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Simulating long-term impacts of cover crops and climate change on crop production and environmental outcomes in the Midwestern United States

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A B S T R A C T

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 understand 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 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.

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1. 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 (FAO, 2011; Walthall et al., 2013; Hatfield et al., 2014; Porter et al., 2014; Amundson et al., 2015; Ray et al., 2015).

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 (Winkler et al., 2012; Daniel, 2015). 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 (ICCIC, 2010; Al-Kaisi et al., 2013). 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 (SWCS, 2003; ICCIC, 2010; Lal et al., 2011; Al-Kaisi et al., 2013; VanLiew et al., 2013).

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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 (Hudson, 1994; Hati et al., 2007; Bhogal et al., 2009). 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 0–5-cm 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 (Keating, 2003; Holzworth et al., 2014). 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 (Huth et al., 2010; Thorburn et al., 2010; Biggs et al., 2013). 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 (Karlen et al., 1999; Kaspar et al., 2006; Guzman and Al-Kaisi, 2010).

There are several model-based evaluations of the impact of cover crops (Feyereisen et al., 2006b; Malone et al., 2007; Farahbakhshazad et al., 2008; Li et al., 2008; Qi et al., 2011; Malone et al., 2014). 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 impacts 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 (N_2O) 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.

2. Materials and methods

2.1. 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

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		Aerial seeding
2002	Maize	17-Apr	25-Apr	30-Sep	10-Sep	235	Aerial seeding
2003	Soybeans	6-May	12-May	30-Sep	2-Oct		Drilled after harvest
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

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