to be 1.48, 1.60, 1.58, and 1.63 g cm$^{-3}$ in the CC treatments and 1.48, 1.62, 1.58, and 1.60 g cm$^{-3}$ in the NC at the 0-10, 10-20, 20-40, and 40-60 cm depths, respectively (Figure 2.3). These values were not statistically significant at any depth and fall within the expected range for soils of this texture and SOC content. However, the $\rho_b$ did not follow the expected trend of increasing with depth between the 10-20 and 20-40 cm layers. This slightly lower mean $\rho_b$ in the deeper layer suggests that there may be a plow pan from historical tillage operations in the 10-20 cm depth. This denser layer may also be due to subsurface compaction from wheel traffic. The slightly lower $\rho_b$ found at this depth in
the CC plots may suggest that the cover crop could be slowly contributing the amelioration of the restrictive denser layer.

The total porosity of the CC treatments at the Mason site was 44, 40, 40, and 38% in the 0-10, 10-20, 20-40, and 40-60 cm depths, respectively (Figure 2.4). The porosity in the corresponding depths of the NC treatment was 44, 39, 41, and 40%. Significant differences were not detected and there seems to be nothing limiting root growth, or air and water transmission at this site.

The “CC treatment” ρb reported for the SEPAC site are not truly representative of a CC treatment effect. These samples were taken in the spring of 2011 before the CC treatment had been established. They are delineated as “CC treatments” throughout this paper to represent baseline analysis for future comparison.

All comparisons between “CC treatment” and NC treatment are only included to establish this baseline. The mean ρb of the silty clay loam soils at the SEPAC site were measured to be 1.26, 1.40, 1.42, and 1.49 g cm⁻³ for CC and 1.28, 1.40, 1.45, and 1.47 g cm⁻³ for the NC, respectively. The total porosity of the “CC treatments” at the SEPAC site was 53, 47, 46, and 44% in the 0-10, 10-20, 20-40, and 40-60 cm depths, respectively. The porosity in corresponding depths of the NC treatment was 52, 47, 45, and 44%.
Figure 2.3: Mason soil bulk density by depth for CC and NC treatments. Same letters within depth indicate no significance between treatments.

Figure 2.4: Mason total porosity by depths for CC and NC treatments. Same letters within depth indicate no significance between treatments.
2.4.2 Soil Moisture Retention Characteristics

FC was determined to be θ at the matric potential of -300 kPa. The θ\textsubscript{FC} in CC treatment at the Gilmore site was determined to be 0.25 and 0.45 cm\textsuperscript{3} cm\textsuperscript{-3} in the 0 - 10 and 10 - 20 cm layers, respectively (Figure 2.5). Comparatively, the θ\textsubscript{FC} for the corresponding depths in the NC treatment was 0.30 and 0.45 cm\textsuperscript{3} cm\textsuperscript{-3}. This decrease of ~17% in the CC was significant (p = 0.036) while no difference was found in the 10-20cm depth.

PWP was determined to be θ at the matric potential of -1500 kPa. The θ\textsubscript{PWP} in CC treatment at the Gilmore site was determined to be 0.14 cm\textsuperscript{3} cm\textsuperscript{-3} in both the 0-10 and 10-20 cm layers. The θ\textsubscript{PWP} for the corresponding depths in the NC treatment was 0.14 and 0.15 cm\textsuperscript{3} cm\textsuperscript{-3}. There was no significance detected, as these were virtually the same values at both depths measured.

The difference between θ\textsubscript{FC} and θ\textsubscript{PWP} is the available water content (θ\textsubscript{AWC}).

Surface layer (0 - 10 cm) θ\textsubscript{AWC} in the CC treatment at the Gilmore site was determined to be 0.11 and 0.31 cm\textsuperscript{3} cm\textsuperscript{-3} in the underlying 10 - 20 cm layer. The θ\textsubscript{AWC} of the 0 - 10 and 10 - 20 cm layers of the NC treatments were measured as 0.16 and 0.30 cm\textsuperscript{3} cm\textsuperscript{-3}, respectively. This decrease of ~31% in the surface layer θ\textsubscript{AWC} was found to be significant (p = 0.041). This response is surprising in that cover crops are generally expected to increase AWC, however this result contradicts what others have found in this region on similar soil types (Dabney et al. 2001).
Figure 2.5: Gilmore soil moisture retention characteristics by depth for CC and NC treatments.
Different letters within the same category represent significant difference between treatments.

The $\theta_{fc}$ of the CC treatment at the Mason site was determined to be 0.24 cm$^3$ cm$^{-3}$ in both the 0 - 10 and 10 - 20 cm depths, respectively, while the corresponding depth $\theta_{fc}$ in the NC treatments were 0.23 and 0.24 cm$^3$ cm$^{-3}$ (Figure 2.6). These values are virtually the same as no treatment effect could be attributed.

The $\theta_{pwp}$ in CC treatment at the Mason site was determined to be 0.017 cm$^3$ cm$^{-3}$ in both the 0 - 10 and 10 - 20 cm layers. Comparatively, the $\theta_{pwp}$ for the corresponding depths in the NC treatment was calculated as 0.014 and 0.02 cm$^3$ cm$^{-3}$ in the 0 - 10 cm and 10 - 20 cm depths, respectively. (0-10 p = 0.087) Even though the $\theta_{pwp}$ of sandy
loam soils are expected to be towards the lower end of the spectrum (in the 0.05-0.08 cm³ cm⁻³) these values are strikingly low and there is some concern about their accuracy.

The Mason site θ_{AWC} for the both CC and NC treatments as well as both 0 - 10 and 10 - 20 cm layers was determined to be 0.22 cm³ cm⁻³. This value is approximately ~66% higher than the expected θ_{AWC} of a soil of this sandy loam texture and soil organic matter content (Saxton and Rawls, 2006). This unexpectedly high value will undoubtedly positively skew the results on the soil quality indexing method undertaken in this study by giving a much larger credit for the water holding capacity of this sandy loam soil.

The θ_{FC} of both the “CC treatment” and the NC treatments at the SEPAC site were determined to be 0.31 and 0.32 cm³ cm⁻³ in the 0 - 10 and 10 - 20 cm depths, respectively. These results suggest that the θ_{FC} in the baseline for this experiment are homogenous, thus a good starting point to serve as a true control for future detection of differences.

The θ_{PWP} in “CC treatment” at the SEPAC site was determined to be 0.13 and 0.14 cm³ cm⁻³ in the 0 - 10 and 10 - 20 cm layers, respectively. Comparatively, the θ_{PWP} for the corresponding depths in the NC treatment was 0.12 and 0.13 cm³ cm⁻³. These values again are indicative that the baseline measurements are rather homogenous and serve as a suitable control to determine differences along the duration of the study.

The SEPAC site θ_{AWC} for the both the 0-10 and 10-20 cm layers was determined to be 0.18 in the “CC treatment”. The θ_{AWC} of the 0-10 and 10-20 cm layers of the NC treatments were measured as 0.19 and 0.18 cm³ cm⁻³, respectively.
Figure 2.6: Mason soil moisture retention characteristics by depth for CC and NC treatments. Different letters within the same category represent significant difference between treatments.

2.4.3 Soil organic carbon and total nitrogen analysis

2.4.3.1 Soil organic carbon concentration and stock

The SOC concentration of the CC treatment at the Gilmore site was determined to be 32.88, 28.72, 16.93, and 16.39 g C kg\(^{-1}\) soil in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm layers, respectively. Comparatively, the corresponding depth SOC concentrations of the NC treatment were 30.81, 27.40, 15.87 and 15.52 g C kg\(^{-1}\) soil (Figure 2.7). Though there was no significant differences found with pairwise comparisons within any individual depth, it is of note that the mean SOC within all depths of the CC plots were
slightly higher than in NC. The relatively high background SOC levels of this Mollisol (inherent in this soil type) may limit the ability of the cover crop to significantly enhance SOC (Olson et al. 2014).

The CC treatment carbon stock at the Gilmore site was 36.72, 38.47, 47.49, and 50 Mg C ha\(^{-1}\) in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively (Figure 2.8). The corresponding depths in the NC treatments had a carbon stock of 35.02, 42.65, 45.02, and 47.79 Mg C ha\(^{-1}\). Thus, the total carbon stock of the CC treatment to a depth of 0.6 m was 173 Mg C ha\(^{-1}\) compared to 170 Mg C ha\(^{-1}\) in the NC. This represents only an insignificant increase of 1.7% C stock. This difference may be attributed to spatial heterogeneity or sampling error as opposed to a CC treatment effect. The fact that measured bulk density was used for the conversion also suggests possible sampling error as bulk density is difficult to measure accurately and is subject to a certain degree of variation. Furthermore, Olson et al. (2014) discusses the inability to accurately calculate changes in C stock attributable to a treatment effect without baseline measurements of the treatment plots, as it may not be a fair assumption that the control plots have reached a steady state.

SOC in the CC treatment at the Mason site was determined to be 8.03, 8.23, 4.71, and 3.01 g C kg\(^{-1}\) in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively (Figure 2.9). SOC in the corresponding depths of the NC treatment were determined to be 7.23, 5.26, 3.29, and 2.95 g C kg\(^{-1}\). Statistically significant differences were found between treatments in the 10-20 and 20-40 cm depths (\(p = 2.02\times10^{-5}\) and \(p = 0.028\)). This represents a 56 and 43% increases in CC SOC in the layers, respectively.
Figure 2.7: Gilmore SOC depth distribution for CC and NC treatments. Same letters within depth indicate no significance between treatments.

Figure 2.8: Gilmore depth distribution C stock for CC and NC treatments. Same letters within depth indicate no significance between treatments.
The CC treatment carbon stock at the Mason site was 0.80, 0.82, 0.47, and 0.30 Mg C ha\(^{-1}\) in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively (Figure 2.10). The corresponding depths in the NC treatments have a carbon stock of 0.72, 0.53, 0.33, and 0.30 Mg C ha\(^{-1}\). Thus, the total carbon stock of the CC treatment to a depth of 0.6 m was 2.39 Mg C ha\(^{-1}\) compared to 1.88 Mg C ha\(^{-1}\) in the NC. A significant difference between treatment carbon stocks was detected in the 10 - 20 and 20 – 40 cm depths, as well as in total C stock (\(p = 2.18\times10^{-5}\), \(p = 0.028\), and \(p = 0.001\)). The observed increase of 27% in total C stock of this sandy loam soil may be in part due to the low background level of SOC suggesting that there is room for further improvement in the SOC of these soils. Since the CC treatment has been in place for approximately 15 years, the rate of carbon sequestration attributable to the CC treatment, if one is willing to assume that the control plots are in equilibrium, is 34 kg C ha\(^{-1}\) year\(^{-1}\) over the first 15 years.

SOC in the “CC treatment” at the SEPAC site was determined to be 14.00, 10.03, 4.91, and 3.03 g C kg\(^{-1}\) in the 0-10, 10-20, 20-40, and 40-60 cm depths, respectively. SOC in the corresponding depths of the NC treatment were determined to be 14.49, 10.00, 5.20, and 3.17 g C kg\(^{-1}\).
Figure 2.9: Mason SOC depth distribution for CC and NC treatments. Different letters within the same depth represent significant difference between treatments.

Figure 2.10: Mason depth distribution of C stock for CC and NC treatments. Different letters within the same depth represent significant difference between treatments.
The “CC treatment” carbon stock at the SEPAC site was 17.62, 13.99, 13.88, and 9.04 Mg C ha\(^{-1}\) in the 0-10, 10-20, 20-40, and 40-60 cm depths, respectively. The corresponding depths in the NC treatments had a carbon stock of 18.59, 14.04, 15.07, and 9.34 Mg C ha\(^{-1}\). Thus, the total carbon stock of the CC treatment to a depth of 0.6 m was 54.53 Mg C ha\(^{-1}\) compared to 57.04 Mg C ha\(^{-1}\) in the NC. As was expected, significant differences in carbon stock within depths or in total were not detected. This recording of C stock values will be beneficial for future assessment as establishing the baseline requirement will help to address the issues in calculating sequestration rates addressed by Olson et al. (2014).

2.4.3.2 Total nitrogen concentration and stock

As was expected, TN concentration and N stock followed similar patterns to what was observed with the SOC and C stock at all three sites. The Gilmore site CC treatment means for TN were found to be 2.42, 2.11, 1.27, and 0.97 g N kg\(^{-1}\) soil, for the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively (Figure 2.11). For the corresponding soil depths in the NC treatment mean TN values were measured to be 2.29, 2.04, 1.20, and 0.87 g N kg\(^{-1}\) soil. These results suggest that there was no treatment affect on TN. However, as was observed with SOC, there were slightly higher levels of TN within all depths with a decrease in TN with depth.

The CC treatment nitrogen stock at the Gilmore site was 2.71, 2.82, 3.35, and 2.95 Mg N ha\(^{-1}\) in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively (Figure 2.12). The corresponding depths in the NC treatments had a carbon stock of 2.54, 3.02,
3.61, and 2.65 Mg N ha\(^{-1}\). Thus, the total nitrogen stock of the CC treatment to a depth of 0.6 m was 11.83 Mg N ha\(^{-1}\) compared to 11.82 in the NC. This represents relatively no change in nitrogen stock of this clay loam Iowa soil.

The Mason site CC treatment means for TN were found to be 0.83, 0.87, 0.52, and 0.39 g N kg\(^{-1}\) soil, for the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively (Figure 2.13). For the corresponding soil depths in the NC treatment mean TN values were measured to be 0.85, 0.59, 0.43, and 0.38 g N kg\(^{-1}\) soil. A significant difference was found between the treatments in the 10 - 20 cm depth (\(p = 0.008\)). Significant differences in SOC were also found within this depth at the Gilmore site. Reflecting the coupled nature of SOC and TN.

![Figure 2.11: Gilmore TN depth distribution for CC and NC treatments. Same letters within depth indicate no significance between treatments.](image-url)
The Mason site CC treatment means for TN were found to be 0.83, 0.87, 0.52, and 0.39 g N kg\(^{-1}\) soil, for the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively (Figure 2.13). For the corresponding soil depths in the NC treatment mean TN values were measured to be 0.85, 0.59, 0.43, and 0.38 g N kg\(^{-1}\) soil. A significant difference was found between the treatments in the 10 - 20 cm depth (\(p = 0.008\)). Significant differences in SOC were also found within this depth at the Gilmore site. Reflecting the coupled nature of SOC and TN.

The CC treatment nitrogen stock at the Mason site was 1.24, 1.40, 1.64, and 1.27 Mg N ha\(^{-1}\) in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively (Figure 2.14). The corresponding depths in the NC treatments had a carbon stock of 1.28, 0.96,
1.34, and 1.24 Mg N ha\(^{-1}\). Thus, the total nitrogen stock of the CC treatment to a depth of 0.6 m was 5.55 Mg N ha\(^{-1}\) compared to 4.82 Mg N ha\(^{-1}\) in the NC treatment. A significant difference was detected in the 10 - 20 cm depth (\(p = 0.012\)).

![Figure 2.13: Mason TN depth distribution for CC and NC treatments. Different letters within the same depth represent significant difference between treatments.](image)

The SEPAC site “CC treatment” means for TN were found to be 1.45, 1.22, 0.75, and 0.50 g N kg\(^{-1}\) soil, for the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively. For the corresponding soil depths in the NC treatment mean TN values were measured to be 1.48, 1.21, 0.77, and 0.52 g N kg\(^{-1}\) soil.
The “CC treatment” nitrogen stock at the SEPAC site was 1.82, 1.70, 2.13, and 1.49 Mg N ha\(^{-1}\) in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively. The corresponding depths in the NC treatments had a carbon stock of 1.89, 1.70, 2.23, and 1.52 Mg N ha\(^{-1}\). Thus, the total nitrogen stock of the CC treatment to a depth of 0.6 m was 7.14 Mg N ha\(^{-1}\) compared to 7.34 Mg N ha\(^{-1}\) in the NC. Again, these values were expected to be nearly identical and this expectation was met.

2.4.3.3 C:N Ratios

C:N ratios > 20:1 indicate the immobilization of N which creates problems for plant uptake of N. The C:N values at all sites (Table 2.2) were found to be under this
threshold value and do not indicate N immobilization. The Gilmore site CC treatment means for C:N ratios were found to be 13.59, 13.64, 14.63, and 17.13 for the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively. For the corresponding soil depths in the NC treatment mean C:N ratios were calculated as 13.32, 13.40, 12.71, and 18.56. There were no significant differences detected in any depth.

The Mason site CC treatment means for C:N ratios were found to be 10.06, 10.17, 10.07, and 9.00, for the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively. For the corresponding soil depths in the NC treatment mean C:N ratios were calculated 8.68, 8.90, 7.71, and 7.81. A significant difference was found in the 20 - 40 cm layer (p = 0.024) where the C:N ratio of the CC treatment was 31% higher than the NC treatment.

The SEPAC site “CC treatment” mean C:N ratios were found to 9.72, 8.25, 6.60, and 6.31, for the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively. For the corresponding soil depths in the NC treatment mean C:N ratios were calculated as 9.83, 8.26, 6.74, and 6.22. There were no significant differences detected in any depth.
<table>
<thead>
<tr>
<th>Site</th>
<th>Depth</th>
<th>C:N Ratio</th>
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<th></th>
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</thead>
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<td></td>
<td>10-20 cm</td>
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<tr>
<td></td>
<td>20-40 cm</td>
<td>14.63</td>
<td>12.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40-60 cm</td>
<td>17.13</td>
<td>18.56</td>
<td></td>
</tr>
<tr>
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<td>0-10 cm</td>
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<td>8.68</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>10.17</td>
<td>8.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20-40 cm</td>
<td>10.07 a</td>
<td>7.71 b</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40-60 cm</td>
<td>9.00</td>
<td>7.81</td>
<td></td>
</tr>
<tr>
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<td>9.83</td>
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</tr>
<tr>
<td></td>
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<td>40-60 cm</td>
<td>6.31</td>
<td>6.22</td>
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</tr>
</tbody>
</table>

Table 2.3: C:N ratios by depth and site for CC and NC treatments. Different letters within the same depth represent significant difference between treatments (p < 0.05).

2.4.4 pH

The recommended pH range for soils to produce corn and soybean are between 6.0 and 7.0, in the slightly acidic to neutral range (Vitosh et al. 2000). The measured soil pH values in the CC treatments at the Gilmore site were 7.62, 7.46, 7.74, and 8.04 in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively (Table 2.3). The corresponding depths in the NC treatments had pH values of 7.67, 7.47, 7.88, and 7.98. There were no significant differences attributable to the CC treatment. These values are beyond the upper end of the required range and may be somewhat limiting the yield.
output. However, this increased pH range is common in this region as Ca$^{2+}$ and Mg$^{2+}$ containing carbonates are usually present in Mollisols in Iowa.

The pH values of the soil in the CC treatments at the Mason site were 5.87, 6.04, 6.33, and 6.91 in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively. The corresponding depths in the NC treatments had pH values of 5.73, 5.81, 6.38, and 6.77. There were no significant differences attributable to the CC treatment. Though not significant there is a slightly higher pH in the CC treatment. This agrees with what other researchers have found. Eckert (1991) observed that a rye winter cover crop slightly increased pH when corn followed rye and concluded that this was due to rye’s assimilation of NH$_4$. These surface values are slightly more acidic than the recommended values for corn production, but not acidic enough to warrant liming application at this point in time. However, with continued N fertilizer application a liming management will likely be recommended in the near future.

The soil pH values of the “CC treatments” at the SEPAC site were 7.05, 5.83, 5.26, and 5.31 in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively. The corresponding depths in the NC treatments had pH values of 7.08, 5.83, 5.38, and 5.48. There were no significant differences attributable to the CC treatment. The subsurface values are acidic enough to warrant lime application as Mg deficiencies are expected in the corn and soybean biomass, which may limit production. Lime application was conducted at this experiment (fall of 2012) thus has no impact on the soil discussion of
this paper, however must be considered in the next chapter discussing grain yields before and after liming.

<table>
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<td></td>
<td>40-60 cm</td>
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</tr>
<tr>
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<td>5.8</td>
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<td>5.3</td>
</tr>
<tr>
<td></td>
<td>40-60 cm</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Table 2.4: Soil pH by depth and site for CC and NC treatments. NS within any site at any depth

2.4.5 CEC and clay activity ratios

Cation exchange capacity (CEC) is the total capacity of a soil to hold exchangeable cations \((Ca^{2+}, Mg^{2+}, K^+, Na^+ H^+, \text{ and } Al^{3+})\). CEC is an inherent soil property closely related to clay % and type and is not influenced very much through management.
practice (though it is related to SOM and can be altered through increases). It influences the soils ability to hold onto essential nutrients and provides a buffer against soil acidification. The CEC of the CC treatments at the Gilmore site were 30.8, 32.5, 31.5, and 32.5 cmol kg$^{-1}$ in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively (Table 2.5). The corresponding depths in the NC treatments had CEC values of 31.5, 31.7, 31.3, and 32.9 cmol kg$^{-1}$. There were no significant differences between treatments. These CEC values are common for dark Mollisols in Iowa.

The clay activity ratios of the CC treatments at the Gilmore site were 1.00, 0.98, 0.95, and 0.98 in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively (Table 2.5). The corresponding depths in the NC treatments had clay activity ratios of 0.99, 0.97, 0.96, and 1.04. Clay activity ratios of > 0.7 are considered to be high activity clays (Matocha, 2006) and these soils fall within this category. These clay activity ratios are often used as a proxy for clay mineralogy when there is no mineralogical data available (Olson et al. 2000) as is the case in this study. Based on these values, the clay type in this location is likely vermiculite. This is required information for the soil quality indexing used in the following section.

The CEC of the CC treatments at the Mason site were 6.9, 6.8, 7.5, and 9.7 cmol kg$^{-1}$ in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively. The corresponding depths in the NC treatments had CEC values of 6.3, 5.9, 8.3, and 9.9 cmol kg$^{-1}$. There were no significant differences between treatments. These sandy soils have relatively low clay % (ranging from 2 - 17% with a mean of 14% in the surface layer), therefore must rely on the soil organic matter for the retention of nutrients in the soil.
The clay activity ratios of the CC treatments at the Mason site were 0.27, 0.27, 0.40, and 0.49 in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively. The corresponding depths in the NC treatments had clay activity ratios of 0.28, 0.25, 0.47, and 0.53. There were no significant differences between treatments. Clay activity ratios < 0.3 are considered to be low activity. These soils, at least in the upper 20 cm fall within this category, suggesting that the dominant clay mineral is highly weathered kaolinite.

The CEC of the “CC treatments” at the SEPAC site were 10.3, 8.4, 10.5, and 11.6 cmol kg\(^{-1}\) in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively. The corresponding depths in the NC treatments had CEC values of 10.1, 8.5, 10.9, and 11.6 cmol kg\(^{-1}\). There were no significant differences between treatments. These CEC values are extremely low for a silt loam textured soil and may be prone to deficiencies in K\(^{+}\) and Mg\(^{2+}\). These soils were also found to be relatively low in SOC and the addition of CC may help increase SOC, thus increase CEC over time.

The clay activity ratios of the “CC treatments” at the SEPAC site were 0.41, 0.29, 0.31, and 0.35 in the 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths, respectively. The corresponding depths in the NC treatments had clay activity ratios of 0.37, 0.30, 0.30, and 0.36. These ratios, as with the Mason site, indicate that kaolinite is the likely mineralogy of the clay fraction.
Table 2.5: CEC and clay activity ratios by depth and site for CC and NC treatments.
NS within any depth at any site

2.5 SOIL QUALITY INDEX RESULTS

Soil quality indicators refer to measureable soil attributes that influence the
capacity of a soil to perform crop production or environmental functions (Arshad and
Martin, 2002). The soil quality indicators selected for this study included $\rho_b$, AWC, pH,
and SOC. The selection of this particular set of indicators was due to their inclusion in
the CS-CAP internal database and the fact that they all have scoring curves developed
within SMAF. Each of these indicators will be discussed in turn in the following sections
and finally an integrated soil quality score will be presented.
2.5.1 Bulk density Soil Quality Scores

Statistically significant differences in \( \rho_b \) were not detected between treatments in the surface (0 - 10 cm) layer at any of the three sites. Measured mean \( \rho_b \) for the Gilmore site was 1.12 and 1.14 g cm\(^{-3} \) for the CC and NC treatments, respectively. These measured values, when considered in conjunction with soil texture (clay loam), suborder (Udoll), and clay mineralogy (assumed to be vermiculite based on the relatively high clay activity ratio and the soil order not being Vertisol) are converted through the SMAF to \( \rho_b \) soil quality scores of 0.78 and 0.80, for CC and NC, respectively (Figure 2.15). There was a high amount of variability with scores ranging from 0.23 – 0.99.

Measured mean \( \rho_b \) observed at the Mason site was 1.48 g cm\(^{-3} \) for both the CC and NC treatments. When these values were scored in SMAF with respect to texture (sandy loam), suborder (Udalf), and clay mineralogy (kaolinite: scored as “other” in SMAF) the SQ scored for \( \rho_b \) were 0.83 and 0.82 for the CC and NC treatments, respectively. These measured \( \rho_b \) values are significantly higher than what was observed at the Gilmore site, however due to the underlying inherent texture, suborder and clay mineralogy the SQ scores are relatively the same.

Measured mean \( \rho_b \) observed at the SEPAC site were 1.26 and 1.28 for the “CC” and NC treatments, respectively. When these values were scored in SMAF with respect to texture (sandy clay loam), suborder (Udalf), and clay mineralogy (kaolinite: scored as “other” in SMAF) the SQ scored for \( \rho_b \) were 0.66 and 0.62 for the “CC and NC treatments, respectively. These \( \rho_b \) values are significantly higher than what was
determined in the Gilmore site, however due to the underlying inherent texture, suborder and clay mineralogy the SQ scores were significantly lower. This is due to the fact that the SMAF suggests that for this particular soil, under this particular land-use the $\rho_b$ indicates a lower quality than the other two sites.

2.5.2 Available Water Content Soil Quality Scores

Statistically significant differences in AWC SQ scores were not detected between treatments in the surface (0-10 cm) layer at any of the three sites. Significant treatment differences were found in the calculated AWC at the Gilmore site of 0.11 and 0.16 cm$^3$ cm$^{-3}$. However, when these values were scored within SMAF with respect to the soil texture and suborder, using a sinusoidal scoring function the SQ scores for AWC were 0.72 and 0.75 for CC and NC, respectively (Figure 2.16). SMAF does not score AWC, nor any property on a linear scale, thus the 31% difference in raw AWC only translates to a 4% increase in SQ score.
Measured mean AWC observed at the Mason site were 0.22 cm$^3$ cm$^{-3}$ for both the CC and NC treatments. When these values were scored in SMAF with respect to texture and suborder the resulting AWC SQ scores were both 0.99. This suggests that considering the texture and inherent organic matter of the Udalf suborder these soils have reached the maximum AWC of their full potential.

Measured mean AWC observed at the SEPAC site were 0.18 and 0.19 cm$^3$ cm$^{-3}$ for the “CC” and NC treatments, respectively. When these values were scored in SMAF with respect to texture and suborder the resulting AWC SQ scores were 0.70 and 0.71 for the “CC” and NC, respectively. Considering these are baseline measurements, and the CC treatment has not been in effect yet, these similar values are expected.

Figure 2.15: Surface (0 – 10 cm) bulk density soil quality scores for CC and NC treatments. Same letters within site indicate no significance between treatments
Figure 2.16: Surface (0 – 10 cm) available water capacity soil quality scores for CC and NC treatments. Same letters within site indicate no significance between treatments

2.5.3 pH Soil Quality Scores

Statistically significant differences in pH SQ were not detected between treatments in the surface (0-10 cm) layer at any of the three sites. The pH values determined at the Gilmore site were 7.62 and 7.67 for the CC and NC treatments, respectively. When these values were scored within SMAF with respect to target crop (corn) that has an optimal pH value of 6.2 ± 1.5 these measured values translate to pH SQ scores of 0.95 and 0.94 for CC and NC treatments, respectively. These observed pH values are slightly alkaline due to carbonates, however still within acceptable ranges for corn production.
The pH values determined at the Mason site were 5.87 and 5.73 for the CC and NC treatments, respectively. When these values were scored within SMAF with respect to target crop (corn) these measured values translate to pH SQ scores of 0.93 and 0.90 for CC and NC treatments, respectively. These observed pH values are slightly acidic due, however still within acceptable ranges for corn production.

The pH values determined at the SEPAC site were 7.05 and 7.08 for the “CC” and NC treatments, respectively. When these values were scored within SMAF the values translate to pH SQ scores of 0.93 and 0.92 for CC and NC treatments, respectively.

2.5.4 Soil Organic Carbon Soil Quality Scores

Statistically significant treatment differences for SOC SQ scores were not found at any of the three sites using the $\alpha = 0.05$ threshold. However, if the critical $\alpha$ is 0.10, significant difference was found at the Mason site in the surface layer.

The SOC values determined at the Gilmore site were 32.88 and 30.81 g C kg$^{-1}$ soil for the CC and NC treatments, respectively. When these values were scored within SMAF with respect to texture (clay loam), suborder (Udodd), and climatic region (SMAF classification hi/hi, meaning > 170 growing degree days and > 550 mm annual precipitation) these measured values are scored as 0.89 and 0.85 for the CC and NC treatments, respectively. This can be interpreted as the CC plots have reached 89% of their SOC potential while the NC plots have reached 85%.
The SOC values determined at the Mason site were 8.03 and 7.23 g C kg\(^{-1}\) soil for the CC and NC treatments, respectively. When these values were scored within SMAF with respect to texture (sandy loam), suborder (Udalf), and climatic region (SMAF classification hi/hi) these measured values are scored as 0.35 and 0.27 for the CC and NC treatments, respectively (\(p = 0.078\)). This treatment difference is significant at the \(\alpha = 0.10\) level. This score suggests that the CC treatment is having a significant affect on soil quality helping these sandy loam soils increase on their potential for SOC storage.

The SOC values determined at the SEPAC site were 14.00 and 14.49 g C kg\(^{-1}\) soil for the CC and NC treatments, respectively. When these values were scored within SMAF with respect to texture (silty clay loam), suborder (Udalf), and climatic region
(SMAF classification hi/hi) these measured values are scored as 0.44 and 0.47 for the CC and NC treatments, respectively. This relatively low value reflects that these particular soils have the capability to significantly increase their SOC storage capacity and with proper management it can be realized.

Figure 2.18: Surface (0 – 10 cm) soil organic carbon soil quality scores for CC and NC treatments. Different letters within the same site represent significant difference between treatments (p < 0.1).

2.5.5 Soil quality indices

The SQI scores calculated at the Gilmore site (CC SQI = 82.41, NC SQI = 84.81) fall within the ranges of SQI recently reported by others (approx. 75 – 90) using SMAF to
investigate annual croplands in the Midwestern U.S. (Joekla et al. 2011; Stott et al. 2011; Stott et al. 2013; Karlen et al. 2014). The cover crop treatment differences were not significant for any individual indicator or the total SQI at this site.

The SQI scores calculated at the Mason site (CC SQI = 77.63, NC SQI = 74.39) also fall within the ranges of SQI suggested above and were found to be statistically different at the $\alpha = 0.10$ level ($p = 0.076$). The only individually scored indicator that was significantly different was SOC. This result suggests that cover cropping with rye for 15 years in these sandy loam soils has led to a detectable increase in overall soil quality.

The SQI scores calculated at the SEPAC site (“CC” SQI = 68.34, NC SQI = 68.07) do not fall within the ranges of SQI suggested above. These soils scored slightly lower than the soils at the other two sites. This result suggests that with time these soils can be managed back towards a higher quality. The inclusion of cover crops at this site is likely a step in the right direction.

2.6 CONCLUSIONS

There was an insignificant, yet observable trend, of decreased $\rho_b$ values in the CC treatments within all depths studied at the Gilmore site. The NC treatment at this site had low $\rho_b$ values throughout the profile, therefore a treatment effect of decreased $\rho_b$ through cover crop root development and subsequent degradation may be present yet difficult to detect. In the sandy loam soils at the Mason site, where the NC treatment surface $\rho_b$ values where slightly higher, there was evidence of a plow pan in the 10-20
cm depth. Within this depth there was a slightly lower mean $\rho_b$ for the CC treatment, suggesting that rye cover crop rooting may be ameliorating the plow pan.

![Soil Quality Scores](image)

**Figure 2.19:** Surface (0 – 10 cm) soil quality scores for CC and NC treatments. Different letters within the same site represent significant difference between treatments ($p < 0.1$).

When the $\rho_b$ values were converted to SQ scores there was no indication that cover cropping was enhancing soil quality through improvements in the 0-10 cm layer. However, this result was limited to the surface layer and if summed throughout the entire profile, or at least through 20 cm, where the Mason plow pan was detected, there may be evidence otherwise.

Available water content was significantly reduced (~31%) in the surface layer at the Gilmore site. This result is surprising and contradicts other studies investigating the impact of cover crops on AWC (Daniel *et al.* 1999; Dabney *et al.* 2001). No treatment
effect on AWC was detected at the Mason site. When the AWC was converted to SQ scores there was no indication that cover crops were enhancing soil quality in the surface layer.

The Gilmore site SOC, C stock, TN, and N stock values followed similar trends as to what was observed in $\rho_b$, only inverted, with slightly higher values observed in the CC treatments. When the SOC concentrations were converted to SQ scores there was evidence that cover crops had led to higher soil quality through enhancing the C pool at the Mason site. Though the Mason site scored relatively low in both CC and NC treatments ($CC = 0.35$ NC = 0.27), there was an approximate 30% increase in SOC SQ score attributable to the addition of winter rye to the rotation.

The soil quality indices calculated by SMAF with $\rho_b$, AWC, pH, and SOC included as indicators in the minimum data set were 82.41 and 84.81 for CC and NC at the Gilmore site, respectively. This suggests that these soils are inherently high in quality and the addition of cover crops has led to no change in overall soil quality. Conversely, there was a significant increase in soil quality on the sandy loam soils at the Mason site attributable to winter rye cover crop. The SQI at this site were reported as 77.63 for the CC treatment and 74.39 for the NC treatment. This increase in SQI is most likely due to the increased soil organic matter as the only individual indicator that contributed to this increase was that of SOC. The baseline establishment of soil quality at the SEPAC site can be used in future study to assess the dynamic trend in soil quality.
References


Chapter 3: CORN AND SOYBEAN YIELDS AS AFFECTED BY CEREAL RYE COVER CROP

3.1 Abstract

This study analyzed four years of a corn (Zea mays L.) - soybean (Glycine max L.) rotation [with cereal rye (Secale cereal L.) cover crop (CC) and without (NC)] at three sites in the U.S. Corn Belt (a Mollisol in northwest Iowa and Alfisols in central Michigan and southeast Indiana) with the primary objective of examining the affect of cereal rye cover cropping on grain yields. The hypothesis was that corn grain yields would be neither enhanced or limited by the inclusion of cereal rye into the rotation, whereas the soybean yields following cereal rye would be increased.

Significant differences between sites in both CC and NC treatments were found in three of four years. These differences were likely driven more by region and climate than by management. However, treatment differences in grain yields within any individual site were only found in one of the twenty-one site-year observations (2014 Iowa CC corn grain yields = 7.85 Mg ha⁻¹, NC corn grain yield = 6.74 Mg ha⁻¹, p = 0.056). Overall, there was no indication that cereal rye cover crop had any affect on grain yields in either corn or soybean. The conclusions are that since no yield penalties were realized and due to the ancillary environmental benefits that cover crops provide their
inclusion in corn-soybean rotations is justified and therefore should be recommended as best management practice in the U.S. Corn Belt.

3.2 INTRODUCTION

Agricultural goals are often aimed at short-term economic gains; therefore management practices are only considered when they pose no threat to cash crop yields. Singer et al. (2007) estimated between 15 and 20% of farmers in the U.S. Corn Belt have used cover crops (CC) in their systems and that between 18 and 35% of farmers in the region perceived a yield advantage. Due to variability in the cost of farm inputs and concerns about the environmental impact of agriculture there is growing interest in society to pursue cropping systems that provide ecosystem services beyond maximizing crop yield (Schipanksi et al. 2014). Nonetheless, yield returns will always be, and should always be, an important aspect of sustainable agriculture. Despite the well-documented potential for environmental benefits from the inclusion of winter CC (Lal et al., 1991; Langdale et al., 1991; Throup-Kristensen et al., 2003) both positive and negative effects on the subsequent cash crop have been observed.

In some years, a rye cover crop limits corn growth because it uses too much water in the spring (Munawar et al., 1990). Additionally, rye may deplete or immobilize soil nitrogen causing early season nitrogen stress of corn (Karlen and Doran, 1991). Eckert (1988) reported 3% reduction in corn yields in Ohio and Johnson et al. (1998) reported a 17% corn yield penalty in Iowa following winter rye. Conversely, Sundermeier and Hoorman (2010) reported a 2% corn yield benefit in continuous corn
with the inclusion of winter rye in Ohio. In a meta-analysis of corn yields following grass cover crops using 71 observations from 26 independent studies throughout the U.S. and Canada, Miguez and Bollero (2005) calculated that the mean response ratio of corn yield was 0.99 with a 95 confidence interval that included 1, signifying that the inclusion of grass cover crop neither benefitted nor limited corn grain yield. However, the inclusion of grass cover crops into the rotation could still be beneficial in systems where the priority is improving soil and water quality. Grass cover crops have proven effective in conserving N fertilizer and preventing the losses of NO$_3$-N into surrounding water supplies, thus grass cover crops can effectively be used following corn preceding a crop that will not require N fertilizer (i.e. soybean).

Rye has been reported to improve (Warnes et al. 1991; Williams et al. 2000), decrease (Ekert, 1988; Reddy, 2001), and have no affect on subsequent soybean yields (Wagner-Riddle et al. 1994; Reddy, 2003; Ruffo et al. 2004). The negative effect of rye on soybean yields has been attributed to poor germination due to excessive soil cover and decreased soil temperature (Ekert, 1988) while the benefits are often attributed to improved weed control (Warnes et al. 1991; Ruffo et al. 2004).

The objective of the present study is to examine the affect of cereal rye cover cropping on corn and soybean yields. The hypothesis was that corn grain yields would be neither enhanced or limited by the inclusion of cereal rye into the rotation, whereas the soybean yields following cereal rye would be increased. To test these hypotheses three case studies were investigated over four growing seasons. These case studies were on a Mollisol (Nicollet series: Fine-loamy, mixed, superactive, mesic Aquic

3.3 METHODS AND MATERIALS

Three corn-soybean (with [CC] and without [NC] cereal rye cover crop) rotations located in northwest Iowa [Iowa State University Agriculture Drainage Water Quality-Research and Demonstration Site (Gilmore) near Gilmore City, IA (42°74’ N, 94°49’ W)], southeast Indiana [Southeast Purdue Agriculture Center (SEPAC) near Butlerville, IN (39°02’ N, 85°54’ W’)], and central Michigan [Michigan State University Agronomy Farm: Mason Research Farm near East Lansing, MI (42°62’ N, 84°43’ W)] were selected for this study. These sites were selected on account of their geographic, climatic, and soil differences, with the aim of incorporating sites from western, central, and eastern reaches of the U.S. Corn Belt.

For each site, four years of corn and soybean yield data were collected along with the dry biomass of the preceding winter rye (when applicable as the CC treatment was not started at the SEPAC site until following the 2011 cash crop). Table 3.1 indicates relevant field management dates for all three sites.

3.3.1 Gilmore site

The corn-soybean rotation at the Gilmore site was established in 1989 with winter rye cover crop incorporated in the mid 1990s. The study is on a Nicollet (Fine-
loamy, mixed, superactive, mesic Aquic Hapludoll) soil series with an historic land use of prairie grass and wetlands. The Nicollet series consists of very deep, somewhat poorly drained soils that formed in calcareous loamy glacial till on till plains and moraines. Slopes range from 0 to 5 percent. Mean annual temperature and precipitation is 9°C and 660 mm, respectively (USDA Soil Survey).

3.3.2 Mason site

The Mason site has been under row cropping since the late 1800’s while the plots used for this study were established in the mid-1990s. The study is on a Capac (Fine-loamy, mixed active, mesic Aquic Glossudalf) soil series with an historic land use of forest. The Capac series consists of very deep, somewhat poorly drained soils formed in loam or clay loam till. These soils are on moraines and till plains. Slope ranges from 0 to 6 percent. Mean annual temperature and precipitation are 8.3°C and 813 mm, respectively (USDA Soil Survey).

3.3.3 SEPAC site

SEPAC site had been under light disc tillage and corn-soybean rotation since the mid-1990s. Cover crops were included into the rotation in the fall of 2011 and the plots were converted to NT in 2012. The study is on a Nabb (Fine-silty, mixed, active, mesic Aquic Fragiudalf) soil series with an historic land use of forest. The Nabb series consists of very deep, moderately well drained soils that formed in loess and the underlying Paleosol in till. They are moderately deep to a fragipan and are on till plains. Slope
ranges from 0 to 6 percent. Mean annual temperature and precipitation is 12°C and 1092 mm, respectively (USDA Soil Survey).

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<th>Soybean planting</th>
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Table 3.1: Dates of field management for three sites over four years.
*plots going into corn, **plots going into soybean, ***plots going into both corn and soybean
3.3.4 Corn and soybean yield and rye biomass sampling

Two representative one-meter rows of both corn and soybean were hand harvested and weighed in the field on various dates throughout the study (Table 3.1). Grain was shelled and oven dried to determine grain moisture. All yields were converted to 15.5% gravimetric moisture content for corn and 13% gravimetric moisture content for soybean and scaled up to represent Mg ha⁻¹ equivalence.

Cereal rye was sampled in the spring within one week of chemical termination. A 0.25 m² representative sample was clipped at the soil surface and separated from weedy biomass. This sample was then oven dried at 60 °C to calculate total dry biomass.

3.3.5 Statistical analysis

Data for yield was analyzed by year using the General Linear Procedure (GLM) of SAS version 9.2 (SAS Institute, 2008). Site, treatment (CC and NC) and their interactions were considered fixed effects, while rep was considered as a random effect. Mean separation was determined using the PDIFF procedure and significance was declared at p ≤ 0.10.
3.4 RESULTS AND DISCUSSION

3.4.1 2011 corn and soybean yields and rye biomass

There were no differences in mean corn (15.5% moisture corrected) or soybean (13% moisture corrected) yields between sites or treatment at any individual site in 2011.

The CC and NC corn yields at the Gilmore site were 9.66 and 9.99 Mg ha\(^{-1}\), respectively (Figure 3.1). Soybean grain yields at the Gilmore site ranged from 1.55 to 3.06 Mg ha\(^{-1}\) with a mean of 2.48 Mg ha\(^{-1}\) for both the CC and the NC treatment. The rye was terminated one week before planting in the plots going into corn and had accumulated 316 kg ha\(^{-1}\). The rye in the plots going into soybean had accumulated 555 kg ha\(^{-1}\) and was terminated on the same day the soybean was planted. This nine-day lag in termination of rye corresponds to ~75% more rye biomass in the plots going into soybean compared to those going into corn. The relatively short time span between rye termination and corn planting may have negatively impacted the germination of the corn through allelopathic effects or by immobilizing N when the corn needed it during the early stages of development. Both allelopathic effects and N immobilization may hinder corn growth if rye is not terminated early enough prior to seeding corn.

Conversely, soybeans tend to tolerate more rye biomass and do not seem to be affected by termination closer to the cash crop planting date.

In 2011 at the Mason site, all plots were planted in corn. The CC and NC corn grain yields averaged 8.79 and 9.55 Mg ha\(^{-1}\), respectively in 2011 (Figure 3.2). The
difference in mean yields is nearly 1 Mg ha\(^{-1}\), however there was a high amount of variability in both treatments with yields ranging from 5.49 Mg ha\(^{-1}\) to 11.93 Mg ha\(^{-1}\) in the CC treatments and from 6.57 Mg ha\(^{-1}\) to 12.19 Mg ha\(^{-1}\) in the NC treatments. The rye preceding the corn in the CC treatment was not sampled and the termination date was not recorded so inferences as to the potential reasons for yield reductions are difficult to make.

The “CC” treatment at the SEPAC site had not been started yet as the winter rye was not established until after the 2011-growing season. However, the corn plots that would go into winter rye averaged 9.34 Mg ha\(^{-1}\) while the NC plots averaged 9.08 Mg ha\(^{-1}\) (Figure 3.3). The soybean plots that would go into CC treatment in subsequent years averaged 3.98Mg ha\(^{-1}\), whereas the plots continuing as NC treatments averaged 2.89 Mg ha\(^{-1}\).

3.4.2 2012 corn and soybean yields and rye biomass

Significant differences in both corn and soybean yields were found between the Gilmore and SEPAC sites during the drought year of 2012. However, differences between CC and NC in either corn or soybean yields were not detected at any individual site. The differences between sites yields were likely driven more by temperature and precipitation variability or seed variety/hybrids than by either soil characteristics or management.

The 2012 CC and NC corn yields at the Gilmore site were 8.53 and 8.81 Mg ha\(^{-1}\), respectively. The soybean yields of CC treatment at Gilmore averaged 1.86 Mg ha\(^{-1}\)
while the NC soybean yields mean was 1.82 Mg ha\(^{-1}\). The rye biomass accumulated in the plots going into corn was 162 kg ha\(^{-1}\) and 324 kg ha\(^{-1}\) for the plots going into soybean. The rye going into soybean was allowed to grow for nearly a month longer than the rye going into corn allowing for the biomass to double before termination. However, in wetter years (see the 2013 results at this site) this increase in rye biomass in the final month can far exceed the growth in this dry year. The Gilmore corn yields under both treatments were significantly higher than those at the Mason site (CC \(p = 0.055\), NC \(p = 0.043\)) while the NC yields were significantly higher than at the SEPAC site (\(p = 0.067\)). This is most likely due to climatic differences between sites, however the relatively high SOC concentration and clay content of the Mollisols in Iowa compared to the Alfisols in Michigan and Indiana may have also played a role. With 2012 being a drought year at all three sites, the elevated SOC and clay may have allowed for the Gilmore site to retain more soil moisture throughout the summer growing season. However, the 2012 soybean yields for the CC treatment at the Gilmore site were significantly lower than the yields at the SEPAC site (\(p = 0.073\)). This lower soybean yield under cover crop at the Gilmore site is the opposite of what happened with respect to the corn yields. This is likely due to the difference in moisture requirements for corn and soybean with corn being more susceptible to yield loss under water stress and each crop requiring sufficient water supply at different growth stages.

The 2012 corn and soybean yields at the Mason site averaged 6.56 and 2.17 Mg ha\(^{-1}\) for the CC treatment and 6.72 and 2.27 Mg ha\(^{-1}\) for the NC treatment, respectively. The average rye biomass for the plots going into corn was 420 kg ha\(^{-1}\) and 427 kg ha\(^{-1}\) for
the plots going into soybean. This result was expected as they were planted and terminated on the same days. These corn yields were significantly lower than those observed at the Gilmore site, due most likely to climatic differences, however the sandy Michigan soils water-holding capacity likely explain some of the differences. No significance between treatments was observed at this site.

Corn and soybean yields during 2012 at the SEPAC site averaged 6.76 and 2.53 Mg ha$^{-1}$ for the CC treatment and 6.24 and 2.43 Mg ha$^{-1}$ for the NC treatment, respectively. In the first year of CC treatment at this site the average rye biomass for the plots going into corn was 1321 kg ha$^{-1}$ and 1353 kg ha$^{-1}$ for the plots going into soybean. This rye biomass growth was substantially higher than what was observed at either Gilmore or the Mason site and is likely due to a much earlier planting date in the previous fall and an earlier spring warm-up. Both corn and soybean yields were significantly lower than those observed at the Gilmore site but no significance between treatments within this site were observed. Though not statistically different both corn and soybean means of the NC treatments were lower than grain means in the CC treatment.

3.4.3 2013 corn and soybean yields and rye biomass

Significant differences in both corn and soybean yields for both CC and NC treatments were found between all sites in 2013. However, treatment differences were not detected within any individual site.
The 2013 Gilmore corn yields were 9.12 and 8.54 Mg ha\(^{-1}\) for the CC and NC treatments, respectively. The soybean yields at this site were 2.47 Mg ha\(^{-1}\) for the CC treatment and 2.42 Mg ha\(^{-1}\) for the NC treatment. Rye biomass in the corn phase of the rotation accumulated 137 kg ha\(^{-1}\) whereas the plots going into soybean yielded 523 kg ha\(^{-1}\) rye. The rye going into soybean was allowed nearly one month more of spring growth before termination, compared to the rye going into corn, leading to significantly more rye biomass (282\% more) input into the soybean plots. There were seven consecutive months of above long-term average precipitation totals in northwest Iowa leading up to a 69 mm deficit in July when the corn was in the critical tasselling stage (Hillacker, 2013). The explanation for the slight increase in the CC corn yield means may have been due to soil conservation benefits from the mulching effect of the rye residue left on the surface. This situation, where there is sufficient spring rainfall to provide rye biomass and dry summer conditions, may be where cover crops are most beneficial from a soil moisture perspective.

Corn yields for the 2013-growing season at the Mason site were 7.04Mg ha\(^{-1}\) for the CC treatment and 7.44 Mg ha\(^{-1}\) for the NC treatment. Soybean yields under CC and NC treatments for this site-year combination were 2.71 Mg ha\(^{-1}\) and 2.34 Mg ha\(^{-1}\), respectively. The rye biomass accumulated in the plots going into corn was 201 kg ha\(^{-1}\); which was nearly the same as the 254 kg ha\(^{-1}\) of biomass accumulated in the plots going into soybean. No significance was detected between treatments at this site. These corn yields were significantly lower than those observed at both the Gilmore and SEPAC sites.
Corn and soybean yields during 2013 at the SEPAC site averaged 13.41 and 13.58 Mg ha\(^{-1}\) for the CC treatment and 4.57 and 4.64 Mg ha\(^{-1}\) for the NC treatment, respectively. In the second year of CC treatment at this site the average rye biomass for the plots going into corn was 889 kg ha\(^{-1}\) and 3102 kg ha\(^{-1}\) for the plots going into soybean. Both the corn and soybean yields under CC and NC treatments were significantly higher than yields at Gilmore or Mason. Furthermore, these plots were converted to no-till following spring chisel plow in 2011. The significant increase in corn and soybean yields observed in 2013 and 2014, compared to 2011 and 2012 at the SEPAC site may be related to the conversion to no-till, however there are no control tilled plots maintained at the site to test this hypothesis.

3.4.4 2014 corn and soybean yields and rye biomass

Significant differences in both corn and soybean yields for both CC and NC treatments were found between all sites in 2014.

The 2014 Gilmore corn yields were 7.85 and 6.74 Mg ha\(^{-1}\) for the CC and NC treatments, respectively. This was a significantly (\(p = 0.056\)) higher corn yield representing a 16% increase in the CC treatment. Precipitation in northwest Iowa during July of 2014, when the corn was in the important tasselling stage, was 51 mm below the long-term averages (Hillaker, 2014). This decrease in precipitation may have affected grain development in the NC plots while the corn following rye was buffered against the moisture stress through mulch effect of the rye. The rye preceding the corn was terminated 18 days before corn planting, however, the total biomass was not
collected. The soybean yields at this site were 2.05 Mg ha$^{-1}$ for the CC treatment and 2.15 Mg ha$^{-1}$ for the NC treatment.

Corn yields for the 2014-growing season at the Mason site were 9.08 Mg ha$^{-1}$ for the CC treatment and 8.90 Mg ha$^{-1}$ for the NC treatment. Soybean yields under CC and NC treatments for this site-year combination were 3.64 Mg ha$^{-1}$ and 3.78 Mg ha$^{-1}$ respectively. The rye biomass for plots going into corn was 199 kg ha$^{-1}$ and 346 kg ha$^{-1}$ for plots going into soybean. These corn and soybean yields under both CC and NC treatments are significantly higher than the Gilmore yields and significantly lower than the SEPAC yields.

Corn and soybean yields during 2014 at the SEPAC site averaged 12.96 and 12.83 Mg ha$^{-1}$ for the CC treatment and 4.52 and 4.43 Mg ha$^{-1}$ for the NC treatment, respectively. In the first year of CC treatment at this site the average rye biomass for the plots going into corn was 1232 kg ha$^{-1}$ and 2918 kg ha$^{-1}$ for the plots going into soybean. Though the yields at the SPEAC site for both corn and soybean under CC and NC treatments were significantly higher than those at the Gilmore and the Mason sites there were no differences detected with the SEPAC site in 2014.
Figure 3.1: Gilmore corn and soybean yields (2011 – 2014) for CC and NC treatments. Different letter within year indicates significance at the $p < 0.10$ level.

Figure 3.2: Mason corn and soybean yields (2011 – 2014) for CC and NC treatments. Same letter indicates no significance within year.
Figure 3.3: SEPAC corn and soybean yields (2011 – 2014) for CC and NC treatments. Same letter indicates no significance within year. In 2011 “CC” treatments were not preceded by cereal rye.

3.4.5 Three- and four-year corn soybean harvest

The four-year average yields at the Gilmore site for the CC and NC treatments were 8.79 and 8.52 Mg ha\(^{-1}\) for corn and 2.22 Mg ha\(^{-1}\) for soybean under both treatments. The four-year average yields at the Mason site for the CC and NC treatments were 7.98 and 8.04 Mg ha\(^{-1}\) for corn and the three-year average yields for soybean were 2.84 and 2.80 Mg ha\(^{-1}\), respectively. The three-year average corn yields at the SEPAC site were 11.04 Mg ha\(^{-1}\) for the CC treatment and 10.88 Mg ha\(^{-1}\) for the NC treatments. Three average soybean yields were 3.87 and 3.83 Mg ha\(^{-1}\) for the CC and
NC treatments, respectively. The three-year averages are considered because the CC treatment had not yet started in 2011.

The multiple-year average corn yields were slightly higher for two of three sites in CC than NC treatments, where as the soybean multiple-year averages were relatively the same at all three sites. This indicates that there was neither a yield benefit nor a penalty by including winter rye cover crop into the rotation. With the potential to increase SOC and scavenge N, rye cover crops should be recommended to farmers in this region. However, as the cost of including rye is solely born by the producer while the benefits are shared through all members of society, cost share programs should be implemented to encourage farmers to adapt cover crops into their management systems.

3.5 CONCLUSIONS

There were significant differences between sites in three of the four years observed during this study for both corn and soybean yields under CC and NC treatments. However, only one site-treatment difference was observed in any year (Gilmore 2014 corn yields for CC = 7.85 Mg ha\(^{-1}\) NC = 6.74 Mg ha\(^{-1}\) p = 0.056).

The hypothesized affect of cereal rye on corn yields was confirmed in ten of eleven site-year combinations. There was not a significant reduction in corn grain yields associated with rye cover cropping. However, most farmers tend to shy away from following a grass with another grass (such as corn following rye) out of fear they will suffer yield losses. Biculture cover crop, such as cereal rye and hairy vetch combination,
Figure 3.4: Three and four-year average corn and soybean yields for three sites under CC and NC treatments.
Gilmore corn and soybean are four-year averages (2011-2014)
Mason corn is four-year average (2011-2014) and soybean is three-year average (2012-2014)
SEPAC corn and soybean are three-year averages (2012-2014)

...may enhance corn grain yields while protecting soil from erosion and surface and groundwater from NO$_3$-N leaching and should be recommended to farmers in the U.S. Corn Belt. This is an example of a win-win scenario that should be acted upon.

The hypothesized affect of cereal rye on subsequent soybean yields was not observed in any of the site-year combinations of this study. However, arguably more importantly, the soybean yields were not decreased either. The results of this study coincide with the soybean yields following rye observed by Wagner-Riddle *et al.* (1994),...
Reddy (2003), and Ruffo et al. (2004). Based on these results and the numerous environmental benefits associated with cereal rye cover cropping it should be recommended to farmers in the U.S. Corn Belt to include cereal rye into their rotations preceding soybean.

Furthermore, since the cost (economic, time, and otherwise) of cover cropping is currently born by the farmers while the majority of benefits are reaped by society as a whole, policy makers should push towards program that include cost share to encourage more U.S. Corn Belt farmers to engage in cover cropping.
REFERENCES


COMPLETE REFERENCE LIST


