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Climate-smart agriculture in Midwest cropping systems: evaluating the benefits and tradeoffs of cover crops

Andrea Diane Basche
Iowa State University

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Andrea Diane Basche

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Program of Study Committee:
Fernando Miguez, Major Professor
Thomas Kaspar
Michael Castellano
Lisa Schulte Moore
Andrew Lenssen

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DEDICATION

This work is dedicated to the future generations of the great state of Iowa, where I have been happy to call home. In particular, I look to the 7th graders at Brody Middle School in Des Moines who I helped teach from 2014-2015, that they may be the future leaders that have the courage, wisdom and foresight to protect the state's rich resources and create a better world for all.

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ABSTRACT

Climate-smart agriculture is a framework to develop and implement agricultural systems that facilitate reduced greenhouse gas emissions and increase resilience and productivity in the context of a changing climate. Winter cover crops are known to decrease soil erosion, increase soil carbon, improve water retention and have been hypothesized to reduce nitrous oxide emissions. Therefore they offer the potential to buffer projected climate change impacts for Midwestern agriculture, including increased rainfall variability. The overall objective of this dissertation research was to evaluate the mitigation and adaptation potential of cover crops in determining their efficacy as a climate-smart agricultural practice. In a global meta-analysis, it was found that cover crops do not universally reduce nitrous oxide emissions from the soil surface but that grass species and chemical termination methods are less likely to increase emissions. An analysis of seven years of crop and soil data found that the long-term use of a winter rye cover crop in a no-till maize-soybean rotation improved water retained in the soil profile and increased plant available water content by 21-22%, without sacrificing maize or soybean growth and yields. Finally, the simulation of a winter rye cover crop in a future climate predicted the practice's ability to reduce nitrous oxide emissions by up to 34%, offset soil carbon decline by 3% and decrease erosion losses by 11-29% without significantly impacting maize or soybean yields. However, the cover crop is not predicted to offset crop yield declines that may occur because of temperature and water stressors. Taken together, this research illustrates that in the context of climate adaptation and mitigation, the greatest potential benefits from a winter rye cover crop in this region are preventing soil erosion, improving soil water retention, and potentially reducing nitrous oxide emissions from the soil surface.

CHAPTER 1

GENERAL INTRODUCTION

"Out of the long list of nature's gifts to man, none is perhaps as utterly essential as the soil."
-Hugh Hammond Bennett

"A community might explore what kind of agriculture it should put on the landscape that would continue to produce a sufficient amount of food anticipating three shocks: oil reaching $300 a barrel, having only half the amount of freshwater currently available, and experiencing twice the number of severe weather events. Imagining a farming system that would be sustainable under those circumstances might prepare the community for some of the changes coming their way in the decades ahead."
-Fred Kirschenmann

Agriculture in a Future Climate

Future climate change poses tremendous risks to agricultural productivity. These risks, specific to field crops, include declines in yield, increased stressors due to floods, droughts, weeds, pests and diseases, the degradation of soil and a reduction in reliability of water resources (Hatfield, 2014; Porter et al., 2014; Walthall, 2013). A great deal of attention has been paid to the future impacts for the Midwestern United States, and the state of Iowa in particular, given that it is a national leader in commodity crop production, growing 15.5% of domestic corn and 12.5% of soybeans (USDA-NASS, 2014b). Further, the Midwestern "Corn Belt" produces one-third of corn (*Zea mays*) globally and one-quarter of its soybeans (*Glycine max*) (FAOSTAT, 2015; USDA-NASS, 2015). Therefore, climate impacts to agriculture in this region have global implications.

Scientists in Iowa recognize that major agricultural impacts will center on changes to the hydrological cycle (ICCIC, 2010). One reason for a focus on water impacts is that Iowa sits at the nexus of two dueling moisture regimes: the Gulf of Mexico to the south, where moisture is projected to increase and the North American monsoon to the west where moisture is projected to decrease (Takle, 2010). This makes precise projections for precipitation more difficult as actual changes will be a result of how those broader continental patterns shift. However, analyses of historical records indicate that rainfall variability has already increased and research with climate models indicates that it will continue to do so. Over the Midwestern United States, Groisman et al. (2012) found that compared to the 1948-1978 period, in the most recent 30 years of analysis there was a 40% increase in the frequency of daily rain events above 3 inches and multiday rain events above 6 inches. Mallakpour and Villarini (2015) analyzed stream flow data from 1962-2011 and found a significant increase in flood frequency in 34% of the stations analyzed, including approximately two dozen locations in Iowa. Global climate model analyses included in 2014 National Climate Assessment projected there will be increases in the number of days in the top 2% of heavy rainfall, the amount of rain falling in the wettest five days of the year, as well as a greater number of consecutively dry days (Pryor et al., 2014). In another assessment of a regional climate model for the Midwest, Daniel (2015) found that for the period of 2041-2070 there was an increase of 9% for the wettest 99th percentile of days and 15% for wettest 99.9th percentile of days compared to the 1971-2000 period. These observations are in agreement with the 5th IPCC Assessment's that the relationship of a warmer atmosphere and an increase in water vapor as extremely likely, where the positive feedback loop with temperature amplifies erratic and variable hydrological patterns (IPCC, 2013).

Given the projected trend toward more rainfall variation in the Midwest, it is important to note how such variation impacts the agricultural landscape. Drought years have proven problematic for soil quality and agricultural productivity. In 2012, one of the lowest 10% years for rainfall and number one warmest average year on record for Iowa (IEM Climodat, 2015), 100% of counties in the state experienced severe drought with negative impacts to soil structure such as crusting, cracking and a deterioration of soil aggregates. Such negative indicators of soil tilth reduce the ease of plant root water access, which ultimately has the potential to decrease grain yield (Al-Kaisi et al., 2013). This situation became reality when Iowa corn yields in 2012 averaged 137 bushels acre^{-1}, roughly 24% below the trend line (Al-Kaisi et al., 2013; USDA-NASS, 2014b). Interactions with increased temperature trends become important, as rising temperatures are projected to not only decrease corn and soybean yields significantly but to increase variability in yield (Challinor et al., 2014; Diffenbaugh et al., 2012; Schlenker and Roberts, 2009). Further, Lobell et al. (2014) projected that maize drought yield declines, resulting from increased water stress factors, will grow more prominent given the management trend toward yield gains from higher planting densities.

On the other end of the rainfall spectrum, impacts from flood events create their own detrimental effects. In 2008 for example, floods and heavy rainfall in Iowa resulted in some regions of the state losing more than 50 tons of soil per acre (Rogovska and Cruse, 2010) or approximately 4.2 mm year^{-1}. Putting that number into a longer-term sustainability context, Montgomery (2007) calculated a soil production rate aggregated over 1,600 studies to be 0.036 mm year^{-1}. Therefore, these parts of Iowa lost more than 100 times the rate of soil production in a single year. Further, erosion rates are predicted to grow non-linearly with precipitation increases, with changes ranging from 16-58% increases (Nearing, 2001). In Iowa, soil erosion has the potential to greatly impact economic output given the documented decline in corn yields that accompanies the loss of topsoil (Schertz, 1983). Further, more intense periods of rainfall offer greater likelihood of runoff, nitrogen and phosphorus losses (Tilman et al., 2001; VanLiew et al., 2013), which perpetuates a cycle of declining soil productivity and adverse effects on water quality.

Climate-smart Agriculture: Assessment to implementation

Beyond the Midwest, the international community has begun to prioritize conservation technologies in agriculture. The Food and Agriculture Organization (FAO) of the United Nations defines climate-smart agriculture as *"agriculture that sustainably increases productivity, resilience (adaptation), reduces/removes GHGs (mitigation), and enhances achievement of national food security and development"* (FAO, 2011). Adaptation efforts must create the capacity to cope with more frequent, increasingly difficult conditions and gradual changes in climate, even though it often is not possible to anticipate their precise nature (FAO, 2011). Climate-smart agriculture emerged as a framework in 2010, driven by the international community, as a concept to develop and implement agricultural systems that simultaneously facilitate climate adaptation and mitigation. Climate-smart agriculture may include practices which are already in use, but the approach also emphasizes implementation (Scherr et al., 2012). In this vein, scientists note that the research community must document ways that farmers, industry, consumers, and government can move toward, expand, or shift the "space" allowing multiple benefits to be achieved from sustainable farming practices (Beddington et al., 2012) and to envision landscapes that are resilient to future change (Kirschenmann, 2010). Further, other university scientists are prototyping such efforts to coordinate with multiple stakeholders in generating projects that simultaneously work to reduce economic and environmental risks faced by farmers, agribusiness and others (Jordan et al., 2013). Such efforts serve as possible models for facilitating adoption of climate-smart practices.

While there may be some broad continuity across the globe in defining climate-smart agriculture, this investigation must be done for all regions and must evaluate multi-functional goals, given the complexities of the current agricultural landscape (FAO, 2011). Moving toward a more resilient agricultural system is a complex task involving intertwined social, agronomic and economic factors that underpin individual on-farm decision-making, where perceived mitigation and adaptation efforts may be incongruent with reducing multiple climate risks. For example, a majority of farmers in Central to Eastern Corn Belt believe additional tile drainage is an adaptive measure for increased precipitation years (Loy et al., 2013). In addition, over the last several years, grassland conversion to row crops driven by high commodity prices has accelerated (Wright and Wimberly, 2013; Lark et al. 2015) thus, a combination of increasing tile drainage and intensive corn and soybean cropping systems have the potential to contribute to more nitrate loss in surface waters (David et al., 2010). Therefore a driving factor in this research is to understand *what practices will keep cropping systems in the Midwest productive and profitable into the future* given possible unintended consequences inherent in achieving a more multi-functional agricultural system (Figure 1).

Climate Adaptation Strategies: Why soil conservation? Why cover crops?

Many approaches are proposed to adapt agricultural systems to climate change (Easterling et al., 2007; Hatfield et al., 2011; Westgate and Hatfield, 2011; Wolfe, 2013), including improvements in plant genetics (e.g. genetic modifications for drought, enhanced root architectures), soil conservation (e.g. reduced tillage), agronomic management (e.g. shifting planting dates), water technologies (e.g. irrigation) and financial instruments (e.g. crop and weather insurance) (Table 1). Uncertainty around the magnitude of extremes makes adaptation somewhat difficult in how to best prioritize research resources. However, since it is known with some certainty that rainfall variability is an important impact for the Midwest, this is a valuable place to start in framing the discussion around adaptation. Of many of the strategies proposed for adaptation, the focus of this research is on a particular management practice – cover crops – that has promising potential to buffer such rainfall variability into the future because cover crops may offer soil conservation in both wet and dry years. Thus, expanding the use of cover crops should be one in a list of options that have potential as climate-smart practices for the Midwest and offer an important prioritization of soil and water conservation management practices (Delgado et al., 2011; Lal et al., 2011; White, 2015).

Cover crops offer numerous antidotes to the previously discussed climate risks: protection from soil erosion, retention of nutrients and improved water storage (Kaspar and Singer, 2011). Previous erosion studies in Iowa show that oat and cereal rye crops reduced rill erosion by 42-95% and interill erosion by 51-62% (Kaspar et al., 2001), which is on the same order of magnitude that Nearing (2001) projected erosion rates to increase in the future. In addition, the use of cover crops are found to add organic carbon to cropping systems through root and shoot decomposition, known to enhance many physical characteristics of soil, such as improving aggregate stability and reducing compaction (Blanco-Canqui et al., 2013), known benefits to improve soil response in drought (Al-Kaisi et al., 2013). Two global meta-analyses document significant increases in carbon when a cover crop is a component of a crop rotation. McDaniel et al. (2014) found that including cover crops in crop rotations led to an average 8.5% increase in total carbon concentration and Poeplau and Don (2015) calculated an average increase of 0.32 Mg C ha^{-1} yr^{-1}. However, understanding the impact of cover crops on nitrous oxide emissions is critical to determining the overall greenhouse gas budget of the practice (Basche et al., 2014). Further, there is a body of evidence demonstrating improved soil physical characteristics from the use of a cover crop that contribute to soil water dynamics, including increased porosity, decreased bulk density, increased hydraulic conductivity and greater aggregate stability (Klik et al., 1998; Rachman et al., 2003; Sainju et al., 2003; Steele et al., 2012; Villamil et al., 2006). Given the prior evidence suggesting the ability of cover crops to reduce climate risks, it is important to further quantify their impacts and benefits within agricultural systems in the Midwest.

Impact in Cover Crop System	**Idealized ecosystem need in climate change scenario, (ie: ability to buffer flood and drought effects)**	**Hypothesized Cover Crop Change: Improvement (+), Decline (-) or Neutral (+/-)**	**Indicator of Adaptation or Mitigation**
Soil Water (SW)	**Improved soil water storage and infiltration, reduced evaporation**	+	**Adaptation**
Nitrous oxide emissions (N_2O)	**Less nitrous oxide emissions**	+/-	**Mitigation**
Soil erosion (E)	**More erosion prevention, nutrient rich topsoil remains on fields, less water quality impairment**	+	**Adaptation**
Soil carbon (C)	**More soil organic matter added to fields, improved soil structure and water holding capacity**	+	**Adaptation and Mitigation**
Cash crop yields (Y)	**Cover crops will not decrease yields and could eventually lead to an increase**	**+/- moving to +**	**Adaptation**

Figure 1. Conceptual map of cover crop adaptation and mitigation impacts to Midwest Agriculture evaluated in this study. Hypothesized benefits and direction of change (table, top) and magnitude of changes (diagram, below).

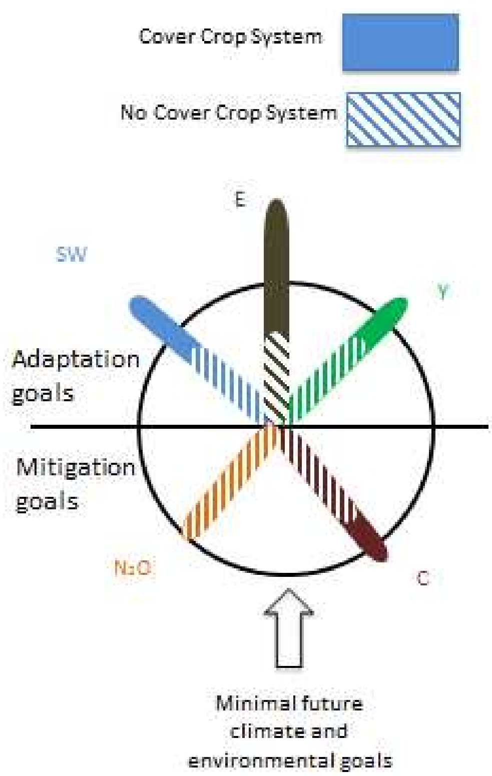

Figure 1 continued. Hypothesized magnitude of changes related to cover crop impacts quantified or predicted in this study.

Table 1. Approaches to agricultural climate adaptation, expected outcomes, limitations and costs. Adapted from Easterling et al. 2007; Wolfe 2013; Hatfield et al. 2013; Westgate and Hatfield 2011

Approaches	**Expected outcomes**	**Limitations and costs**
Plant genetics: plant breeding or genetic modifications	Emphasis for major Midwest crops on drought and heat tolerance, improved performance in extreme years	Potential for high seed and research costs, only successful if implemented in a year when it is actually hotter or drier, could prove difficult to mobilize seed resources in accordance with forecast of particular conditions in timely manner
Soil management: soil conservation, tillage, cover cropping, agroforestry, soil carbon sequestration, integration of perennial vegetation	Conservation practices that improve carbon, subsequently structure and water holding capacity, should buffer both dry and wet seasons – better water utilization and more water in the soil profile	Potential additional costs in labor and management. Need for more funds in research and demonstration of practices.

Table 1 (Continued)

Agronomic management: Planting dates, diversified crop rotations, cultivar choices, pest and weed management, equipment changes to accommodate faster planting	Planting earlier or later to accommodate for variable weather should lead to favorable yield outcomes.	Requires that new cultivars, shifting planting dates, are mobilized in accordance with forecast of particular conditions and in a timely matter. Mobilizing resources in such a manner may be difficult. New technology to plant/harvest in narrower windows is expensive and not an option for all producers.
Water: Irrigation, enhanced water monitoring technology, harvesting technologies	More irrigation has potential to reduce impacts of drought. Monitoring could help manage resources in flood years.	Comes at a high cost with potential challenge of unsustainable use of water depending on region.
Financial instruments: Crop instruments, diversified income streams	Insurance could protect against yield loss in both flood, drought or heat scenarios	High public investment that has the potential to grow with extreme events and market volatility
Human capital: Improved capacity for information sharing, extension and local resources strengthened	Increased capacity, infrastructure and end user tools could aid in dissemination under all climatic outcomes	Requires time and human capital but if coordinated efficiently and effectively costs need not be high (See Beddington et al. 2012, Jordan et al. 2013).

Challenges and Barriers

Despite known benefits, it is estimated that cover crops are used on only 2.3% of harvested agricultural land in the Midwestern United States and on only 1.6% of the land for Iowa (USDA-NASS, 2014a). Arbuckle and Ferrell (2012) found that in a survey of Iowa farmers 61% of respondents believe there is not enough time between harvest and winter to justify their use. Farmers cite challenges with the additional labor, time and management required for cover crop use as well as their potential to decrease cash crop yields as concerns with the practice (SARE-CTIC, 2013). Arbuckle and Roesch-McNally (In Press) also found that higher levels of perceived risks, such as compromising cash crop yields and delaying spring planting, were negatively associated with cover crop adoption for Iowa farmers. This analysis also concluded that more access to information and technical assistance were critical factors for those farmers in their decision to adopt the practice. Similarly, Singer et al. (2007) also point to a need for more educational programs focused on cover crop management. Leading practitioners and researchers cite a need to better quantify longer-term impacts; specifically, research supporting an absence of yield decrease, which may help offset short-term producer concerns (Carlson and Stockwell, 2013; Mine et al., 2014). Therefore the objectives of this research are aimed toward advancing our understanding of long-term cover crop impacts with the ultimate goal of informing their broader adoption on the landscape.

Dissertation Organization

The overall objective of this research was to advance scientific understanding of how cover crops impact the long-term carbon, water and nitrogen dynamics in Midwest cropping systems. Specifically, this research will focus on quantifying nitrous oxide emissions, soil water dynamics, cash crop yield trends, soil erosion and changes in soil carbon. In the aggregate, quantifying these impacts will help determine the value of cover crops as a climate-smart strategy for the future. The overarching hypothesis motivating this work is that cover crops can improve key adaption and mitigation indicators to Midwest cropping systems.

Chapter one investigates nitrous oxide (N_2O), a major agricultural greenhouse gas loss, in agroecosystems including cover crops, using meta-analysis methodology. The objectives of the meta-analysis were to summarize quantitatively the effect of cover crops on nitrous oxide emissions and to improve an understanding of the mechanisms behind this effect, through evaluating the effect of both environmental and management variables.

Chapter two is an analysis of data collected over seven years (2008-2014) from a long term research site in Central Iowa to understand how the continuous use of cover crop affected crop and soil dynamics over a series of wetter and drier years, given that more rainfall variability is projected for the Midwest. My research questions for this project were: How is soil water content affected by the winter rye cover crop? How is soil water storage affected by the cover crop? Which soil water retention properties are affected by the cover crop? Does the water use from the cover crop negatively impact maize and soybean growth?

Chapter three utilizes a cropping systems platform (APSIM) calibrated with data from a field site in Central Iowa with a winter rye cover crop and control treatment for more than thirteen years. The APSIM platform was specifically designed to answer questions on interactions of management and climate and the goal of this project was to quantify several indicators of climate adaptation and mitigation, such as long term yield impacts, organic matter changes, soil erosion and nitrous oxide emissions.

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CHAPTER 2

DO COVER CROPS INCREASE OR DECREASE NITROUS OXIDE EMISSIONS? A META-ANALYSIS

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Andrea D. Basche[1,2], Fernando E. Miguez[3], Thomas C. Kaspar[4], and Michael J. Castellano[5]

Abstract

There are many environmental benefits to incorporating cover crops into crop rotations, such as their potential to decrease soil erosion, reduce nitrate leaching and increase soil organic matter. Some of these benefits impact other agroecosystem processes, such as greenhouse gas emissions. In particular, there is not a consensus in the literature regarding the effect of cover crops on N_2O emissions. Compared to site-specific studies, meta-analysis can provide a more general investigation into these effects. Twenty-six peer reviewed articles including 106 observations of cover crop effects on N_2O emissions from the soil surface were analyzed according to their response ratio, the natural log of the N_2O flux with a cover crop divided by the N_2O flux without a cover crop (LRR). Forty percent of observations had negative LRRs, indicating a cover crop treatment which decreased N_2O, while 60% had positive LRRs indicating a cover crop treatment which increased N_2O. There was a significant interaction between N rate and the type of cover crop where legumes had higher LRRs at lower N rates than non-legume species. When cover crop residues were incorporated into the soil, LRRs were significantly

1. Graduate Research Assistant, Department of Agronomy, Iowa State University
2. Primary Researcher and Author
3. Assistant Professor, Department of Agronomy, Iowa State University
4. U.S.D.A. Agricultural Research Service, National Laboratory for Agriculture and the Environment, Ames, Iowa
5. Associate Professor, Department of Agronomy, Iowa State University

higher than those where residue was not incorporated. Geographies with higher total precipitation and variability in precipitation tended to produce higher LRRs. Finally, data points measured during cover crop decomposition had large positive LRRs and were larger than those measured when the cover crop was alive. In contrast, those data points measuring for a full year had LRRs close to zero, indicating that there was a balance between periods when cover crops increased N_2O and periods when cover crops decreased emissions. Therefore, N_2O measurements over the entire year may be needed to determine the net effect of cover crops on N_2O. The data included in this meta-analysis indicate some overarching crop management practices that reduce direct N_2O emissions from the soil surface such as no soil incorporation of residues and using non-legume cover crop species. However, our results demonstrate that cover crops do not always reduce direct N_2O emissions from the soil surface in the short term and that more work is needed to understand the full global warming potential of cover crop management.

Key words: cover crops—global warming potential—meta-analysis—nitrous oxide

Introduction

Agricultural soils account for 69% of nitrous oxide (N_2O) emissions in the United States (US EPA 2013). This occurs because nitrogen (N) is an essential nutrient for agricultural production: N is added to soil as N fertilizer and manure, released from soil organic matter, and has high reactivity and mobility in terrestrial ecosystems (Robertson and Vitousek 2009). Fertilizer N recovery efficiency for major cereal production is less than 50% and even as low as 20% (Cassman et al. 2002), which potentially makes large quantities of N available for the biological processes that release N_2O. Nitrous oxide, which has 300 times the radiative forcing per mass unit compared to carbon dioxide (CO_2), has been calculated to be the largest contributor to global warming potential from agricultural cropping systems (US EPA 2013; IPCC 2007; Robertson et al. 2000). Therefore, small reductions in N_2O emissions from agricultural soils can have an overall large impact on global warming potential. The challenge is to find agricultural management practices with consistent reductions in N_2O emissions across locations, cropping systems, and years given the high spatial and temporal variability of emissions (Venterea et al. 2012).

Emissions of N_2O from terrestrial ecosystems are a function of available mineral N, soil water content, the availability of electron donors (such as labile C) and soil physical properties (Davidson et al. 2000; Firestone and Davidson 1989, Venterea et al. 2012). Cover crops may impact aspects of all these processes in ways that could potentially increase or decrease N_2O emissions as is outlined in table 1. For example, a growing cover crop can decrease soil mineral N by incorporating it into its biomass, while a legume cover crop may increase soil mineral N via N fixation (Kaspar and Singer 2011). While alive, cover crops can decrease soil water through transpiration. After termination, the mulching effect of cover crop residues on the soil surface may increase soil water and the potential for denitrification depending upon timing of precipitation (Dabney 1998). Additionally, decomposing cover crop residues can temporarily immobilize soil N and then later increase soil pools of labile C and inorganic N (Kaspar and Singer 2011; Steenwerth and Belina 2008) which will also impact dynamics of N_2O emissions.

There are many well researched benefits to incorporating cover crops into crop rotations, such as their potential to decrease soil erosion, reduce nitrate (NO_3^-) leaching, increase soil organic matter, reduce pest and weed pressure, and provide additional soil N for cash crops (Kaspar and Singer 2011; Doran and Smith 1991). However, the net impact of cover crops on N_2O is not well understood (Cavigelli et al. 2012; Cavigelli and Parkin 2012). Although cover crops may temporarily decrease soil nitrate (NO_3^-) pools and leaching losses, C can be the substrate limiting N_2O emissions in some agroecosystems; in these situations, a cover crop's contribution to the labile C pool can enhance N_2O emissions from the soil surface (Mitchell et al. 2013).

Meta-analysis is an approach that can be used to improve understanding of the factors affecting N_2O emissions through the systematic review and quantitative summary of effect size from individual studies. Many studies investigating cover crops and N_2O are conducted on short time scales (≤ 2 years) under specific management and climate conditions which may make it difficult to detect differences. Meta-analysis allows these studies to be pooled and the factors affecting N_2O emissions investigated. The effect of other conservation practices on N_2O emissions have been similarly evaluated using meta-analytic methods (Six et al. 2004; Van Kessel et al. 2013) but none to our knowledge that have used meta-analysis to examine the existing literature on cover crops effects on N_2O.

The objectives of this study were to use a meta-analysis approach to: 1. examine the relative impact of cover crops on N_2O emissions; and, 2. determine what management and environmental factors contribute to variability in cover crop effects on N_2O emissions. There were several factors that we hypothesized would have a large contribution to this variability. First, we hypothesized that the type of cover crop (legume versus non-legume) would have different effects on N_2O emissions; namely legumes would have a greater potential to increase N_2O emissions versus non-legumes. Second, we hypothesized that precipitation and cover crop biomass would impact N_2O emissions because denitrification also requires anaerobic conditions and C. Finally, we hypothesized that the timing of measurements was influential in how cover crops impact N_2O, namely that the period immediately following cover crop termination and the subsequent decomposition would have the largest N_2O emissions because of N and C release from residues.

Materials and Methods

Database Development. For the purposes of this study, we defined a cover crop as a plant not intended to be harvested that is grown during a fallow period between harvest and planting of two cash crops. This included treatments labeled as cover crops, green manures, or catch crops. A literature review utilizing electronic databases Google Scholar and Web of Science was conducted with the following search string: "nitrous oxide emissions *or* greenhouse gas emissions *and* cover crops *or* green manures *or* catch crops." This combination of key terms resulted in approximately five thousand papers. To reduce the number of papers included in the meta-analysis the following criteria were applied:

1. Studies in which the cover crop is not harvested and is grown between the harvest and planting of cash crops.
2. Studies reporting N_2O measurements.
3. Studies with a control treatment varying only in the inclusion of a cover crop and keeping all other management practices such as tillage and N additions equal.
4. Studies that provided enough information (standard errors, standard deviations, coefficients of variation, etc.) about experimental error either in the published paper or in information that was provided by the authors when contacted to allow for an estimate of within study variance.
5. Studies published before December 2012.

On the basis of these criteria, 26 peer reviewed studies, representing 19 field expeririments (83 observations), two growth chamber studies (9 observations), and five modeling experiments with validation data (14 observations) were selected for inclusion in a database (table 2, n=106 observations).

We omitted studies measuring emissions from cover crop treatments where the cover crop was not grown in the soil on which the measurements were taken (Bhattacharyya et al. 2012; Petersen et al. 2013). We also omitted papers analyzing emissions of varied cropping rotations if they did not have a true control treatment aligning with the cover crop treatment, as these would not allow for a proper comparison (Liebig et al. 2010; Gomes et al. 2009). If an experimental design matched our criteria, but the publication did not include enough detail to perform required calculations, authors were contacted when possible to obtain this information.

Data Analysis. Environmental and management factors were included in the database to examine factors that might be correlated with variabilility among observations. The full list of these factors is summarized in table 3 and describes categorical versus numeric variables and the number of observations included in each analysis. For some of the factors, information that was not directly available in the studies was derived from other sources and is described below.

Precipitation: Unless the rainfall data was explicitly reported by the experiments, NOAA's Global Historical Climatology Network-Daily database was utilized (http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/index.php) from the closest available stations over the specific range of dates when N_2O was sampled.

Soil Properties: Reported values for soil texture (% sand, silt, clay), pH, organic C and drainage class categorization, were directly included in the database. If these values were not reported, the Web Soil Survey (Soil Survey Staff 2012) or literature for experiments conducted on the same fields was utilized. Drainage for non-U.S. sites was determined either via contacting individual authors or by soil classification. Soil classification was determined by the referenced literature and all sites were converted to one of the World Reference Base Group and US Soil Classification Group equivalents using Krasilnikov et al. (2009).

Period of N_2O measurement: The included experiments varied in the length of time and time of year over which N_2O emissions were measured. Thus, we divided the observations based on the time periods into the following categories: 1. Full year; 2. Cover crop growth; 3. Cover crop decomposition; 4. Cash crop growth.

These divisions allowed for an analysis of how cover crops influence N_2O fluxes at different times of the year. For full year, the included observations measured throughout the entire span of at least one entire year. For cover crop growth, the period coincided with the time that the cover crop was alive and growing. In many studies, this aligned with the winter season. For cover crop decomposition, the period coincided with the time of cover crop termination and potential incorporation into the soil. Depending upon the design of the experiments, this period lasted between two weeks at minimum and two months at maximum. This period often aligned

Table 1. Drivers of N_2O loss and potential influential factors investigated in the meta-analysis. A full description of database variables appears in Table 3.

Denitrification Driver	**Database Factor**
Mineral nitrogen	• C:N residue ratio • Type of cover crop • Incorporation of residue • N fertilizer rate Tillage
Reactive carbon	• Soil Organic Carbon • Biomass input from cover crop • Type of cover crop • Incorporation of residue • Tillage
Soil water	• Biomass input from cover crop • Precipitation • Drainage
Soil physical properties	• Bulk density • Soil texture

with the spring season as well as fertilization events. For cash crop growth, the period coincided with the growth of the main cash crop. This period often aligned with the summer and fall.

The dependent variable was the ratio between the N_2O flux with a cover crop treatment to N_2O flux without a cover crop:

$$RR = \frac{\text{N2O emissions Cover Crop Treatment}}{\text{N2O emissions No Cover Crop Treatment}} \qquad [1]$$

Response ratios (RR) were calculated for all combinations of cover crop and no cover crop (control) treatments within studies where these treatment pairs varied solely in the inculsion of a cover crop. Thus, the number of observations obtained from each study for the meta-analysis varied according to the study's experimental design. Within studies, different cover crop treatments (factorial experiments investigating for example tillage and cover crops), measurement periods (N_2O emissions reported by season or by individual years), or different species of cover crops were all counted as individual observations and response ratios were determined for each of them.

Then equation [1] was natural log transformed (Hedges et al. 1999) to normalize the data. The log ratio ensure that changes in the numerator and denominator are affected equally.

$$LRR = \ln RR \qquad [2]$$

Within study error (V_i) was calculated following the method of Hedges et al. (1999), using reported estimates of variances and converting to standard deviations based on experimental replications:

$$Vi = \frac{\mathrm{SD}cc^2}{\mathrm{n}cc{*}\mathrm{y}cc^2} + \frac{\mathrm{SD}ncc^2}{\mathrm{n}ncc{*}\mathrm{y}ncc^2} \qquad [3]$$

where SD*cc* is the standard deviation of the cover crop treatment, n*cc* is the replications of the cover crop treatment, y*cc* is the mean N_2O emissions of the cover crop treatment and *ncc* represents the N_2O emissions of the control or no cover crop treament. Equation [3] assumes that reported means are normally distributed.

The first step of the analysis was to determine if there was homogeneity among the LRR values from all the studies in the dataset (Hedges and Olkin 1985; Miguez and Bollero 2005). This tests the assumption that all of the LRR values came from the same population. If the test is significant, the effect of cover crops varied among observations and other factors were affecting the response. If the test was not significant, then we could conclude that the cover crops had a similar effect across observations.

An inverse variance weighting factor (W_i) was used in this step to weight each of the 106 LRR values, where studies with larger variances were weighted less heavily in the analysis. This is one way by which we can account for the assumed unequal variances among studies (Hedges et al. 1999).

$$Wi = {}^{1}\!/_{Vi} \qquad [4]$$

In the next step of the analysis, mixed model regression analyses were conducted to individually examine the relative effects of each of the 18 environmental and management factors on LRR (ln of response ratio) while accounting for the variation between studies (St-

Pierre 2001) with the weighting factor [4]. The database's environmental and management factors were treated as fixed effects while study and intercept were treated as random effects. The statistical model used was:

$$L_{ij} = \beta_o + s_i + \beta_1 A_{ij} + b_i A_{ij} + e_{ij} \qquad [5]$$

L_{ij} is natural log of the response ratio of i^{th} study, receiving j^{th} level of fixed factor A (factors in the analysis, table 3). β_o is the overall intercept across all studies. s_i is the random effect due to the i^{th} level of study ($i = 1,\ldots,26$). β_1 is the fixed regression coefficient of L_i on A across all studies. b_i is random effect of study i on the regression coefficient β_1. e_{ij} is the residual error. This general model was first used to test each of the 18 factors individually. In these analyses, the N rate factor was found to have the largest effect on L_{ij}. Next, a second series of regression analyses were performed using models with the N rate factor plus one of the other 17 factors and its interaction with N rate. The statistical analysis was performed using the MIXED procedures of SAS (SAS Institute 2010).

For studies that simultaneously measured changes to NO_3^- leaching, response ratios were generated to estimate the effect of the cover crop on these N fluxes. These response ratios represent the natural log of NO_3^- leaching in the study's cover crop treatment divided by the measured value from the no cover crop treatment. When analyzed alongside the N_2O LRR values created in the same manner, these values provide a more complete understanding of a cover crops role in these parts of the N cycling.

Finally, a sensitivity analysis was performed in order to test the robustness of the database and overall conclusions. We repeated the homogeneity test and mixed model regression analyses excluding all individual field and growth chamber studies one at a time as well as for a subset of the data excluding all of the modeling studies (Tudoreanu and Phillips 2004; Philibert et al. 2012). This provided an indication of whether the dominant factors were still significant as the database changed.

Table 2. Summary of studies included in the meta-analysis

Cash Crop(s)	**Cover Crop(s)**	**Location**	**Reference**
Oats	Non-Legume and Legume	Scotland, UK	Baggs et al. 2000
Corn	Non-Legume and Legume	Maryland, USA	Rosecrance et al. 2000†
Rice-Wheat	Legume	Ludhiana, India	Aulakh et al. 2001
Rice	Legume	Jiangxi, China	Xiong et al. 2002
Wheat-Corn	Non-Legume and Legume	England, UK	Baggs et al. 2003
Corn	Non-Legume	England, UK	Sarkodie-Addo et al. 2003
Corn	Legume	Nyabeda, Kenya	Millar et al. 2004
Barley	Non-Legume	Foulum, Denmark	Olesen et al. 2004*
Soybean	Non-Legume	Iowa, USA	Parkin et al. 2006†
Corn-Soybean	Non-Legume	Iowa, USA	Parkin and Kaspar 2006
Corn-Soybean	Non-Legume	Illinois, USA	Tonitto et al. 2007*
Corn-Soybean	Non-Legume and Legume	Iowa, USA	Farahbakhshazad et al. 2008*
Corn-Soybean	Non-Legume	Michigan, USA	Fronning et al. 2008
Grapes	Non-Legume	California, USA	Steenwerth and Belina 2008
Rice	Non-Legume and Legume	Kanto Plains, Japan	Zhaorigetu et al. 2008
Corn-Pasture-Alfalfa	Non-Legume	Pennsylvania, USA	Chianese et al. 2009*
Corn-Soybean	Non-Legume	Iowa, USA	Jarecki et al. 2009
Corn Silage	Legume	Turin, Italy	Alluvione et al. 2010
Corn-Tomato, Tomato-Cotton, Tomato-Safflower-Corn-Wheat	Non-Legume and Legume	California, USA	De Gryze et al. 2010*
Tomato	Legume	California, USA	Kallenbach et. al 2010

Table 2 (continued)

Corn	Non-Legume	Michigan, USA	McSwiney et al. 2010
Tomato	Non-Legume	California, USA	Barrios-Masias et al. 2011
Corn	Non-Legume	New York, USA	Dietzel et al. 2011
Barley	Non-Legume	Foulum, Denmark	Petersen et al. 2011
Corn-Soybean	Non-Legume	Indiana, USA	Smith et al. 2011
Tomato	Non-Legume	California, USA	Smukler et al. 2012

Notes
*Model simulation experiment
†Growth chamber experiment

Table 3. Description of database factors included to analyze variability in the cover crop effects on N_2O.

Factor	**Description of Categorical Factors and Range for Numerical Factors**	**Number of Observations**
Tillage	No Tillage, Conventional Tillage	74
C:N residue ratio	9-48	57
Soil bulk density	1.2-2.65	67
pH	5.5-8.1	89
Type of cover crop	Legume, Non-Legume, Biculture	106
N rate (kg ha^{-1})	0-303 (kg/ha)	103
Soil incorporation of residues	Yes, No	84
Kill date	Days between cover crop termination and cash crop planting (1-25)	71
% Sand	8%-80%	106
% Silt	11%-73%	106
% Clay	5%-45%	106
% Organic carbon 0-30 cm	0.38% -2.10%	97
Cover crop biomass (kg/ha)	280-14400	65
Total precipitation (mm)	11-906	77
Standard deviation precipitation (mm)	0.5-40	77
Drainage	Well-drained, Poorly-drained	69
Period of measurement	Full Year, Cover crop growth, Cover crop decomposition, Cash crop growth	80
Experiment type	Field, Model, Growth Chamber	106

Results and Discussion

Overall. A test of homogeneity for the data set was significant (entire data set p=<0.0001, excluding modeling studies in sensitivity analysis p=<0.0001), indicating that the LRRs varied significantly among observations. This means that the effect of cover crops varied among the data points in our analysis and that other factors were affecting the response. Forty percent of the studies assessed in this analysis showed that cover crops decreased N_2O emissions (negative LRR) and 60% of the studies showed that cover crops increased N_2O emissions (positive LRR; figure 1). To analyze these general trends, other factors that potentially affect N_2O emissions are discussed separately. Table 4 presents the results of the regression analysis of factors affecting the LRR including regression coefficients for the continuous variables. Positive coefficients indicate that LRR increases with increases the independent variable, while negative coefficients

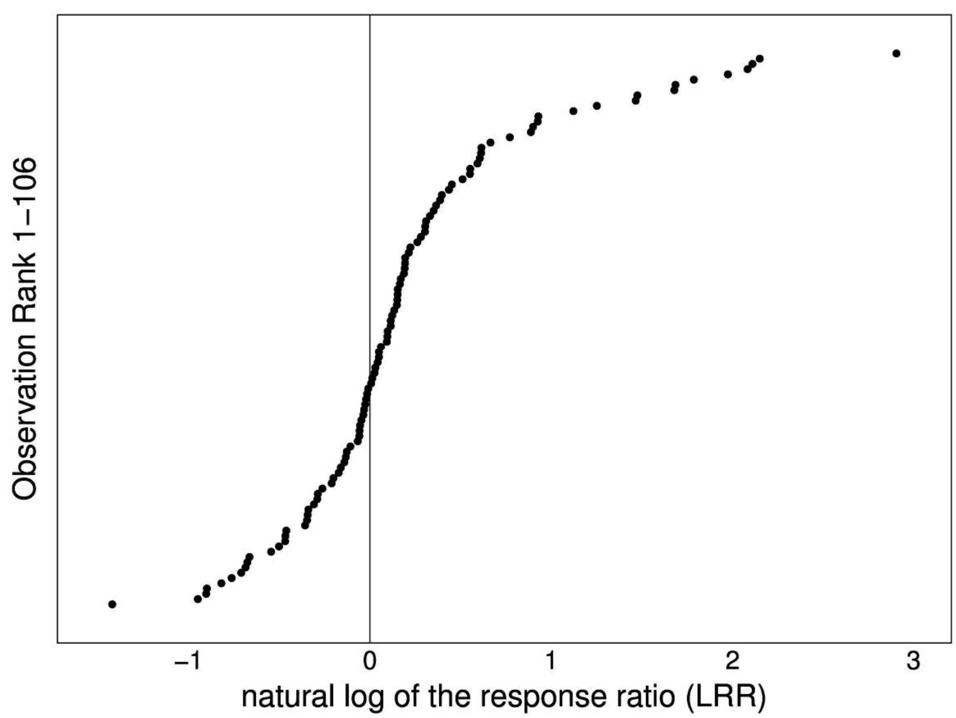

Figure 1. Natural log of response ratios (LRR) for 106 observations in the dataset, where the response ratio represents the N_2O flux with a cover crop divided by the N_2O flux without a cover crop.

indicate that the LRR decreases with increases in the independent variable.

Nitrogen Rate. It is well documented that higher N rates increase N_2O emissions (Eichner 1990; Bouwman et al. 2002; Stehfast and Bouwman 2005). Our statistical analyses evaluating management and environmental factors revealed that N rate explained more of the LRR variability than other factors (table 4). In the sensitivity analysis, N rate was significant (at the p<0.0001 level) when excluding the modeling experiments and in 100% of the regression analyses when excluding each of the 19 field and 2 growth chamber studies. As a result, interactions with N rate and other factors were investigated.

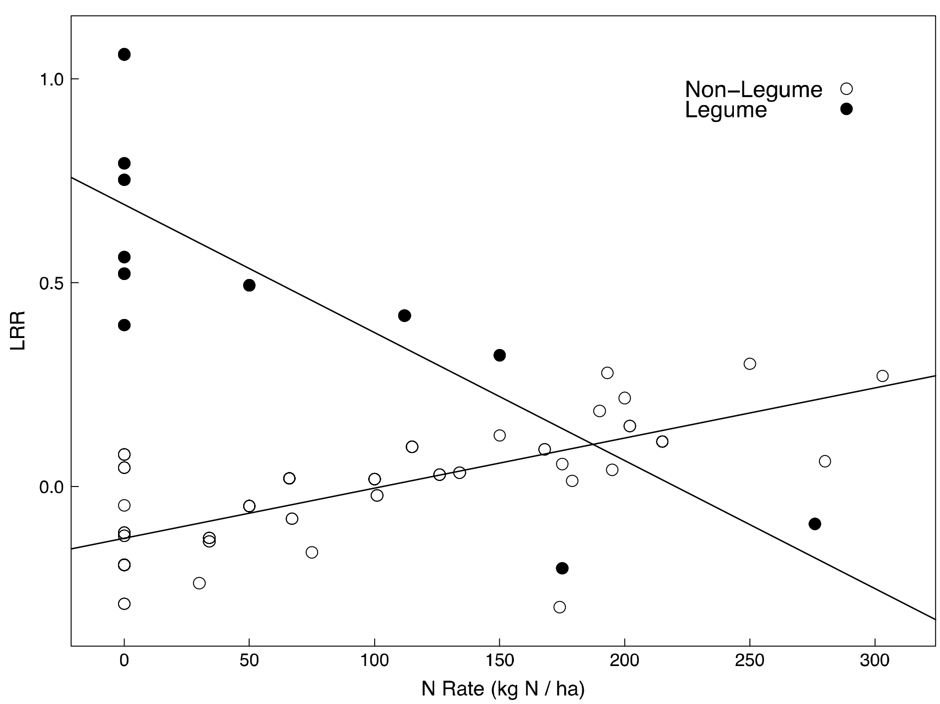

Figure 2. Response ratios of legume versus grass cover crop species as a function of fertilizer N rate. At the 0 N rate, legume cover crops have a higher response ratio than grass cover crop species. Across a range of N application rates, the response ratio for non-legume cover crop species only increases slightly; for legumes the trend declines.

Table 4. F, p values for all environmental and management factors in the mixed model regression analysis. Regression coefficients are presented for the continuous variables analyzed.

Source	DF	Error DF	Regression Coefficient	F Value	Pr > F
Tillage	1	54		2.7	0.106
C:N residue ratio	1	43	-0.04	2.17	0.1483
Soil bulk density	1	51	0.97	2.7	0.1063
pH	1	65	0.68	15.57	0.0002
Type of cover crop	2	78		2.51	0.0878
N Rate	1	77	0.00	364.58	<.0001
Soil Incorporation	1	64		5.84	0.0186
Kill Date	1	53	-0.03	1.14	0.2901
% Sand	1	79	0.36	0.36	0.5494
% Silt	1	79	-0.24	0.12	0.7297
% Clay	1	79	-1.23	0.65	0.4217
% OC	1	74	-0.56	4.05	0.0478
Cover Crop Biomass	1	49	0.00	0.74	0.3947
Total precipitation	1	58	-0.00	8.49	0.0051
Standard deviation precipitation	1	58	0.11	10.66	0.0018
Drainage	1	54		0.03	0.8693
Period of Measurement	3	57		54.94	<.0001
Experiment Type	2	80		0.73	0.4862

There was a significant interaction between the type of cover crop and N rate (figure 2). When no additional N is applied (0 N application rate), legumes exhibited higher LRRs than non-legume species. This is consistent with the results of Gomes et al. (2009) who found that legume cover crop residues, which have C:N ratios less than 25, stimulated N mineralization rates in maize systems with no additional N applications. Because a significant quantity of mineralized N is subsequently nitrified, this many enhance NO_3^- substrate for N_2O production.

In a laboratory incubation experiment, Huang et al. (2004) observed that low C:N crop residue ratios increased N_2O emissions. Consistent with the negative relationship between crop residue C:N ratios and N_2O emissions in the absence of additional N inputs, non-legume cover crops showed a slight increase in LRRs as N fertilizer rate increased, reflecting the importance of both C and N for the denitrification process.

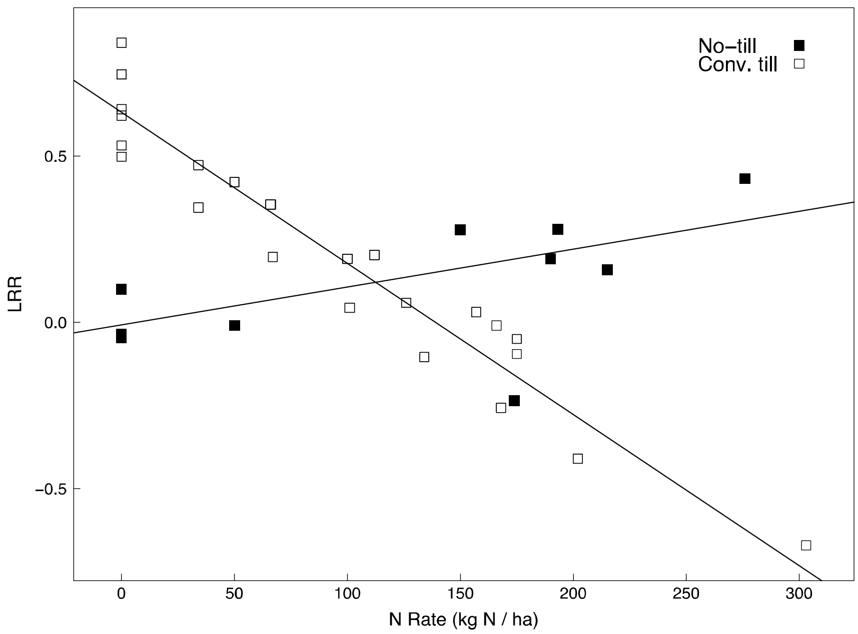

Figure 3. Response ratios (natural log of N_2O flux with a cover crop divided by the N_2O flux without a cover crop) of conventionally tilled and no tilled systems as a function of N application rate. Cover crops reduced response ratios at higher N rates in conventionally managed systems. No till systems increased response ratios slightly (compared to

There was also a significant interaction between N rate and tillage system (figure 3). Mechanical soil disturbances have been observed to stimulate C mineralization and net N mineralization (House et al. 1984; Beare et al. 1994; Omonode et al. 2011) due to the disruption of soil aggregates which expose organic C to microbial decomposition. In no-till systems, LRRs slightly increased with increasing N rate. This may have occurred because increasing cover crop biomass on the soil surface with increasing N fertilizer rate could have mulched the soil surface keeping it slightly wetter. In conventionally tilled systems, lower N rates tended to result in positive LRRs. This suggests that at higher N rates in a conventionally tilled system, the cover crop may contribute to a reduction in N_2O emissions relative to the control treatment without cover crops.

Further, even negative LRRs (cover crop treatments reduced N_2O) may not reflect a large reduction in the overall magnitude of N_2O emissions, particularly with high N fertilization rates. Table 5 includes a subset of studies reporting N_2O in kg ha^{-1} (LRRs were generated using the reported units which varied by study and the length of measurement) to demonstrate the magnitude of changes with and without cover crops. Cover crops reduced N_2O emissions at high N rates (~1-2 kg N_2O difference in study 1 & 2) or by a neglibile amount at 0 N rates (study 3). In other studies, cover crops increased N_2O emissions by 2 to 4 kg ha^{-1}at higher N rates (study 4 & 5). Finally, study 6 indicated a large increase (~40 kg N_2O) in N_2O emissions at a 0 N rate, given the large N contribution from a legume cover crop and the anaerobic soil conditions in the cropping system. Further, this large release of N_2O occurred while the cover crop was decomposing, a period observed to have high N_2O emissions (figure 5, discussion below).

Type of Cover Crop. Cover crops were categorized into the following types: legume (such as clover, vetch, field bean, pea varieties), non-legume (such as cereal rye, annual ryegrass, oats, wheat, radish mustards), and bi-culture species (such as vetch and rye mixes). In general, legumes typically resulted in positive LRRs while the LRRs for non-legume and biculture species were close to zero (figure 4). Statistical analysis revealed that there was a significant difference at the $p<0.10$ level in response ratios between the legume, cover crop type non-legume and bi-culture groups. In the sensitivity analysis excluding the five modeling studies, type was found to be significant (p=0.002) and we thus cannot reject our hypothesis that cover crop type influences cover crop impact on N_2O emissions. Because cover crops take up N that might otherwise be lost to leaching or because legume cover crops can fix N, cover crops may increase soil N availability during decomposition and thus, may increase the available NO_3 substrate for denitrification and N_2O emissions within agricultural fields.

Table 5. Magnitude of N_2O changes with and without cover crops for database subset.

No cover crop N_2O emissions (kg N/ha)	**Cover crop N_2O emissions (kg N/ha)**	**Cropping system and CC species**	**Measurement period**	**N application rate**	**Reference**
7.5	5.3	Corn in Corn Soybean, 70% rye/ 30% oat	Full year	175 kg/ha	Jarecki et al. 2009
3.7	2.3	Soybean, Winter Rye	Winter (cover crop growth)	195 kg/ha	Parkin et al. 2006
1.5	1.4	Soybean in Corn Soybean, Annual Ryegrass	Full year	0 N	Smith et al. 2011
11.3	15.4	Corn in Corn Soybean, Winter Rye	Full year	215 kg/ha	Parkin and Kaspar 2006
3.8	5.1	Corn in Corn Soybean, Annual Ryegrass	Full year	193 kg/ha	Smith et al. 2011
9.3	50.2	Rice-Wheat, Sesbania	Spring (cover crop decomposition)	0 N (176 kg/ha from legume CC)	Aulakh et al. 2001

Period of Measurement. Based on the period of measurement, cover crops influenced N_2O dynamics differently throughout the year (p<0.0001). The sensitivity analysis further revealed that period of measurement was significant (at the p<0.05 level) in 95% of the statistical models when excluding individual studies. Data points based on measurements made across an entire year had an average response ratio close to zero compared to the other periods of measurement (figure 5). This may suggest that there is a net neutral effect of a cover crop on N_2O emissions when measured over longer timescales. Figure 5 illustrates that even if particular periods of the year see larger N_2O impacts of a cover crop, a full year time scale may actually find a net neutral effect. More long-term field experiments measuring N_2O over the entire year are needed to better understand these dynamics.

Our analysis indicated that the highest LRRs were data points measuring during the cover crop decomposition period, consistent with our hypothesis. Rosecrance et al. (2000) observed the largest N_2O fluxes over the course of a growth chamber experiment in the five days post cover crop termination with rye, vetch and a mixture of both (C:N of 21, 10 and 14 respectively). They concluded that additional C substrate plus available mineral N contributed to high N_2O emissions during this period. Aukulah et al. (2001) also found that N_2O production was highest in the initial four week period following legume cover crop soil incorporation in a flooded rice system. They attributed this to the interaction between NO_3^- and organic C availability, given that soil water content and temperature remained consistently favorable for denitrification. Sarkodie-Addo et al. (2003) measured NO_3^-, NH_4^+ and N_2O for 55 days post incorporation of a wheat and winter rye cover crop with and without fertilizer. Fertilized plots had positive LRRs and non-fertilized plots had negative LRRs. They reported that the decrease in N_2O emissions with cover crops in the non-fertilized plots could be a result of temporary N immobilization from the cover crop's C contribution. The results of the studies measuring N_2O during the cover crop decomposition period suggest that N_2O emissions are affected by the interaction of C input and N availability. Cover crop residues with low C:N ratios generally increased N_2O emissions (positive LRR, figure 6) during the decomposition period. This is consistent with observations of Millar et al. (2004) that N_2O from systems with legume cover crops were positively correlated with residue N content. Further, the positive LRR observed during the growth of the cash crop may indicate that there is still some cover crop decomposition happening during this period.

Studies measuring during the growth of the cover crop period had the lowest mean LRR of all the periods of measurement (figure 5). This could be a result of cover crop N uptake as well as the fact that this period often occurred during the winter when temperatures are lower. Temperature is important because microbial process rates including N mineralization, nitrification and denitrification exponentially decline with decreasing temperature (Stanford et al. 1975). In a growth chamber study, in which temperature was controlled, Parkin et al. (2006) found that winter rye cultivated with manure treatments reduced available soil NO_3^- as well as N_2O emissions compared with levels measured in the no cover crop treated pots. This suggests that crop N uptake creates a larger sink for the soil mineral-N pool than N_2O emissions or NO_3^- leaching. Dietzel et al. (2011) measured N_2O emissions in a maize-winter rye cover crop system over two winter and spring seasons. The two years varied significantly in winter conditions which altered the soil water status by changing the frequency of freezing and thawing cycles. The warmer winter resulted in more negative LRRs than the colder winter when more freeze thaw cycles were present. In this study, the cover crop response ratio's dependence on weather variability may further illustrate the value of measuring over multiple seasons or years (larger time scales) to better understand annual cover crop N_2O dynamics.

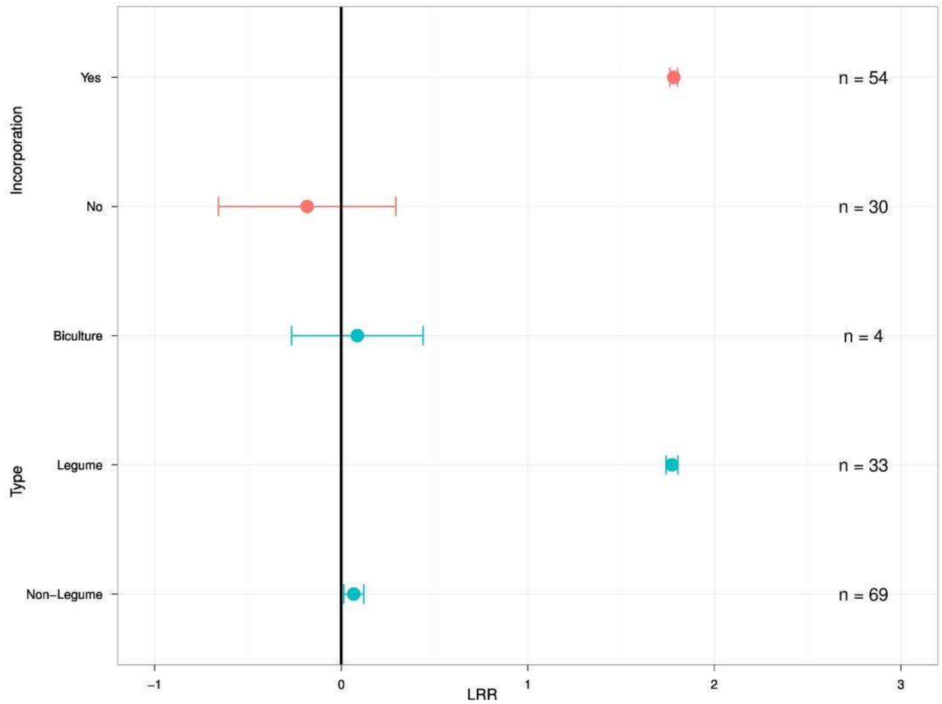

Figure 4. Mean response ratios (and 95% confidence intervals) for management factors included in the meta-analysis: the type of cover crop and soil incorporation of cover crop residues.

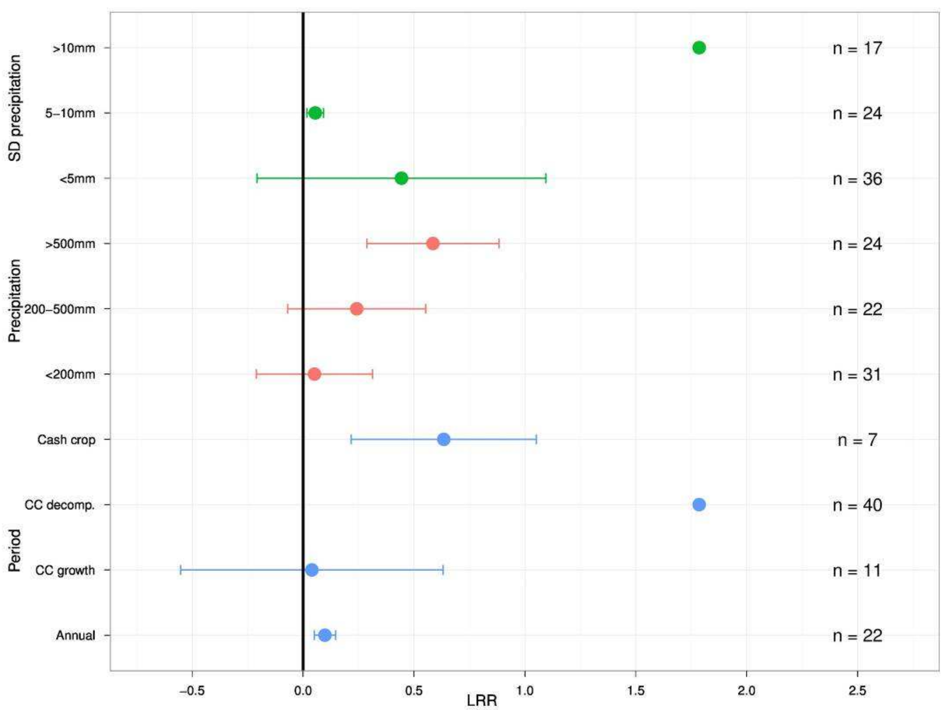

Figure 5. Mean response ratios (and 95% confidence intervals) for environmental factors included in the meta-analysis: the period of measurement, the total precipitation over the measurement period and the standard deviation of precipitation over that period.

Soil Incorporation. In our analysis, LRRs for studies that incorporated cover crop residues into the soil were significantly higher than those for studies that left the residues on the soil surface (p=0.02; figure 4). Of the studies where incorporation where reported, 19 of the 20 highest positive response ratios in the database where incorporation was reported were cover crop treatments where residues had been incorporated into the soil. The sensitivity analysis also found that soil incorporation was significant (p<0.05) in 81% of the models when excluding individual studies. Incorporation of cover crop residues contributes to an increase in N_2O emissions through several potential effects: incorporation of cover crop residues increases N mineralization rates of both soil organic matter and cover crop residues and it contributes to greater NO_3^- availability and denitrification (Firestone and Davidson 1989). Incorporation of cover crops residues also likely increases soil temperature and thus, the potential for denitrification compared with soil covered with residues (Omonode et al. 2011). Lastly, anaerobic conditions for denitrification of cover crop N is more likely to occur if the residues are incorporated with tillage rather than left on the surface (Kaspar and Singer 2011). Thus, our analysis indicated that incorporating aboveground cover crop residues led to relative increases in N_2O emissions through a variety of mechanisms.

Precipitation. The episodic nature of N_2O emissions results in part from the requirement for denitrification for anaerobic soil conditions, which usually occur following large or intense precipitation events (Davidson et al. 2000). Cover crops may alter the soil water status and the potential for anaerobic conditions in several ways, including decreased soil evaporation, increased rainfall infiltration, and transpiration of stored soil water during cover crop growth (Unger and Vigil 1990). To evaluate the soil water status and potential for anaerobic condition of a study, we utilized total precipitation over the measurement period as well as the standard deviation of the rainfall as indicators for conditions favoring development of anaerobic soil conditions and denitrification. Similarly, the DNDC model (Li et al. 1992) uses daily precipitation along with other variables as a predictor of the N_2O emissions. Other models like APSIM (Thorburn et al. 2010) use water filled pore space as a predictor of N_2O emissions.

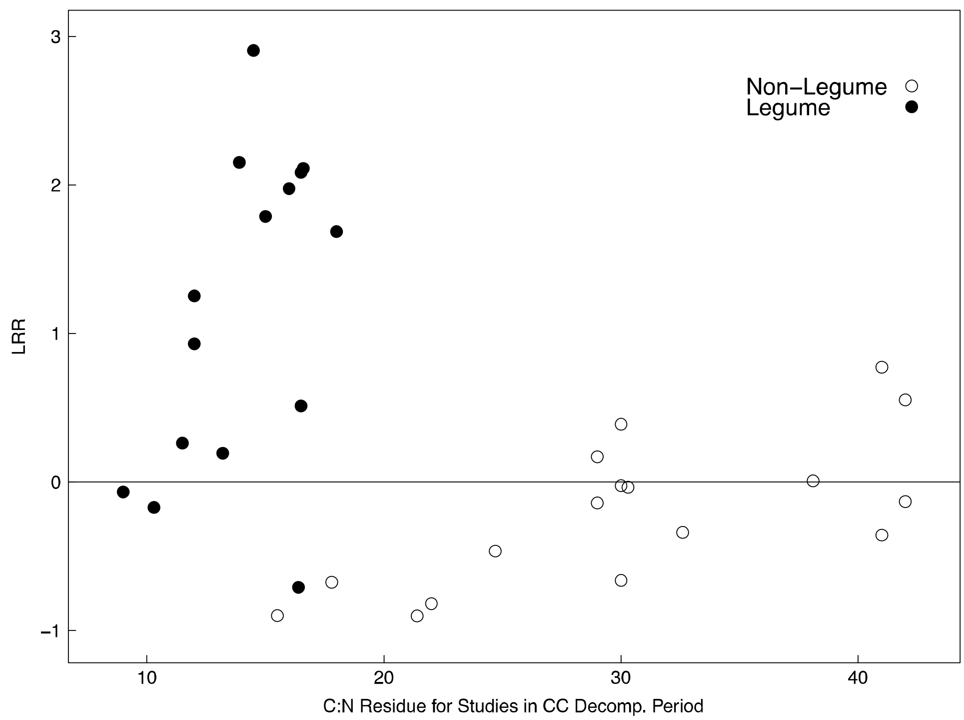

Figure 6. Response ratios for observations measured during the cover crop decomposition period as a function of the residue C:N ratio. Legume species and those species with lower C:N ratios frequently led to an increase in N_2O emissions, as indicated by the positive response ratios.

In the statistical model testing the effect of precipitation values on LRRs, total precipitation and (p=0.005) and the standard deviation of precipitation (p=0.002) were significant (figure 5). As we hypothesized, precipitation is an important factor impacting the LRRs. Total precipitation, however, was significant at the p<0.1 level in 86% of the statistical models excluding individual studies, while the standard deviation of precipitation was significant at the $p<0.05$ level in 95% of the statistical models. Studies with legume cover crops had a more pronounced trend toward increased response ratios as the total precipitation and standard deviation of precipitation increased. All of the observations (20 points representing seven different studies, where 77 total points were included in this part of the analysis) with a standard deviation of precipitation above 8.8 mm had positive LRRs. This may indicate that regardless of other factors (such as cover crop type), above a threshold of rainfall variability, a cover cropped agroecosystem is more susceptible to N_2O emissions than one without a cover crop. Novoa and Tejeda (2006) noted that N_2O emissions from applied plant residues were predicted in part by rainfall. This could be a result of a cover crop residue maintaining higher soil moisture and providing labile carbon, along with the timing of high intensity rainfall events.

Soil Organic Carbon. Soil organic carbon (SOC) has a strong impact on N transformations including the denitrification process (Davidson et al. 2000). In addition, many models (APSIM, DAYCENT, DNDC, EPIC, *ecosys*) capable of simulating N_2O emissions include SOC as a predictor (Li et al. 1992; Adler et al. 2007; De Gryze et al. 2010; Thorburn et al. 2010). Cover crops are a source of C and therefore the amount and quality of additional biomass has the potential to alter N_2O emissions. Two factors were categorized and analyzed to evaluate the effect of SOC on LRRs: percent organic C in the topsoil and total cover crop biomass. The percent organic C of the topsoil was found to be significant in the statistical model testing its effect on the LRR ($p=0.04$). With larger SOC values in the topsoil, the LRR showed a small decline. Bouwman et al. (2002) found significantly larger N_2O emissions in soils with 3-6% organic C versus those with 1-3%. However, the experiments included in this analysis had a much smaller range of SOC values (0.38%-2.10%, table 3) which may be one reason we observed no relationship between SOC and N_2O emissions. It is possible that at lower background levels of SOC, higher LRRs could be a result of a larger cover crop effect due to C limitation. Additionally, our analysis indicated that the total amount of cover crop biomass did not have a significant effect on LRRs, although there was a trend toward higher LRRs as biomass increased (data not shown). Contrary to our hypothesis that cover crop biomass would be an important factor controlling N_2O emissions we found inconclusive evidence of this. The sensitivity analysis found cover crop biomass significant at the $p<0.10$ level in 62% of the regression analyses excluding individual studies. Robinson and Conroy (1999) found that when elevated CO_2 levels increased plant productivity, subsequent additional C substrate for microbes contributed to consumption of more soil oxygen than could be replaced by diffusion. This led to anerobic soil conditions and increased denitrification. This mechanism seems consistent with our analysis, given the relationships in the dataset with LRRs, SOC, cover crop biomass and precipitation. It also underscores multiple interconnections between C and N cycling in agroecosystems.

Cover Crops and Global Warming Potential. Nitrate lost through leaching from agricultural fields is subject to denitrification and N_2O emissions off-site, which would not be reflected in the on-site measurements of N_2O emissions from the soil surface. Therefore, given the ability of cover crops to reduce nitrate leaching, cover crops may contribute to an overall decrease in net global warming potential. Mosier et al. (1998) estimated indirect N_2O emissions resulting from leaching and runoff to be 2.5% of total leached N. They further calculated that indirect denitrification (for example, from leaching and runoff) emissions constitute 25% of global N_2O emissions from agricultural soils. For studies measuring leaching losses in this meta-analysis, mean change in NO_3^- loss with a cover crop was significantly lower than the slight increase to neutral effect on direct N_2O emissions (figure 7). This is consistent with the results of Tonitto et al. (2006) who found that on average non-legume cover cropped systems reduced nitrate leaching by 70% and legume cover cropped systems reduced nitrate leaching by 40%. Even though indirect estimates of N_2O emissions are variable, this is an important impact to consider that would not be included in the LRR for direct emissions used in our analysis.

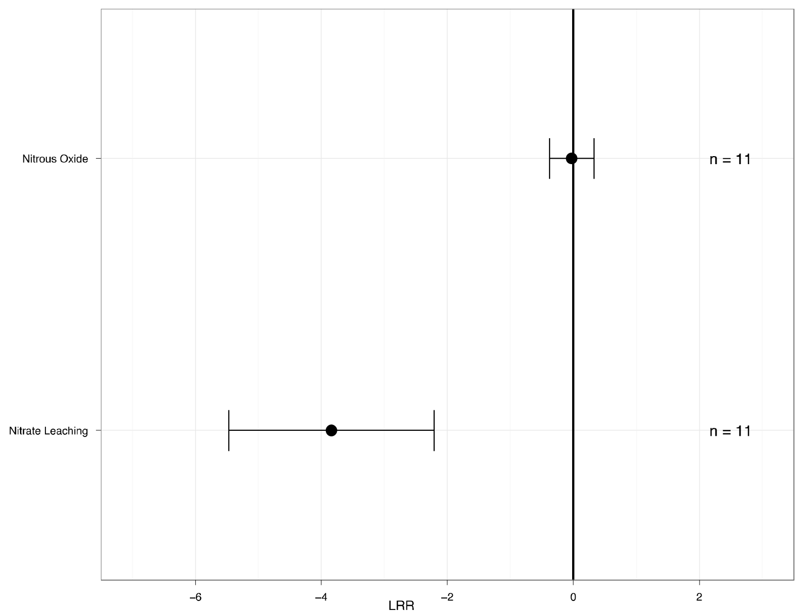

Figure 7. The mean nitrate leaching response ratios (natural log of the nitrate leaching with a cover crop divided by the nitrate leaching without a cover crop) and 95% confidence intervals compared to the mean N_2O response ratios from three studies measuring both. Ten of the 11 points were measured during the cover crop growth period. Although this represents only a small subset of the data base, it could further suggest that cover crop N uptake during growth decreases leaching losses and subsequent indirect N_2O emissions.

One modeling experiment (De Gryze et al. 2010) and two field experiments (Fronning et al. 2008; Smith et al. 2011), reported net global warming potentials (GWP) that were neutral or negative (indicating mitigative potential) when cover crops were present. In our database, only these three studies included full net global warming potentials, measuring change in SOC (or soil

CO_2 respiration), N_2O and CH_4. De Gryze et al. (2010) found that the net decrease in global warming potential was primarily a result of increased SOC storage in cover cropped systems. More multi-year field trials and modeling efforts are needed to better understand the long term effect of cover crops on the net global warming potential of agroecosystems.

Summary and Conclusions

This meta-analysis found that cover crops increased N_2O emissions from the soil surface in 60% of published observations while cover crops decreased N_2O emissions from the soil surface in 40% of observations. There are both environmental and management factors that modified the impact of cover crops on N_2O emissions, including fertilizer N rate, soil incorporation, the period of measurement and rainfall. Legume cover crops had higher relative N_2O emissions at low N rates and lower emissions at high N rates whereas N_2O emissions of non-legume cover crops increased as N rate increased. In general, it seems that cover crops have a greater potential to reduce N_2O emissions when non-legume species are utilized and cover crop residue is not incorporated into the soil. Our analysis also found that cover crops on average only lead to a small or negligible increase in N_2O emissions when measured for time periods of one year or greater. To understand the full global impact of cover crops on N_2O emissions, more field research with measurements over extended time periods is needed to examine the temporal component of N_2O emissions and better accounting for cover crop reductions in indirect N_2O emissions from leached N should also be considered.

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CHAPTER 3

SOIL WATER IMPROVEMENTS WITH THE LONG-TERM USE OF A WINTER RYE COVER CROP

A paper to be submitted to *Agricultural Water Management*

Andrea D. Basche[1,2], Thomas C. Kaspar[3], Sotirios V. Archontoulis[4], Dan B. Jaynes[3], Timothy B. Parkin[3], Thomas J. Sauer[3], Fernando E. Miguez[4]

Abstract

The Midwestern United States, a region that produces one-third of maize and one-quarter of soybeans globally, is projected to experience increasing rainfall variability with future climate change. One approach to mitigate climate impacts is to utilize crop and soil management practices that enhance soil water storage, reducing the risks of flooding and runoff as well as drought-induced crop water stress. While some research indicates that a winter cover crop in maize-soybean rotations increases soil water availability, producers continue to be concerned that water use by cover crops will reduce water for a following cash crop. We analyzed continuous in-field soil water measurements from 2008 to 2014 at a Central Iowa research site that has included a winter rye cover crop in a maize-soybean rotation for thirteen years. This period of study included years in the top third of wettest on record (2008, 2010, 2014) as well as years in the driest bottom third (2012, 2013). We found the cover crop treatment to have significantly higher soil water storage from 2012-2014 when compared to the no cover crop

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1. Graduate Research Assistant, Department of Agronomy, Iowa State University
2. Primary Researcher and Author
3. U.S.D.A. Agricultural Research Service, National Laboratory for Agriculture and the Environment, Ames, Iowa
4. Assistant Professor, Department of Agronomy, Iowa State University

treatment and in most years greater soil water content later in the growing season when a cover crop was present. We further found that the winter rye cover crop significantly increased the field capacity water content by 10-11% and plant available water by 21-22%. Finally, in 2013 and 2014, we measured maize and soybean biomass every 2-3 weeks and did not see treatment differences in crop growth, leaf area or nitrogen uptake. Final crop yields were not statistically different between the cover and no cover crop treatment in any of the seven years of this analysis. This research indicates that for this location in Central Iowa the long-term use of a winter rye cover crop can improve soil water dynamics without sacrificing cash crop growth.

Introduction

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

Employing management practices that improve soil water dynamics (i.e. processes such as increased storage and enhanced infiltration) is one approach to mitigate the impacts of extreme precipitation events, on a field and landscape scale. Several alternative cropping systems have been tested to determine their impacts on soil water dynamics in the Midwestern United States. Qi et al. (2011) found that a rye cover crop increased soil water storage, compared to a maize-soybean cropping system. Brye et al. (2000) found that a prairie ecosystem maintained higher soil water content deeper in the soil profile, and had larger evapotranspiration and less drainage than a maize cropping system. Further, Daigh et al. (2014b) attributed lower cumulative drainage and decreased peak flows in prairie and cover cropped systems to higher evapotranspiration and lower soil water, beneficial improvements for heavy rainfall events.

Further, there is a complex interaction of soil physical, and chemical properties that contribute to soil water storage capacity, including soil carbon, aggregation and porosity (Emerson, 1995; Hudson, 1994; Kay, 1998). There is a body of evidence that cover crops can increase soil carbon (Kaspar and Singer, 2011; McDaniel et al., 2014; Moore et al., 2014; Poeplau and Don, 2015) as well as soil physical properties which improve soil water dynamics (Daigh et al., 2014a; Steele et al., 2012; Villamil et al., 2006). Growing an over winter cover crop between the harvest of maize and soybeans does not take acres out of production and is one strategy for mitigating environmental impacts of Midwestern agriculture (EPA, 2008; INRS, 2012). However, survey data (SARE-CTIC, 2013, 2014) and leading practitioners (Carlson and Stockwell, 2013) indicate that producers are concerned that cover crops may reduce water availability for the following cash crop. Thus, even though cover crops provide many benefits, producers might be reluctant to adopt them if they increase the risk of water stress for the cash crop.

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

Materials and Methods

Field site

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

Table 1. Management dates and operation information

Year	Cash Crop	Cover Crop Termination Date	Cash Crop Planting Date	Harvest Date	Cover Crop Planting Date	Total N applied kg ha^{-1}
2008	Maize	29-Apr	14-May	28-Oct	29-Oct	198
2009	Soybean	21-May	22-May	28-Sep	28-Sep	
2010	Maize	19-Apr	29-Apr	16-Sep	17-Sep	198
2011	Soybean	5-May	18-May	29-Sep	30-Sep	
2012	Maize	23-Apr	4-May	19-Sep	4-Sep*	175
2013	Soybean	13-May	23-May	20-Oct	4-Sep*	
2014	Maize	10-Apr	6-May	17-Oct	9-Sep*	196
	*Winter rye cover crop was broadcast seeded before maize and soybean harvest					

Soil water and soil physical property analysis

Soil volumetric water content (θ) was estimated using a TDR Theta Probe Soil Moisture Sensor (Model Type ML2x, Delta-T Devices, Cambridge, United Kingdom) hourly at depths of 5, 10 and 15-cm from 2008-2011 and at 5, 15 and 30-cm from 2012-2014. Voltage measurements were converted to a dielectric constant then to the volumetric water content, using the calibration equation for Des Moines Lobe soils based on the work of Kaleita et al. (2005). The TDR Probes were installed at two locations in three of the four experimental replications, vertically at 5-cm and horizontally at the lower depths. Sensors were removed only when necessary to accommodate field machinery operations and were replaced immediately following completion. Soil water storage was calculated by sectioning the available depths (0 to 5-cm, 5 to 10-cm, and 10 to 15-cm in 2008-2011; 0 to 5-cm, 5 to 15-cm and 15 to 30-cm in 2012-2014), assuming that the soil water content (θ) level was equal throughout that whole depth and multiplying the depth (cm) by corresponding soil water level (mm^3 mm^{-3}). The cumulative soil water storage (SWS) values were calculated by integrating over the individual storage values for the three available depths.

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

Intact soil cores (7.6-cm by 7.6-cm) were sampled to approximately 4 to 11.6-cm and 21 to 28.6-cm depths in July 2013 when soybeans were in the V4 developmental stage. Two subsamples per plot were taken at each depth, with one subsample in a typically wheel trafficked row and one a typically non-wheel trafficked row to try to capture within plot variability and any differences resulting from wheel traffic compaction. For the purposes of this experiment, we define field capacity as the water retained in the soil at -33 kPa pressure, an approximation thought to represent the ability of the soil to retain water after internal drainage has ceased

(Hillel, 1998), which we also considered the upper limit of plant available water (Veihmeyer and Hendrickson, 1950). We define the permanent wilting point as water retained at -1500 kPa, an approximation thought to represent the soil wetness at which point a plant cannot recover turgidity (Hillel, 1998) which we also considered to be the lower limit of plant available water (Veihmeyer and Hendrickson, 1950). Cores were analyzed at the Soil, Water and Plant Testing Laboratory at Colorado State University for water retention (water content) at field capacity (-33 kPa) with a pressure plate cell apparatus and at saturation (0 kPa) by wetting intact cores and weighing for percent water content (Klute, 1986). To detect treatment differences at the lower end of the water retention curve (-1500 kPa), in April 2015 we utilized soil samples from October 2014 at 0-15-cm and 15-30-cm using the Decagon WP4C Water Potential Meter (Dew Point PotentiaMeter, Decagon Devices, Inc, Pullman, WA). Water potential meters, such as the WP4C, convert sample readings of temperature and dew point to water activity (Campbell et al., 1973) and it is suggested that these types of instruments are best suited for measurement of very dry soils (Gee et al., 1992) when hydraulic conductivity is too low for water equilibration to occur in the soil sample (Gee et al., 2002). We mixed approximately a 30-g sample of air-dry soil with 6-mL of water according to suggested protocol to wet soils to a water content wetter than -1500 kPa. We then equilibrated the soil samples in closed vessels for several days at room temperature. Then we added approximately 3.5-g of soil to the instrument’s stainless steel sample cups, capped with a lid and allowed the samples to equilibrate for another 24 hours. Matric potentials of the samples were measured in the WP4C chamber after which they were weighed, air-dried for a short period (20-40 minutes) and this procedure was repeated at least three times.

This procedure allowed us to bracket the -1500 kPa water potential. Samples were then dried at 103°C for 48 hours and weighed to calculate water content at the corresponding matric potential readings. Values for the water content corresponding to -1500 kPa were interpolated using a regression line from the three sample readings (Campbell, 2007). Finally, the particle size analysis was performed using the pipette method (Gee and Or, 2002).

Crop growth and partitioning analysis

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

Statistical analysis

Volumetric soil water content data has a number of characteristics: 1. It has a high measurement frequency (sub-daily); 2. Measurements are highly correlated (i.e. one day of soil water content measurement is very similar to the previous day); 3. Measurements are highly influenced by precipitation events which cause sudden increases in the values. To capture the pattern of this type of data we chose to use a smoothing splines approach. Splines are constructed from polynomial interpolation between knots which need to be estimated (Silverman, 1985). We fit individual equations for θ at each depth (5-cm, 10-cm, 15-cm, 30-cm) and each time period (spring and summer) using a generalized linear mixed model (SAS Institute, 2008). For simplicity we conducted separate analyses for each year and depth. In our approach we accounted for the autocorrelation by fitting an autoregressive model. Similar approaches have been used to describe the relationship of daily evapotranspiration over a season (Hankerson et al., 2012) and nitrogen fluxes in time (Cook et al., 2010; Dietzel, 2014). We manually adjusted the number of splines in each time period and depth analysis and we also evaluated residual plots and considered AIC (Akaike information criteria) and BIC (Bayesian information criteria) values. These criteria represent the relative skill in model selection that optimizes parameters with residual error, necessary steps for selecting the most appropriate statistical model (Archontoulis and Miguez, 2015). Treatment and time (day of year) were considered fixed effects. In analyzing treatment differences (cover crop versus no cover crop) in water content, we chose to emphasize specific days as the average treatment differences over an entire period are not necessarily relevant (Cleveland and Devlin, 1988). As stated previously, we chose to focus our water content analysis on the spring and late summer periods. For soil water storage we explored differences over the entire growing season (April through October) for each year in our dataset, summed over the depths available, with the same generalized linear mixed model where treatment and time (day of year) were considered fixed effects. We assessed statistical significance at $p<0.10$ for soil water content values and soil water storage values given the large potential for variability between plots.

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

Results and Discussion

Research question 1: How is soil water content affected by the cover crop?

We hypothesized that during the spring period we would see evidence that the growing cover crop depleted θ. We also hypothesized that if the cover crop had caused accumulated improvements in soil properties (i.e. surface residue cover, aggregation, soil organic matter, porosity) over time, there could be evidence of greater θ in later periods of the year. Several patterns emerged in separating differences in soil water content in the cover crop and no cover crop treatments. In comparing θ on individual days we found that during the spring periods (ten days before cover crop termination and ten days after cash crop planting) of 2009, 2010 and 2013 there were some days that had significantly lower θ in the cover crop plots compared with the no cover crop plots (Table S1). In 2009, for example, it took five days for θ to return to the same levels in the two treatments, where the cover crop plots were 0.03-0.04 mm^3 mm^{-3} (0.016 mm^3 mm^{-3} standard error), representing a 10-15% lower valuethan the no cover crop plots from May 23 to May 27 (DOY 143-147) at the 5-cm and 10-cm depths (Figure 1, Table S1). In spite of the lower spring soil water levels in the cover crop treatment plots, in five of the seven years θ was replenished to the statistically same level as the no cover crop treatment plots by the time cash crop planting occurred. We conclude that the cover crop does use water in the spring, but rainfall is usually able to replenish soil water levels, even over a series of wetter and drier springs (197mm of rain in 2008 compared to 21mm of rain in period in 2012 during the periods illustrated in Figure 1). Cover crop water use in this region has been estimated to be between 20 to 60 mm by simulation models where soil evaporation is predicted to be reduced by a cover crop between 2-18% (Basche et al., 2015; Malone et al., 2007). Spring cover crop transpiration of 20 to 60 mm represents approximately 5% of the total precipitation in Central Iowa or 10-30% of the historical April-May average rainfall which is 194 mm (IEM, 2015). At our field site, this only reduced soil water levels to statistically different levels at maize and soybean planting in two of seven spring seasons.

During the summer period, in six of the seven years (all but 2011), we found higher average values of θ at lower depths in the soil profile (15-cm and 30-cm) in the cover crop plots. For example, during August and September of 2009, there was significantly higher θ (0.02-0.03 mm^3 mm^{-3} with a standard error of 0.016 mm^3 mm^{-3}, representing an increase of 8-12%) at the 15-cm depth for about a two week period, a year when total rainfall equaled 946mm, an above average rainfall year (815mm is 100-year average for this location) (Figure 1). Further, there were several days in late September and early October 2012 (data not shown) when θ at 15-cm and 30-cm depths were significantly higher in the WCC by approximately 0.02-0.03 mm^3 mm^{-3} (8-12%). This was a year when total annual rainfall equaled 637mm, which was below average for this location. We also detected about a two-week period in mid-August 2014 when θ at 15-cm was 0.02-0.03 mm^3 mm^{-3} higher (standard error of 0.013 mm^3 mm^{-3}, or a 9-13% increase) in the cover crop treatment. Because of measurement and experimental error, we found that the average θ needed to be different by approximately 0.02-0.03 mm^3 mm^{-3} between treatments to detect significant differences. These values for least significant differences are similar with those observed by other research in similar soils and cropping systems (Daigh et al., 2014a; Daigh et al., 2014b).

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

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

Spring **Summer**

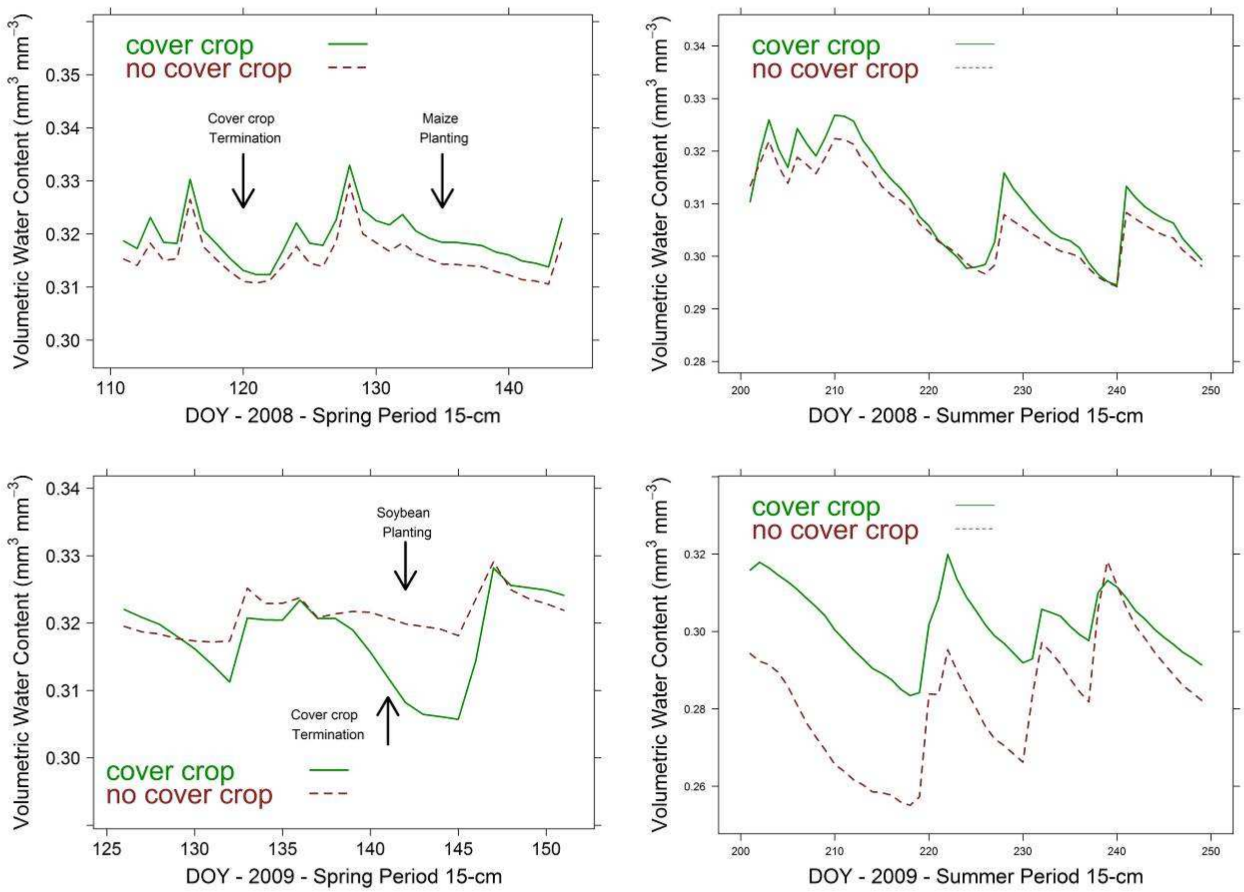

Figure 1. Soil water content at 15-cm across the seven spring and summer days of year (DOY)

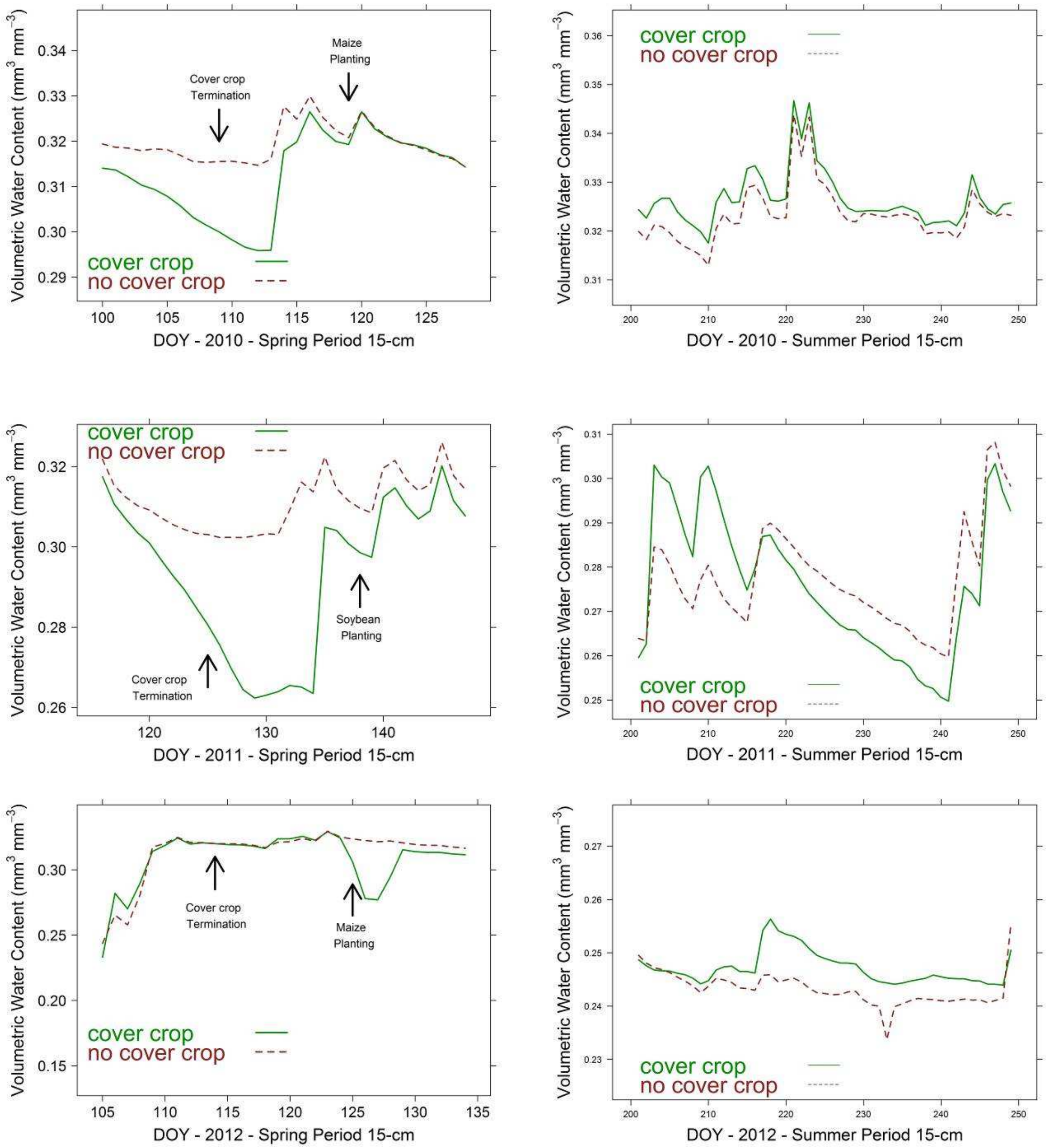

Figure 1 (Continued**)**

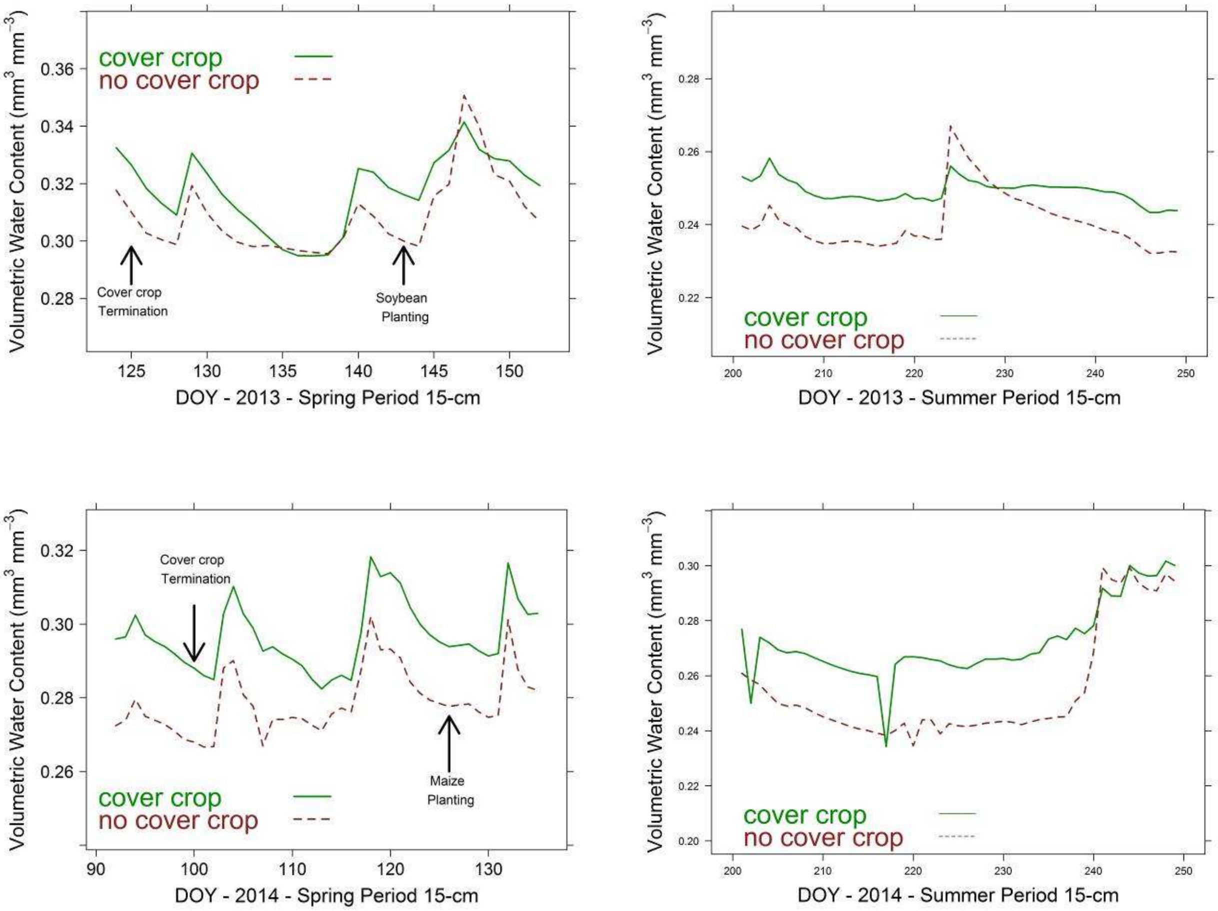

Figure 1 (Continued)

Table 2. Annual precipitation (IEM, 2015) and spring precipitation (from field site rain gauge) during the years of the analysis.

Year	Annual Precipitation (mm)	April-May Precipitation (mm)
2008	1274	242
2009	946	216
2010	1287	178
2011	816	209
2012	637	35

Table 2 (Continued)

2013	695	335
2014	1023	230
Avg	954	206

Research question 2: How is soil water storage affected by the cover crop?

We hypothesized that the calculated soil water storage (SWS) values, based on the sum of the soil water content values multiplied by the measurement depth, would show evidence of higher levels with the inclusion of the cover crop, given the potential for the cover crop to reduce soil evaporation as well as to accrue changes (i.e. carbon, porosity) that facilitate water storage. We found a significant effect of treatment for average SWS during the entire growing season (DOY 100 through DOY 300) in 2012, 2013 and 2014 (Table 3), where soil water storage in the cover crop treatment was generally higher throughout the season (Figure 2). These are the three years for which we had measurements down to 30-cm as opposed to measurements from 2008-2011 only at the 0 to 15-cm depth. Thus, our results demonstrate higher SWS lower in the soil profile with a cover crop, similar to the pattern in θ and suggest that the effect of the cover crop may be more pronounced at depths greater than 15-cm. Similar to our study, Daigh et al. (2014a) used daily measurements of volumetric water content to calculate SWS values and also found that a rye cover crop led to an increase in soil water storage during the drought of 2012 at a closely located field site. A cover crop contributing to improved SWS increases could be a result of several soil physical changes reported to occur after their continued use, including increased porosity and enhanced aggregation (Liu et al., 2005; Rachman et al., 2003; Sainju et al., 2003; Villamil et al., 2006).

Table 3. Soil water storage effects over the April through October growing season period (Day of year 100-300)

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

Pr>F values. In 2011 sensors were only functioning in one replication each treatment. Spline represents the curve fitting parameter

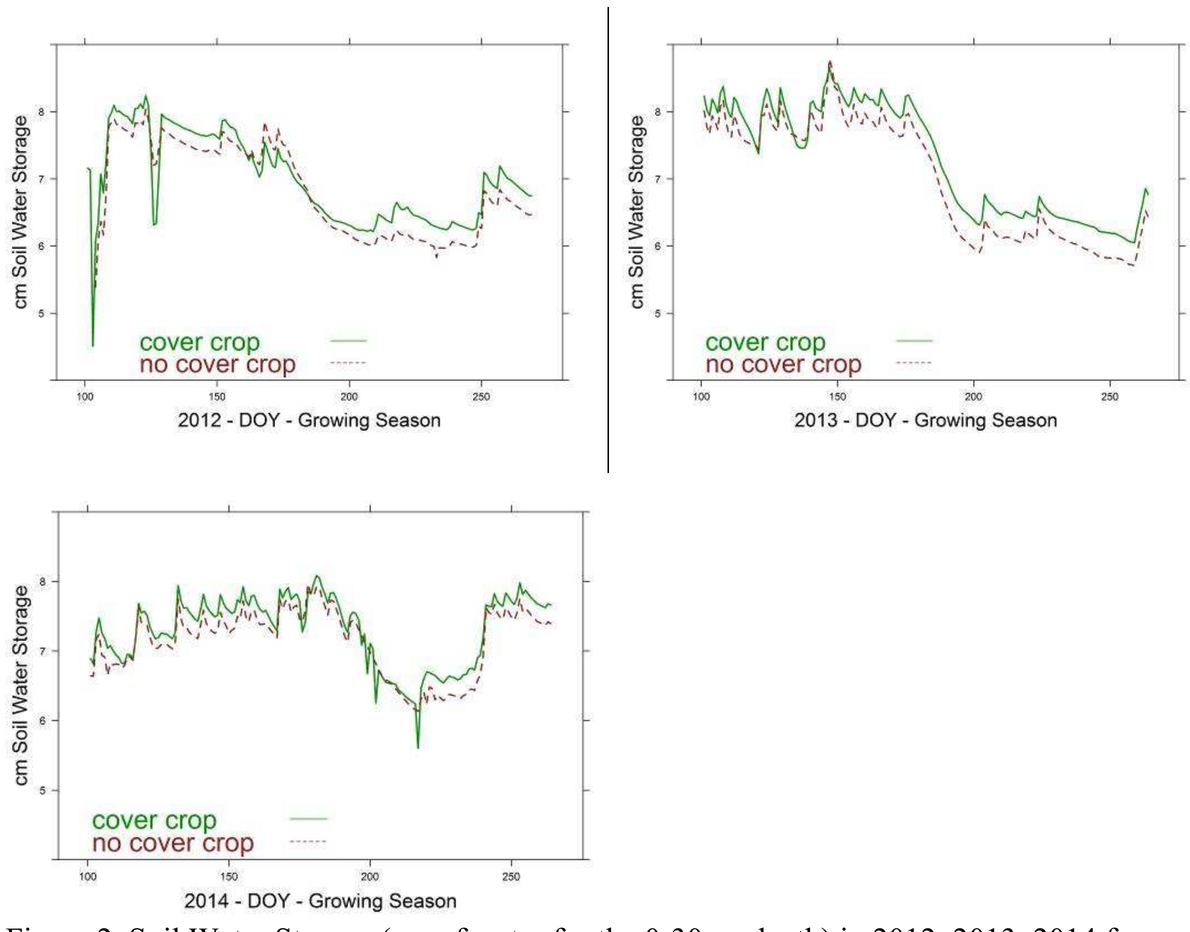

Figure 2. Soil Water Storage (cm of water for the 0-30cm depth) in 2012, 2013, 2014 from early April through late October (DOY - day of year 100 through 265) where the cover crop soil water storage was significantly higher than the no cover crop treatment

Research question 3: Which soil water retention properties are affected by the cover crop?

There are a few reports of a cover crop increasing water retention at field capacity (Bilek, 2007; Lal et al., 1979; Patrick et al., 1957) or increases in plant available water content (Villamil et al., 2006) and therefore we hypothesized that we might see an increase in plant available water due to water retention properties with the addition of the cover crop. We found a significant effect of treatment for the water content at field capacity where the change in the cover crop treatment represented an increase of 10.9% and 10.0% at the 0-15-cm and 15-30-cm depths, respectively (Table 4). The pattern in the field capacity increase observed in the cover crop plots is not likely attributed to differences in soil texture between the treatments, as the cover crop plots had slightly less clay and higher sand contents content than the no cover crop plots (Table 4), which might actually lead to a decrease in field capacity water content. There was still a significant difference between the mean treatment value for field capacity in the two treatments when we analyzed the data using both sand and clay as covariates (data not shown). As a result of higher field capacity values in the cover crop treatment, we found increases of 21.1% and 21.9% for plant available water at the 0-15-cm and 15-30-cm depths, respectively (Table 4).

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

In terms of soil aggregation, there is a known relationship between water retention and aggregate size distribution (Guber et al., 2004). In general, aggregation and a mixture of aggregate size classes increases the number of mesopores in the soil. Mesopores are thought to contain the water between 10 kPa and 1500 kPa, and can be influenced by management such as cover crops in no-till systems (Kay, 1998). The contribution of cover crop roots was found to be essential for improvements to soil aggregate stability to occur, compared to incorporation of only the aboveground plant residue (Benoit et al., 1962). In a maize-soybean rotation in Illinois, Villamil et al. (2006) found that winter cover crops increased water aggregate stability, soil organic matter and mesoporosity, which in turn increased plant available water. Dao (1993) attributed greater water availability at equivalent suction gradients to increased porosity when comparing a no-till to a moldboard plow tilled soil. Franzluebbers (2002) found an important effect of management by depth, evidenced by greater infiltration rates related to a higher ratio of carbon in the 0 to 3-cm and 6 to 12-cm depths in no-till compared to conventionally tilled soils. Thus, it seems reasonable that the increase in soil water content at field capacity in our study could be a result of cover crop shoots and roots increasing soil carbon and soil aggregation as well as pore space.

Table 4. Soil texture, bulk density as well as the volumetric water content at saturation, field capacity, permanent wilting point and plant available water for the treatments at two depths.

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

Values with the same lowercase letters (by column) indicate no significant differences (treatment by depth difference at $p<0.05$)

Research Question 4: Does the water use from the cover crop negatively impact maize and soybean growth?

We hypothesized that we would not see negative impacts to maize or soybean growth between the two treatments, particularly if the cover crop showed increases in soil water during the main crop growing season. In general we found the growth and N accumulation patterns of soybeans in the cover crop and no cover crop treatments to be very similar. Over the soybean sampling period in 2013, we did not detect any notable differences in biomass or leaf area between the cover crop and no cover crop treatments (Figure 4). However one sampling date (August 21, DOY 233) did show significantly higher biomass in the cover crop treatment. There were also no significant differences between treatments in total plant N for any of the sampling dates (Table S2). Final soybean grain yields in 2013 were nearly identical in both treatments, equaling 2.99 Mg ha^{-1} in the cover crop treatment and 2.96 Mg ha^{-1} in the no cover crop treatment. For maize in 2014, we similarly did not detect differences in biomass and leaf area between the cover crop and no cover crop treatments (Figure 4). Further, in our analysis of plant nitrogen (Figure 5), we found that there was significantly higher total nitrogen in the cover cropped maize plants on two sampling dates (DOY 174 June 23 V7 and DOY 198 July 17 VT). On the last sampling date of the season (DOY 251 Sept 8 R5) there was no significant difference in total plant nitrogen (leaves, stems and kernels) combined between the treatments, yet the harvested maize kernels showed significantly higher nitrogen content (kg N ha^{-1}) in the cover crop treatment (Figure 5). Similar to soybeans in 2013, final maize grain yields in 2014 were nearly identical in the two treatments, where the cover crop treatment yielded 12.4 Mg ha^{-1} and the no cover crop treatment 12.5 Mg ha^{-1}. Although we did not measure biomass throughout the growing seasons of 2008-2012, there were no significant differences (at the $p<0.05$ level) between the cover crop and no cover crop treatments in final yields for maize or soybeans (Table 5) (Kaspar et al., 2012). In the drought year of 2012, the grain yield of the cover crop treatment was of 0.5 Mg ha^{-1} (9 bushels $acre^{-1}$) less than yield without a cover crop, which was close to the least significant difference of 0.6 Mg ha^{-1}, but there was no evidence to indicate this was a result of water stress, as soil moisture levels were higher in the cover crop treatment during the summer period (Figure 1).

The strong relationship between cumulative plant biomass and cumulative transpiration is well documented for both irrigated and rainfed cropping systems (Stockle et al., 1994; Suyker and Verma, 2009; Tolk and Howell, 2009; Walker, 1986). We did not detect differences in aboveground maize and soybean biomass (as well as final crop yields) between the cover crop and no cover crop treatments (Table, which suggest similar transpiration patterns between the treatments. This further suggests that differences in soil water between treatments may not be attributable to differences in main crop plant transpiration, at least in the two seasons for which we have biomass measurements during the growing season. In addition, there were not any years with significant differences in drainage from 2002-2012, and on average the cover crop reduced annual drainage flow by 26 mm (Kaspar et al., 2007; Kaspar et al., 2012). Thus, considering all components of the water balance, if transpiration of main crop is unchanged and drainage is slightly decreased, if at all, then it seems reasonable that the cover crop treatment reduced soil evaporation and/or increased soil water storage at our research site.

We can draw further inferences from our data in terms of maize and soybean crop water limitations following a winter rye cover crop. While small maize yield decreases after cereal cover crops in the North Central region of the United States are not uncommon (Miguez and Bollero, 2005), our results do not suggest that the cover crop's water use or nitrogen uptake negatively affected maize or soybean growth at any stage of development. Mourtzinis et al. (2015) measured maize growth partitioning and final yields and found that a winter rye cover crop did not have a significant effect on grain yields in six environments but did increase maize biomass (stover) in one location. We recognize that our results are specific to a region that is generally not water-limited, although lessons from the cover crop's impact and subsequent management recommendations as a result are applicable to regions receiving less water. Whish et al. (2009) found that simulations for 31 locations in wheat producing regions of Australia that a millet cover crop ahead of wheat as opposed to fallow only negatively impacted wheat growth in 2% of seasons if the cover crop was planted early or removed after 50% cover was achieved. Joyce et al. (2002) found reduced runoff and increased water storage up to 47mm with a winter cover crop in the Sacramento Valley of California, but that to avoid impact to following cash crops, the cover crop must be terminated prior to additional evapotranspiration driven water losses. We found evidence in two of seven years that spring precipitation did not replenish soil water levels after the transpiration depletion from a growing cover crop before main crop planting. Producers concerned about high cover crop biomass and low precipitation in the spring can effectively use early termination, a method that has proven successful in other drier regions..

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

Year	**Main crop yield cover crop** Mg ha^{-1}		**Main crop yield no cover crop** Mg ha^{-1}		**Least significant difference** Mg ha^{-1}
2008	13.5		13.3		0.4
2009	2.4		2.4		0.2
2010	11.1		11.1		1.6
2011	3.6		3.6		0.2
2012	10.9		11.4		0.6
2013	3.0		3.0		0.2
2014	12.4		12.5		0.6
Average	Maize 12.0	Soybean 3.0	Maize 12.1	Soybean 3.0	

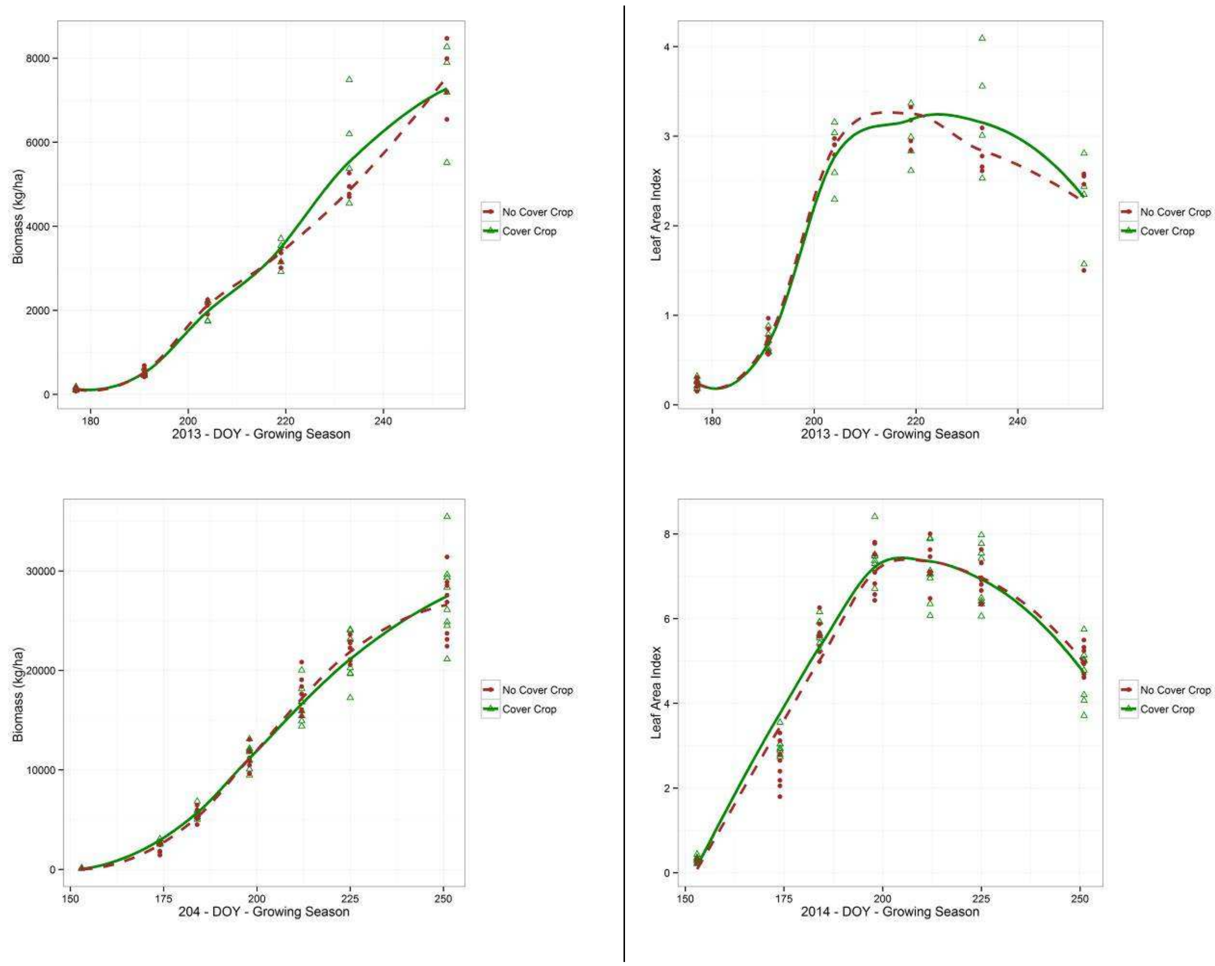

Figure 4. Soybean biomass and leaf area for measurement days of year (DOY) during the growing season in 2013(above). Maize biomass and leaf area for measurement days of year (DOY) during the growing season in 2014 (below).

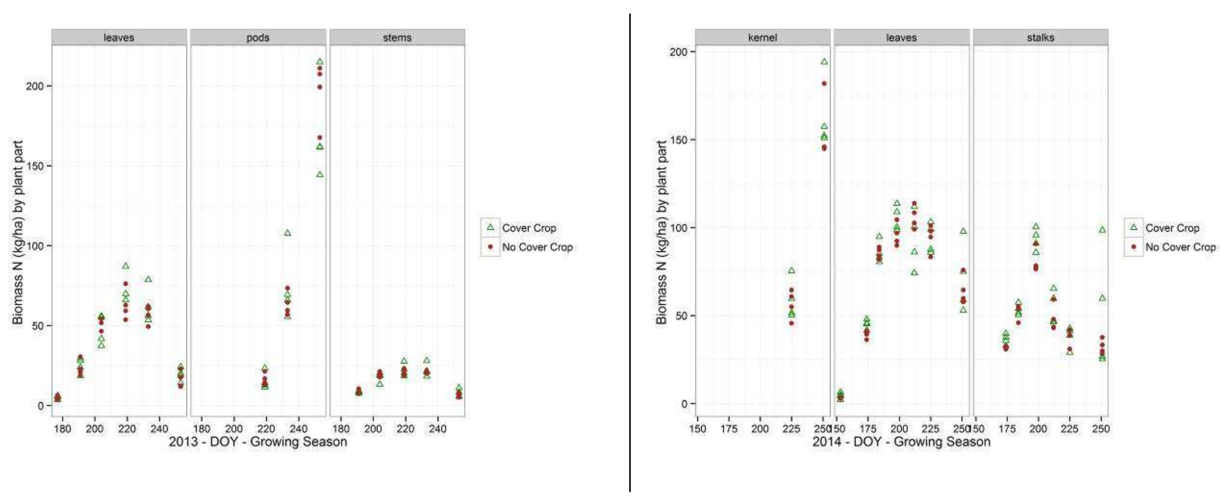

Figure 5. Soybean biomass N by plant part for measurement days of year (DOY) during the growing season in 2013 (left) and maize biomass N by plant part in 2014 (right).

Conclusion

In this study we found that over a seven-year period, including a series of wetter, hotter and drier years, that the consecutive use of a winter rye cover crop contributed to improved soil water content and soil water storage in a maize-soybean cropping system. We detected evidence of soil water use of a transpiring cover crop in the spring but that rainfall was able to replenish the soil to the same level in both the cover crop and no cover crop treatments by maize and soybean planting most springs. The cover crop increased the water retained in the soil at water potentials associated with field capacity (-33 kPa) by 10-11% as well as increasing plant available water by 21-22%. In the most recent two years of the experiment we further found that the rye cover crop did not have any negative effects on maize or soybean biomass and leaf area and did not significantly change final crop yields in any of the seven years of this study. Our analysis indicates that the long-term use of a winter rye cover crop in this region, if managed appropriately, can improve soil water dynamics without sacrificing cash crop growth and yield.

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CHAPTER 4

SIMULATING LONG-TERM IMPACTS OF COVER CROPS AND CLIMATE CHANGE ON CROP PRODUCTION AND ENVIRONMENTAL OUTCOMES IN THE MIDWESTERN UNITED STATES

A paper in revision with *Agriculture, Ecosystems and the Environment*

Andrea D. Basche[1,3], Sotirios V. Archontoulis[3], Thomas C. Kaspar[4], Dan B. Jaynes[4], Timothy B. Parkin[4], Fernando E. Miguez[3]

Abstract

It is critical to evaluate conservation practices that protect soil and water resources from climate change in the Midwestern United States, a region that produces one-quarter of the world's soybeans and one-third of the world's maize. An over-winter cover crop in a maize-soybean rotation offers multiple potential benefits that can reduce the impacts of higher temperatures and more variable rainfall; some of the anticipated changes for the Midwest. In this experiment we used the Agricultural Production Systems sIMulator (APSIM) to quantify how winter rye cover crops impact crop production and environmental outcomes, given future climate change. We first tested APSIM with data from a long-term maize-soybean rotation with and without winter rye cover crop field site. Our modeling work predicted that the winter rye cover crop has a neutral effect on maize and soybean yields over the 45 year simulation period but increases in minimum and maximum temperatures were associated with reduced yields of 1.6%-2.7% by decade. Soil carbon decreased in both the cover crop and no cover crop simulations, although the cover crop

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1. Graduate Research Assistant, Department of Agronomy, Iowa State University
2. Primary Researcher and Author
3. Assistant Professor, Department of Agronomy, Iowa State University
4. U.S.D.A. Agricultural Research Service, National Laboratory for Agriculture and the Environment, Ames, Iowa

is able to significantly offset (3% less loss over 45 years) this decline compared to the no cover crop simulation. Our predictions showed that the cover crop led to an 11-29% reduction in erosion and up to a 34% decrease in nitrous oxide emissions (N_2O). However, the cover crop is unable to offset future predicted yield declines and does not increase the overall carbon balance relative to current soil conditions.

Keywords: climate change, cereal rye cover crop, maize, soybean, greenhouse gas, soil carbon, soil erosion, APSIM, Midwest United States

Introduction

The Midwestern United States is known for its high agricultural productivity, as the region is a national leader in commodity crop production, specifically maize and soybeans (USDA-NASS, 2015). The Midwest "Corn Belt" region accounts for >80% of national productivity for these two commodities which represents approximately one-quarter to one-third of global output (FAOSTAT, 2015; USDA-NASS, 2015). Therefore, potential climate change impacts to agriculture in this region have global implications. Climate change is already known to threaten the built-in adaptive capabilities of the Earth System's ecology (Steffen et al., 2015). In agro-ecological managed systems, human decision-making is required to develop adaptive management capabilities for climate risks that directly threaten the soil and water resources and agricultural productivity (Amundson et al., 2015; FAO, 2011; Hatfield, 2014; Porter et al., 2014; Ray et al., 2015; Walthall, 2013).

In general, analyses performed using historical data for the Midwest over the last several decades indicate an increase in the frequency of heavy rainfall (Groisman et al., 2012) and flood events (Mallakpour and Villarini, 2015). Further, global climate model analyses agree that trends of increased rainfall variability will continue and potentially increase in the region

(Daniel, 2015; Winkler et al., 2012). Increases in rainfall variability can have many impacts on agriculture, and range from waterlogged soils delaying spring planting and decreasing crop productivity to drought-driven crop failure as was experienced across the region in 2012 (Al-Kaisi et al., 2013; ICCIC, 2010). In light of these climate-driven risks to production and natural resources, advancing our understanding of soil and water conservation management practices as well as increasing their levels of adoption are urgent priorities (Al-Kaisi et al., 2013; ICCIC, 2010; Lal et al., 2011; SWCS, 2003; VanLiew et al., 2013).

To mitigate risks from both excess rainfall and drought events, management practices that improve water infiltration, store soil water, and reduce runoff and erosion should be employed (Stewart and Peterson, 2015). The addition of an over-winter cover crop in an annual cropping system, such as maize and soybeans where the soil is left bare without living plants for about half of the year, is one approach that could help meet all of these goals (Kaspar and Singer, 2011). Improved water infiltration may be achieved both by structural soil changes as well as by the addition of soil organic matter (Bhogal et al., 2009; Hati et al., 2007; Hudson, 1994). Several studies highlight the soil water or soil structural improvements (i.e. decreasing bulk density, increased water-aggregate stability; increased macroporosity) of utilizing a cover crop for several years in maize-based systems (Kaspar and Singer, 2011). Cover crops are also known to increase soil organic matter between 9% and 85% depending upon biomass accumulation and region-specific soil and climate conditions (Kaspar and Singer, 2011). More recent research in Iowa found a 15% higher soil organic matter content (at 0-5cm depth) nine years after a winter rye cover crop was added to a maize silage rotation (Moore et al., 2014). Further, in a global meta-analysis, Poeplau and Don (2015) calculated that cover crops increased soil carbon in the 0-22-cm depth by 0.32 Mg ha^{-1} over several decades. Cover crops have reduced erosion from rainfall events by up to 95% (Kaspar et al., 2001) and cropping systems with full cover compared to bare soil are found to decrease erosive soil losses by at least 50% (Labrière et al., 2015).

Given that most field experiments are conducted in the short-term (<5 years) and even longer-term experiments (>10 years) cannot take into account future weather trends, one way to extrapolate short-term results in time is by using process-based simulation models. The APSIM platform, the Agricultural Production Systems sIMulator, is an advanced simulator of cropping systems capable of simulating growth of several crop species, water balance, carbon and nitrogen transformations, and soil erosion (Holzworth et al., 2014; Keating, 2003). It was developed to predict the long-term impacts of cropping systems such as crop rotations in relation to greenhouse gas emissions and climate change (Biggs et al., 2013; Huth et al., 2010; Thorburn et al., 2010). As one example, modeling platforms, like APSIM, can be used to understand how climatic change will impact soil carbon given that the long-term balance is a result of the interactions of climate, crop, soil and management conditions. In Iowa's naturally carbon-rich soils, field data confirms that it can be difficult to detect how alternative management affects soil carbon (Guzman and Al-Kaisi, 2010; Karlen et al., 1999; Kaspar et al., 2006).

There are several model-based evaluations of the impact of cover crops (Farahbakhshazad et al., 2008; Feyereisen et al., 2006b; Li et al., 2008; Malone et al., 2007; Malone et al., 2014; Qi et al., 2011a). Much of this work, however, was focused on simulating cover crop reductions of nitrate leaching losses (Feyereisen et al., 2006b; Malone et al., 2007; Malone et al., 2014) while others were theoretical studies without measures of cover crop growth (Farahbakhshazad et al., 2008; Schipanski et al., 2014). While it is important to predict the impact of cover crops on nitrate leaching losses given the emphasis on cover crops as a water quality improvement tool (EPA, 2008; INRS, 2012), there are other in-field soil benefits to utilizing cover crops, such as erosion prevention and organic matter accumulation, which have not been measured or simulated for long-term cover crop use in this region.

We hypothesize that the addition of a cover crop will lead to an improvement in environmental variables and crop production in the context of climate change. We had two major objectives in this study. The first was to use APSIM to assess predicted long-term impact of cover crops on maize and soybean production. Our second objective was to assess the predicted improvements that cover crops offer to several environmental variables, including soil carbon, soil erosion and nitrous oxide emissions. We utilized both future climate scenarios as well as long term weather data with no greenhouse gas forcing to meet both of these objectives. Using the two sets of weather scenarios should demonstrate the relative impact of climate change on both crop production and environmental goals. Given the predominance of maize production globally, enhancing our understanding of conservation practices within the Midwest can serve as a model for other maize growing regions.

Materials and Methods

Overview

In this study we simulated maize and soybean production as well as environmental variables using APSIM (version 7.5). We based our model performance testing and simulations on data from a long-term field site in Central Iowa. The cropping systems model APSIM was chosen because of its flexible modules, particularly in management and cropping sequences (Holzworth et al., 2014). Recently Archontoulis et al. (2014a) tested several APSIM modules for Central Iowa and found acceptable model predictions. In this study the following APSIM modules were configured into the simulation platform: maize, soybean, soilN (organic matter and N), surfaceOM (residue), SWIM (Soil Water Infiltration and Movement), soil temperature, erosion and a modified wheat module to represent the winter rye cover crop.

The Kelly Tile Experiment was established in 1999 in Boone County, Iowa (42.05N, 93.71W) on a 3.7-ha field. The site includes six experimental treatments in a maize-soybean rotation with four replicates (30.5-m wide and 42.7-m long). For the purposes of this modeling study we utilized data from two treatments: the no-till maize/soybean rotation and the no-till maize/soybean rotation with a winter rye cover crop grown every year. These treatments represent a long-term record of cover crop impacts within maize-soybean cropping systems, the predominant land use pattern across the Midwest Corn Belt.

Maize was planted between mid-April and early May in even-numbered years and soybeans in early to mid-May in the odd-numbered years. In maize years, nitrogen fertilizer was applied at planting and post planting as a side-dress in mid-June at rates varying from 246 kg ha^{-1} in the early years to 175 kg ha^{-1} in the latter years. Higher N rates were used in the early years because of the transition to no-till and to provide non-limiting N supplies. The winter rye cover crop was drilled following maize and soybean harvests every year except for the fall of 2001, 2002, 2012 and 2013 when it was overseeded into the standing crops in the late summer. The winter rye cover crop was terminated with glyphosate prior to maize and soybean planting where timing depended upon the following crop and weather conditions. The major management dates including cover crop planting and termination dates are outlined in Table 1. For more details related to field site management, see Kaspar et al. (2007) and Kaspar et al. (2012).

Subsurface drainage tiles consisting of 7.62-cm diameter perforated plastic were installed at the onset of the experiment lengthwise down the center of each plot at a depth of 1.2-m in 1999. Soil moisture sensors were installed in 2008 in three of the four experimental replications to measure volumetric water content. Two TDR Theta Probe Soil Moisture sensors (Kaleita et al., 2005; Parkin and Kaspar, 2004; Unidata Manual, 2007) were present in each replication to capture within plot variability. From 2008-2011 continuous hourly measurements were reported at 5, 10 and 15-cm depths and from 2012-2014 at 5, 15 and 30-cm depths.

2.2. Statistical analysis

Model performance was evaluated with root mean square error (RMSE) and relative root mean square error (RRMSE) providing indicators of the goodness of fit between the model predictions and field observed values. Model efficiency (perfect fit between predictions and observations equals 1) was also calculated to interpret the predictive ability of the model. These indices were calculated with the equations found in Makowski et al. (2007). Model application analyses comparing treatment effects (no cover crop versus with cover crop) and effects of weather (future climate change scenarios versus randomly generated weather scenarios) were performed using the MIXED procedures in SAS with each climate scenario as a random effect and weather and treatment as fixed effects. The interactions between treatment, climate scenario and GCM-generated or randomly-generated weather scenario were also included. The effect of time, in this case year into the future (2015 to 2060) was included as a repeated measure and the variance-covariance matrix of the residuals was modeled using an autoregressive structure (SAS Institute 2010).

Calibration protocol

For model calibration and validation, we utilized available data for grain yields, maize and soybean biomass, cover crop biomass, soil moisture, soil temperature and soil carbon as outlined in Table 2. We utilized climate data from the Iowa Environmental Mesonet (IEM, 2015). We incorporated the calibration dataset into APSIM to visualize model performance with

Table 1. Management dates and operations

Year	Cash Crop	Cover Crop Termination Date	Cash Crop Planting Date	Harvest Date	Cover crop planting	Total N applied kg ha^{-1}	Cover Crop Seeding Method
2001					20-Aug		
2002	Maize	17-Apr	25-Apr	30-Sep	10-Sep	235	Aerial seeding
2003	Soybeans	6-May	12-May	30-Sep	2-Oct		Aerial seeding
2004	Maize	16-Apr	28-Apr	4-Oct	6-Oct	246	Drilled after harvest
2005	Soybeans	25-Apr	6-May	30-Sep	30-Sep		Drilled after harvest
2006	Maize	21-Apr	4-May	20-Oct	24-Oct	225	Drilled after harvest
2007	Soybeans	10-May	22-May	26-Sep	28-Sep		Drilled after harvest
2008	Maize	29-Apr	14-May	28-Oct	29-Oct	198	Drilled after harvest
2009	Soybeans	21-May	22-May	28-Sep	28-Sep		Drilled after harvest
2010	Maize	19-Apr	29-Apr	16-Sep	17-Sep	198	Drilled after harvest
2011	Soybeans	5-May	18-May	29-Sep	30-Sep		Drilled after harvest
2012	Maize	23-Apr	4-May	19-Sep	4-Sep	175	Aerial seeding
2013	Soybeans	13-May	23-May	20-Oct	4-Sep		Aerial seeding
2014	Maize	10-Apr	6-May	17-Oct	9-Sep	196	Aerial seeding

measurements (data from Table 2). We then followed an iterative process in which we assessed how well the measured data fit to model simulations, following the order of crop phenology, soil temperature, soil water, soil N, plant biomass, maize and soybean carbon and nitrogen partitioning and yield. This same calibration protocol was followed by Archontoulis et al. (2014a). Maize and soybean genotypes changed over time in the field but in the model we considered the same cultivars over time due to the lack of cultivar specific information. This introduces some uncertainty and unexplained variation in model predictions as compared to measurements.

Given the extensive data available from the experimental site we utilized the field site measurements from 2003-2008 for model calibration and data from 2009-2014 for model evaluation. We ran APSIM sequentially and we considered a spin up period of 10 years for the fast decomposing organic matter pools to stabilize (referred to as BIOM for the microbial and FOM for the fresh organic matter pool) which for our objectives aligns with other APSIM work (Bryan et al., 2014). Highlights from our model testing are detailed in the methods section and results of model application for future climate change appear in the results and discussion.

Table 2. Measured field data used in model calibration and validation

Measured Data	Dates of data utilized for initialization and calibration	Dates of data utilized for validation	References
Yields: maize and soybeans	2003-2008	2009-2014	Kaspar et al. 2007, Kaspar et al. 2012, Kaspar (unpublished)
Maize biomass, leaf area and C/N allocation	n/a	In 2014 Every 2-3 weeks during the growing season	Basche (2015)
Soybean biomass, leaf area and C/N allocation	n/a	In 2013 Every 2-3 weeks during the growing season	Basche (2015)
Soil carbon	2003	2010, 2014	Kaspar et al. (unpublished), Supplemental Material
Cover crop biomass	2003-2008	2009-2014	Kaspar et al. 2007, Kaspar et al. 2012, Kaspar (unpublished)
Soil moisture	2008	2009-2014	Basche (2015)
Soil temperature	2008	2009-2014	Supplemental material

Soil profile chemical and physical properties

The parameter values to run the model (Table 3) are based on site-specific measurements supplemented with information from the Web Soil Survey (Soil Survey Staff) when necessary (depths > 1.2 m). These values are reasonable for our chosen field site as they are within the range of those used by Archontoulis et al. (2014a) and Malone et al. (2007) for Central Iowa APSIM studies. The partitioning of carbon into the more active and passive organic pools also followed the parameters utilized by Archontoulis et al. (2014a) and Malone et al. (2007).

We tested the model at the site with respect to soil organic carbon dynamics in the relatively short period of the field study. The observed soil carbon data shows significant differences between years and between depths, but no significant differences between treatments (Figure S1a-S1b). At the field site, carbon data showed a small decline in 2014, while predicted carbon values begin to show declines after about twenty years of the simulation.

Table 3: Soil module input parameters

Depth (cm)	**Bulk density g cm^{-3}**	**Air Dry mm^3 mm^{-3}**	**Lower limit mm^3 mm^{-3}**	**Drainage upper limit mm^3 mm^{-3}**	**Saturation mm^3 mm^{-3}**	**Organic Carbon %**	**pH**	**Fraction biom carbon (0-1)**	**Fraction inert carbon (0-1)**
0-15	1.30	0.115	0.161	0.300	0.430	2.986	6.6	0.035	0.40
15-30	1.270	0.125	0.173	0.310	0.479	2.340	6.6	0.019	0.500
30-60	1.30	0.125	0.173	0.310	0.459	1.200	6.6	0.014	0.640
60-90	1.350	0.135	0.173	0.310	0.459	0.940	6.6	0.010	0.800
90-120	1.420	0.155	0.173	0.310	0.453	0.940	6.7	0.010	0.800
120-150	1.830	0.152	0.173	0.310	0.403	0.500	7.8	0.010	0.816
150-180	1.830	0.152	0.173	0.310	0.403	0.350	7.8	0.010	0.816

Soil water

The SWIM module in APSIM simulates water balance using the Richard's equation and was selected over the default soil water module in APSIM (SOILWAT) because of its capability to simulate water flow in tiles (Malone et al., 2007). For a detailed description of the SWIM model see Verburg et al. (1996) and Huth et al. (2012). Soil water dynamics were manually calibrated using the available field dataset from 2008-2014 (Table 2 & 3). The main parameters we focused on were the drainage upper limit, lower limit, saturation and hydraulic conductivity, which were manually calibrated. The model simulated 5-cm depth volumetric water content with a RRMSE error of 14% and RMSE of 0.05 $mm^3\ mm^{-3}$ during model calibration and RRMSE of 27% and RMSE of 0.06 $mm^3\ mm^{-3}$ during model validation. At the 15-cm depth, the model simulated volumetric water content with a RRMSE error of 12% and RMSE of 0.04 $mm^3\ mm^{-3}$ during the calibration period and with a RRMSE error of 19% and RMSE of 0.06 $mm^3\ mm^{-3}$ during the validation period (Figure S2a, S2b). Overall the calculated statistical values fell within the range reported for soil moisture simulations (Archontoulis et al., 2014a; Dietzel, 2014).

Soil Temperature

An alternative soil temperature model available in APSIM (APSIM Documentation) was utilized in this study as it performed better compared to the default model. Archontoulis et al. (2014a) found that both available soil temperature models in APSIM performed well in Iowa during the growing season, but the one based on Campbell (1985) and described and utilized by Chauhan et al. (2007) was superior to the default. The optional soil temp module requires additional inputs of boundary layer conductance (set to 20 $J\ s^{-1}\ m^{-1}\ K^{-1}$) and clay content (25%) for the soil.

Model predictions at the 5-cm depth had a RRMSE of 11.8% and RMSE of 2.2°C during the calibration period and RRMSE 12.2% and RMSE of 2.2°C during the validation period. At 15-cm, APSIM predicted a RRMSE of 7.9% and RMSE of 1.4°C for the calibration period and a RRMSE of 10.4% and RMSE of 1.8°C for the validation period (Figure S3a, S3b). The optional soil temperature module compared to the default module decreased RMSE from 5.7°C to 2.2°C at 5-cm and 5.0°C to 1.4°C (during the validation period). Model efficiency values for soil temperature were 0.81 for the 5-cm depth calibration period, 0.86 for the validation period and 0.91 for the 15-cm depth calibration period and 0.89 during the validation period. In general, APSIM predicted lower soil temperatures in the month of April in the cover crop plots (pre-termination) by about 1-2°C (0-30cm depths).

Grain crop yields

Cultivar specific parameters for maize and soybean were used based on the work of Archontoulis et al. (2014a, b). A typical 110 day maturity maize hybrid and group 2.5 maturity soybean cultivar were used. The model simulated maize yields for both treatments with a RRMSE of 12% and RMSE of 1547 kg ha^{-1} and soybean yields for both treatments with a RRMSE of 25% and RMSE of 775 kg ha^{-1}. For the maize and soybean yields there is a slight trend toward over prediction (Figure S4a, S4b). This is most likely attributed to biotic factors that are not represented in the current APSIM version. APSIM does not at this time represent all of the processes that might occur over a growing season, such as disease, weed, or pest pressure or allelopathic effects of rye before maize (Barnes and Putnam, 1986; Kessavalou and Walters, 1997; Raimbault et al., 1990, 1991; Tollenaar et al., 1993) which might also lead to yield declines. This could also be a result of maintaining the same cultivar from year to year in the simulation.

Winter rye cover crop

Cereal rye is not listed as a crop model in APSIM version 7.5 so we chose to work with the APSIM-wheat crop module as it represented the most similar available plant. When cereal rye is grown as a winter cover crop in the Midwest, it generally does not reach the heading stage of development. Therefore we chose to focus model changes on the known differences between wheat and cereal rye impacting vegetative growth stages to try to improve its performance as a cover crop in Iowa, beginning with an American wheat cultivar (*yecora*) (Table S1).

In the wheat model, we changed the optimal temperature from 26 to 18°C and maximum temperature from 34 to 30°C (Nalborczyk and Sowa, 2001; Nuttonson, 1958) and left the base temperature at its default of 0°C. Daily biomass accumulation is calculated as the minimum of two processes, one limited by light (radiation use efficiency, 1.24g MJ^{-1}) and the other by water (transpiration efficiency, 0.006 kPa g m^{-2}). This daily dry matter is adjusted further to account for water and nitrogen limitations. Leaf development is driven by temperature based on a phyllochron interval (75 degree days °C). Between emergence and floral initiation (representing the whole of vegetative growth of a cover crop in the system we are modeling), vernalization effect on phenology was adjusted accordingly to fit our region. Higher vernalization values result in delayed accumulation of thermal time and slower phenological development. To improve model predictions we increased vernalization to a value of 5 units, the value used by Malone et al. (2007). In some years, rye cover crop was overseeded into standing maize and soybeans. Therefore we utilized the CANOPY module in ASPIM to allow crop competition for resources and better representation of intercropping aspects. When this rule is utilized, APSIM partitions the available radiation between the two growing plants according to their ability to intercept radiation.

We found that a major issue in the model's ability to capture year-to-year variability came in the seeding method at the field site. Not surprisingly, the years (in the autumns of 2001, 2002, 2012 and 2013) when the winter cover crop was broadcast seeded the model tended to overpredict rye biomass. Without any changes, the model would assume proper seed to soil contact, germination rates, and cereal rye plant populations that a broadcast seeding on the residue cover soil surface cannot achieve. To correct this (as visual observations have confirmed slower germination and lower plant populations in the field) we delayed planting in aerial seeding years by three weeks and reduced the seeding rate by 50%. Other aspects of cover crop management are outlined in the supplemental material. We also investigated nitrogen uptake of the cover crop including leaf nitrogen concentration. Improvements in rye biomass and nitrogen uptake predictions were derived by altering the parameters outlined in the supplemental material.

The average predicted biomass values over the calibration and validation period were reasonable (Figure S5a), with an RRMSE of 56% and RMSE of 895 kg ha^{-1}. The default (uncalibrated) APSIM wheat crop module parameters results in an RRMSE of 91% and an RMSE of 1457 kg ha^{-1}**.** Average winter rye biomass predicted by APSIM during this period was 1411 kg ha^{-1} compared to average observed field values of 1596 kg ha^{-1}. On average, APSIM predicted cover crop biomass well but did not always capture year to year variability especially in 2003, 2005, and 2011. The simulated N uptake values had an RMSE is 19 kg ha^{-1} and RRMSE is 41.9% (Figure S5b) which is higher than the range reported by Feyereisen et al. (2006a). We evaluated the statistics for the yields of the two cash crops combined with aboveground biomass for the cover crop in the rotation and these values had a predicted RRMSE of 19% and model efficiency of 0.94. This indicates very acceptable model performance for plant growth observations.

<u>Erosion module</u>

The erosion model was coupled to the simulation for the model application phase of this study. We utilized the Freebairn erosion module in APSIM which is built from a modified USLE equation (Freebairn and Wockner, 1986a, b; Littleboy et al., 1989). It was revised to include a greater effect of surface cover and runoff, the main factors that can be affected by management within the APSIM framework. The calculation of erosion is based on cover and runoff volume and uses slope-length, erodibility, and supporting practice factors. The surface cover value is derived from the surface organic matter module and accounts for combined crop and residue covers on the soil surface. The runoff value is derived from SWIM. We assumed a soil erodibility factor of 0.29 based on a loam soil with > 2% organic matter (Stewart, 1975) and a slope of 1% for the experimental site. To estimate a range of values of erosion prevention for our region, we also investigated slopes of 2% and 5% in our model application. Further, we explored how changes in the USLE supporting practice factor (P) would change erosion predictions, as this is an explicit input in the erosion module while crop management (C) is not explicitly included as described above (APSIM Documentation). We used a supporting practice factor for the cover crop of 0.9, which we consider to be conservative. Arabi et al. (2008) used a supporting practice factor (P factor in RUSLE) of 0.55 in SWAT where residue cover equaled 500 kg ha^{-1} which would be a low total for cover crop residue at our research site. For the erosion application scenarios, we chose four representative global climate model future weather scenarios.

Model application

We generated future weather predictions using the methodology of the AgMIP Guide For Running Climate Scenario Generation Tools with R (AgMIP, 2013). We utilized 20 different Coupled Model Intercomparison Project 5 (CMIP5) global climate model (GCM) outputs and ran simulations through 2060. We utilized GCM outputs with representative carbon pathway (RCP) 4.5, which represents a “stabilization” scenario where radiative forcing stabilizes by 2100 and an average global temperature increase of 1.8°C by 2100 relative to pre-industrial levels (IPCC, 2013). We also utilized several randomly generated meteorological files based on current trends to look for differences between the long-term climate record compared to a future weather accounting for changes due to greenhouse gas forcings (referred to as GCM-generated scenarios and randomly-generated weather scenarios) (Figure S6a-S6d).

For these simulations, we set soybean to be planted every odd numbered year on May 15 and maize every even numbered year on May 1. We set maize to be fertilized on June 1 with a rate of 198 kg ha^{-1} of liquid urea-nitrate representing an average value for the field site. For the cover crop, we utilized model set up to represent direct drilled planting after maize on October 20 and after soybean harvest on October 1. The cover crop was terminated before the maize growing season on April 15 and soybean years on May 1. Attempts to represent the cover crop management with the aerial seeding set up showed a bias toward over prediction that was not reflective of actual field growth. Therefore, we chose a more conservative cover crop planting window, which would better represent cover crop planting and termination dates between typical harvest and planting for a maize-soybean rotation in our region.

Results and Discussion

Crop Production Impacts of Climate Change and Cover Crops

<u>Cover crop impacts on maize and soybean yields</u>

Yield predictions resulted in non-significant differences for both maize (p=0.92) and soybean (p=0.94) between the cover crop and no cover treatments over the simulation period (2015 to 2060) In the short-term (2000-2005), Kaspar et al. (2007) found one year with significantly lower maize yields in the cover crop treatment, which they attributed to management challenges with cover crop termination. The other four years of maize and soybean yields had non-significant differences between treatments. For the later years of the experiment (2006-2010), Kaspar et al. (2012) reported no statistical differences between maize and soybean yields in the following five growing seasons at the field site. This level of agreement with the field data gives us confidence in our predictions for yield differences between the two treatments.

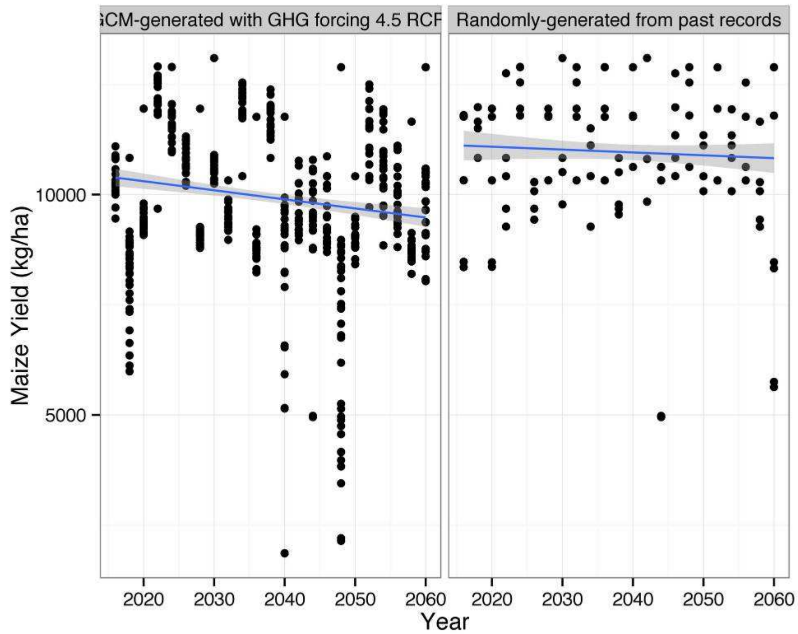

Figure 1a. Maize yields predicted by APSIM through 2060 for the cover crop and no cover crop treatments for each of the 20 global climate model (future) generated future weather scenarios and the five randomly generated weather scenarios (random), beginning in 2015. Trend line in gray.

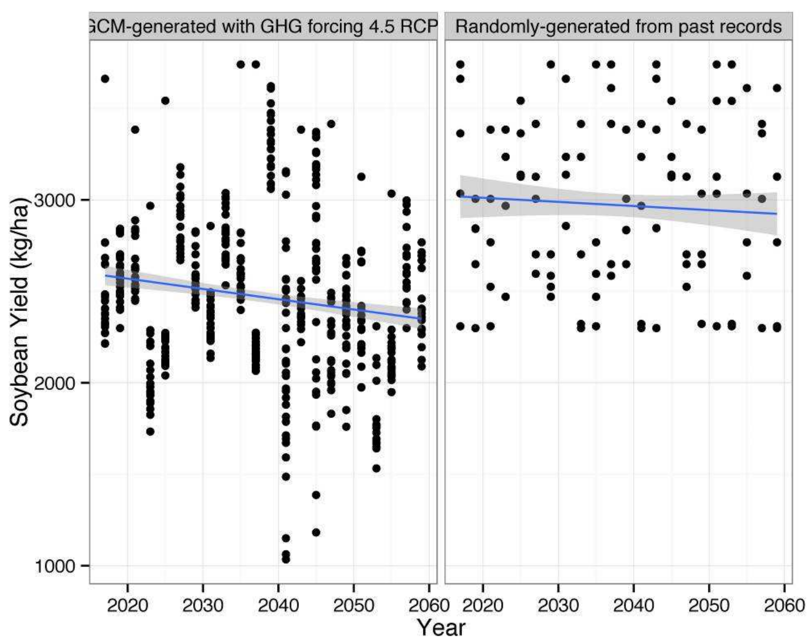

Figure 1b. Soybean yields predicted by APSIM.

To better understand the mechanisms behind the predicted differences between the treatments, we analyzed the movement of carbon, nitrogen and water in the model. Model predictions indicated that in the cover crop treatment the carbon levels in the two rapidly cycling carbon pools (BIOM and FOM pools) were higher compared to no cover crop treatment as a result of additional C input from the cover crop. We found greater nitrogen immobilization in the cover crop treatments most years from April until July (average increase between the two simulations of 13 kg ha^{-1} yr^{-1}), as well as higher gross mineralization rates for the cover crop treatment (average increase between the two simulations of 17 kg ha^{-1} yr^{-1}. The resulting net mineralization rate was only slightly higher in the cover crop simulation and this might be one of the reasons why the simulated rye cover crop had minor impacts on following crop yields (results not shown). We believe that the greater gross mineralization rate was the result of the low C/N ratio of the rye above ground biomass (~16) that contributes to higher N availability and the greater immobilization imposed by the high below ground root C/N ratio (~40). The amount of above and below ground rye biomass was variable from year-to-year, which generated variability in N cycling.

In our analysis of water dynamics, APSIM predicted higher soil water levels in the cover crop plots before and after cover crop termination at both 5-cm and 15-cm, with a more noticeable increase at 5-cm, due to lower soil evaporation predictions during this period. In the field, we observed greater evidence of soil water depletion (as compared to APSIM predictions) as the winter rye cover crop grows, but in the simulations as well as in the field observations spring rainfall in Iowa restores soil moisture to the same level in both treatments. Further, as cash crop growth proceeded, soil water predictions tended to be the same in the cover crop and no cover crop simulations (Figure S7a, S7b). APSIM predicted nearly identical maize and soybean crop water use in the two treatments (results not shown) and field observations of maize and soybean biomass did not indicate growth differences between the cover and no cover crop treatments during two growing seasons (Basche et al., 2015). The predicted changes suggest that APSIM is representing the dynamics of reduced evaporation, improved infiltration and cover crop water use, but perhaps not to the extent that is observed in the field, where we saw greater evidence of crop water use or reduced evaporation. The small predicted differences in water and nitrogen could be the reason that the model predicts no major yield effects. If the model was able to capture the full extent of cover crop impacts, there might be potential to yield improvements over time, as is often reported by farmers (SARE-CTIC, 2013, 2014, 2015).

Climate change impacts on maize and soybean yields

Throughout the duration of the simulation period (through 2060), both maize and soybean (in the cover and no cover treatments) show a trend toward a decrease in yield (Figure 1a, 1b) with an average decline of 1.6% by decade in maize and 2.7% by decade in soybeans for the GCM-generated weather scenarios. We found that the GCM-generated weather files predict several mechanisms that could lead to crop yield declines that are different than the randomly-generated weather files, including more years with significant crop water stress as well as greater soil water demand and evapotranspiration (results not shown). The greenhouse gas forcing in the GCM-generated weather files and increased temperature trends (Figure S6a, S6b) appear to be responsible for driving the increase water demands and stressors. We further found that the GCM-generated weather scenarios with a lower increased temperature trend lead to smaller rates of yield decline (results not shown).

In this analysis planting dates and cultivars were not changed for both the cash crops as well as for the cover crop. Therefore our results may not fully reflect adaptation in management for earlier cash crop planting dates and later cash crop maturities that farmers may utilize in the future (Sacks and Kucharik, 2011) which could lead to an advantageously longer growing season for maize and soybeans. This might in part account for the small yield decline in the randomly-generated weather scenarios. It should also be noted that our analysis does not include effects of increasing carbon dioxide atmospheric concentration, which has the potential to offset some, but not all, of the other future climate change impacts (Long et al., 2006; Long et al., 2004). Further, Hatfield et al. (2011) note that the potential impacts on water use efficiency from carbon dioxide increases will be offset by crop loss associated with heat stress, increases in evaporative demand and or decreases in water availability. The yield declines predicted by APSIM in our experiment are within the range predicted by other reported studies evaluating climate change scenarios. A summary of crop and climate change modeling studies, Porter et al. (2014) found that for the major cereal crops in temperature regions, average predicted declines were from 0-2% by decade into the future. The IPCC's summary also points to an increase in the number of studies reporting yield declines as well as an increase in the percent decline by decade as 2100 is approached.

Winter rye cover crop biomass

During this 45-year simulation period, the average predicted cover crop biomass is 1300 kg ha^{-1} (standard error of 800 kg ha^{-1}) over all of the weather scenarios (Figure 2). We further observed a slight increase in cover crop growth in the GCM-generated weather scenarios that is not present in the randomly generated weather scenarios. This is further evidence that the predictions of a decrease in crop yields and an increase in over winter cover crop growth result from the increasing temperature trend. However, there are years after 2040 where predictions of rye cover crop biomass are both very high (> 4000 kg ha^{-1}) and very low (< 500 kg ha^{-1}), which demonstrates that even with a warming trend, not every year will experience very high cover crop biomass. In terms of water impacts, the cover crop treatment was predicted to reduce soil evaporation between 2-18% with the greater reductions coming in drier seasons. Cover crop transpiration in the fall reached approximately 10 mm and 50 mm in the spring in high biomass years (results not shown). One adaptation strategy for farmers not accounted for in our analysis is the lengthening of the growing season for maize and soybeans (3.1.2.). However, the planting window utilized in our model application is conservative enough not to overestimate potential growing degree units available for cover crop growth into the future. The conservative planting window, even more so then utilized at our research site, is likely the reason that the randomly-generated weather scenarios predict lower than observed cover crop biomass.

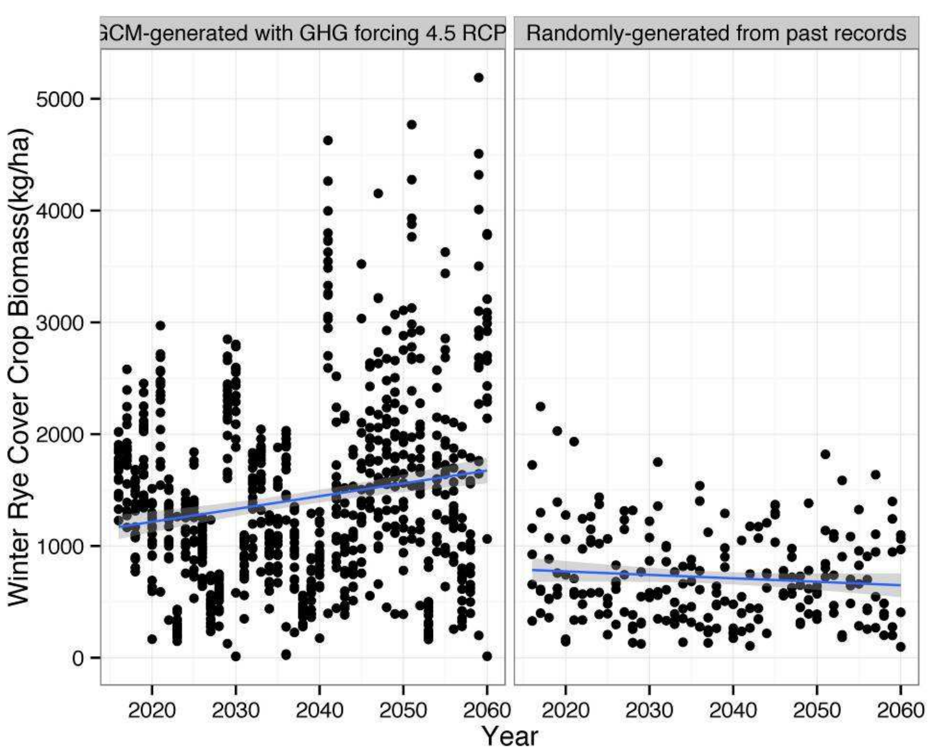

Figure 2. Biomass predictions for the winter rye cover crop for each of the 20 global climate model (future) generated future weather scenarios and the five randomly generated weather scenarios (random), beginning in 2015. Trend line in gray.

<u>Wet and dry year analysis</u>

As addressed previously, APSIM predicted only minor, non-significant maize and soybean yield differences between the cover and no cover crop treatments which over the period of the 45-year simulation. However, the yield declines that did occur in both maize and soybean in the cover crop treatments were predicted in years with lower rainfall totals. In general, declines ranged from 1-10% in maize and 1-30% in soybean in a limited number of years where rainfall was more than 25% below average (Figure S8a, S8b) or less than 690mm. We found that the model tended to predict more water stress in these years in the cover crop plots in the mid-summer period (results not shown) which could account for the reduced crop yield. The predictions demonstrate that the cover crop could compete with the cash crop for water in abnormally dry years. Whish et al. (2009) similarly found that a millet cover crop before wheat in a semi-arid region of Australia only impacted wheat years in 2% of years when properly managed. This trend of water stress in mid-summer is not something we observed in the field in 2012, the single year on record at our site with close to this abnormally low amount of rainfall (637 mm). Although there was a non-significant maize yield reduction in the cover crop treatment, our analysis of the soil water record indicated higher moisture levels at 5-cm, 15-cm and 30-cm depths during the grain fill period for maize (Basche et al., 2015). Even with the competition for soil water predicted by APSIM in the very dry seasons, yield reductions predicted in the cover crop treatment are relatively small in these years.

Environmental Impacts of Cover Crops and Climate Change

<u>Soil Carbon</u>

The model predicted increases in soil carbon at the 0-15-cm depths but decreases in the lower depths of the soil profile. In the GCM-generated weather scenarios, the cover crop treatment showed a soil carbon increase of 0.12% while in the no cover crop treatment soil carbon was essentially unchanged with a predicted difference of -0.02% between 2015 and 2060 at the 0-15-cm depth (results not shown). This represented a significant difference between treatments ($p<0.0001$). In the randomly generated weather scenarios, carbon at the 0-15-cm depth increased by 0.14% in the cover crop treatment and 0.08% in the no cover crop treatment ($p=0.007$ between treatments). At the 0-30-cm depth, APSIM predicted carbon declines in both treatments and weather scenarios, although the declines were not uniform (Figure 3). In the GCM-generated weather scenarios, predictions for the total mass of carbon over the 0-30cm depth show significant differences between the treatments ($p<0.0001$), with the no cover crop treatment losing an average of 5000 kg ha^{-1} more than the cover crop plots over the simulation period (annual loss of 110 kg $ha^{-1}y^{-1}$). This represents a decline in carbon mass of 6% in the no cover crop treatment and 3% in the cover crop treatment over the 2015 to 2060 period. The randomly generated weather scenarios show significant differences between treatments as well ($p=0.01$), with the no cover crop treatment losing an average of 71 kg ha^{-1} yr^{-1} (3% decline) more than the cover crop plots (2% decline). We also compared the relative contribution of weather scenario (GCM-generated versus randomly-generated) and treatment (cover or no cover crop) to this soil carbon decline. We found very similar effects of treatment ($p=0.008$) to the impact of future climate change ($p=0.017$) at the 0- 30-cm depth. However our analysis of statistical model residual error indicates a greater effect of a cover crop treatment than weather; although the comparison is somewhat imbalanced by the fact that we have more GCM-generated weather scenarios than randomly generated scenarios. Our results seem to indicate that even without a warmer climate change scenario, soil carbon would decline over several decades at our research site. The cover crop, however, is able to offset some of that declining trend.

These results are substantiated by long-term field trials as well as modeling efforts. Over sixty years of cultivation, wheat-fallow rotations in Oregon lost carbon at the 0-30-cm and 30-60-cm depth (Rasmussen et al., 1998). Rasmussen et al. (1998) note that few long-term experiments measure data below 30-cm, resulting in further uncertainty in soil carbon changes. In Illinois, the Morrow Plots measured carbon declines in the 0-20-cm depth over ninety years in multiple crop rotations even with adequate fertilizer (continuous maize, maize-oats, maize-oats-hay) (Huggins et al., 1998; Odell et al., 1984). Prior APSIM modeling results predict soil carbon declines into the 21st century in Iowa, where the incorporation of a winter rye cover crop can help to slow the rate of carbon loss (Dietzel, 2014). Luo et al. (2011) predicted temperature driven carbon declines at a particular site in Australia with levels of decomposable carbon similar to our research site.

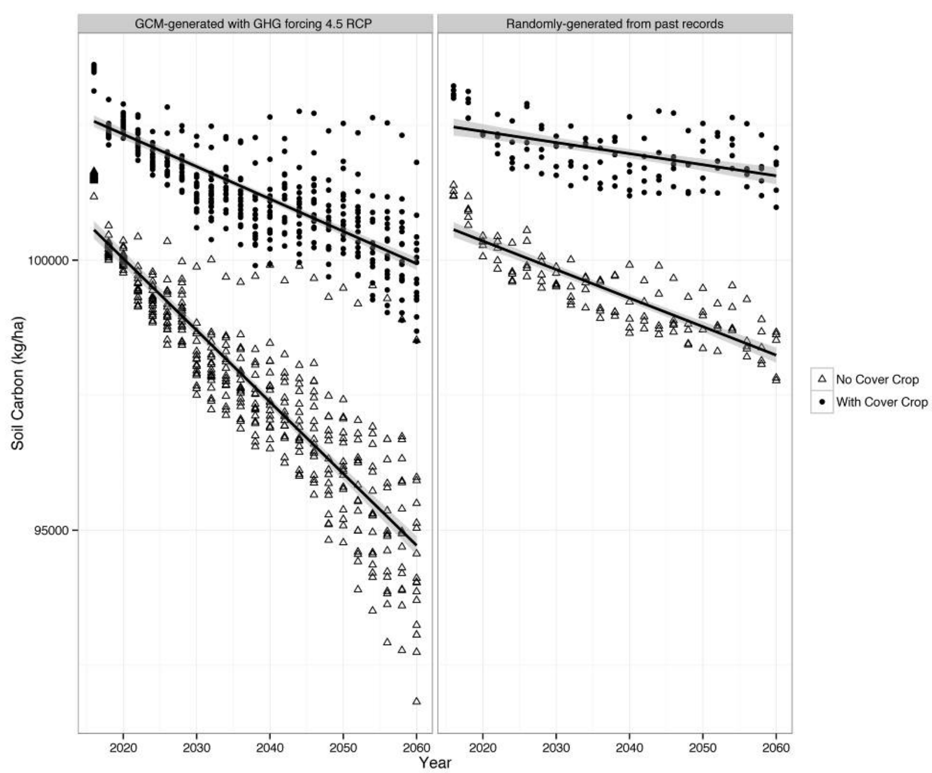

Figure 3. Predicted soil carbon changes from 2015- 2060 at the 0-30cm depth for the cover (circles) and no cover crop (triangles) simulations.

Prior modeling suggests that management can have a greater influence on soil carbon sequestration than future climate change. Thomson et al. (2006) reported that the cropping system (no-till double cropped wheat-maize versus conventional-till continuous wheat) had a more important influence on carbon sequestration than the climate change scenario. Similarly, Lugato and Berti (2008) reported that recommended management practices (such as no-till, manure management and grassland conversion) had a greater effect on carbon sequestration than the climate change scenario. The relative contribution of these factors likely varies in different locations and cropping systems and even with the use of a biophysical model like APSIM can be difficult to discern.

APSIM predictions for carbon decomposition rates are dependent upon soil temperature, soil water and the C:N ratio of the soil organic matter pools (Probert et al., 1998). Given the performance of carbon, water and temperature in model testing (Figure S1-S3), we also believe the long-term carbon predictions to be plausible. The overall decline in carbon in the future weather scenarios could be a result of soil temperature increases projected into the future (Figure S6d) driving carbon decomposition to a declining level that the addition of a cover crop cannot completely reverse. It could also be a result of the future weather scenarios predicting yield declines which resulted in lower overall carbon residue inputs. These simulations, however, do not take into account the effect of increasing atmospheric CO_2 levels on cash crop or cover crop growth. We conclude that the cover crop has the potential to serve as an adaptation strategy to slow some of the soil carbon loss. However, the cover crop may not be able to completely overcome future climate change effects on soil carbon declines as the maize-soybean rotation results in soil carbon loss under the current climate.

Soil Erosion

Soil loss prevented in the cover crop treatment ranged from an 11% to 29% reduction in erosion (1% slope) compared to the no cover treatment (Table S2). These percentages were basically unchanged when we increased field slope to 2% and 5%. We also explored the impacts of changing the supporting practice factor in the erosion module which resulted in predictions of erosion prevention from a cover crop increasing to 20% to 36% (Table S2). This range in erosion prevention resulted from the different future weather scenarios utilized. We would expect this given that the APSIM erosion module predicts erosion in part based on runoff resulting from rainfall projections.

There are several limitations to our current erosion reduction estimates. Model calculations rely heavily on ground cover and may not account for all of the physical forces by which a plant's roots would prevent residue, soil, and water movement, which might explain in part why percentages showed only minor changes when slope was increased. Further, surface roughness factors and peak runoff rates are not included in erosion calculations (APSIM Documentation). Finally there are limitations to the current downscaling capabilities of global climate models to accurately reflect daily precipitation changes into the future which might have the greatest impact on erosion. Nearing et al. (2004) estimate that erosion increases will be 1.7 times greater than annual rainfall increases in the future. If the increase in rainfall intensity is not well estimated by current downscaling techniques of global climate models then this could lead to an underestimation of erosion impacts in general.

In spite of these limitations, these estimates are reasonable considering that these are cumulative values (over wetter and drier years) and the direction of the model is consistent with our understanding of crop and soil processes. At a field site closely located to the one used in this study for calibration of the model, Kaspar et al. (2001) measured significant reductions in inter-rill erosion rates before cover crop termination in late April in three consecutive years (48%-62%) and even larger reductions in rill erosion rates (86%-93%) when a rye cover crop was grown over winter following no-till soybeans on a 4.5% slope. Thus, we believe for long term averages the APSIM predictions for cover crop reductions are reasonable and demonstrate that the cover crop, even in a no-till system, can have a significant effect on erosion reduction in the context of climate change.

Nitrous Oxide Emissions

Prior work indicates that cover crops do not consistently reduce nitrous oxide emissions from the soil surface (Basche et al., 2014), given their ability to reduce soil N, increase surface residue, increase or decrease soil water, and increase soil carbon, all of which could increase or decrease nitrous oxide loss. Given these complex interactions, we utilized our calibrated model to explore the impact of the cover crop on N_2O emissions with climate change scenarios. APSIM calculates N_2O emissions based upon soil carbon, soil water, soil temperature, and soil pH and soil NO_3-N (Thorburn et al., 2010). Predictions for nitrous oxide varied by future weather scenario utilized, where the range was from an increase in N_2O with the cover crop of 0.2% and a decrease of 33.5% (Figure 4). Of the factors that a cover crop might influence – soil nitrate, active carbon, soil moisture and soil temperature – our analysis of selected weather scenarios found that the reduction in soil nitrate was most responsible for the cover crop's reduction in nitrous oxide emissions (results not shown). In many years and weather scenarios there were large decreases in soil nitrate in the cover crop simulation and therefore we infer that this is the reason for the decreased nitrous oxide predictions. As a point of comparison, a meta-analysis found that the traditional management of a cover crop in a maize-soybean system in the Midwest (non-legume plant species that is chemically terminated) does not lead to a net difference in nitrous oxide emissions (Basche et al., 2014). Further, the GCM-generated future scenarios with higher temperature projections tended to predict the greatest N_2O emission reduction from the cover crop treatments, where those that project no temperature increases predicted smaller decreases in N_2O emissions (as well as the one weather scenario predicting a minor N_2O increase) from the cover crop (Figure 4). This indicates that in a warmer climate, the cover crop could act as a potential mitigation strategy. Field trials in Iowa maize-soybean rotations testing the effect of cover crops on N_2O emissions are mixed. Parkin and Kaspar (2006) found small insignificant emissions increases in three of four site-experiment years, while Jarecki et al. (2009) and Mitchell et al. (2013) measured increases with a cover crop in some of their site-experiment years. A controlled environment study found more consistent declines in N_2O

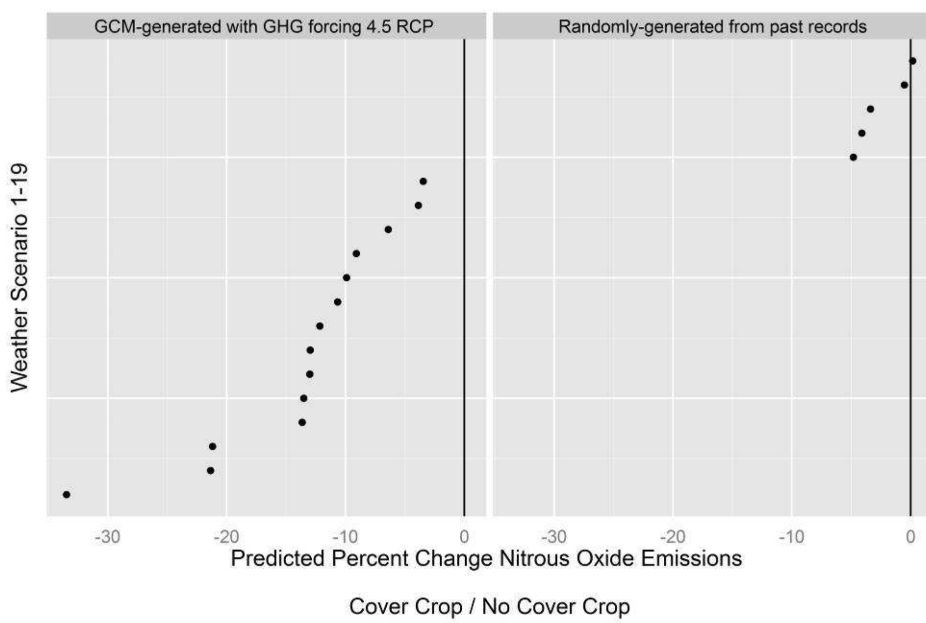

Figure 4. Predictions of the nitrous oxide response ratio (with cover crop / no cover crop) from a subset of nineteen weather scenarios. Across a series of varied weather conditions, APSIM predicts that for our location and management, the cover crop generally reduces nitrous oxide emissions.

emissions after manure applications when a winter rye cover crop was alive and taking up nitrate (Parkin et al., 2006) after soybean harvest. In the aggregate, research in Iowa demonstrates a net neutral effect of cover crops on nitrous oxide emissions and whereas this modeling simulation predicts that under projected future climate conditions, a winter rye cover crop in a maize-soybean rotation can lead to declines in N_2O emissions.

Conclusion

From this study, we conclude that in the long-term a winter rye cover crop had neutral long term effects on maize and soybean yields. However, climate change scenarios predict yield declines in both of the treatments. An average cover crop biomass of 1300 kg ha^{-1} yr^{-1} results in significant improvements to environmental impacts, including an average erosion reduction of 11-23%. Although soil carbon declines at lower depths in the soil profile (>15cm) in both treatments and weather scenarios, the cover crop simulation is able to offset that loss by 3%. In the GCM-generated climate change scenarios, carbon decline results from declining crop yields and increasing soil temperatures. Most weather scenarios predict soil nitrous oxide emissions reductions with the winter rye cover crop. Our results show that with future projected climate change, a winter rye cover crop does not lead to soil carbon increases and cannot offset future projected yield declines, however soil N_2O emissions are generally decreased and erosion prevention is increased. Thus, there is evidence of the cover crop improving outcomes with future weather but perhaps not enough to offset all potential future changes that the region may experience. Additionally, we understand that the model simulations do not fully reflect changes in soil structure, pest, diseases, and nutrient cycling that the cover crop cause over time. Given the current understanding of regional climate changes, this research demonstrates that it will continue to be a challenge to design cropping systems that enhance future soil and water resources. Future modeling efforts could investigate the potential benefit of carbon dioxide increases, longer growing seasons, and improved cover crop cultivars or species mixes to offset more of the anticipated climatic change in the Midwestern United States.

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CHAPTER 5

SUMMARY AND CONCLUSIONS

The overall objective of this dissertation research was to evaluate the mitigation and adaptation potential of cover crops in the context of future climate change in Midwest agroecosystems. Specifically, these projects quantified the impact of a winter rye cover crop on nitrous oxide emissions, soil water, cash crop yields, soil organic matter and soil erosion in maize-soybean crop rotations. This work aimed to advance scientific understanding of how cover crops impact carbon, water and nitrogen dynamics in Midwest cropping systems, using both process-based and statistical modeling approaches, to better inform their use with producers in the region.

Chapter two found that cover crops do not universally reduce nitrous oxide emissions from the soil surface. However, there is a greater chance for nitrous oxide reductions when cover crops are managed as they generally are in Midwest cropping systems, with a grass species and chemical termination method. Chapter three showed that a cereal rye cover crop increased water retained in the soil profile and led to 21-22% increases in plant available water content (30-cm depth). Further, over this series of seven characteristically different rainfall years, the cover crop did not demonstrate negative effects on cash crop growth and yields. Chapter four found that in modeling the effects of future climate, a cereal rye cover crop in a no-till maize-soybean rotation has the potential to reduce erosion losses by 11-29%, decrease nitrous oxide losses by up to 34%, and offset carbon declines by 3%. However, our modeling efforts did not find evidence that the cereal rye cover crop would offset a trend in declining yields, induced by the expected increase in temperatures and water stress.

This research illustrates also that in the context of climate adaptation and mitigation, the greatest potential benefits from a winter rye cover crop are preventing soil erosion, improving soil water retention, and potentially reducing nitrous oxide emissions from the soil surface. Although in these projects it was not assessed, it is also well documented that cover crops have a large potential to reduce nitrate leaching, preventing further nitrous oxide emissions downstream. While the cover crop may add to greater levels of soil carbon compared to a no cover crop system, we did not find evidence the cover crop leads to a positive soil carbon balance, relative to current conditions. This work also did not find evidence that the continued use of a cover crop leads to yield improvements over time. It should be noted, however, that increased maize and soybean yields is something continually reported by farmers (SARE-CTIC, 2013, 2014, 2015) and that the modeling platform utilized in this study may not incorporate all of the dynamics affected by cover cropping practices.

Future Research

This research demonstrates that it remains a challenge to design cropping systems that mitigate all potential risks posed by the changing climate. As a research community, we must work toward creatively expanding the current conceptualization of agricultural systems and envision those that achieve multi-functionality, as desired by producers and society. Two major research areas can stem from this research, the first being the questions surrounding climate risk mitigation and the second related to cover crop management in the Midwest.

Toward a climate-smart Midwest

There are several big picture questions that can help focus the direction of future research related to climate mitigation and adaptation in the Midwest. For example: How much carbon is needed to maintain a neutral to positive balance given future climate change? Is soil carbon the critical component required to maintain agroecosystem functions? Are there cropping systems that would be regenerative versus extractive for soil and water resources? Will it be possible to prevent erosion and runoff in heavy downpour events or to prevent crop yield decline in a severe drought? What is the role of precision management? How can such systems be incentivized to expand acreage? How is food security integrated into a more strategic climate adaptation plan for the region?

Investigating these complex questions will undoubtedly require multiple research approaches. As this work demonstrates, the use of a cover crop does not offset all future climate impacts so a similar investigation (potentially using long-term field data and process-based models) evaluating multiple practices – such as perennial crops, diversified crop rotations including small grains and integrated livestock systems - would be beneficial. We should also continue to analyze long-term datasets to tease out how weather impacts diverse cropping practices (Gaudin et al., 2015) where such data exists. Soil carbon is known to be an important regulator of many agroecosystem functions, however given the high fertility in soils such as those found in Iowa, many research projects have demonstrated the difficulty in maintaining or increasing it over time (Dietzel, 2014; Huggins et al., 1998). Thus it will be important to consider and investigate other important factors in the context of climate risk reduction, including how to manage the impacts of rainfall variability. In my upcoming research fellowship, I plan to investigate water impacts from conservation practices on a regional scale. As outlined in the introduction, multiple climate risk management approaches exist; they range from plant genetics to financial instruments to agronomic management. Soil management, as investigated in this study, is one of the most cost effective and broadly beneficial (for individual producers and the public) of these strategies and should continue to be an emphasis of public research investment.

Cover crops in the Midwest

Increasing cover crop acreage not only in Iowa but also in the Midwest and across the country is a current focus of much research and dedicated programmatic efforts from government, non-profit and private sector entities. Given that producers in the Midwest continually express that seeding and establishment is a major obstacle to utilizing and managing cover crops (Mine et al., 2014; SARE-CTIC, 2013, 2014, 2015), an important research need to scale up their use is to advance practices that ensure proper seeding and establishment within the timeframe available to maize-soybean systems. Further, receiving robust environmental benefits from cover crops, as quantified in this dissertation, requires adequate growth year over year, which cannot occur without successful seeding. Options for expanding cover crop establishment range from advances in equipment technology to exploring the productivity of shorter season maize and soybean cultivars to diversifying crop rotations, all of which could allow for an extended cover crop planting window.

Another specific challenge in Iowa will be the development of and research with non-grass and mixed cover crop species. Given the risk averse nature of many Iowa producers, it will remain important to continue studying the impacts of alternate cover crop species on cash crop yields beyond cereal rye (Arbuckle and Roesch-McNally, In Press). Undoubtedly cereal rye is one of only a few species that can reliably be grown within the confines of the maize-soybean winter window, and therefore addressing issues with reliable seeding and establishment will allow for greater opportunities with more non-grass cover crop species.

Social science research aimed toward increasing cover crop adoption could include a more thorough economic analysis accounting for the positive environmental benefits, on a field and regional scale, provided by the use of cover crops and could build off of similar analyses to this investigation. Focus group discussions with Iowa farmers uncovered a desire to fully quantify soil erosion and nutrient loss prevented with cover crops, such that costs and benefits are more equalized compared to non-conservation management (Roesch-McNally et al., In Preparation). Another important social science inquiry should be on how outreach efforts target both producers and landowners. For example this includes the large percentage of women landowners in the state of Iowa who may have a different set of priorities as compared to land renters (Carter, 2015). The continued feedback of social and biophysical is critical to advancing conservation in the region.

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APPENDIX A

SUPPLEMENTAL MATERIAL CHAPTER 3

Table S1 ANOVA table for the day of year contrasts evaluated for soil water content treatment differences

Spring Period

Year	DOY	Depth	Estimated CC-NCC diff $mm^3 mm^{-3}$	Standard Error	DF	t Value	Adj P	Notes / * Sig at P<0.1
2008	110	5cm	0.01496	0.01779	72	0.84	0.4031	
2008	115	5cm	0.01396	0.01768	72	0.79	0.4323	
2008	120	5cm	0.007651	0.01752	72	0.44	0.6636	Cover Crop Term Date
2008	125	5cm	0.01344	0.01764	72	0.76	0.4487	
2008	130	5cm	0.01663	0.01764	72	0.94	0.3489	
2008	135	5cm	0.01291	0.01752	72	0.74	0.4636	Maize Planting Date
2008	140	5cm	0.004346	0.01768	72	0.25	0.8066	
2008	145	5cm	0.003607	0.01779	72	0.2	0.8399	
2008	110	10cm	0.01023	0.01106	72	0.92	0.3584	
2008	115	10cm	0.01027	0.01101	72	0.93	0.3539	
2008	120	10cm	0.005319	0.01093	72	0.49	0.6279	Cover Crop Term Date
2008	125	10cm	0.01059	0.01099	72	0.96	0.3385	
2008	130	10cm	0.01204	0.01099	72	1.1	0.2769	
2008	135	10cm	0.01102	0.01093	72	1.01	0.3166	Maize Planting Date
2008	140	10cm	0.00892	0.01101	72	0.81	0.4204	
2008	145	10cm	0.009503	0.01106	72	0.86	0.3932	
2008	110	15cm	0.003389	0.01117	72	0.3	0.7625	
2008	115	15cm	0.003024	0.01112	72	0.27	0.7864	
2008	120	15cm	0.001692	0.01104	72	0.15	0.8787	Cover Crop Term Date
2008	125	15cm	0.004139	0.0111	72	0.37	0.7103	
2008	130	15cm	0.004462	0.0111	72	0.4	0.6889	
2008	135	15cm	0.003963	0.01104	72	0.36	0.7207	Maize Planting Date
2008	140	15cm	0.003731	0.01112	72	0.34	0.7382	
2008	145	15cm	0.004268	0.01117	72	0.38	0.7036	
2009	130	5cm	-0.01565	0.01555	36	-1.01	0.321	
2009	135	5cm	0.003273	0.01554	36	0.21	0.8344	
2009	141	5cm	-0.03567	0.01553	36	-2.3	0.0276	* Cover Crop Term Date
2009	142	5cm	-0.04052	0.0155	36	-2.61	0.013	* So Planting

Table S1 (Continued)

2009	145	5cm	-0.0414	0.0155	36	-2.67	0.0113	*
2009	146	5cm	-0.02816	0.0155	36	-1.82	0.0776	*
2009	147	5cm	-0.01304	0.01554	36	-0.84	0.4069	SW takes 5 days to reach NS diff
2009	150	5cm	-0.01391	0.01554	36	-0.9	0.3767	
2009	130	10cm	-0.02293	0.01004	36	-2.28	0.0284	
2009	135	10cm	-0.01016	0.01003	36	-1.01	0.318	
2009	141	10cm	-0.02486	0.01003	36	-2.48	0.018	* Cover Crop Term Date
2009	142	10cm	-0.02901	0.01	36	-2.9	0.0063	* Soybean Planting
2009	145	10cm	-0.03018	0.01	36	-3.02	0.0047	*
2009	146	10cm	-0.01876	0.01	36	-1.88	0.0688	*
2009	147	10cm	-0.00315	0.01003	36	-0.31	0.7551	SW takes 5 days to reach NS diff
2009	150	10cm	-0.00065	0.01003	36	-0.07	0.9483	
2009	130	15cm	-0.00335	0.01433	36	-0.23	0.8163	
2009	135	15cm	-0.00232	0.01433	36	-0.16	0.8721	
2009	141	15cm	-0.00887	0.01433	36	-0.62	0.5398	Cover Crop Term Date
2009	142	15cm	-0.01184	0.01432	36	-0.83	0.4139	Soy Planting
2009	145	15cm	-0.013	0.01432	36	-0.91	0.3701	No SW differences at 15-cm depth
2009	146	15cm	-0.00854	0.01432	36	-0.6	0.5549	
2009	147	15cm	-0.00131	0.01433	36	-0.09	0.9276	
2009	150	15cm	0.002116	0.01433	36	0.15	0.8834	
2010	100	5cm	0.003672	0.01227	52	0.3	0.766	
2010	105	5cm	-0.02031	0.01133	52	-1.79	0.0788	*
2010	109	5cm	-0.02775	0.01131	52	-2.45	0.0175	* Cover Crop Term Date
2010	115	5cm	0.00558	0.01115	52	0.5	0.6188	
2010	119	5cm	0.009007	0.0116	52	0.78	0.4412	Maize Planting Date
2010	125	5cm	0.001162	0.01133	52	0.1	0.9187	
2010	100	10cm	-0.00647	0.01326	52	-0.49	0.6278	
2010	105	10cm	-0.01837	0.01301	52	-1.41	0.1639	
2010	109	10cm	-0.03085	0.01301	52	-2.37	0.0214	* Cover Crop Term Date
2010	115	10cm	-0.01062	0.01297	52	-0.82	0.4165	
2010	119	10cm	-0.0045	0.01309	52	-0.34	0.7322	Maize Planting Date
2010	125	10cm	-0.00362	0.01301	52	-0.28	0.7817	
2010	100	15cm	-0.00501	0.01152	52	-0.43	0.6655	
2010	105	15cm	-0.01025	0.01141	52	-0.9	0.3733	

Table S1 (Continued)

2010	109	15cm	-0.01575	0.01141	52	-1.38	0.1735	No SW differences at 15-cm depth
2010	115	15cm	-0.0071	0.0114	52	-0.62	0.536	
2010	119	15cm	-0.00172	0.01145	52	-0.15	0.8811	
2010	125	15cm	0.000127	0.01141	52	0.01	0.9912	
2012	105	5cm	0.01056	0.03686	54	0.29	0.7755	
2012	110	5cm	-0.01339	0.03609	54	-0.37	0.712	
2012	114	5cm	-0.00743	0.03609	54	-0.21	0.8377	Cover Crop Term Date
2012	120	5cm	-0.01094	0.03646	54	-0.3	0.7652	
2012	125	5cm	-0.02055	0.03654	54	-0.56	0.5761	Maize Planting Date
2012	130	5cm	0.01442	0.03609	54	0.4	0.691	
2012	105	15cm	0.01676	0.04226	54	0.4	0.6932	
2012	110	15cm	-0.00354	0.04183	54	-0.08	0.9329	
2012	114	15cm	-0.0006	0.04183	54	-0.01	0.9885	Cover Crop Term Date
2012	120	15cm	0.003089	0.04203	54	0.07	0.9417	
2012	125	15cm	-0.01981	0.04208	54	-0.47	0.6397	Maize Planting Date
2012	130	15cm	-0.003	0.04183	54	-0.07	0.9431	
2012	105	30cm	0.03821	0.04125	54	0.93	0.3584	
2012	110	30cm	0.01267	0.04078	54	0.31	0.7572	
2012	114	30cm	0.01587	0.04078	54	0.39	0.6987	Cover Crop Term Date
2012	120	30cm	0.01875	0.04101	54	0.46	0.6493	
2012	125	30cm	-0.00382	0.04105	54	-0.09	0.9262	Maize Planting Date
2012	130	30cm	0.01464	0.04078	54	0.36	0.7209	
2013	125	5cm	0.000944	0.01237	72	0.08	0.9394	
2013	133	5cm	-0.01158	0.01203	72	-0.96	0.339	Cover Crop Term Date
2013	138	5cm	-0.0331	0.01195	72	-2.77	0.0071	*
2013	143	5cm	0.007225	0.01203	72	0.6	0.5499	Soy Planting- SW levels are same
2013	148	5cm	-0.01233	0.01158	72	-1.07	0.2903	
2013	125	15cm	0.01647	0.0125	72	1.32	0.1919	
2013	133	15cm	0.008097	0.01235	72	0.66	0.5141	Cover Crop Term Date
2013	138	15cm	-0.00153	0.01232	72	-0.12	0.9014	
2013	143	15cm	0.0149	0.01235	72	1.21	0.2316	Soy Planting
2013	148	15cm	-0.00459	0.01214	72	-0.38	0.7063	
2013	125	30cm	0.01169	0.01056	72	1.11	0.2721	
2013	133	30cm	0.007679	0.01053	72	0.73	0.4681	Cover Crop Term Date

Table S1 (Continued)

2013	138	30cm	0.003506	0.01052	72	0.33	0.7399	
2013	143	30cm	0.01175	0.01053	72	1.12	0.268	Soy Planting
2013	148	30cm	0.000109	0.01048	72	0.01	0.9917	
2014	90	5cm	0.0284	0.02992	72	0.95	0.3457	
2014	100	5cm	0.01986	0.02917	72	0.68	0.4981	Cover Crop Term Date
2014	110	5cm	0.006043	0.02949	72	0.2	0.8382	
2014	126	5cm	0.006411	0.02917	72	0.22	0.8266	Maize Planting Date
2014	135	5cm	0.02108	0.02992	72	0.7	0.4834	
2014	90	15cm	0.02417	0.0124	72	1.95	0.055	* Sig higher in CC
2014	100	15cm	0.01981	0.01206	72	1.64	0.1049	Cover Crop Term Date
2014	110	15cm	0.01533	0.0122	72	1.26	0.2131	
2014	126	15cm	0.01637	0.01206	72	1.36	0.1788	Maize Planting Date
2014	135	15cm	0.02094	0.0124	72	1.69	0.0955	* Sig higher in CC
2014	90	30cm	0.02611	0.01077	72	2.43	0.0178	* Sig higher in CC
2014	100	30cm	0.003441	0.01057	72	0.33	0.7458	Cover Crop Term Date
2014	110	30cm	0.001536	0.01065	72	0.14	0.8858	
2014	126	30cm	0.003059	0.01057	72	0.29	0.7732	Maize Planting Date
2014	135	30cm	0.004904	0.01077	72	0.46	0.6501	

Summer Analysis

Year	DOY	Depth	Estimated CC-NCC diff $mm^3\ mm^{-3}$	Standard Error	DF	t Value	Adj P	* Sig at P<0.1
2008	200	5cm	-0.01353	0.01506	112	-0.9	0.3708	
2008	210	5cm	0.00052	0.01498	112	0.03	0.9723	
2008	220	5cm	-0.00904	0.01488	112	-0.61	0.5447	
2008	230	5cm	-0.01198	0.01488	112	-0.8	0.4227	
2008	240	5cm	-0.01422	0.01498	112	-0.95	0.3444	
2008	250	5cm	-0.01649	0.01506	112	-1.09	0.276	
2008	200	10cm	-0.00251	0.01178	112	-0.21	0.8317	
2008	210	10cm	0.009357	0.01173	112	0.8	0.4266	
2008	220	10cm	0.000752	0.01166	112	0.06	0.9487	
2008	230	10cm	0.00641	0.01166	112	0.55	0.5835	
2008	240	10cm	0.000064	0.01173	112	0.01	0.9957	
2008	250	10cm	-0.00185	0.01178	112	-0.16	0.8757	
2008	200	15cm	-0.00305	0.01179	112	-0.26	0.7962	

Table S1 (Continued)

2008	210	15cm	0.004487	0.01176	112	0.38	0.7035	
2008	220	15cm	0.000953	0.01173	112	0.08	0.9354	
2008	230	15cm	0.00555	0.01173	112	0.47	0.6371	
2008	240	15cm	0.001243	0.01176	112	0.11	0.916	
2008	250	15cm	0.001204	0.01179	112	0.1	0.9188	
2009	200	5cm	-0.0079	0.01958	76	-0.4	0.6876	
2009	210	5cm	0.00179	0.01957	76	0.09	0.9273	
2009	220	5cm	0.01399	0.01953	76	0.72	0.476	
2009	230	5cm	0.008199	0.01953	76	0.42	0.6757	
2009	240	5cm	0.00382	0.01957	76	0.2	0.8458	
2009	250	5cm	-0.01436	0.01958	76	-0.73	0.4656	
2009	200	10cm	-0.00789	0.01323	76	-0.6	0.5528	
2009	210	10cm	-0.003	0.01322	76	-0.23	0.8211	
2009	220	10cm	0.004287	0.01315	76	0.33	0.7453	
2009	230	10cm	-0.00102	0.01315	76	-0.08	0.9384	
2009	240	10cm	-0.00433	0.01322	76	-0.33	0.7439	
2009	250	10cm	-0.00117	0.01323	76	-0.09	0.93	
2009	200	15cm	0.02157	0.0165	76	1.31	0.1949	
2009	202	15cm	0.02558	0.0165	76	1.55	0.1251	
2009	205	15cm	0.02703	0.01649	76	1.64	0.1054	*
2009	206	15cm	0.02991	0.01649	76	1.81	0.0737	*
2009	208	15cm	0.03374	0.01639	76	2.06	0.043	*
2009	210	15cm	0.03476	0.01649	76	2.11	0.0383	*
2009	212	15cm	0.0334	0.01639	76	2.04	0.045	*
2009	215	15cm	0.03116	0.01645	76	1.89	0.062	*
2009	218	15cm	0.03004	0.01645	76	1.83	0.0718	*
2009	220	15cm	0.01978	0.01645	76	1.2	0.2329	
2009	222	15cm	0.02463	0.01645	76	1.5	0.1385	
2009	230	15cm	0.02341	0.01645	76	1.42	0.1588	
2009	240	15cm	-0.0004	0.01649	76	-0.02	0.9807	
2009	250	15cm	0.00918	0.0165	76	0.56	0.5795	
2010	200	5cm	0.005325	0.009638	152	0.55	0.5814	
2010	210	5cm	0.001971	0.00963	152	0.2	0.8381	
2010	220	5cm	0.004115	0.009574	152	0.43	0.6679	
2010	230	5cm	-0.00022	0.009574	152	-0.02	0.9816	
2010	240	5cm	0.000656	0.00963	152	0.07	0.9458	
2010	250	5cm	0.001292	0.009638	152	0.13	0.8935	
2010	200	10cm	0.000122	0.008721	152	0.01	0.9889	
2010	210	10cm	0.000961	0.008715	152	0.11	0.9124	
2010	220	10cm	0.001493	0.008678	152	0.17	0.8637	
2010	230	10cm	-0.00388	0.008678	152	-0.45	0.6555	
2010	240	10cm	-0.00094	0.008715	152	-0.11	0.9145	

Table S1 (Continued)

2010	250	10cm	0.000131	0.008721	152	0.02	0.9881
2010	200	15cm	0.004461	0.007924	152	0.56	0.5742
2010	210	15cm	0.004582	0.007919	152	0.58	0.5637
2010	220	15cm	0.003805	0.007888	152	0.48	0.6302
2010	230	15cm	0.000607	0.007888	152	0.08	0.9388
2010	240	15cm	0.002231	0.007919	152	0.28	0.7785
2010	250	15cm	0.002528	0.007924	152	0.32	0.7502
2012	200	5cm	-0.00575	0.01684	114	-0.34	0.7333
2012	210	5cm	0.009478	0.01665	114	0.57	0.5703
2012	220	5cm	0.01741	0.01666	114	1.05	0.2982
2012	230	5cm	0.01256	0.0164	114	0.77	0.4454
2012	240	5cm	0.01021	0.0164	114	0.62	0.5348
2012	250	5cm	0.01812	0.01666	114	1.09	0.2789
2012	260	5cm	0.007272	0.01665	114	0.44	0.6631
2012	270	5cm	0.003873	0.01684	114	0.23	0.8185
2012	200	15cm	-0.00083	0.02234	84	-0.04	0.9705
2012	210	15cm	0.001633	0.01985	84	0.08	0.9346
2012	220	15cm	0.009554	0.02103	84	0.45	0.6508
2012	230	15cm	0.005873	0.0203	84	0.29	0.7731
2012	240	15cm	0.003858	0.02025	84	0.19	0.8493
2012	250	15cm	-0.00529	0.0209	84	-0.25	0.8007
2012	260	15cm	-0.00109	0.02025	84	-0.05	0.9571
2012	262	15cm	-0.00186	0.02061	84	-0.09	0.9283
2012	264	15cm	-0.00184	0.0203	84	-0.09	0.9278
2012	266	15cm	-0.00204	0.02036	84	-0.1	0.9204
2012	270	15cm	-0.00162	0.0203	84	-0.08	0.9364
2012	280	15cm	0.01003	0.02103	84	0.48	0.6348
2012	285	15cm	0.02861	0.02036	84	1.41	0.1636
2012	286	15cm	0.03097	0.0198	84	1.56	0.1216
2012	287	15cm	0.03234	0.02033	84	1.59	0.1154
2012	288	15cm	0.03244	0.02091	84	1.55	0.1246
2012	289	15cm	0.03114	0.02031	84	1.53	0.1289
2012	290	15cm	0.02903	0.01985	84	1.46	0.1473
2012	300	15cm	0.02493	0.02234	84	1.12	0.2676
2012	200	30cm	0.01213	0.02339	84	0.52	0.6055
2012	210	30cm	0.01378	0.02105	84	0.65	0.5144
2012	220	30cm	0.01597	0.02217	84	0.72	0.4732
2012	230	30cm	0.01577	0.02148	84	0.73	0.4651
2012	240	30cm	0.01432	0.02143	84	0.67	0.5059
2012	250	30cm	0.01227	0.02205	84	0.56	0.5792
2012	260	30cm	0.01931	0.02143	84	0.9	0.37
2012	262	30cm	0.01913	0.02177	84	0.88	0.382

Table S1 (Continued)

2012	264	30cm	0.0191	0.02148	84	0.89	0.3765	
2012	266	30cm	0.01883	0.02153	84	0.87	0.3843	
2012	270	30cm	0.01089	0.02148	84	0.51	0.6134	
2012	280	30cm	0.004364	0.02217	84	0.2	0.8444	
2012	285	30cm	0.02565	0.02153	84	1.19	0.2369	
2012	286	30cm	0.03144	0.021	84	1.5	0.1382	
2012	287	30cm	0.0357	0.02151	84	1.66	0.1006	*
2012	288	30cm	0.03703	0.02206	84	1.68	0.0969	*
2012	289	30cm	0.03457	0.02149	84	1.61	0.1114	
2012	290	30cm	0.02969	0.02105	84	1.41	0.1621	
2012	300	30cm	0.01949	0.02339	84	0.83	0.4071	
2013	200	5cm	0.001702	0.009174	152	0.19	0.8531	
2013	210	5cm	-0.00507	0.009159	152	-0.55	0.5806	
2013	220	5cm	-0.00925	0.009055	152	-1.02	0.3087	
2013	230	5cm	0.000364	0.009055	152	0.04	0.968	
2013	240	5cm	-0.00007	0.009159	152	-0.01	0.9939	
2013	250	5cm	0.001469	0.009174	152	0.16	0.873	
2013	200	15cm	0.01357	0.01402	152	0.97	0.3346	
2013	210	15cm	0.01239	0.01402	152	0.88	0.3782	
2013	220	15cm	0.009825	0.014	152	0.7	0.4839	
2013	230	15cm	0.001439	0.014	152	0.1	0.9183	
2013	240	15cm	0.01005	0.01402	152	0.72	0.4747	
2013	250	15cm	0.01126	0.01402	152	0.8	0.4234	
2013	200	30cm	0.02233	0.01668	152	1.34	0.1826	
2013	210	30cm	0.02127	0.01668	152	1.28	0.2042	
2013	220	30cm	0.01876	0.01668	152	1.13	0.2623	
2013	230	30cm	0.01809	0.01668	152	1.08	0.2799	
2013	240	30cm	0.02027	0.01668	152	1.22	0.2261	
2013	250	30cm	0.02068	0.01668	152	1.24	0.217	
2014	200	5cm	0.001294	0.02101	152	0.06	0.951	
2014	210	5cm	-0.02726	0.021	152	-1.3	0.1962	
2014	220	5cm	-0.02532	0.02093	152	-1.21	0.2282	
2014	228	5cm	-0.02269	0.02093	152	-1.08	0.2801	
2014	231	5cm	-0.01503	0.02082	152	-0.72	0.4712	
2014	233	5cm	-0.01784	0.02093	152	-0.85	0.3954	
2014	235	5cm	-0.02305	0.02093	152	-1.1	0.2726	
2014	240	5cm	-0.00221	0.021	152	-0.11	0.9164	
2014	250	5cm	0.01877	0.02101	152	0.89	0.3729	
2014	200	15cm	0.01601	0.01352	152	1.18	0.238	
2014	210	15cm	0.02026	0.01351	152	1.5	0.1356	
2014	220	15cm	0.02877	0.01341	152	2.15	0.0335	*
2014	228	15cm	0.02323	0.01342	152	1.73	0.0854	*

Table S1 (Continued)

2014	231	15cm	0.023	0.01326	152	1.74	0.0847	*
2014	233	15cm	0.02388	0.01342	152	1.78	0.0771	*
2014	235	15cm	0.02803	0.01341	152	2.09	0.0383	*
2014	240	15cm	0.009288	0.01351	152	0.69	0.4927	
2014	250	15cm	0.00575	0.01352	152	0.43	0.6712	
2014	200	30cm	0.002815	0.01807	152	0.16	0.8764	
2014	210	30cm	0.0049	0.01806	152	0.27	0.7865	
2014	220	30cm	0.02366	0.01798	152	1.32	0.1903	
2014	228	30cm	0.01733	0.01799	152	0.96	0.3369	
2014	231	30cm	0.01487	0.01785	152	0.83	0.4061	
2014	233	30cm	0.01773	0.01799	152	0.99	0.3259	
2014	235	30cm	0.01778	0.01798	152	0.99	0.3243	
2014	240	30cm	0.01504	0.01806	152	0.83	0.4064	
2014	250	30cm	0.006134	0.01807	152	0.34	0.7348	

Table S2 Aboveground plant sample dates, plant N and growth stages for cash crops in experiment. * represents a sampling date where there was a difference between treatments at the $p<0.05$ level

2013 Soybeans Total Plant N (n=4 reps)

Date	Cover kg ha^{-1} (SE)	No Cover kg ha^{-1} (SE)	Growth Stage
6/26/2013	5.1 (0.6)	5.0 (0.6)	V2
7/10/2013	33.6 (2.5)	32.9 (2.5)	R1
7/23/2013	65.3 (6.1)	71.0 (6.1)	R3
8/7/2013	109.8 (6.3)	100.6 (6.3)	R4/R5
8/21/2013	159.4 (11.4)	141.3 (11.4)	R6
9/10/2013	197.6 (12.5)	219.2 (12.5)	R7

2014 Corn Total Plant N Uptake (n=4 reps)

Date	Cover kg ha^{-1}	No Cover kg ha^{-1}	Growth Stage	Notes
6/2/2014	4.4 (0.7)	3.2 (0.7)	V3	
6/23/2014	81.8 (1.4)	71.0 (1.4)	V7	*
7/3/2014	139.4 (2.9)	137.8 (2.9)	V9	
7/17/2014	198.6 (6.3)	176.7 (6.3)	V11/VT	*
7/31/2014	147.8 (8.4)	154.4 (8.4)	R2	Kernels were too small to remove and grind
8/13/2014	191.2 (6.4)	188.3 (6.4)	R2/R3	
9/8/2014	287.5 (26.8)	251.4 (26.8)	R5	

APPENDIX B

SUPPLEMENTAL MATERIAL CHAPTER 4

Table S1. Changes to the winter rye cover crop module

Plant and Environment	**Default value**	**New value**
Optimum temp	26°C	18°C
Ceiling temp	34°C	30°C
Vernalization sensitivity	2.5	5
Soil water required for germination at seeding depth	0 mm mm^{-1}	0.15 mm mm^{-1}
Extinction coefficient	0.5	0.35
Management differences with seeding method	**Aerial Seeding**	**Direct Drilling**
Seeding depth	1mm	10mm
Seeding rate	50 plants m^{-2}	100 plants m^{-2}
Planting date	Actual planting date from Table 2 plus three weeks (assumed additional requirement for germination)	Actual planting date from Table 2

Table S2. Erosion Predictions

	Climate Scenario	**GCM or randomly generated**	**Field Slope**	**P Factor For Cover Crop Treatment**	**Percent Erosion Reduced With Cover Crop**
Baseline: field slope 1% and no change in P factor	ACCESS	GCM	1%	1	23.5
	BCC-CSM	GCM	1%	1	20.3
	BNU-ESM	GCM	1%	1	19.3
	CanESM2	GCM	1%	1	10.6
	CCSM4	GCM	1%	1	19.2
	CESM1-BGC	GCM	1%	1	20
	GFDL-G	GCM	1%	1	21.4
	GFDL-M	GCM	1%	1	16.9

Table S2 (Continued)

	inmcm4	GCM	1%	1	15.2
	IPSL-LR		GCM	1%	1
	met1	Randomly generated	1%	1	18.8
	met2	Randomly generated	1%	1	12.5
	met3	Randomly generated	1%	1	13.9
	met4	Randomly generated	1%	1	13.5
	met5	Randomly generated	1%	1	10.7
	MIROC-ESM	GCM	1%	1	13.7
	MIROC5	GCM	1%	1	28.9
	MPI-LR	GCM	1%	1	25
	MPI-MR	GCM	1%	1	16.3
	CanESM2	GCM	2%	1	16.4
Field slope changes	CESM1-BGC	GCM	2%	1	10.3
	MIROC-ESM	GCM	2%	1	20.2
	MPI-MR	GCM	2%	1	28.8
	CanESM2	GCM	5%	1	16.9
	CESM1-BGC	GCM	5%	1	10.4
	MIROC-ESM	GCM	5%	1	20.1
	MPI-MR	GCM	5%	1	28.6
	CanESM2	GCM	1%	0.9	17
P factor changes	CESM1-BGC	GCM	1%	0.9	19.5
	MIROC-ESM	GCM	1%	0.9	28.1
	MPI-MR	GCM	1%	0.9	35.8

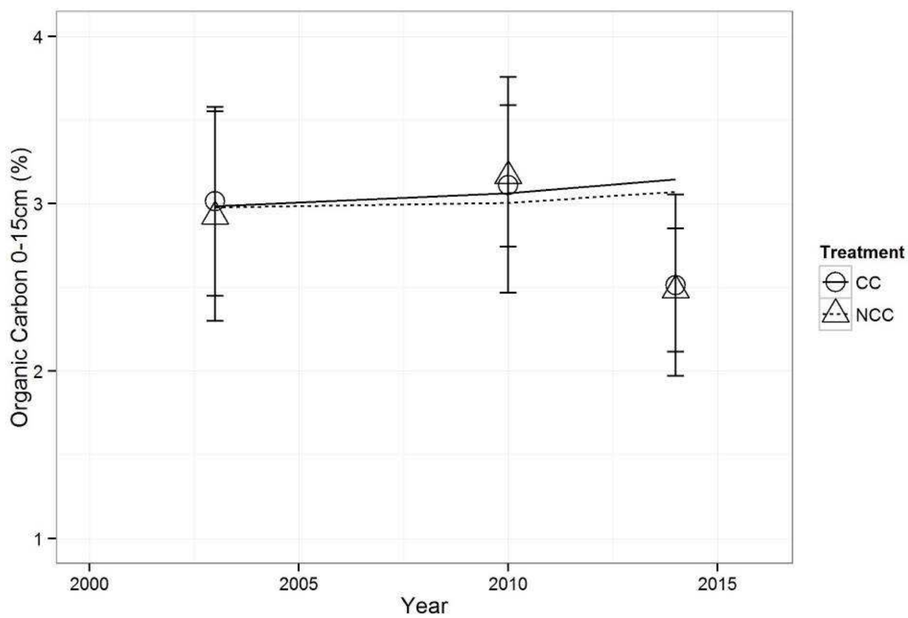


Figure S1a Soil carbon predictions (lines) and observations (2003, 2010, 2014 symbols) for the cover crop and no cover crop treatments for the 0-15-cm depth

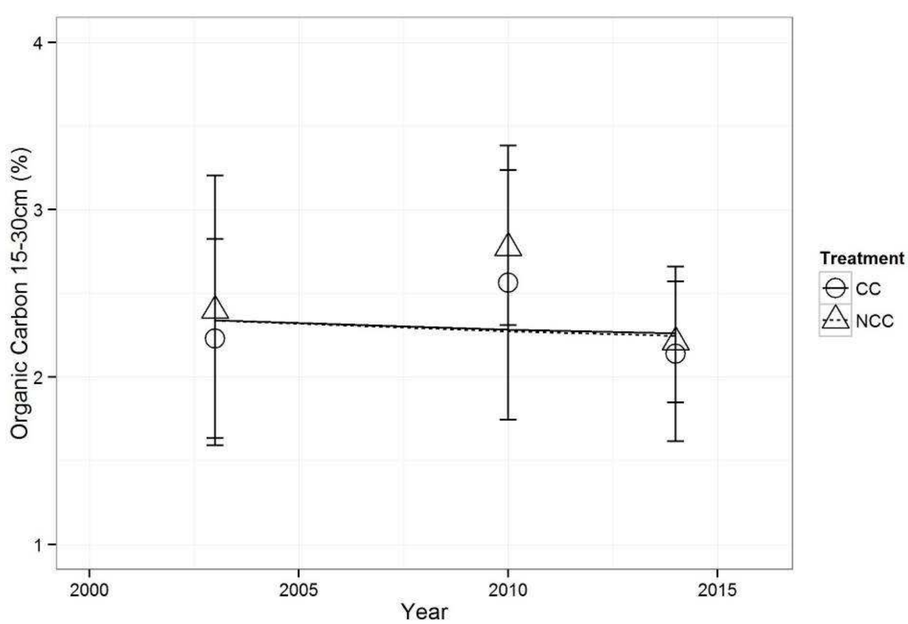


Figure S1b. Soil carbon predictions (lines) and observations (2003, 2010, 2014 symbols) for the cover crop and no cover crop treatments for the 15-30-cm depth.

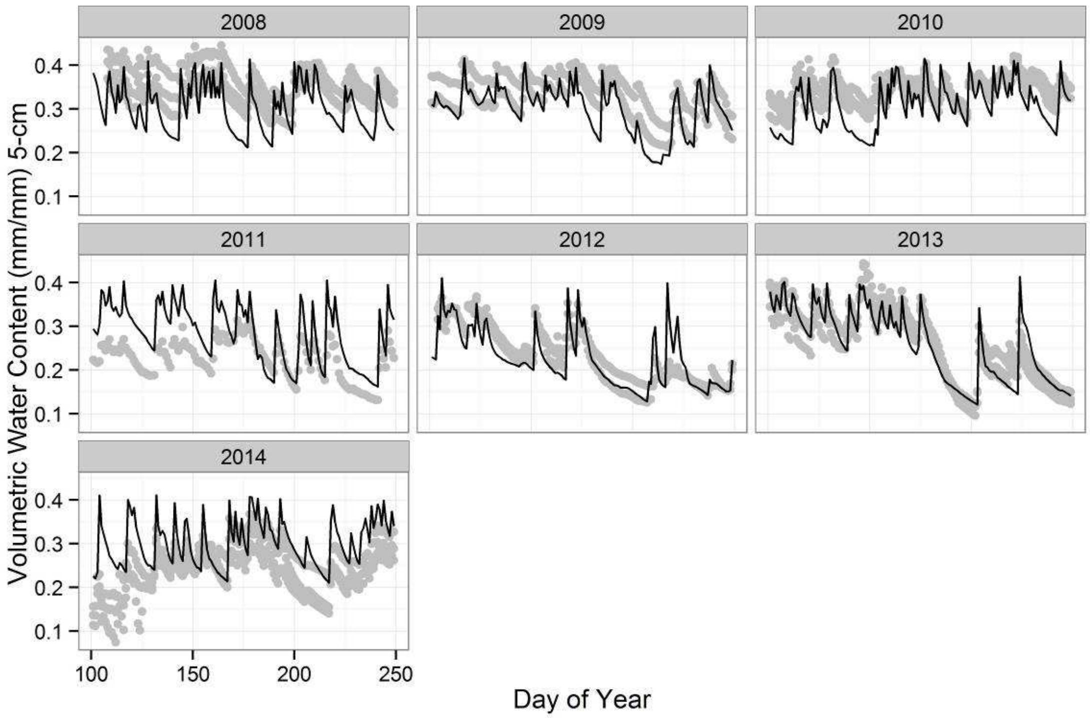


Figure S2a. Soil water at the 5-cm depth in the no cover crop plots. Gray dots represent plot level soil moisture in the field, black line represents APSIM predicted values.

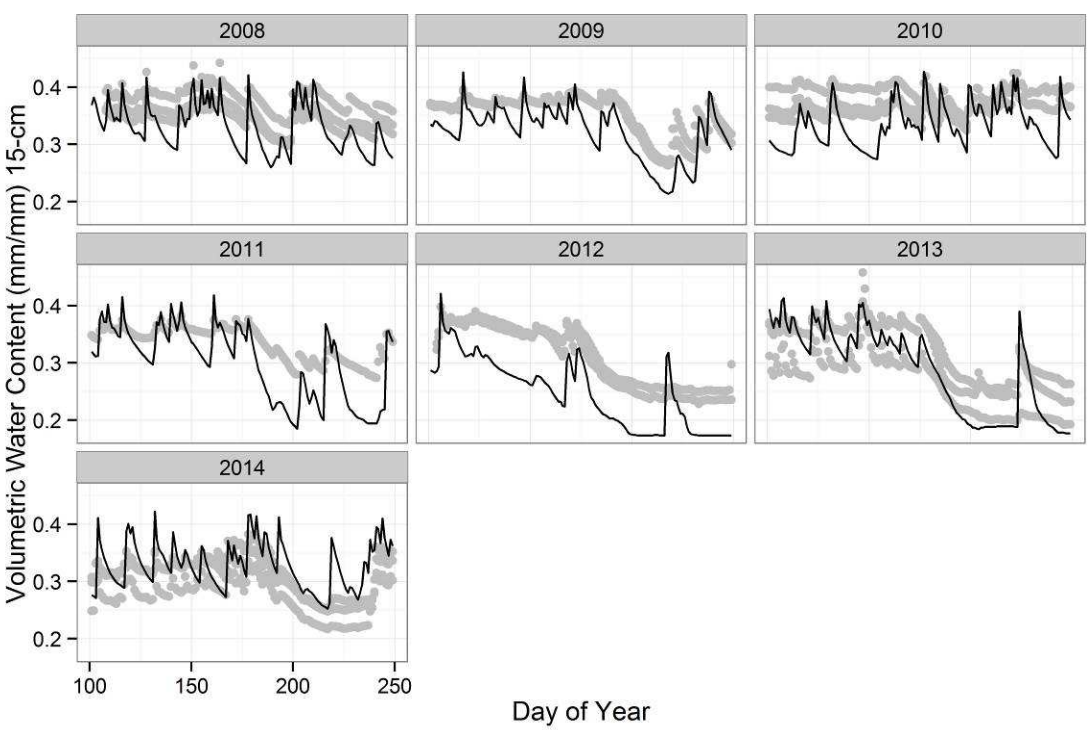


Figure S2b. Soil water at the 15-cm depth in the no cover crop plots. Gray dots represent plot level soil moisture in the field, black line represents APSIM predicted values.

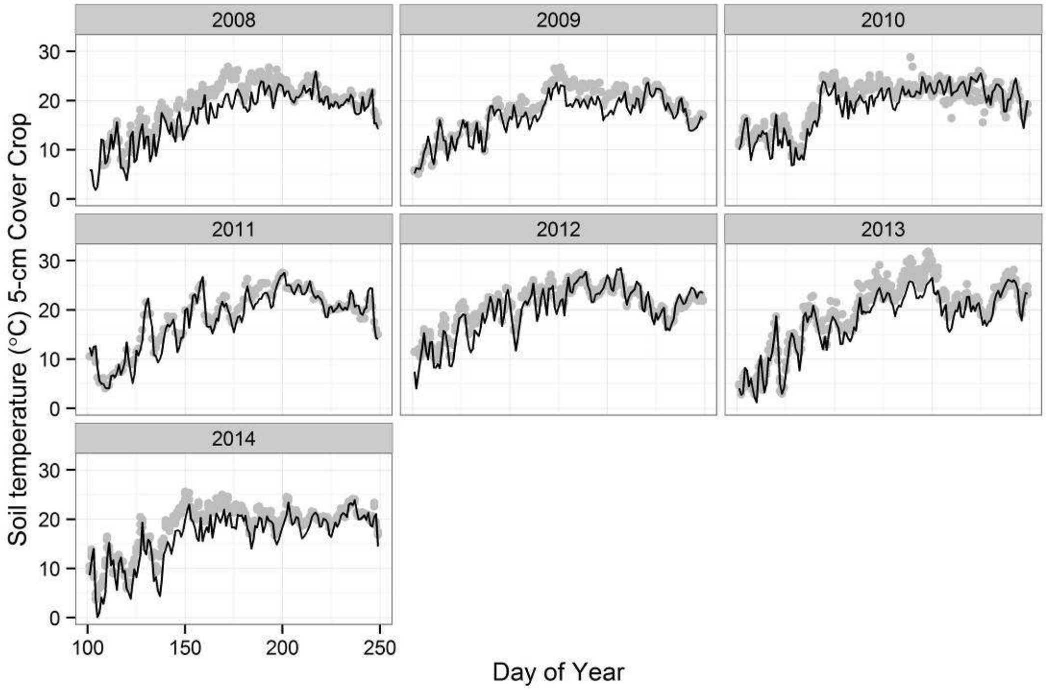


Figure S3a. Soil temperature at the 5-cm depth with cover crop treatment. Gray dots represent plot level soil temperature in the field, black line represents APSIM predicted values.

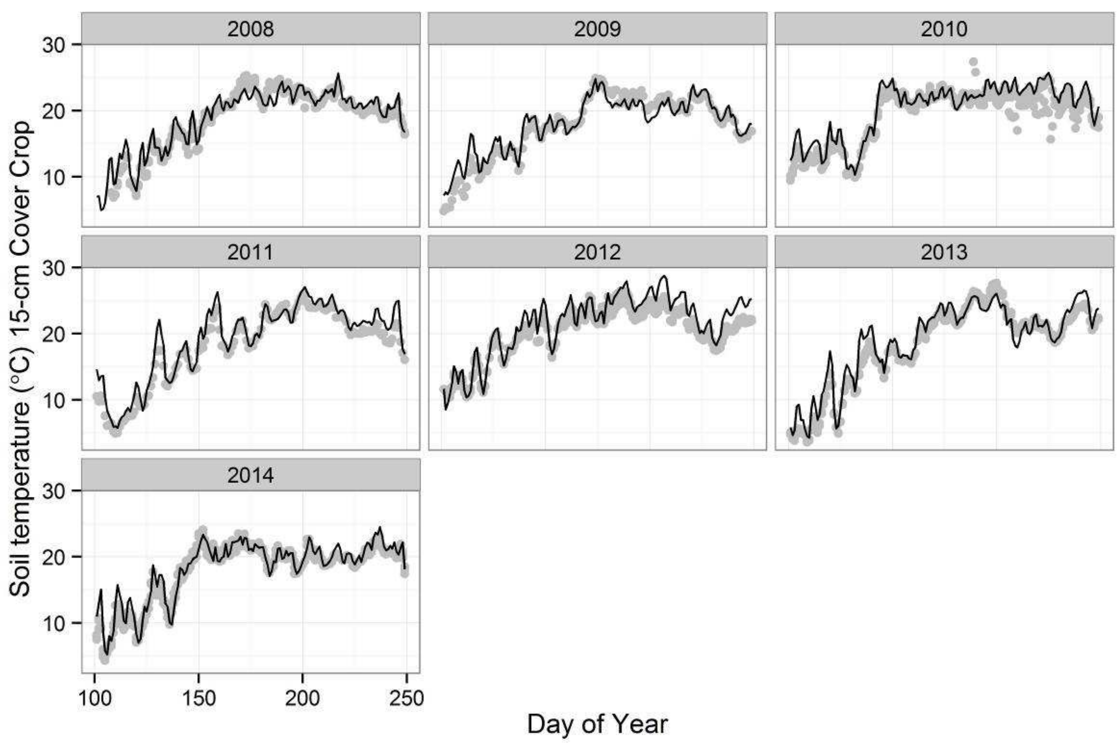


Figure S3b. Soil temperature at the 15-cm depth with cover crop treatment. Gray dots represent plot level soil temperature in the field, black line represents APSIM predicted values.

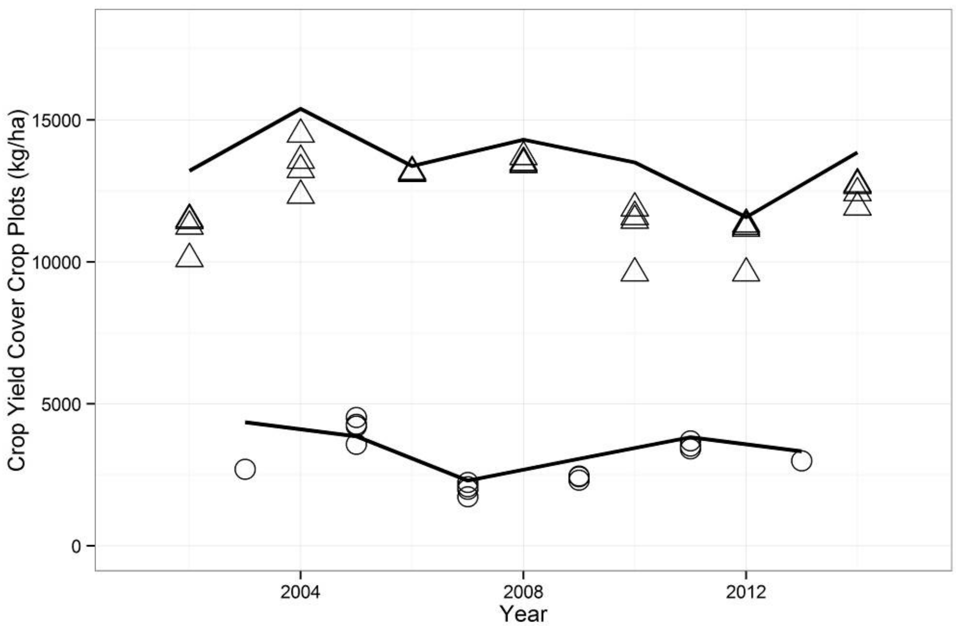


Figure S4a. Predicted (lines) and observed (n=4 replications) grain yields for maize (triangles) and soybeans (circles) in the cover crop treatment.

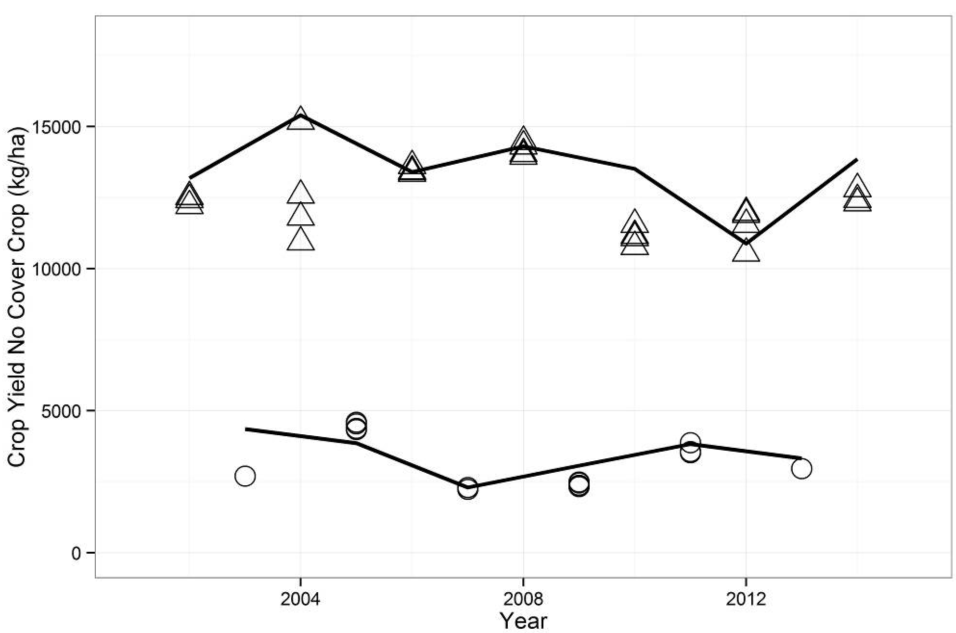
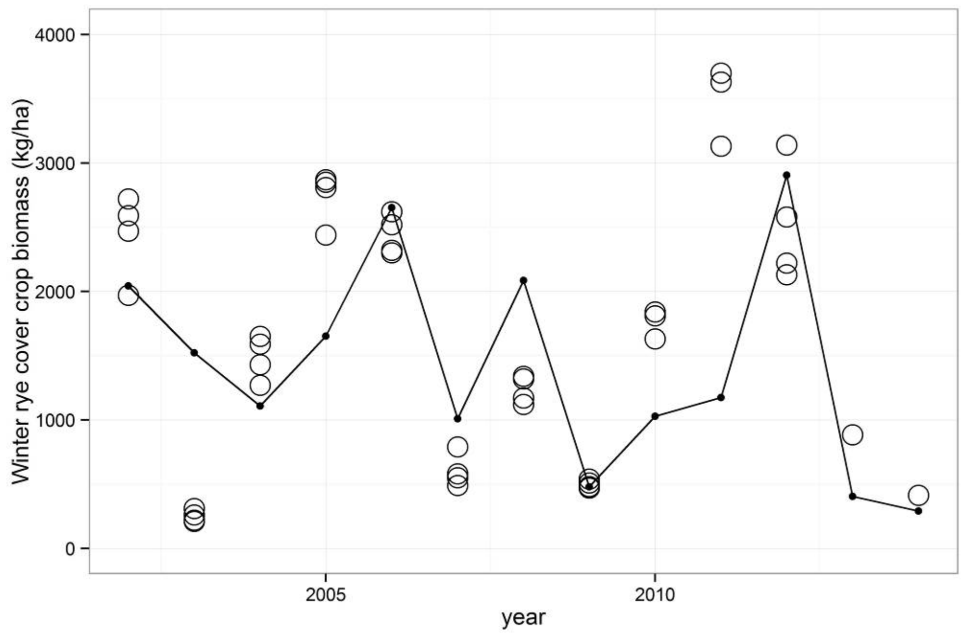
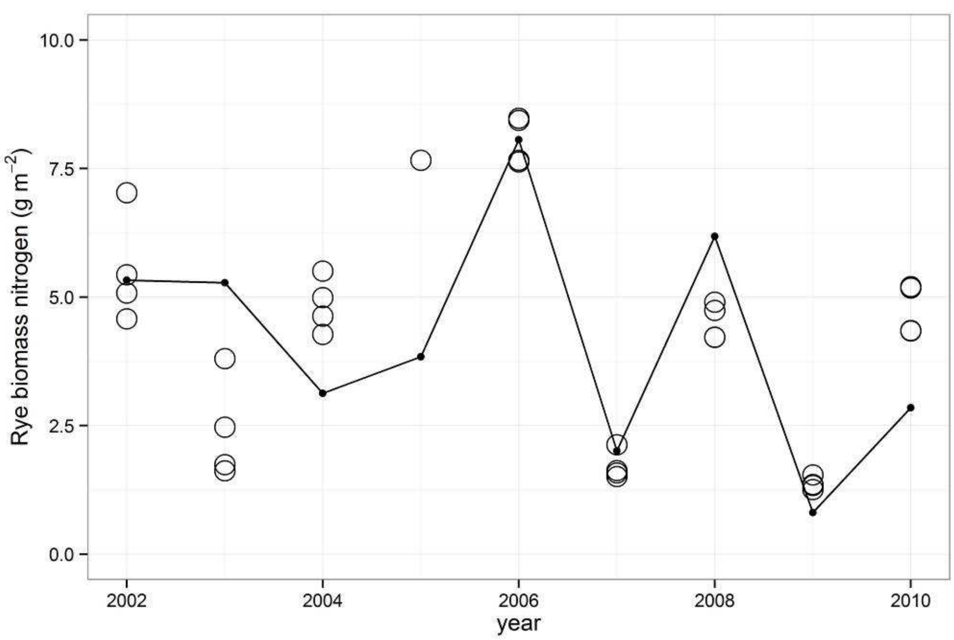


Figure S4b. Predicted (lines) and observed (n=4 replications) grain yields for maize (triangles) and soybeans (circles) in the no cover crop plots treatment.



S5a. Predictions (line) and observed rye biomass data (circles, n=4 replications) from 2002-2014.



S5b. Predictions (line) and observations (circles, n=4 replications) of nitrogen in winter rye cover crop biomass for available field data from 2002-2010.

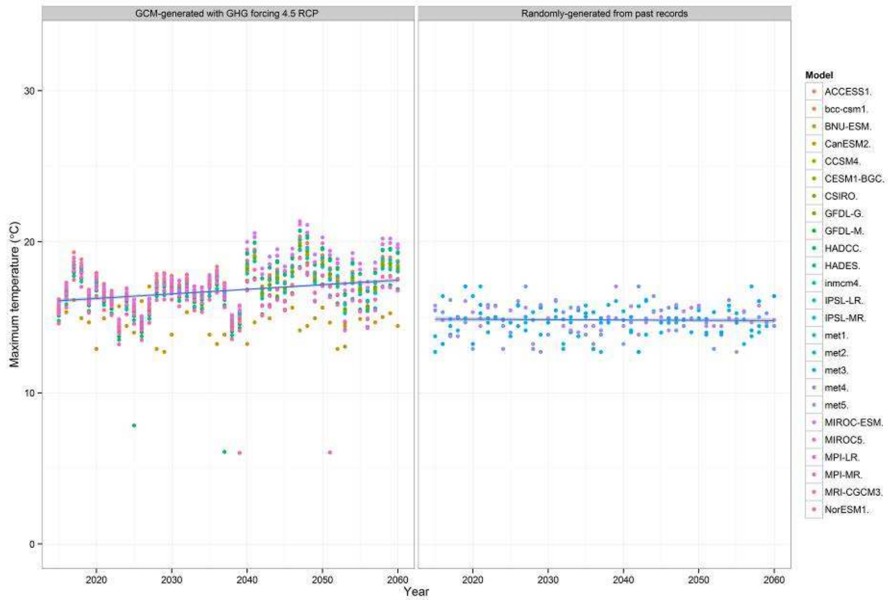


Figure S6a. Maximum temperature during the growing season (April through November) over the 45 years of the simulation. Randomly generated weather (met1-met5) represents simulations created with prior weather records. Future scenarios come from twenty different global climate models with RCP 4.5 following the AgMIP project protocol. Future weather shows an increasing trend from approximately 23°C to 26°C by 2060.

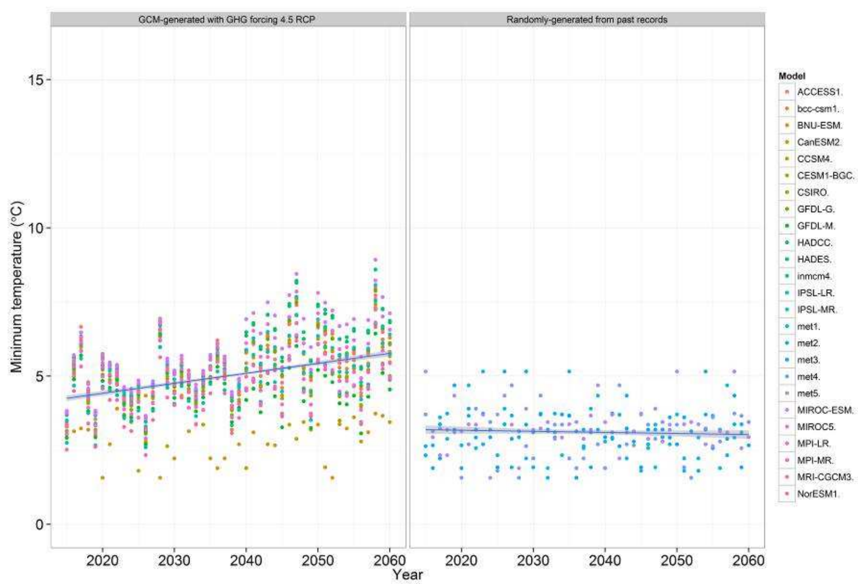


Figure S6b. Minimum temperature during the growing season (April through November) over the 45 years of the simulation. Randomly generated weather (met1-met5) represents simulations created with prior weather records. Future scenarios come from twenty different global climate models with RCP 4.5 following the AgMIP project protocol. Future weather shows an increasing trend from approximately 12°C to 14°C by 2060.

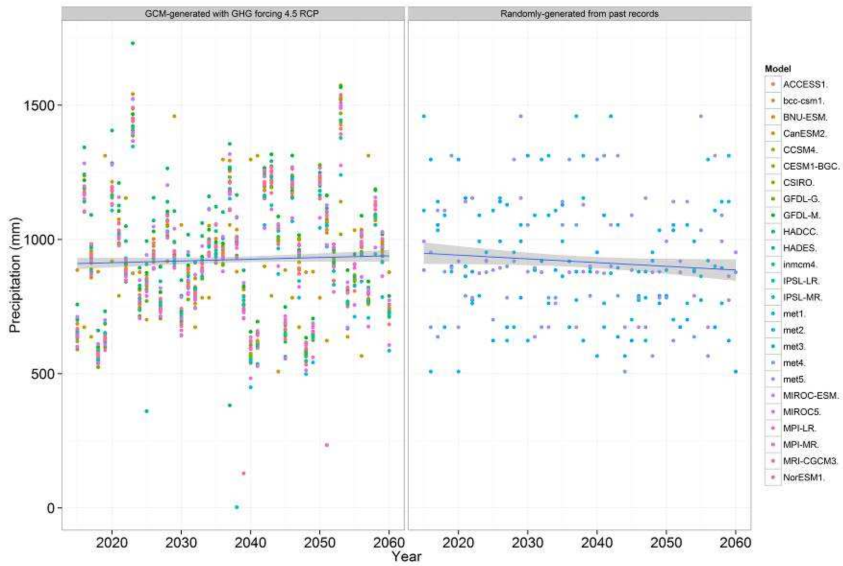


Figure S6c. Rainfall during the growing season (April through November) over the 45 years of the simulation. Randomly generated weather (met1-met5) represents simulations created with prior weather records. Future scenarios come from twenty different global climate models with RCP 4.5 following the AgMIP project protocol.

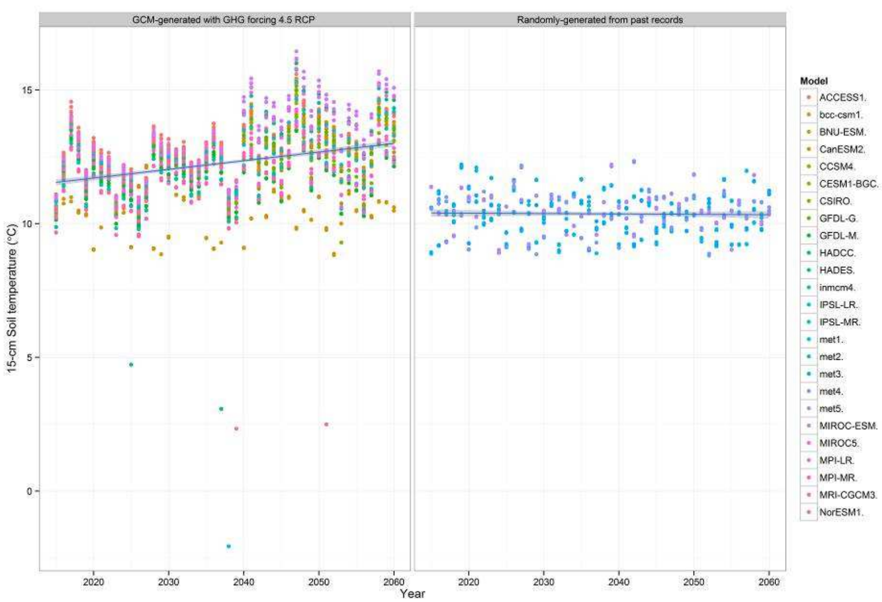
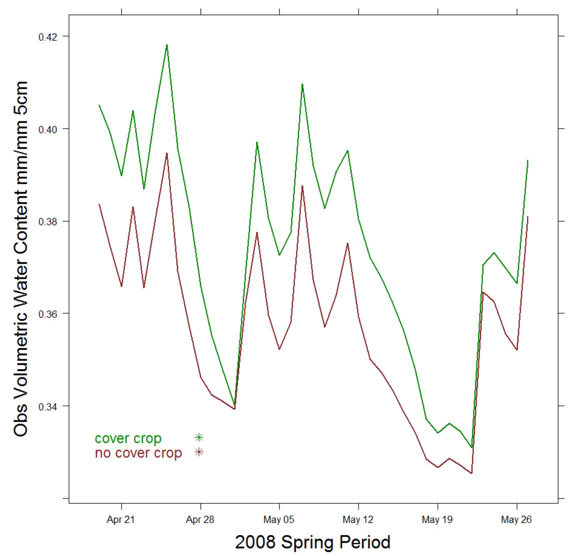


Figure S6d. Soil temperature predctions at 15cm during the growing season (April through November) over the 45 years of the simulation. Randomly generated weather (met1-met5) represents simulations created with prior weather records. Future scenarios come from twenty different global climate models with RCP 4.5 following the AgMIP project protocol. These predict an increase in soil temperatures (following the air temperature change) which could be responsible in part for the decline in soil carbon at lower depths.



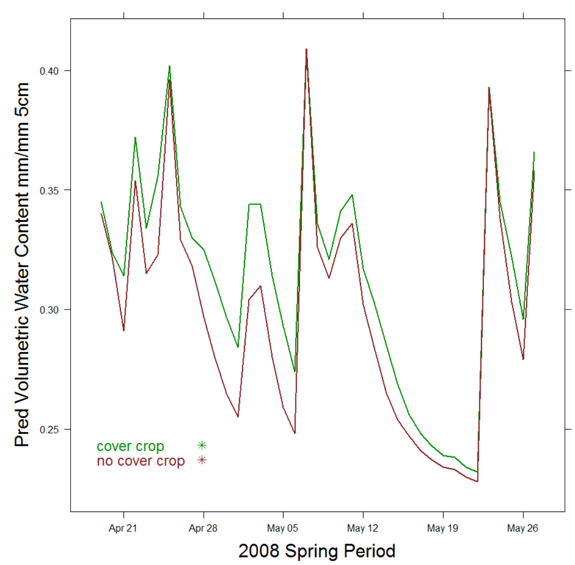
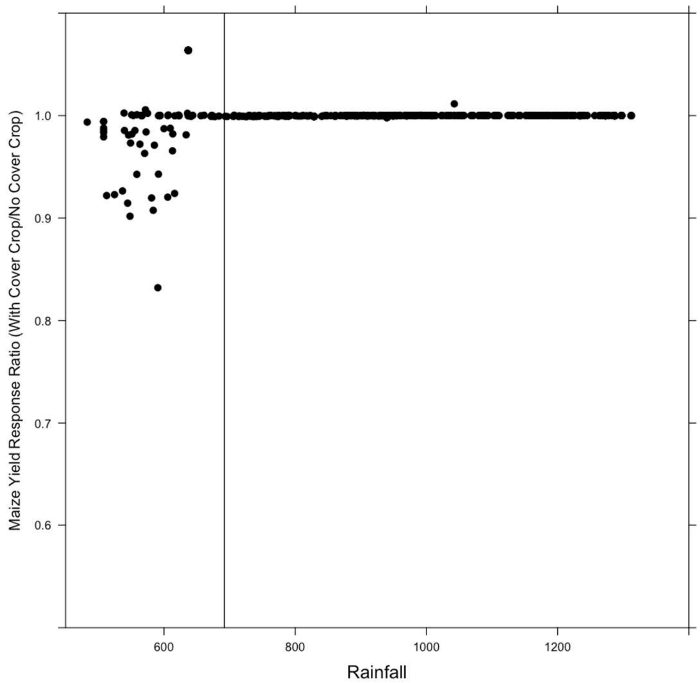


Figure S7. A comparison of soil water simulations (S7a, top) and observations in 2008 (S7b, bottom) during the spring period. In 2008, the cover crop was terminated on April 29 and maize planted on May 14. APSIM predicts higher soil water levels during this period in the cover crop plots as well as subsequent decreases in soil evaporation. By the time cash crop planting occurs, APSIM predicts the same soil water levels in both plots. The general pattern observed at the field site for the late spring period was that the soil water in the plots were the same in both treatments or higher in the cover crop plots at the time of cash crop planting.



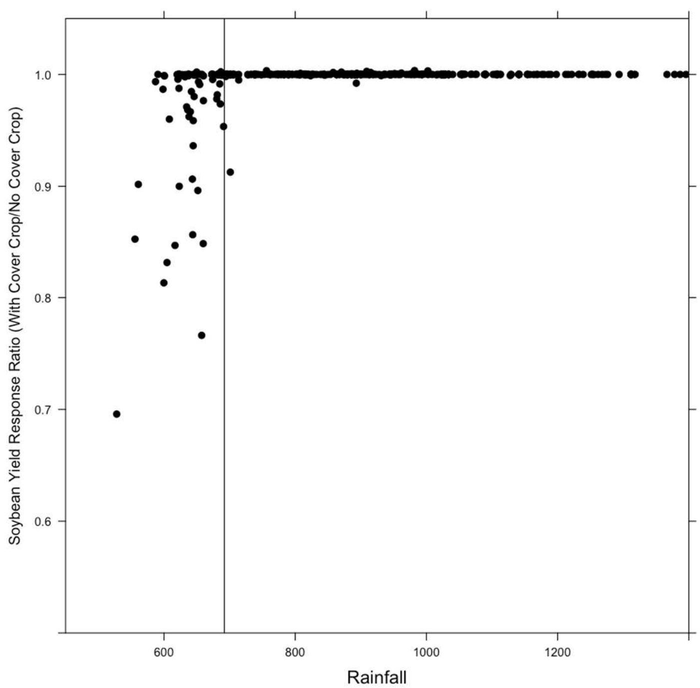


Figure S8a (above) and Figure S8b (below). Cash crop response ratio (yield with cover crop / yield without cover crop) as a function of rainfall. Figure S8a represents the trend in maize and S8b in soybeans. Annual rainfall for the weather scenarios used in this analysis had a mean of 923mm. The dashed line represents a 25% departure from the predicted mean of precipitation, or approximately 690mm. Below that threshold, APSIM generally predicts small yield declines in the cover crop treatment, as a result of competition for water in the early maize and soybean growing season.