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Rye cover crop effects on maize: A system-level analysis

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ABSTRACT

Inclusion of a rye cover crop into maize-based systems can offer environmental benefits, but adoption of the practice in the US Midwest is still low. This is related to the possible risk of reduced maize yields following rye. We hypothesized that the magnitude of rye effects on maize yields and drainage water and nitrate (NO_3)-N losses would be proportionally related to rye biomass. We tested this hypothesis by analyzing data from continuous maize treatments (with and without cover crop) in Iowa, US, that were fertilized following recommendations from late spring nitrate tests. Dataset included measurements (2009–2014) of soil water and temperature, drainage water and NO_3-N losses, soil NO_3, rye shoot and root biomass and C:N, and maize yields. We supplemented our analysis with a literature review and the use of a cropping systems model (APSIM) to calculate trade-offs in system performance characteristics. Experimentally, rye cover crop reduced drainage by 12% and NO_3-N losses by 20% (or 31% per unit of N applied), and maize yields by 6%. We also found minimal effects on soil temperature, water deficits that reduced yields only during drought years (2012 and 2013), and lower NO_3-N losses that were related to reduced NO_3-N concentrations in drainage. Results also revealed a linear relationship between drainage and precipitation ($r^2 = 0.96$), and rye transpiration and shoot biomass ($r^2 = 0.84$). Model scenario analysis (4 termination dates × 30 years) indicated that rye cover crop decreases NO_3-N losses (-25.5 ± 26%) but does not always reduce drainage water (-3.9 ± 13%) or grain yields (-1.84 ± 6%), which is consistent with experimental and literature results. However, analysis of the synthesized measured and simulated dataset do not support a strong relationship between these variables and rye biomass. These results are valuable for decision-making and add new fundamental knowledge on rye water and nitrogen use.

1. Introduction

Inclusion of winter cover crops in high-input rain-fed maize (*Zea mays* L.)-based cropping systems is a conservation practice for enhancing the environmental performance of these systems (Kaspar and Singer, 2011; Thorup-Kristensen et al., 2003). Cover crop shoots protect soil from erosion (Kaspar et al., 2001), and roots take up residual NO_3-N from the soil during the fall-to-spring fallow period, reducing the movement of nutrients into surface and ground water (Dinnes et al., 2002; Kaspar et al., 2012, 2007; Salmerón et al., 2010). The use of cover crops also has the potential to provide long-term soil quality benefits such as improving carbon sequestration and soil physical properties (Basche et al., 2016a; Blanco-Canqui et al., 2015; Kaspar and Singer, 2011; Moore et al., 2014), and other ecosystem services such as weed and pest suppression and beneficial insect conservation (Schipanski et al., 2014). Water quality degradation, especially NO_3 pollution of surface waters, is the most pressing environmental impact of these systems in the US Midwest. Cover crops have been promoted as one of the most viable options for reaching water quality goals set in the Midwest (e.g. Iowa Nutrient Reduction Strategy; Iowa Deptartment of Agriculture and Land Stewarship, 2013) because of their lower cost of adoption compared to built infrastructure such as denitrifying bioreactors and wetlands (Christianson et al., 2013; Dinnes et al., 2002).

Despite the evidence of the benefits of cover crops and the existence of incentives such as cost-share programs, adoption of the practice lags behind targets. Current records indicate that cover crops are used in only 1.55% of Iowa row-crop farmland (National Agricultural Statistics Service, 2016). In the Midwest, winter rye

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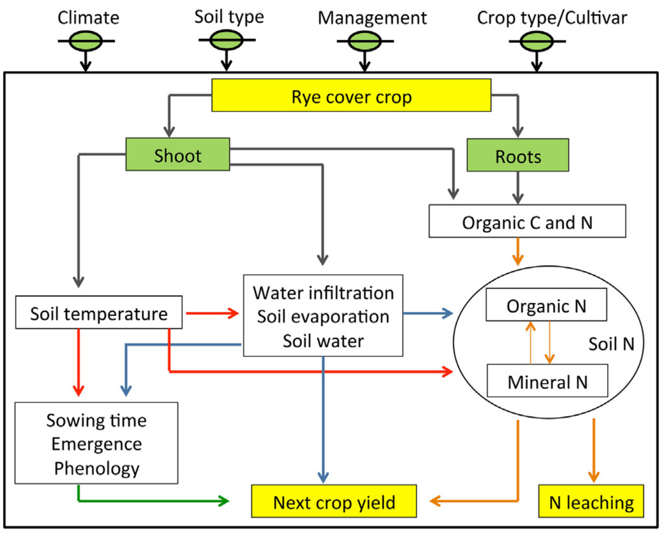

Fig. 1. A generalized diagram showing the abiotic mechanisms by which rye cover crop can affect crop yield and N losses in maize-based systems.

(*Cereale secale* L.) is a commonly used cover crop species (Singer, 2008) because it can withstand harsh winter conditions and has superior growth and N uptake compared to other species (Johnson et al., 1998; Kaspar and Bakker, 2015). Some studies have reported reductions in maize yield following a rye cover crop (Iqbal et al., 2015; Johnson et al., 1998; Kaspar and Bakker, 2015; Krueger et al., 2012, 2011; Pantoja et al., 2015; Singer and Kohler, 2005; Singer et al., 2008), although rye and other grass winter cover crops do not consistently reduce maize yields in the Midwest (Basche et al., 2016a; Miguez and Bollero, 2005). Nonetheless, concerns regarding possible negative yield impacts of rye on maize have been found to be an impediment to the adoption of cover crops by producers (Arbuckle and Roesch-McNally, 2015). To promote the adoption of the practice, quantification of the actual risks and the trade-offs associated with cover crop use, along with the development of risk abatement strategies, are necessary (Arbuckle and Roesch-McNally, 2015; Carlson and Stockwell, 2013).

Miguez and Bollero (2005) identified that the effect of grass cover crops on maize yields throughout US studies was neutral, although significant variation existed across these studies. Similarly, rye cover crops generally reduce NO_3-N loss but the magnitude of the leaching-reduction effect also varies widely across years, locations and management (Dabney et al., 2010; Dinnes et al., 2002; Kaspar and Singer, 2011; Thorup-Kristensen et al., 2003). This indicates that rye effects on the maize system depend on specific combinations of management choices and environmental conditions. Most studies have focused on quantifying rye effects on final maize yields and/or annual NO_3-N losses, and many knowledge gaps still exist regarding the mechanisms by which rye affects these systems. Broadly speaking, rye effects on maize can be grouped into biotic and abiotic factors. Biotic factors include pests and disease pressure (Acharya et al., 2016; Bakker et al., 2016) and allelopathy (Dhima et al., 2006; Duiker and Curran, 2005; Raimbult et al., 1991; Tollenaar et al., 1993), and at present are not well understood (Blanco-Canqui et al., 2015). A larger body of evidence exists for abiotic factors, which allowed us to develop a generalized framework of the abiotic effects of rye on the maize system (Fig. 1). Literature findings have shown maize yield reductions following rye cover crop to be related to depletion of soil moisture (Krueger et al., 2011; Mirsky et al., 2015; Raimbult et al., 1991; Unger and Vigil, 1998) and/or plant available N (Crandall et al., 2005; Kessavalou and Walters, 1999; Krueger et al., 2011; Tollenaar et al., 1993), or to a mulching effect that reduces soil temperature and seedling growth (Munawar et al., 1990; Teasdale and Mohler, 1993). More specifically, rye abiotic effects on the maize system can arise from changes in the soil via: 1) the addition of organic C and N (shoot and root); 2) changes in soil surface cover that alter soil temperature and water dynamics; and 3) changes in the state variables such as inorganic N and soil water at the time of cover crop termination (Fig. 1). The magnitude of these changes affects the system differently, which may explain the wide variation in yield and NO_3-N leaching responses to rye cover crops across different studies.

The amount of biomass produced by crops is strongly related to their water and N use (Gastal and Lemaire, 2002; Sinclair and de Wit, 1975; Sinclair and Rufty, 2012). For rye cover crops, this could mean that the greater the biomass, the higher the potential to alter water, N and temperature dynamics, resulting in increases in the potential for both yield penalty and reductions in NO_3-N losses. Krueger et al. (2011) and Pantoja et al. (2015) found rye biomass production to have a direct relationship to maize yield penalty, while Malone et al. (2014) found in a modeling study that rye N uptake had a strong relationship with NO_3-N losses. In this study, we hypothesized that the magnitude of rye cover crop abiotic effects on maize yields and environmental performance variables such as drainage water and NO_3-N losses would be proportionally related to its biomass production. We tested this hypothesis and examined the underlying crop-soil dynamics that would support such a scenario by analyzing six years of data from a no-till continuous maize (with and without rye cover crop) experiment carried out in central Iowa, US. This dataset was collected over years that crops experienced drought, flood and historically average weather, and included measurements of many system variables shown in Fig. 1. We supplemented our analysis by using a calibrated cropping systems model for this site (Dietzel et al., 2016) to better understand growth-limiting factors and soil-crop dynamics with variability in both weather (30 years) and management (four simulated rye termination dates within a year). To our knowledge, current literature lacks a system-level analysis of the effect of rye on maize in which the most important system variables are analyzed simultaneously. Such analysis is necessary to further our understanding of the abiotic mechanisms by which rye impacts maize and the environmental performance of the system, and to provide baselines for quantifying trade-offs and risks associated with this practice.

2. Materials and methods

2.1. Experimental site and measurements

2.1.1. Soil

The dataset used in this study was derived from observations collected from 2009 to 2014 in the Comparison of Biofuel Systems (COBS) experiment. This experiment was conducted in a 9-ha field that is part of the Iowa State University Agronomy and Agricultural Engineering Research Farm, in Boone County, Iowa (41.92°N, 93.75°W). The soil is a Webster silty clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquoll) and Nicollet loam (fine-loamy, mixed, superactive, mesic Aquic Hapludoll), characterized by high soil organic matter (~5%) and water holding capacity. Soil at the experiment site was artificially drained with corrugated plastic subsurface drains. For more details about soil characteristics and management we refer the reader to Daigh et al. (2014, 2015), Jarchow et al. (2015) and Dietzel et al. (2016, 2015).

2.1.2. Weather

Precipitation, temperature, and radiation were recorded hourly from a weather station at the site. Historical weather data were retrieved from DAYMET (Thornton et al., 2014). The average annual