Field Crops Research 196 (2016) 145–159

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

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

Rafael A. Martinez-Feria[a,*], Ranae Dietzel[a], Matt Liebman[a], Matthew J. Helmers[b], Sotirios V. Archontoulis[a]

[a] Department of Agronomy, Iowa State University, Ames, IA, USA
[b] Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA, USA

ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form 20 June 2016
Accepted 21 June 2016
Available online 8 August 2016

Keywords:
Rye cover crop
Maize
Nitrogen cycling
Water use
APSIM

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

* Corresponding author.
E-mail address: rmartine@iastate.edu (R.A. Martinez-Feria).

http://dx.doi.org/10.1016/j.fcr.2016.06.016
0378-4290/

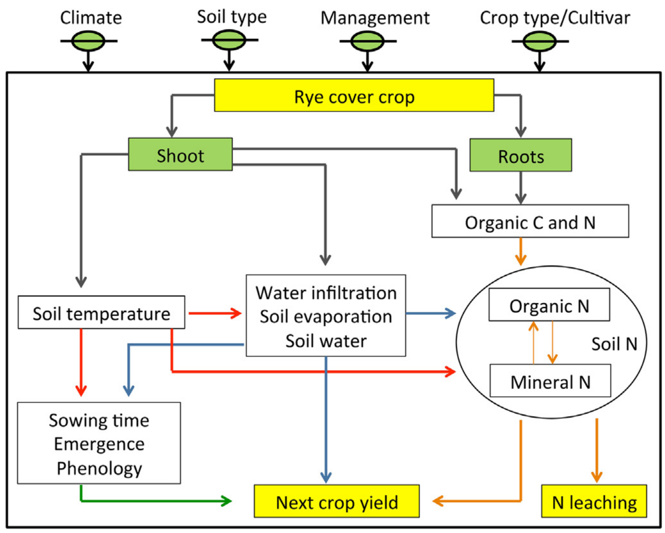

Fig. 1. A generalized diagram showing the abiotic mechanisms by which rye cover crop can affect crop yield and N losses in maize-based systems.

(*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

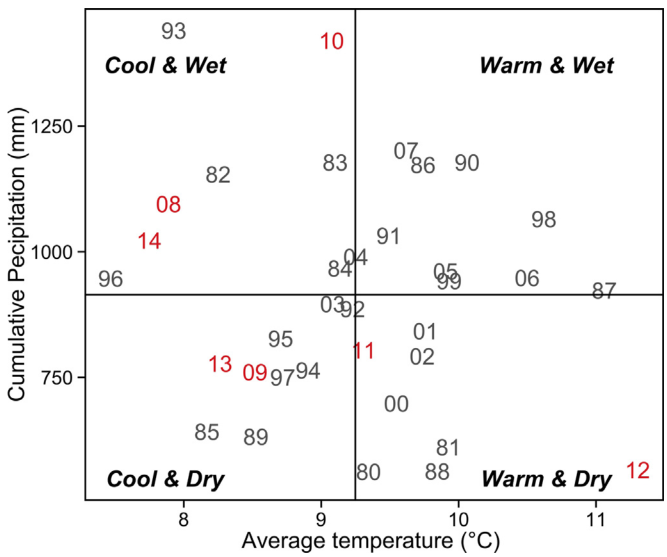

Fig. 2. Annual temperature and precipitation summaries for the experimental years (2008–2014; shown in red) compared to historical weather years (1980–2007; shown in gray). Vertical and horizontal lines show the average annual temperature and precipitation, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

daily temperature for the site is 9.4 °C with an average frost-free growing season of 155 days (April to mid-October). During fallow periods (October to April) the average daily mean temperature is 1.4 °C. The average annual precipitation (including melted snow) is 935 mm. During the experiment period, the site experienced flood- and drought-inducing conditions (Fig. 2). The year 2010 was among the wettest on record, while 2012 and 2013 included periods of extremely low precipitation during summer. The year 2012 registered one of the lowest annual precipitations on record (656 mm). Even though the year 2013 registered about normal annual precipitation, the rainfall events were heavily concentrated in the May-June period and very dry conditions prevailed during mid-summer and early fall. The winter of 2013–2014 was extremely cold, with 26 days with daily average temperatures below −15 °C. The 2014 growing season remained relatively cool with average daily temperatures about 0.9 °C below the historical average. The site also experienced nearly average weather conditions in 2011 (Fig. 2).

2.1.3. Management

The experiment at COBS employed a spatially balanced complete block design with four blocks and six different cropping system treatments (plot size: 27 m × 61 m). In this study, we analyzed observations from the continuous maize system (CC) and continuous maize with rye cover crop system (CCW) treatments. At maize harvest, grain and 50% of the residue (stover) was removed from the system each year from both treatments. The plots were managed without tillage. Weeds and diseases were controlled chemically. Maize was planted in rows spaced at 76 cm at a rate of 79,500 seeds ha^{-1}. Two maize hybrids with 104-day relative maturity were used (Agrigold 6325 VT3 from 2009 to 2011 and Pioneer P0448XR thereafter). Rye cover crop variety 'Rymin' was planted a few days after maize stover harvest at a seeding rate of 300,000 seeds ha^{-1} and row spacing of 20 cm. Rye was chemically terminated during vegetative growth with glyphosate (N-[phosphonomethyl]glycine, 0.39-0.45 L a.i. ha^{-1}) the following spring before maize plantings. Table 1 provides details on management for both crops. Nitrogen fertilization was split-applied between planting and the maize sixth leaf stage (V6; as defined in Abendroth et al., 2011) following the recommendations from a

Table 1
Summary of dates of major field activities for continuous maize (CC) and the continuous maize with rye cover crop (CCW) treatments.

Year	Rye[a]		Maize				
	Termination[b]	Planting	Planting	LSNT[c]	Side-dress	Harvest	
						Grain[d]	Stover
2008	–	31-Oct	15-May	17-Jun	24-Jun	21-Oct	30-Oct
2009	6-May	6-Nov	8-May	9-Jun	17-Jun	21-Oct	6-Nov
2010	5-May	4-Oct	6-May	7-Jun	17-Jun	29-Sep	1-Oct
2011	10-May	10-Oct	11-May	7-Jun	29-Jun	3-Oct	3-Oct
2012	18-Apr	1-Oct	11-May	6-Jun	12-Jun	25-Sep	27-Sep
2013	7-May	21-Oct	17-May	20-Jun	28-Jun	9-Oct	14-Oct
2014	8-May	–	15-May	10-Jun	16-Jun	10-Oct	21-Oct

[a] Only for the CCW treatment.
[b] Total rye biomass (root + shoot) was determined a few days before termination.
[c] LSNT: late spring soil nitrate test at maize sixth leaf stage.
[d] Total maize biomass (shoot) was determined a few days before grain harvest.

Table 2
Amount of nitrogen applied to the continuous maize (CC) and the continuous maize with rye cover crop (CCW) treatments during the experiment. The nitrogen fertilizer type was liquid urea-ammonium-nitrate (32%) and was injected to a depth of 7.5 cm.

Year	At planting	Side-dressed (at maize sixth leaf stage)		Total	
		CC	CCW	CC	CCW
	(kg N ha^{-1})				
2008	73	101	101	174	174
2009	84	84	134	168	218
2010	87	36	82	123	169
2011	87	56	134	143	221
2012	87	112	134	199	221
2013	90	112	90	202	180
2014	84	95	78	179	162
Average	84.6	85.1	107.6	169.7	192.1

late spring nitrogen test (LSNT; Blackmer et al., 1997) using a critical soil NO_3-N concentration of 25 mg kg^{-1}. Table 2 provides details on N fertilization for maize.

2.1.4. Soil temperature, moisture and nitrate measurements

Soil temperature and volumetric soil water content were measured from 2009 to 2013 with Decagon 5TE ECH$_2$O sensors and Em50 data loggers (Decagon Devices Inc., Pullman, WA, US) at 5, 10, 17.5, 35, and 50 cm depths every 30 min. The sensors were installed in 2008 at one point per plot (midway between center and border of the plots), resulting in 4 replicates per treatment at each depth. Further details are available in Daigh et al. (2014) and Dietzel et al. (2016). Using these data we calculated average daily soil temperatures for three soil layers: 5–15 cm, 15–30 cm and 30–50 cm, and daily total soil water content (mm) for 0–15 cm, 0–30 cm and 0–50 cm soil profiles. Details on calculations are given in the supplementary materials (S1 and S2). Soil nitrate measurements were collected to a depth of 30 cm in each plot shortly prior V6 every year and soil NO_3-N concentration was determined colorimetrically using the cadmium reduction method (Gelderman and Beegle, 2012) and expressed in mg N kg^{-1} soil, and in kg N ha^{-1} using the average value of 1.4 g cm^{-3} for bulk density in the top 30 cm soil depth (Dietzel et al., 2016).

2.1.5. Subsurface drainage water volume and nitrate-N losses

Subsurface drains were installed at ~1.1 m depth along the center and border of the plots (long-side direction) in the spring of 2009. Effluent from the center subsurface drains (hereafter drainage) was measured and recorded every 5 min using in-flow meters throughout the drainage period (i.e., early March to early December). Daily cumulative flow values were calculated and expressed in mm. Water samples were obtained through an orifice that diverted ~0.1% of drained water flow into a plastic container. Samples were collected periodically (twice weekly), stored at 4 °C, and subjected to colorimetric analysis to determine NO_3-N concentrations. Further details about system setup, instrumentation and chemical analysis method were provided by Daigh et al. (2014, 2015). Nitrate-N losses were calculated by multiplying results from colorimetric analysis by the drainage recorded during a given collection period and expressed in kg N ha^{-1}. Annual flow-weighted NO_3-N concentrations in drainage water were calculated by dividing cumulative annual NO_3-N losses by the annual drainage water volume, and expressed in mg N L^{-1}. Additionally, given that N fertilization rates applied to maize were not uniform across the CC and CCW treatments (LSNT-based rates; Table 2), NO_3-N losses were also expressed as percentage of N fertilization in kg of N loss 100 kg^{-1} of N applied.

2.1.6. Crop measurements

Rye biomass samples were collected a few days before rye termination (Table 1). Rye aboveground biomass (hereafter shoot) was sampled from four random areas per plot (1.34 m^2 total). Rye roots were sampled by digging plants with a spade to a 15-cm depth (roots and shoots separated at the crown level) in 2009. In the following years (2010–2013), root mass was determined by collecting four 32-mm-diameter soil cores, two cores on the row and two from between rye rows, at a 30-cm depth. Roots were separated from the bulk soil using a soil elutriator as described by Wiles et al. (1996) and Jarchow and Liebman (2012). Shoot and root samples were dried in a forced-air oven at 60 °C until constant weight. Dry samples were weighed, ground to a fine powder (< 1 mm) and concentrations of C and N were determined by combustion analysis at the Soil and Plant Analysis Laboratory at Iowa State University (Ames, Iowa). In 2014, only shoot biomass weight was determined. Rye water use was estimated with a soil water balance difference method. This was done by summing the differences between CC and CCW in soil water (0–50 cm soil profile) and water loss through subsurface drainage. This estimate should be a good proxy for rye transpiration.

Maize grain yields were measured from the center 12 rows of each plot using a John Deere 9550 combine harvester. Maize aboveground biomass was measured a few days before harvest by collecting eight representative plants from each plot (~1 m^2 area). Plants were dried at 60 °C, and weighed. Biomass samples were not collected in 2014. Maize yields and biomass are both expressed on dry matter basis (0% moisture). Maize grain samples were collected to determine N concentration in 2008 (establishment year), 2009, and 2013.

2.2. Modeling analyses

2.2.1. APSIM model and testing

The Agricultural Production Systems sIMulator (APSIM, Holzworth et al., 2014; Keating et al., 2003) is a field-scale cropping system model that operates on a daily time step. Inputs to the model are daily weather, soil, management, cultivars and crop or crops in rotation. Outputs from the model are many soil-plant-atmosphere variables, including crop growth processes, soil water, soil temperature, N and C cycling, and residue dynamics. Details about APSIM and its performance across a range of environments can be found at www.apsim.info and in the following studies for Iowa: Malone et al. (2007); Hammer et al. (2009); Archontoulis et al. (2015, 2014a,b); Dietzel et al. (2016); and Basche et al. (2016a).

Recently, Dietzel et al. (2016) provided a comprehensive calibration and testing of the APSIM model at the COBS site, including the CC and CCW treatments. We built on this work and further tested and improved the model by using additional datasets that included maize grain yields in 2014, maize grain N concentration, and high-resolution measurements (daily from 2009 to 2014) of drainage water volume and NO_3-N losses in subsurface drainage during the drainage period. Our focus was to further improve the representation of rye in the model, given that APSIM, like many other cropping systems platforms (e.g. RZWQM, Malone et al., 2014), does not have a specific rye model and the representation of rye growth and development is through the wheat model with ad-hoc modifications (Basche et al., 2016a; Dietzel et al., 2016). Additionally, we modified two key parameters in the maize model to better reflect growth and N uptake in modern maize hybrids. Details about changes in the specific parameter values in the rye and maize models and their underlying rationale are summarized in Table 3. No changes were made in the soil model. All these changes maintained or improved the version published by Dietzel et al. (2016).

2.2.2. Scenario analysis

We used the improved version of the APSIM model to explore the long-term effect of rye biomass production on maize yields, subsurface drainage and NO_3-N losses. To create variability in rye biomass at termination day, we simulated four different termination dates: 13 April, 25 April, 5 May and 15 May during 30 weather years (1985–2014). These dates reflect the variability in rye termination dates in this region. Maize plantings were 10 days after rye termination using average management practices for this region (Tables 1 and 2), including 50% residue removal, which was specific for the COBS experiment. It should be noted that in the scenario analysis we used the same N-rate (190 kg N ha^{-1} yr^{-1}) in both CC and CCW. Rye planting was 20 Oct every year, which also reflects the average planting date for this region. Simulated results of this analysis were synthesized by calculating relative treatment differences between CC and CCW using the following formula:

$$y = 100\left(\frac{CCW - CC}{CC}\right) \quad (1)$$

where CCW and CC are the simulated values of maize yields, annual cumulative drainage or NO_3-N losses for each simulation treatment. In this scale, positive values represent increases associated with the rye cover crop, while negative values indicate decreases.

2.3. Literature review data collection

To better understand rye effects on N cycling, we synthesized literature data with our measurements and simulations to develop a relationship between rye shoot and root biomass and C:N. Aiming to capture a range of environmental and management conditions, we selected studies conducted within the last 20 years across the US reporting results on a year-treatment-location basis. For studies reporting solely N concentration, C:N ratios were calculated assuming 40% and 33% C content for the shoot and root, respectively, which was based on our experimental findings. Each point in this dataset represented a site-year-treatment observation.

To compare APSIM-simulated relative changes to experimental measurements, we searched for publications reporting rye effects on maize yield, cumulative drainage and/or NO_3-N losses. Relative treatment differences were computed analogously to simulated results from the scenario analysis (Eq. (1)), using a control value on a year-location basis.

2.4. Statistical analyses

2.4.1. Crop and drainage data

Statistical analyses were conducted using R statistical software version 3.2.1 (R Core Team, 2015). To test treatment effects in the measured crop and drainage variables, analyses of variance

Table 3
Details of the improvements made to the APSIM model version published by Dietzel et al. (2016).

Parameter	Change	Rationale and significance
Specific area of residues of wheat (ha kg^{-1})	0.005 to 0.0005	Rye residue surface area at termination (Zadoks stage 25) consists of leaves and young stems, and is very different from that of dry mature stems in wheat residue after harvest (Zadoks stage 99, default value). Reduced soil cover per unit of biomass.
Transpiration efficiency coefficient of wheat (kPa)	6.0 to 4.5	Better fit to estimated values of rye water use (Fig. 7). It suggests that rye is less efficient than wheat in using water.
Maximum rooting depth (cm)	90 to 120	Better fit to rye biomass and NO_3-N leaching data and better reflection of the putative role of rye as a catch crop. These changes increased the ability of rye roots to extract water and nutrients from deeper soil depths.
Soil/root water extraction coefficient for wheat (KL, d^{-1})	From 0.08 to 0.1 for 0 to 40 cm soil layers; from 0.05 to 0.08 for 40 to 90 cm soil layers; 0.04 for 90 to 120 cm soil layer	
Critical grain N concentrations (g kg^{-1})	15 to 12	Better fit to measured grain N content data (Fig. 9) and NO_3-N losses (Fig. 6).
Root penetration resistance coefficient (XF, unit less)	1.0 to 0.5 in soil layers below 60 cm	Improved simulation of NO_3-N losses in years 2012, 2013 and 2014.

(ANOVA) were conducted with the Linear Mixed-effects Model (*lme*) function from the Linear and Nonlinear Mixed Effects Model (*nlme*) package (Pinheiro et al., 2015). The effect of treatments, year and their interactions were considered fixed, while the effect of the year within each block (split-plot in time) was considered random. When the interaction of *treatment* × *year* was significant, simple effects across years were tested using the Test Contrasts of Factor Interactions (*testInteractions*) function from the Post-Hoc Analysis of Interactions (*phia*) package (De Rosario Martínez, 2015). Data tested using this method were rye measurements at termination, soil NO_3 test results, maize measurements at harvest, and annual cumulative drainage water volume and NO_3-N losses. Drainage data were transformed prior to conducting ANOVAs using the logarithmic transformation because a Bartlett's test (α=0.05) indicated that variances from the different treatments across years were unequal. Simple regression analyses were conducted to test proportionality of the relationship between rye biomass and changes in yield, cumulative drainage and NO_3-N losses, as well as for describing the underlying mechanisms, through relationships between transpiration and rye biomass, and cumulative precipitation and drainage and NO_3-N losses. All these tests were conducted using a significance level of α=0.05.

2.4.2. Soil moisture and temperature data

Time series sensor data were analyzed by conducting ANOVAs at every depth and day of the studied period (analyzed as a completely randomized block design). This method was chosen for its simplicity and ease of interpretation. However, this test may lack power to detect differences (type II error) with days of large variation (e.g. precipitation events) or with missing data. For this reason, we determined it appropriate to use a significance level α=0.1 for the soil water data. For the soil temperature data, a significance level of α=0.05 was considered appropriate given the relatively low treatment variability in these measurements. These analyses were focused on periods when rye effects were expected to be most relevant, 30 days prior to and 30 days after cover crop termination (soil temperature) or until the end of the maize-growing season (soil water).

2.4.3. Non-linear regression model for rye C:N versus biomass

We fitted curves in the form $y = a * x^b$ to the C:N dataset (see Section 2.3), using the Non-linear Least Squares (*nls*) function from the *nlme* package in R (Pinheiro et al., 2015). Prediction intervals ($\alpha = 0.2$) were estimated using the linear approximation method described by Bates and Watts (2007), which is comparable to what has been done for studies on wheat (Justes et al., 1994; Ziadi et al., 2010).

2.4.4. Model goodness of fit

To assess overall APSIM model fit, we a) fitted linear regressions of observed versus model simulated values, and b) computed the coefficient of determination (r^2), the root mean square error (RMSE) and relative mean square error (RRMSE). To assess fit of non-linear models, only the r^2 and RRMSE were computed. The equations can be viewed in Archontoulis and Miguez (2013). The r^2 reflects prediction ability and the higher the value the better. The RMSE and RRMSE reflect simulation error and the lower the value the better.

3. Results

3.1. Rye shoot and root biomass and C:N

Over the 6-yr period, rye shoot biomass at termination day varied from 120 to 2499 kg ha^{-1} (Table 4). The low rye biomass production in 2009 and 2013 coincided with relatively cool spring weather conditions in those years (Fig. 2). In 2014, poor growth was related to winterkill, caused by extremely harsh conditions during that winter. On the other hand, the unusually warm temperatures in February and March of 2012 allowed rye to produce the highest biomass over the 6-year period even when it was terminated about 2–3 weeks earlier than all other years (Table 1). Measured rye root biomass at termination ranged from 57 to 2093 kg ha^{-1}. It should be noted that the biomass recorded for 2009 was widely different to measurements from all other years, probably due to the difference in root sampling method used that year. The corresponding root:shoot for 2010–2013 ranged between 0.75 and 1.9 (Table 4). Rye shoot N uptake varied from 12.5 to 44.6 kg N ha^{-1}, and it was observed that the rye shoot N concentration decreased with increasing shoot weight (Table 4). The ratio of rye biomass to N uptake (nitrogen-use efficiency) was 46 ± 16 for the shoots and

Table 4
Rye cover crop measurements at termination date.

Year	Biomass			C concentration		N concentration		C:N	
	Shoot (kg ha^{-1})	Root[a]	Root:Shoot	Shoot (%)	Root	Shoot (%)	Root	Shoot	Root
2009	365 (72)[b]	57 (12)	0.16 (0.01)	39.2 (0.59)	33.1 (1.25)	3.47 (0.13)	1.26 (0.02)	11.3 (0.32)	26.3 (0.88)
2010	1180 (81)	1564 (137)	1.33 (0.07)	39.3 (0.14)	33.5 (0.79)	2.15 (0.06)	1.58 (0.06)	18.3 (0.49)	21.3 (0.41)
2011	1532 (131)	2093 (311)	1.43 (0.29)	40.9 (0.1)	31.8 (0.37)	1.52 (0.08)	1.05 (0.07)	27.1 (1.4)	30.8 (2.25)
2012	2499 (66)	1872 (185)	0.75 (0.08)	39.2 (0.12)	32.8 (0.25)	1.78 (0.07)	0.98 (0.02)	22.1 (0.85)	33.4 (0.48)
2013	497 (48)	943 (35)	1.94 (0.15)	38.8 (0.15)	30.8 (0.56)	3.31 (0.21)	1.34 (0.05)	11.9 (0.78)	23.2 (1.34)
2014[c]	120 (7.4)	–	–	–	–	–	–	–	–

[a] Samples collected from 0–15 cm depth in 2009 and 0–30 cm the following years.
[b] Values between parenthesis indicate standard error.
[c] Only shoot biomass was collected in 2014.

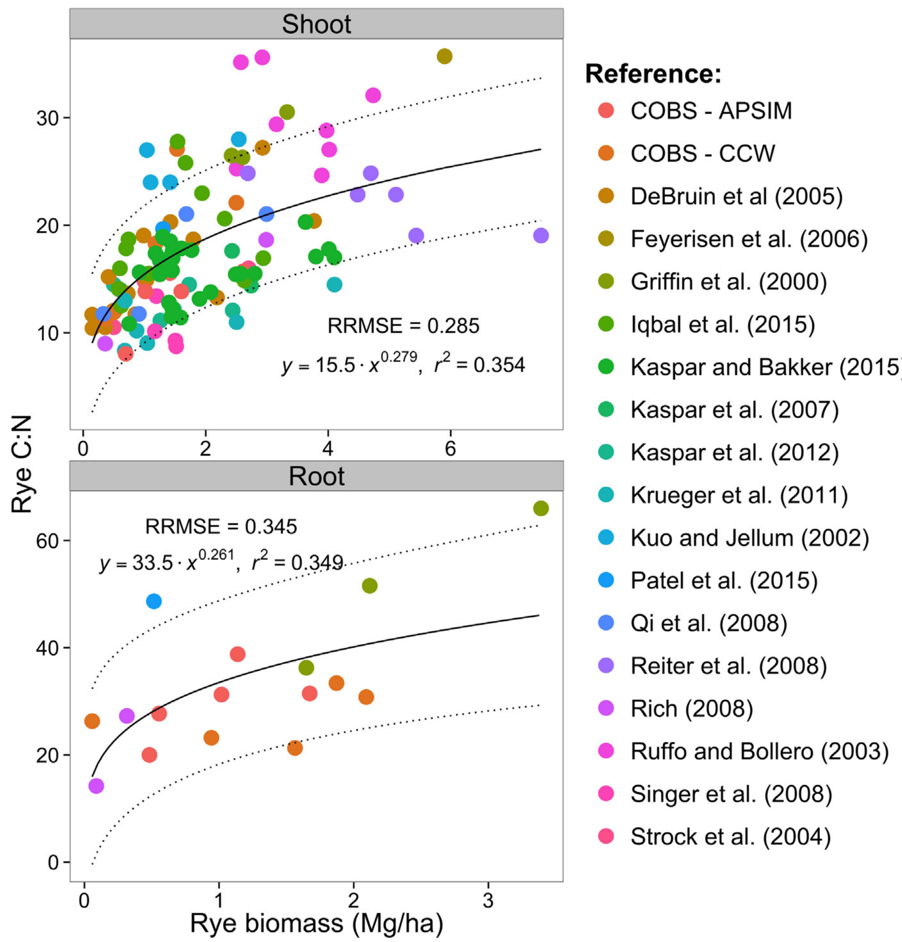

Fig. 3. Relationship between C:N and shoot and root biomass using literature, experimental and simulated values for rye. Dotted lines are the 80% prediction intervals (Bruin et al., 2005; Griffin et al., 2000; Qi et al., 2008; Reiter et al., 2008; Rich, 2008).

almost double for the roots 83 ± 13 kg kg^{-1} N taken up. This difference is due to different N concentrations between shoots and roots (Table 4). The C concentration was also different between shoots and roots (39.5 vs. 32.5%; Table 4) but was relatively stable across the five years measured. The rye shoot C:N ranged from 11.3 to 27.1, while the rye root C:N varied from 23.2 to 33.4 and was higher compared to that of shoots. The relationship between rye C:N and biomass is shown in Fig. 3, with a non-linear regression fitted to experimental and modeling results along with results from other studies carried out in different locations across the US. The analysis showed a strong positive relationship between shoot biomass and C:N (n = 130; RRMSE = 29%), and between C:N of roots and root biomass (n = 16; RRMSE = 35%). A summary of non-linear model fit is provided in the supplementary materials (Table S1). The range of the C:N values measured in our study was generally low given that rye was terminated during the vegetative stages. This places rye cover crop residue as a high quality residue in terms of N cycling.

3.2. Maize biomass and yield

Statistically significant treatment effects ($p < 0.05$) were detected for grain yields and biomass in 2012 and 2013 (Table 5a). The inclusion of a rye cover crop decreased maize yield by 34% (2.6 Mg ha^{-1}) and biomass by 22% (4.0 Mg ha^{-1}) when compared to CC in 2012. The cover crop yield penalty was less severe in 2013, with reductions of 22% (1.9 Mg ha^{-1}) in grain yield and 14% (2.6

Table 5
Treatment effects on soil nitrate (NO_3) concentrations in the top 30 cm soil layer at V6, maize grain yield, maize above ground biomass production (a), and annual drainage variables (b) between continuous maize (CC) and continuous maize with rye cover crop (CCW) systems.

(a) Year	Soil NO_3 at V6 ($mg\,N\,kg^{-1}$ soil)			Maize yield ($Mg\,ha^{-1}$)			Maize biomass ($Mg\,ha^{-1}$)		
	CC	CCW	p[b]	CC	CCW	p	CC	CCW	p
2009	15.3(1.03)[a]	9 (1.22)	<0.001	10.77 (0.28)	11.64 (0.41)	ns	18.67 (0.31)	19.11 (0.48)	ns
2010	21 (3.46)	17.5 (3.93)	ns	8.32 (0.34)	8.66 (0.07)	ns	15.31 (0.25)	15.33 (0.5)	ns
2011	19 (1.73)	10 (1.78)	<0.001	8.19 (0.16)	8.61 (0.28)	ns	13.99 (0.36)	13.72 (0.36)	ns
2012	11.8(0.48)	10 (0.91)	ns	7.56 (0.18)	4.96 (0.16)	<0.001	17.44 (0.14)	13.46 (0.4)	<0.001
2013	13 (3.03)	15.3 (4.48)	ns	8.61 (0.33)	6.75 (0.27)	<0.001	17.06 (0.42)	14.47 (0.63)	<0.001
2014[c]	14.5(3.29)	16.3 (3.47)	ns	8.35 (0.28)	8.61 (0.37)	ns	–	–	–

(b) Year	Drainage water (mm)			Flow-weighted NO_3-N concentration ($mg\,N\,L^{-1}$)			NO_3-N Losses ($kg\,N\,ha^{-1}$)			Normalized NO_3-N Losses ($kg\,N$ loss $100\,kg^{-1}$ N applied)		
	CC	CCW	p	CC	CCW	p	CC	CCW	p	CC	CCW	p
2009	85 (11.9)	89 (16.4)	ns	8.3 (1.08)	8.0 (0.48)	ns	7.3 (1.66)	6.9 (1.0)	ns	4.3 (0.99)	3.1 (0.46)	ns
2010	439 (108.8)	353 (66.8)	ns	7.1 (0.97)	6.8 (1.02)	ns	31 (8.22)	21.9 (1.82)	ns	25.2 (6.68)	13 (1.08)	ns
2011	164 (36.1)	145 (30.8)	ns	7.9 (0.71)	3.6 (0.46)	<0.001	12.6 (2.43)	5.0 (0.78)	0.0046	8.8 (1.7)	2.3 (0.35)	<0.001
2012	50 (12.3)	27 (6.8)	ns	12 (0.47)	2.6 (0.68)	<0.001	5.9 (1.32)	0.6 (0.23)	<0.001	3.0 (0.67)	0.3 (0.11)	<0.001
2013	96 (27.5)	84 (12)	ns	18.8 (2.18)	17.5 (1.39)	ns	16.9 (4.62)	14.3 (1.32)	ns	8.4 (2.29)	7.9 (0.73)	ns
2014	272 (43.3)	273 (29.5)	ns	12.7 (0.44)	13.6 (2.47)	ns	34.1 (4.61)	37.1 (7.62)	ns	19.1 (2.58)	22.9 (4.7)	ns

[a] Values between parenthesis indicate standard error.
[b] ns indicates non-significant treatment effects ($\alpha = 0.05$).
[c] Biomass data was not collected in 2014.

$Mg\,ha^{-1}$) in biomass when compared to CC. Both 2012 and 2013 were dry years (Fig. 2). No significant treatment effects in maize biomass and grain yields were observed in 2009, 2010, 2011 and 2014. Across the six years, the average yield penalty in the CCW treatment was 6%.

3.3. Soil temperature

Soil temperature at different soil depths and time periods was fairly similar between CC and CCW treatments, although the analysis identified a few days with significant differences (22 days in five years; Fig. 4). Days with significant differences were clustered in the period before or near to the termination date, tended to record warmer soil temperatures in the CCW treatment in the subsoil (depth > 15 cm), and differences were small (0.4 °C in 2010 and 1.2 °C in 2013). On these days the top soil layers (5–15 cm) in CCW tended to register cooler temperatures compared to CC (difference of 0.35 °C).

3.4. Soil water content

The soil water fluctuated greatly during the studied periods following precipitation events (Fig. 5). With the exception of 2010 (flood-inducing conditions in mid-summer), the seasonal patterns showed soil water levels near field capacity during the early part of the season (May and June) and a decline in July and August. Most of the statistically significant differences ($p < 0.1$) were detected in the dry years (2009, 2012 and 2013; Fig. 2), at the 0–30 and 0–50 cm soil depths (Fig. 5). In general, periods with significant differences revealed lower soil water content for CCW compared to CC. In 2009, the average water deficit for the period with significant differences was 12 and 20 mm in the 0–30 and 0–50 cm depths, respectively. In 2012, significant differences were observed for 14 days prior to N side dress (~V6), but not later in the season. This was probably related to malfunctions in the moisture sensors during that summer (we speculate due to extreme dryness), which decreased the power of the ANOVAs to detect differences during that year. On average, the soil water deficit in 2012 was 12 and 25 mm for the 0–30 and 0–50 cm depths, respectively. In 2013, CCW had significantly lower soil water in 0–50 cm from maize planting to N side dress day (average deficit of 20 mm), but after this period, the trend reversed and the CCW treatment had higher soil water for 45 days (6.6 mm difference) compared to CC (Fig. 5). Interestingly, the differences in soil moisture were not consistent with the differences in maize yields (Fig. 5 and Table 5a). In 2012, maize yield and soil moisture were both lower in CCW, but in 2013 maize yield was lower and soil moisture was higher in CCW.

3.5. Soil nitrate

Analysis of mid-June soil nitrate samples indicated significant treatment effects ($p < 0.05$), as well as a significant *treatment* × *year* interaction (Table 5a). Rye reduced soil NO_3 concentrations only in 2009 and 2011, by about 6.2 and 9.0 $mg\,kg^{-1}$ respectively. This suggests that rye cover crop had an impact on soil mineral N, but this reduction was most likely negated in this experiment by applying higher N fertilization rates in the CCW treatment (Table 2).

3.6. Subsurface drainage: water and NO_3-N losses

Over the six-year period, inclusion of rye cover crop reduced measured cumulative drained water and NO_3-N losses in subsurface drainage by 12.1% and 20.4%, respectively (Table 5b and Fig. 6). However, statistically significant treatment differences ($p < 0.05$) were not found in any of the studied years for annual water drainage, and only in 2011 and 2012 for NO_3-N losses (Table 5b). Likewise, annual flow-weighted NO_3-N concentration were significantly different between treatments in 2011 and 2012 (Table 5b). When adjusted for N application rate (Table 2) NO_3-N losses were also only significantly reduced in 2011 and 2012 (Table 5b), with 31% reduction in the amount of NO_3-N loss per kg of N applied. As expected, the seasonal patterns between drainage water and NO_3-N losses were similar (Fig. 6). On average, 67% of the water drainage and NO_3-N losses occurred during the maize-growing season (planting to harvest). The highest NO_3-N loss values were recorded in the wet years for both treatments (2010 and 2014; Fig. 2). Regression analysis between cumulative drainage water (*Y*-dependent variable, Fig. 7) and precipitation registered during the drainage period (*X*-explanatory) showed a strong relationship: $y = 0.34\,(x - 162)$; $r^2 = 0.97$; n=12, where the value of 162 mm

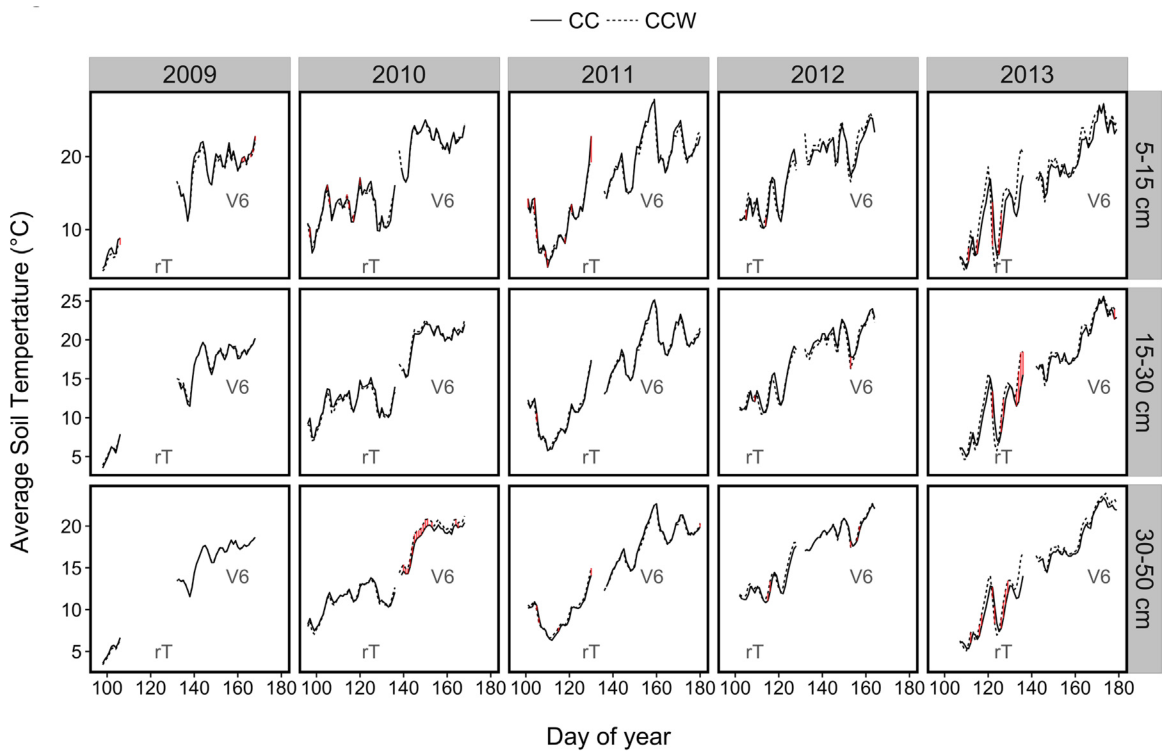

Fig. 4. Average soil temperatures at 5–15 cm, 15–30 cm and 30–50 cm depths for the continuous maize (CC) and the continuous maize with rye cover crop (CCW) treatments. Regions shaded in red (when visible) indicate days where statistically significant differences (α = 0.05) between treatments were detected. Dates of rye termination (rT) and maize sixth leaf stage (V6) are included for reference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

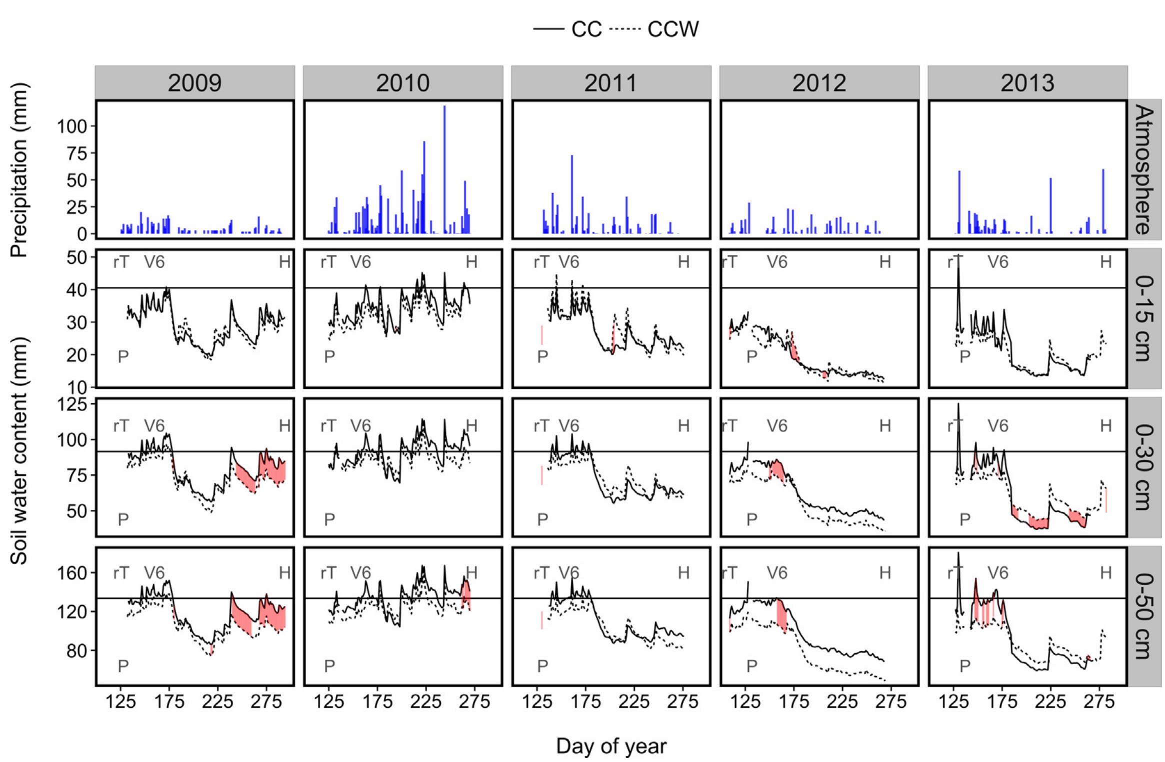

Fig. 5. Seasonal changes in soil profile water content (mm per depth) for the continuous maize (CC) and the continuous maize with rye cover crop (CCW) treatments for the 0–15 cm, 0–30 cm and 0–50 cm depths. Top panes show the recorded precipitation at the site. Horizontal lines in every soil water pane show field capacity. Regions shaded in red indicate days where statistically significant differences (α = 0.1) between treatments were detected. Dates of rye termination (rT), maize planting (P), maize sixth leaf stage (V6) and maize harvest (H) are included for reference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

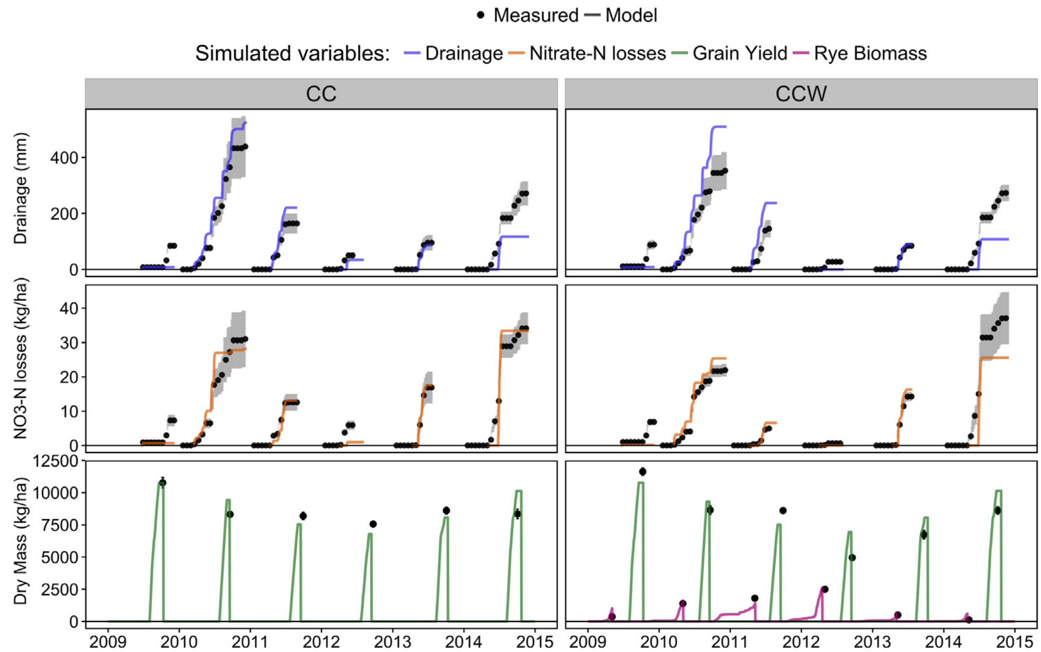

Fig. 6. Measured (points) and simulated (lines) cumulative drainage water and NO_3-N losses in subsurface drainage, maize yields, and rye shoot biomass. Shaded area and error bars indicate standard error of measured data.

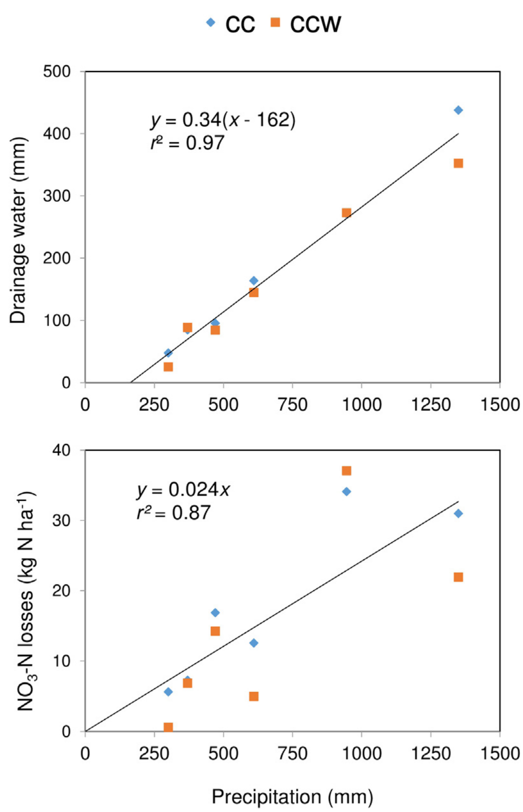

Fig. 7. Relationships between cumulative precipitation and drainage water volume to nitrate (NO_3)-N losses in subsurface drainage during the drainage season.

denotes the minimum precipitation amount required to initiate soil water flow to subsurface drainage, and the 0.34 slope coefficient denotes the portion of the precipitation water that ends up in subsurface drainage systems. Similarly, the relationship between NO_3-N losses (Y) and precipitation (X) was in the form: $y = 0.024x$; $r^2 = 0.87$; n = 12, where the value of 0.024 is the NO_3-N losses per each mm of precipitation registered during the drainage period.

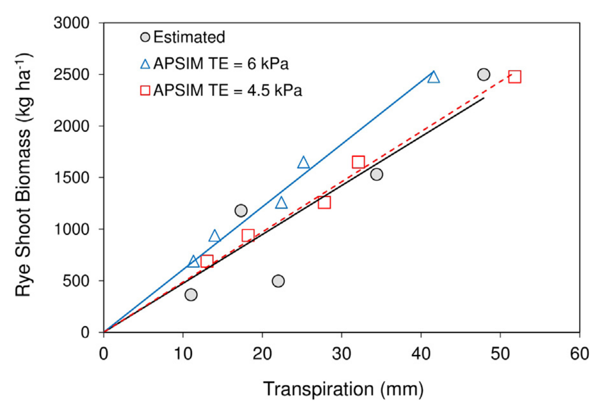

Fig. 8. Rye shoot biomass versus water use (transpiration) as estimated by a water balance difference method using experimental data (●; $y = 47.414x$, $r^2 = 0.8279$), and by the APSIM model using two sets of transpiration efficiency coefficients (TE) (△; $y = 60.773x$, $r^2 = 0.9824$ and □; $y = 48.636x$, $r^2 = 0.9877$). Each of the five points reflects a year (2009–2013).

3.7. Rye transpiration (water use)

The cumulative treatment difference in soil water profile and subsurface drainage on rye termination day was used to estimate rye transpiration. Results indicated that rye transpiration ranged from 11 to 44 mm over the study period and that a strong relationship exists between transpiration and shoot biomass ($r^2 = 0.83$; Fig. 8). The slope of the regression equation indicated that 47 kg ha^{-1} are produced per mm of water used. APSIM model simulations were of the same magnitude and confirmed the robustness of this approach to estimate transpiration for rye.

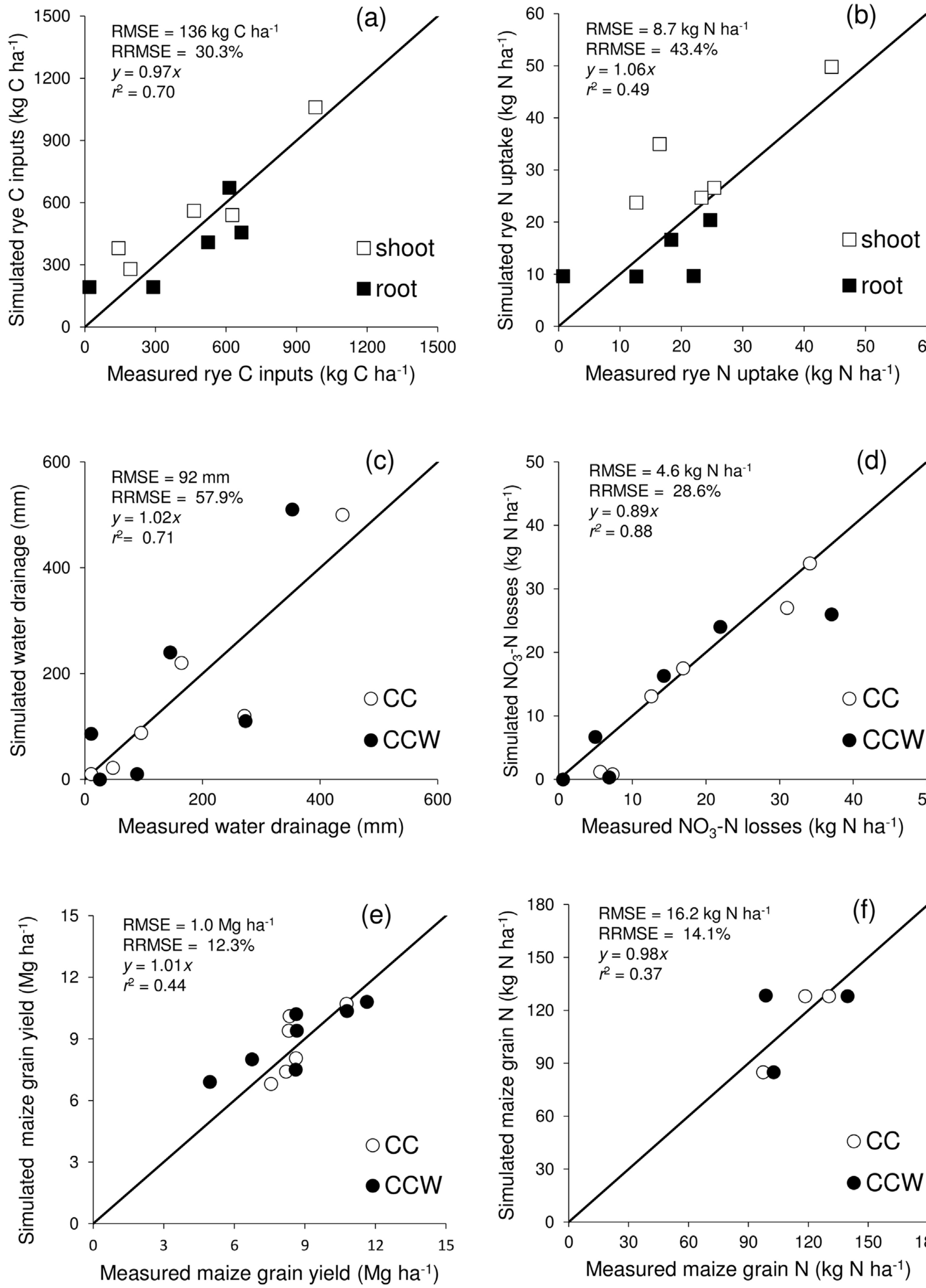

Fig. 9. Measured versus simulated rye root and shoot C input at termination date (a) and rye root and shoot N uptake at termination date (b), annual drainage (c), annual NO_3-N losses (d), maize grain yields (d) and grain N concentration (f) for continuous maize (CC) and continuous maize with rye cover crop (CCW) treatments.

3.8. Model simulations and scenario analysis

The additional changes made in the rye and maize models (Table 3) maintained or improved the overall prediction ability of APSIM compared to the version presented by Dietzel et al. (2016). Noticeable improvements in the simulation process or new tests are presented here (Figs. 6 and 9). For all of the other processes such as soil water, temperature, biomass, soil nitrate, and soil-root CO_2 emissions, we refer to graphs and statistics presented by Dietzel et al. (2016). In general, the model performed well for all system variables and captured satisfactorily the year-to-year variation. Precision was good for yields (RRMSE = 12.3%), grain N concentrations (RRMSE = 14.1%) and annual NO_3-N losses (RRMSE = 28%), although the model tended to under predict years with higher NO_3-N losses. Simulations were less precise for drainage water and the rye C and N data (RRMSE = 57.9%, 30.3% and 43.4%, respectively), although model predictions were fairly accurate (evidenced by the slope of regression equation of simulated vs. predicted ~1; Fig. 9). This means that the long-term simulations were unbiased, and that the average response is reliable. A detailed discussion of the challenges identified for modeling rye cover crop growth and NO_3-N losses in subsurface drainage is provided in the supplementary materials (S3).

The range of simulated rye biomass (1.9 ± 1.3 Mg ha^{-1}), C:N (15.5 ± 5.6 and 32.3 ± 7.8 for shoots and roots, respectively), root:shoot (0.65 ± 0.12), water (39 ± 27 mm) and total nitrogen use (67 ± 40 kg ha^{-1}) were within the range of values measured in this study (Table 4 and Fig. 7), with a later termination date associated with greater rye growth. The model simulated overall decreases in annual NO_3-N losses (-25.5 ± 26%), though it did not consistently simulate reductions in annual drainage water (-3.9 ± 13%) and maize grain yields (-1.84 ± 6%). Summary of results from model scenario analysis by termination date are included in the supplementary materials (Table S2). Regression analyses of this simulated dataset (n=120; 4 termination dates × 30 yr) showed that increases in rye shoot biomass were not associated with reductions in maize yield and water drainage ($p > 0.05$; Fig. 10). For NO_3-N losses the relationship between rye biomass was significant ($p < 0.001$), but this was with poor prediction power, ($r^2 = 0.23$). Combined analysis of experimental and literature data yielded similar results to model simulations, although measured values did show a significant relationship for drainage in addition to NO_3-N losses (Fig. 10).

4. Discussion

In this study, we approached rye cover crop abiotic effects on maize yields and environmental performance from a systems perspective (Fig. 1). Initially, we hypothesized that the magnitude of rye effects on maize yields and environmental performance variables such as cumulative drainage water and NO_3-N losses would be proportionally related to rye biomass production, an easily measurable trait. Experimental, literature and modeling results did not support the hypothesized relationship for yield (Fig. 10), meaning that rye biomass at termination date was not a good predictor of cover crop effects on maize yields. This lack of relationship may be because other factors, such as water and nitrogen stresses around flowering and grain filling periods (Çakir, 2004; Ciampitti and Vyn, 2011; Salmerón et al., 2011), may be more important than small changes in soil water and nitrogen at maize planting (Fig. 1). Additionally, Kaspar and Bakker (2015) found that decreases in maize yield following winter cereal cover crops are sometimes related to lower crop population densities, which seems to suggest that biotic stresses such as allelopathy and increased disease pressure or other factors may also play an important role.

Our experimental results combined with literature values suggest a significant relationship between rye biomass and changes in drainage water volume, but modeling results do not support this hypothesis (Fig. 10). The lack of a strong relationship between simulated changes in drained water and rye biomass is probably due to compensatory effects between rye water use and spring precipitation (see discussion on soil water below), or to the fact that most of the drainage in this site occurs during the maize growing season (67%, Fig. 6), or both. For the NO_3-N losses, we found a significant proportional relationship for both measured and simulated values (Fig. 10), presumably due to a rye N recycling effect, but this relationship was associated with large variability ($r^2 = 0.23$), which may be related to the variability in C:N of the rye biomass at termination (Fig. 3). Malone et al. (2014) simulated 40 site-climatic conditions in the US using RZWQM model and found a strong relationship between rye N uptake and reduction in nitrate leaching (slope = 40%, $r^2 = 0.90$). Using rye N uptake as a predictor, our modeling results showed a stronger relationship to reduction in NO_3-N losses than biomass (slope = 41.8%, $r^2 = 0.52$), but the experimental results did not confirm this relationship (data not shown). Below we synthesize experimental, simulated and literature results to better understand the complex interactions and dynamics in the rye-maize system.

4.1. Soil temperature effects are minor suggesting negligible impacts on maize seedling emergence

High-resolution, multi-soil profile temperature results that covered five contrasting years (wet, drought, and average years; Fig. 2), different rye biomass levels (0–2.5 Mg/ha; Table 4) and thus shading capacities, showed very minor treatment effects (Fig. 4). In the top soil layer, the decrease in soil temperature caused by rye was less than 0.7 °C by the time of rye termination, and none by the time of maize planting (Fig. 4), indicating that the temperature effect of rye on maize seedling emergence was minimal. This also means that the putative shading role of rye and its effects on soil water evaporation savings (Fig. 1) is probably lower than previously believed in simulation model studies (Basche et al., 2016a; Dietzel et al., 2016). If soil water evaporation savings existed, then the additional water in the CCW treatment should have resulted in higher soil moisture levels in the profile or in higher drainage rates or in higher maize yields in the drought years. None of this was true (Table 5a, and Figs. 5 and 6) providing further evidence that rye shading effect and consequent evaporation savings are much lower than believed. That was the reason for improving parameters in the rye model related to ground cover shade (Table 3).

4.2. Soil water stress caused maize yield penalty in drought years via different mechanisms

Previous research with model simulations has estimated that rye can deplete up to 60 mm of soil water in this region (Basche et al., 2016a; Malone et al., 2007). In Iowa, May-June rainfalls are about 260 mm, while the soil water holding capacity is generally above 180 mm, thus combined can minimize the effect of rye transpiration (up to 50 mm; Fig. 8). A recent study in a nearby location provided evidence for this, showing that spring precipitation replenished soil moisture of cover crop plots to levels comparable to the no-cover-crop control by the time of corn emergence (Basche et al., 2016b). However, this seems to not be fully true in years with below average precipitation (i.e. dry years: 15 out of 35 cases; Fig. 2). In our study, there were two drought years (2012 and 2013; Fig. 2) and in those years we observed maize yield penalties (Table 5a) and significant treatment differences in soil moisture (Fig. 5). However, the drought-induced conditions were different between 2012 and 2013 (see precipitation patterns in Fig. 5). Examination of soil water deficits coupled with APSIM model sensitivity analyses (not shown) indicated that a water deficit of 24 mm at rye termination and its subsequent carry-over throughout the season (Fig. 5) was probably the main reason for the observed yield penalty in 2012. The deficit most likely impacted photosynthesis, leaf expansion, and kernel number and growth. In the following year (2013), the reason for the yield penalty was either a biotic factor (which is not captured in this analysis) or early season water stress that impacted potential kernel number. The potential kernel number in maize is set before silking (Abendroth et al., 2011), and lowering this potential at that period has irreversible effects on maize yields. This might be the reason for the 2013 yield penalty (see also water deficit before silking and water surplus after silking in CCW; Fig. 5). Many other studies have also noted that lowered maize yields following cover crops are related to early-development stresses (before silking) (Johnson et al., 1998; Krueger et al., 2011; Miguez and Bollero, 2006; Pantoja et al., 2015;

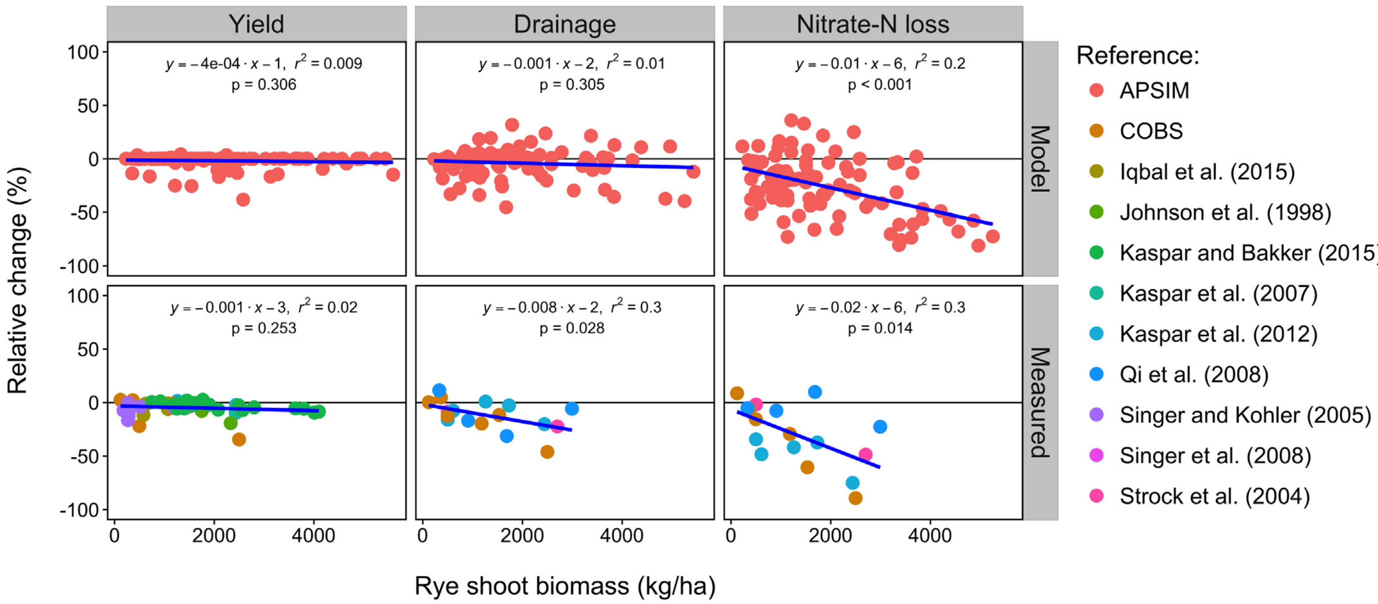

Fig. 10. Simulated relative treatment differences (see Eq. (1)) in maize yield, annual tile drainage and annual NO_3-N losses versus rye biomass production (top panes) compared to relative differences from values reported in studies conducted in the US Midwest (bottom panes) (Qi et al., 2008) Li et al. (2008).

Salmerón et al., 2011). A strategy suggested to avoid water-related yield impacts on maize during drought-inducing conditions could be the early termination of rye cover crop (Krueger et al., 2011). Knowing that one Mg ha^{-1} of rye cover crop growth uses roughly the same amount of water as what is provided by one medium-intensity rainfall event (21.1 mm, see relationship developed in Fig. 8) should provide a baseline to decide appropriate termination timing during these conditions.

4.3. Rye roots have greater potential to immobilize N during decomposition than rye shoots

Another concern regarding inclusion of rye into maize-based systems is possible N immobilization. Experimental results from this study suggest that rye contributes to changes in the way N is cycled through the crop-soil system. Soil NO_3 measurements at V6 (about 40 days after rye termination) showed an average treatment difference (CC vs. CCW) of about 12 kg N ha^{-1} (2.8 mg kg^{-1}; Table 5a), which resulted in the LSNT recommending higher fertilizer application rates for CCW (26 kg N ha^{-1} on average; Table 2). This difference could be related to the fact that not all the N taken up during rye growth may had cycled back into the soil mineral pool by V6. It should be noted, however, that rye took up on average 40 kg N ha^{-1} in its total biomass by the time of its termination (~60% in shoots and ~40% in roots; Table 4), which is about three times greater than the difference observed in soil NO_3 between treatments. This might suggest that at least some portion of rye's organic N could have been mineralized to plant-available inorganic form by V6, although the exact proportion mineralized in this experiment is uncertain given that soil NO_3 concentrations were not measured at rye termination. Nonetheless, Pantoja et al. (2016) was able to show in a recent Iowa study that when following maize in a maize-soybean rotation, 64% of rye shoot N was recycled by the end of the growing season.

Net mineralization of N in rye residues is likely because of the low C:N of rye biomass during the vegetative stages (Table 4). In general, crop residues with C:N < 25-40 tend to favor N mineralization rather than immobilization during their decomposition (Vigil and Kissel, 1991), and the APSIM residue model simulates these dynamics (Thorburn et al., 2005, 2001). The range of rye C:N values found in this study agrees with what has been measured in other studies in Iowa (Pantoja et al., 2016, 2015; Patel et al., 2015), Minnesota (Feyereisen et al., 2006; Krueger et al., 2011; Strock et al., 2004), Illinois (Miguez and Bollero, 2006; Ruffo and Bollero, 2003) and Washington (Kuo and Jellum, 2002). Most importantly, all these studies together synthesized a robust framework that relates rye biomass quantity to its quality and reveals their relationship (Fig. 3). The most important messages from this analysis are: a) decomposition of rye shoot biomass will not tend to immobilize N if it is terminated before 1.57 Mg ha^{-1} of shoot growth (~25C:N in upper prediction interval in Fig. 3.), and b) decomposition of roots is more likely to immobilize N than shoots because of their higher C:N. In this study, however, root C:N was still relatively low (average = 27; Table 4) and consequently net N immobilization from rye root decomposition was probably minimal.

It should be noted that the shoot C:N is mainly regulated by the N concentration and not by the C concentration, which is fairly stable at about 40% in shoots (Table 4; Brennan et al., 2013; Vigil and Kissel, 1991). The N concentration is a function of rye growth stage and biomass production as well as soil supply of N and stand density (leaf to stem ratio). When rye is growing under N limited conditions, the plant will satisfy its minimum requirements (upper confidence intervals in Fig. 3). When rye is growing under non-N limited conditions, the plant will uptake N until it satisfies its "luxurious" requirements (lower confidence intervals in Fig. 3). This explains the data variability in Fig. 3 across literature studies. Another interesting observation from the model analysis is that rye growth in Iowa is not only limited by temperature but also by N availability, and that the amount of the residual soil NO_3 at maize harvest will greatly influence its final biomass production. This is because the contribution of soil organic matter to plant available N during winter months is practically zero due to near freezing temperatures. In our study, the APSIM model estimated that total soil mineralization during the period between rye planting and its termination (Table 1) was in the range between 12 to 38 kg N ha^{-1}, but also that not all of the mineralized N was available for rye uptake because the decomposition of the maize stover (C:N > 70) immobilized some of that N also. In this study, 50% of maize residue was removed at harvest, which probably resulted in different amount of rye growth than if no residue were removed. This also means that rye growth will be maximized in fields with high residual nitrogen after crop harvest.

4.4. Carbon inputs are low but of high quality compared to maize

Rye cover crop terminated during vegetative growth adds a relative small amount of C in the system (160–1800 kg C ha^{-1} yr^{-1}; Tables 4 and S2) of high quality (see section 4.3.). This amount of C is approximately 10% the C added by the maize stover. It should be noted, however, that in this study we found exceptionally high root:shoot at termination day in some years (up to 1.9; Table 4). We discuss possible reasons for this in detail in the supplementary materials (S4) and provide literature comparisons. This is a topic that we investigated further. On the other hand, APSIM model simulated rye root:shoot from 0.57 to 0.79 at termination day, which is reasonable given that rye is terminated at early growth stages (see Zadoks stage on Table S2; Zadoks et al., 1974).

4.5. Rye decreased NO_3-N losses by reducing NO_3-N concentration in drainage rather than drainage water volume

Nitrate-N losses were reduced in two out of the six studied years (2011 and 2012) while no differences were found in drainage water volume in any of the studied years (Table 5b). On the other hand, flow-weighted NO_3-N concentrations in drainage water were also reduced during those years (Table 5b) indicating that NO_3-N losses were probably lower because rye growth reduced soil mineral N concentrations rather than drainage water volume. This is consistent with our modeling results (Fig. 10) and results from other studies in central Iowa (Kaspar et al., 2012, 2007). Over the six experimental years, we observed a 20% reduction in NO_3-N losses relative to CC which represented only 4 kg of N ha^{-1} yr^{-1} (Fig. 6 and Table 5b), approximately 10% of the amount of N taken up by rye (40 kg N ha^{-1} yr^{-1}; Table 4). These reductions are lower than what has been measured in other studies in a nearby location (44% or 20 kg ha^{-1} in Kaspar et al., 2012; 65% or 31 kg ha^{-1} in Kaspar et al., 2007). In this experiment, however, LSNT-based N fertilization resulted in unequal application rates between treatments (higher in CCW from 2009 to 2012 and lower in 2013–2014; Table 2) which could have influenced the results. When the NO_3-N losses are expressed as a percentage of unit of N applied, the benefit of including rye cover crop in this system was 3.3 kg of NO_3-N loss reduced per 100 kg^{-1} of N applied yr^{-1}, which represents a 31% reduction relative to CC (Table 5b). Finally, it should be noted also that rye cover crop here is evaluated on a continuous maize system (with 50% residue removal), rather than a maize-soybean rotation which is more common in the literature. Thus, differences in residue dynamics (i.e. quantity and quality; e.g. faster decomposition of soybean residue than maize residue) may partly account for why the reduction in NO_3-N losses here are relatively smaller than what has been measured elsewhere.

5. Conclusions

Coupling experimental and literature findings with modeling, we provided a system-level analysis of rye cover crop effects on maize and extrapolated results beyond the study period to obtain a more complete picture of the abiotic effects of the inclusion of a rye cover crop in rain-fed maize-based systems. Modeling scenario analysis showed that in the long term, rye improves environmental performance (26% reduction in NO_3-N losses) without consistently reducing maize yields. However, experimental and modeling results did not fully support the hypothesized relationship between rye shoot biomass production (easily measurable trait) and the magnitude of rye abiotic effects on maize yields and environmental performance, which demonstrates the complexity that exists in the rye-maize-soil-atmosphere system (Fig. 1). APSIM was able to replicate measurements well and thus it can be used as a tool to identify combinations of practices that can result in win–win scenarios. This study also provided new data on rye water and N use, which are very important in understanding how the rye cover crop affects the system. Most importantly, we showed that: a) rye cover crop soil-temperature effects were negligible; b) rye water use had the potential to affect yield only when spring rains failed to replenish soil moisture (drought-inducing conditions); c) rye terminated during early vegetative stages had little potential to immobilize plant-available N during their decomposition, d) rye residues provided high quality C inputs (low C:N) of low quantity compared to maize, and e) reduced NO_3-N losses were related to lower NO_3-N concentrations in drainage. We also developed robust empirical models between water and NO_3-N in drainage and precipitation for fast assessments of environmental performance at this site. Potential trade-offs and risks associated with the use of rye cover crop in maize-based systems will always exist given the complex nature of the system. Thus, further research should advance understanding of biotic and abiotic mechanisms by which rye affects yield and environmental performance of the system, as well as the long-term consequences of including rye cover crops in Midwestern cropping systems.

Acknowledgements

This project was supported by the Iowa Nutrient Research Center (project: 'Quantifying temporal and spatial variability in NO_3-N leaching across Iowa'), the United States Department of Agriculture's National Institute of Food and Agriculture (competitive grant No. 2012-67011-1966) and the Agriculture and Food Research Initiative (Hatch project No. 1004346). We thank Robert Ewing, Dave Sundberg, Carl Pedersen and other personnel from the COBS project for contributing to the data collection. We also are grateful to Fernando Miguez, Mike Castellano, and four anonymous reviewers for useful comments during the development of this manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2016.06.016.

References

Çakir, R., 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. Food Crop. Res. 89, 1–16, http://dx.doi.org/10.1016/j.fcr.2004.01.005.

Abendroth, L.J., Elmore, R.W., Boyer, M.J., Marlay, S.K., 2011. Corn growth and development (PMR 1009). Iowa State University Extension, Ames, Iowa.

Acharya, J., Kaspar, T., Moorman, T., Lenssen, A.W., Robertson, A.R., 2016. Effect of cereal rye winter cover crop (Secale cereal) termination on corn seedling diseases. (Abstr.). Phytopathology 106 (S1.1).

Arbuckle, J.G., Roesch-McNally, G., 2015. Cover crop adoption in Iowa: The role of perceived practice characteristics. J. Soil Water Conserv. 70, 418–429, http://dx.doi.org/10.2489/jswc.70.6.418.

Archontoulis, S.V., Miguez, F.E., 2013. Nonlinear regression models and applications in agricultural research. Agron. J 107, 1–13, http://dx.doi.org/10.2134/agronj2012.0506.

Archontoulis, S.V., Miguez, F.E., Moore, K.J., 2014a. Evaluating APSIM maize, soil water, soil nitrogen, manure, and soil temperature modules in the Midwestern United States. Agron. J. 106, 1025–1040, http://dx.doi.org/10.2134/agronj2013.0421.

Archontoulis, S.V., Miguez, F.E., Moore, K.J., 2014b. A methodology and an optimization tool to calibrate phenology of short-day species included in the APSIM PLANT model: Application to soybean. Environ. Model. Softw. 62, 465–477, http://dx.doi.org/10.1016/j.envsoft.2014.04.009.

Archontoulis, S.V., Huber, I., Miguez, F.E., Thorburn, P.J., Laird, D.A., 2015. A model for mechanistic and system assessments of biochar effects on soils and crops and trade-offs. GCB Bioenergy, http://dx.doi.org/10.1111/gcbb.12314.

Bakker, M., Moorman, T.B., Manter, D., Kaspar, T., 2016. Winter rye cover crops as a host for corn seedling pathogens. (Abstr.)6. Phytopathology 106 (S1.2).

Basche, A.D., Archontoulis, S.V., Kaspar, T.C., Jaynes, D.B., Parkin, T.B., Miguez, F.E., 2016a. Simulating long-term impacts of cover crops and climate change on crop production and environmental outcomes in the Midwestern United States. Agric. Ecosyst. Environ. 218, 95–106, http://dx.doi.org/10.1016/j.agee.2015.11.011.
Basche, A.D., Kaspar, T.C., Archontoulis, S., Jaynes, D.B., Sauer, T.J., Parkin, T.B., Miguez, F.E., 2016b. Soil water improvements with the long-term use of a winter rye cover crop. Agric. Water Manag. 172, 40–50, http://dx.doi.org/10.1016/j.agwat.2016.04.006.
Bates, D.M., Watts, D.G., 2007. Nonlinear Regression Analysis and Its Applications, 2nd ed. John Wiley & Sons, Inc., New York, http://dx.doi.org/10.2307/2289810.
Blackmer, A.M., Vos, R.D., Mallarino, A.P., 1997. Nitrogen fertilizer recommendations for corn in Iowa (PM1714). Iowa State University Extension, Ames, Iowa.
Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C.A., Hergert, G.W., 2015. Cover crops and ecosystem services: Insights from studies in temperate soils. Agron. J. 117, 2449–2474, http://dx.doi.org/10.2134/agronj15.0086.
Brennan, E.B., Boyd, N.S., Smith, R.F., 2013. Winter cover crop seeding rate and variety effects during eight years of organic vegetables: III. Cover crop residue quality and nitrogen mineralization. Agron. J. 105, 171–182, http://dx.doi.org/10.2134/agronj2012.0258.
Bruin, J.L., De, Porter, P.M., Jordan, N.R., 2005. Use of a rye cover crop following corn in rotation with soybean in the upper Midwest. Agron. J. 97, 587–598, http://dx.doi.org/10.2134/agronj2005.0587.
Carlson, S., Stockwell, R., 2013. Research priorities for advancing adoption of cover crops in agriculture-intensive regions. J. Agric. Food Syst. Community Dev. 3, 125–129, http://dx.doi.org/10.5304/jafscd.2013.034.017.
Christianson, L., Tyndall, J., Helmers, M., 2013. Financial comparison of seven nitrate reduction strategies for Midwestern agricultural drainage. Water Resour. Econ. 2–3, 30–56, http://dx.doi.org/10.1016/j.wre.2013.09.001.
Ciampitti, I.A., Vyn, T.J., 2011. A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. F. Crop. Res. 121, 2–18, http://dx.doi.org/10.1016/j.fcr.2010.10.009.
Crandall, S.M., Ruffo, M.L., Bollero, G.A., 2005. Cropping system and nitrogen dynamics under a cereal winter cover crop preceding corn. Plant Soil 268, 209–219, http://dx.doi.org/10.1007/s11104-004-0272-x.
Dabney, S.M., Delgado, J.A., Collins, F., Meisinger, J.J., Schomberg, H.H., Liebig, M.A., Kaspar, T., Mitchell, J., 2010. Using cover crops and cropping systems for nitrogen management. In: Delgado, J.A., Follett, R.F. (Eds.), Advances in Nitrogen Management for Water Quality. Soil and Water Conservation Society, Ankeny, Iowa, pp. 230–281.
Daigh, A.L., Zhou, X., Helmers, M.J., Pederson, C.H., Ewing, R., Horton, R., 2014. Subsurface drainage flow and soil water dynamics of reconstructed prairies and corn rotations for biofuel production. Vadose Zo. J. 13, http://dx.doi.org/10.2136/vzj2013.10.0177.
Daigh, A.L.M., Zhou, X., Helmers, M.J., Pederson, C.H., Horton, R., Jarchow, M., Liebman, M., 2015. Subsurface drainage nitrate and total reactive phosphorus losses in bioenergy-based prairies and corn systems. J. Environ. Qual. 44, 1638–1646, http://dx.doi.org/10.2134/jeq2015.02.0080.
De Rosario Martínez, H., 2015. {phia}: Post-hoc interaction analysis.
Dhima, K.V., Vasilakoglou, I.B., Eleftherohorinos, I.G., Lithourgidis, A.S., 2006. Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development. Crop Sci. 46, 345–352, http://dx.doi.org/10.2135/cropsci2005-0186.
Dietzel, R., Jarchow, M.E., Liebman, M., 2015. Above- and belowground growth, biomass, and nitrogen use in maize and reconstructed prairie cropping systems. Crop Sci. 55, 1–14, http://dx.doi.org/10.2135/cropsci2014.08.0572.
Dietzel, R., Liebman, M., Ewing, R., Helmers, M., Horton, R., Jarchow, M., Archontoulis, S., 2016. How efficiently do corn- and soybean-based cropping systems use water? A systems modeling analysis. Glob. Chang. Biol. 22, 666–681, http://dx.doi.org/10.1111/gcb.13101.
Dinnes, D.L., Karlen, D.L., Jaynes, D.B., Kaspar, T.C., Hatfield, J.L., Colvin, T.S., Cambardella, C. a, 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agron. J. 94, 153–171.
Duiker, S.W., Curran, W.S., 2005. Rye cover crop management for corn production in the Northern mid-Atlantic region. Agron. J. 97, 1413–1418, http://dx.doi.org/10.2134/agronj2004.0317.
Feyereisen, G.W., Sands, G.R., Wilson, B.N., Strock, J.S., Porter, P.M., 2006. Plant growth component of a simple rye growth model. Trans. ASABE 49, 1569–1578, http://dx.doi.org/10.13031/2013.22031.
Gastal, F., Lemaire, G., 2002. N uptake and distribution in crops: an agronomical and ecophysiological perspective. J. Exp. Bot. 53, 789–799, http://dx.doi.org/10.1093/jexbot/53.370.789.
Gelderman, R.H., Beegle, D., 2012. Nitrate-Nitrogen. In: Nathan, M.V., Gelderman, R.H. (Eds.), Recommended Chemical Soil Test Procedures for the North Central Region. Missouri Agricultural Experiment Station, Columbia, MO, USA.
Griffin, T., Liebman, M., Jemison, J., 2000. Cover crops for sweet corn production in a short-season environment. Agron. J. 92, 144–151, http://dx.doi.org/10.2134/agronj2000.921144x.
Hammer, G.L., Dong, Z., McLean, G., Doherty, A., Messina, C., Schussler, J., Zinselmeier, C., Paszkiewicz, S., Cooper, M., 2009. Can changes in canopy and/or root system architecture explain historical maize yield trends in the U.S. corn belt? Crop Sci. 49, 299–312, http://dx.doi.org/10.2135/cropsci2008.03.0152.
Holzworth, D.P., Huth, N.I., DeVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., Brown, H., Whish, J.P.M., Verrall, S., Fainges, J., Bell, L.W., Peake, A.S., Poulton, P.L., Hochman, Z., Thorburn, P.J., Gaydon, D.S., Dalgliesh, N.P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F.Y., Wang, E., Hammer, G.L., Robertson, M.J., Dimes, J.P., Whitbread, A.M., Hunt, J., van Rees, H., McClelland, T., Carberry, P.S., Hargreaves, J.N.G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., Keating, B.A., 2014. APSIM—evolution towards a new generation of agricultural systems simulation. Environ. Model. Softw. 62, 327–350, http://dx.doi.org/10.1016/j.envsoft.2014.07.009.
Iowa Deptartment of Agriculture, Land Stewarship, 2013. Iowa Nutrient Reduction Strategy. Iowa Deptartment of Agriculture and Land Stewarship.
Iqbal, J., Mitchell, D.C., Barker, D.W., Miguez, F., Sawyer, J.E., Pantoja, J., Castellano, M.J., 2015. Does nitrogen fertilizer application rate to corn affect nitrous oxide emissions from the rotated soybean crop? J. Environ. Qual. 44, 711–719, http://dx.doi.org/10.2134/jeq2014.09.0378.
Jarchow, M.E., Liebman, M., 2012. Tradeoffs in biomass and nutrient allocation in prairies and corn managed for bioenergy production. Crop Sci. 52, 1330–1342, http://dx.doi.org/10.2135/cropsci2011.09.0481.
Jarchow, M.E., Liebman, M., Dhungel, S., Dietzel, R., Sundberg, D., Anex, R.P., Thompson, M.L., Chua, T., 2015. Trade-offs among agronomic, energetic, and environmental performance characteristics of corn and prairie bioenergy cropping systems. GCB Bioenergy 7, 57–71, http://dx.doi.org/10.1111/gcbb.12096.
Johnson, T.J., Kaspar, T.C., Kohler, K.A., Corak, S.J., Logsdon, S.D., 1998. Oat and rye overseeded into soybean as fall cover crops in the upper Midwest. J. Soil Water Conserv. 53, 276–279.
Justes, E., Mary, B., Meynard, J., Machet, J.-M., Thelier-Huches, 1994. Determination of critical nitrogen dilution curve for winter wheat crops. Ann. Bot. 74, 397–407, http://dx.doi.org/10.1006/anbo.1994.1133.
Kaspar, T.C., Bakker, M.G., 2015. Biomass production of 12 winter cereal cover crop cultivars and their effect on subsequent no-till corn yield. J. Soil Water Conserv. 70, 353–364, http://dx.doi.org/10.2489/jswc.70.6.353.
Kaspar, T.C., Singer, J.W., 2011. The use of cover crops to manage soil. In: Hatfield, J., Sauer, T. (Eds.), Soil Management: Building a Stable Base for Agriculture. Amer Soc Agronomy, Madison, WI, pp. 321–338, http://dx.doi.org/10.2136/2011.soilmanagement.c21.
Kaspar, T.C., Radke, J.K., Laflen, J.M., 2001. Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion. J. Soil Water Conserv. 56, 160–164.
Kaspar, T.C., Jaynes, D.B., Parkin, T.B., Moorman, T.B., 2007. Rye cover crop and gamagrass strip effects on NO3 concentration and load in tile drainage. J. Environ. Qual. 36, 1503–1511, http://dx.doi.org/10.2134/jeq2006.0468.
Kaspar, T.C., Jaynes, D.B., Parkin, T.B., Moorman, T.B., Singer, J.W., 2012. Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. Agric. Water Manag. 110, 25–33, http://dx.doi.org/10.1016/j.agwat.2012.03.010.
Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288, http://dx.doi.org/10.1016/S1161-0301(02)00108-9.
Kessavalou, A., Walters, D.T., 1999. Winter rye cover crop following soybean under conservation tillage: residual soil nitrate. Agron. J. 91, 643–649, http://dx.doi.org/10.2134/agronj1999.914643x.
Krueger, E.S., Ochsner, T.E., Porter, P.M., Baker, J.M., 2011. Winter rye cover crop management influences on soil water, soil nitrate, and corn development. Agron. J. 103, 316–323, http://dx.doi.org/10.2134/agronj2010.0327.
Krueger, E.S., Ochsner, T.E., Baker, J.M., Porter, P.M., Reicosky, D.C., 2012. Rye-corn silage double-cropping reduces corn yield but improves environmental impacts. Agron. J. 104, 888–896, http://dx.doi.org/10.2134/agronj2011.0341.
Kuo, S., Jellum, E.J., 2002. Influence of winter cover crop and residue management on soil nitrogen availability and corn. Agron. J. 94, 501–508, http://dx.doi.org/10.2134/agronj2002.0501.
Li, L., Malone, R.W., Ma, L., Kaspar, T.C., Jaynes, D.B., Saseendran, S., Thorp, a, Yu, K.R., Ahuja, Q., 2008. Winter cover crop effects on nitrate leaching in subsurface drainage as simulated by RZWQM DSSAT. Trans. ASABE 51, 1575–1583, http://dx.doi.org/10.13031/2013.25314.
Malone, R.W., Huth, N., Carberry, P.S., Ma, L., Kaspar, T.C., Karlen, D.L., Meade, T., Kanwar, R.S., Heilman, P., 2007. Evaluating and predicting agricultural management effects under tile drainage using modified APSIM. Geoderma 140, 310–322, http://dx.doi.org/10.1016/j.geoderma.2007.04.014.
Malone, R.W., Jaynes, D.B., Kaspar, T.C., Thorp, K.R., Kladivko, E., Ma, L., James, D.E., Singer, J., Morin, X.K., Searchinger, T., 2014. Cover crops in the upper Midwestern United States: Simulated effect on nitrate leaching with artificial drainage. J. Soil Water Conserv. 69, 292–305, http://dx.doi.org/10.2489/jswc.69.4.292.
Miguez, F.E., Bollero, G.A., 2005. Review of corn yield response under winter cover cropping systems using meta-analytic methods. Crop Sci. 45, 2318–2329, http://dx.doi.org/10.2135/cropsci2005.0014.
Miguez, F.E., Bollero, G.A., 2006. Winter cover crops in Illinois: Evaluation of ecophysical characteristics of corn. Crop Sci. 46, 1536–1545, http://dx.doi.org/10.2135/cropsci2005.09.0306.
Mirsky, S.B., Wells, S.M., Reberg-Horton, S., 2015. Planting date impacts on soil water management, plant growth, and weeds in cover crop-based no-till corn production. Agron. J., http://dx.doi.org/10.2134/agronj14.0524.

Moore, E.B., Wiedenhoeft, M.H., Kaspar, T.C., Cambardella, C.A., 2014. Rye cover crop effects on soil quality in no-till corn silage–soybean cropping systems. Soil Sci. Soc. Am. J. 78, 968, http://dx.doi.org/10.2136/sssaj2013.09.0401.

Munawar, A., Blevins, R.L., Frye, W.W., Saul, M.R., 1990. Tillage and cover crop management for soil water conservation. Agron. J. 82, 773–777, http://dx.doi.org/10.2134/agronj1990.00021962008200040024x.

National Agricultural Statistics Service, 2016. Land use practices by size of farm: 2012 (Table 50) [WWW Document]. United States 2012 Census Agric. National Agricultural Statistics Service, http://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_State_Level/Iowa/st19_1_049_050.pdf (accessed 02.01.16.).

Pantoja, J.L., Woli, K.P., Sawyer, J.E., Barker, D.W., 2015. Corn nitrogen fertilization requirement and corn–soybean productivity with a rye cover crop. Soil Sci. Soc. Am. J., http://dx.doi.org/10.2136/sssaj2015.02.0084.

Pantoja, J.L., Woli, K.P., Sawyer, J.E., Barker, D.W., 2016. Winter rye cover crop biomass production, degradation, and nitrogen recycling. Agron. J. 108, 1–13, http://dx.doi.org/10.2134/agronj2015.0336.

Patel, S., Sawyer, J.E., Lundvall, J.P., Hall, J., 2015. Root and shoot biomass and nutrient composition in a winter rye cover crop. In: Norht Central Extension-Industry Soil Fertility Conference, International Plant Nutrition Institute, Des Moines, Iowa, pp. 116–118.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., R Core Team, 2015. {nlme}: Linear and Nonlinear Mixed Effects Models [WWW Document]. URL http://cran.r-project.org/package=nlme.

Qi, Z., Helmers, M.J., Lawlor, P.A., 2008. Effect of different land covers on nitrate-nitrogen leaching and nitrogen uptake in Iowa. In: ASABE Annual International Meeting, American Society of Agricultural and Biosystems Engineers, Providence, Rhode Island.

R Core Team, 2015. R: A Language and Environment for Statistical Computing [WWW Document]. R Core Team http://www.r-project.org/.

Raimbult, B.A., Vyn, T.J., Tollenaar, M., 1991. Corn response to rye cover crop, tillage methods, and planter options. Agron. J. 83, 287, http://dx.doi.org/10.2134/agronj1991.00021962008300020005x.

Reiter, M.S., Reeves, D.W., Burmester, C.H., Torbert, H.A., 2008. Cotton nitrogen management in a high-residue conservation system: cover crop fertilization. Soil Sci. Soc. Am. J. 72, 1321, http://dx.doi.org/10.2136/sssaj2007.0313.

Rich, J., 2008. Chapter 2: fall planting date of cover crops and cover crop species affect late-fall soil N uptake and spring regrowth. In: Winter Nitrogen Cycling in Agroecosystems as Affected by Snow Cover and Cover Crops (Thesis). Cornell University, Ithaca, NY, pp. 74–110.

Ruffo, M.L., Bollero, G.A., 2003. Modeling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. Agron. J. 95, 900–907, http://dx.doi.org/10.2134/agronj2003.0900.

Salmerón, M., Cavero, J., Quílez, D., Isla, R., 2010. Winter cover crops affect monoculture maize yield and nitrogen leaching under irrigated Mediterranean conditions. Agron. J. 102, 1700–1709, http://dx.doi.org/10.2134/agronj2010.0180.

Salmerón, M., Isla, R., Cavero, J., 2011. Effect of winter cover crop species and planting methods on maize yield and N availability under irrigated Mediterranean conditions. F. Crop. Res. 123, 89–99, http://dx.doi.org/10.1016/j.fcr.2011.05.006.

Schipanski, M.E., Barbercheck, M., Douglas, M.R., Finney, D.M., Haider, K., Kaye, J.P., Kemanian, A.R., Mortensen, D. a., Ryan, M.R., Tooker, J., White, C., 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agric. Syst. 125, 12–22, http://dx.doi.org/10.1016/j.agsy.2013.11.004.

Sinclair, T.R., Rufty, T.W., 2012. Nitrogen and water resources commonly limit crop yield increases, not necessarily plant genetics. Glob. Food Sec. 1, 94–98, http://dx.doi.org/10.1016/j.gfs.2012.07.001.

Sinclair, T.R., de Wit, C.T., 1975. Photosynthate and nitrogen requirements for seed production by various crops. Science 189, 565–567, http://dx.doi.org/10.1126/science.189.4202.565.

Singer, J.W., Kohler, K.A., 2005. Rye cover crop management affects grain yield in a soybean-corn rotation. Crop Manag., http://dx.doi.org/10.1094/CM-2005-0224-02-RS.

Singer, J.W., Cambardella, C.A., Moorman, T.B., 2008. Enhancing nutrient cycling by coupling cover crops with manure injection. Agron. J. 100, 1735–1739, http://dx.doi.org/10.2134/agronj2008.0013x.

Singer, J.W., 2008. Corn Belt assessment of cover crop management and preferences. Agron. J. 100, 1670–1672, http://dx.doi.org/10.2134/agronj2008.0151.

Strock, J.S., Porter, P.M., Russelle, M.P., 2004. Cover cropping to reduce nitrate loss through subsurface drainage. J. Environ. Qual. 1016, 1010–1016, http://dx.doi.org/10.2134/jeq2004.1010.

Teasdale, J.R., Mohler, C.L., 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron. J. 85, 673–680, http://dx.doi.org/10.2134/agronj1993.00021962008500030029x.

Thorburn, P.J., Probert, M.E., Robertson, F.A., 2001. Modelling decomposition of sugar cane surface residues with APSIM-residue. F. Crop. Res. 70, 223–232, http://dx.doi.org/10.1016/S0378-4290(01)00141-1.

Thorburn, P.J., Meier, E.A., Probert, M.E., 2005. Modelling nitrogen dynamics in sugarcane systems: recent advances and applications. F. Crop. Res. 92, 337–351, http://dx.doi.org/10.1016/j.fcr.2005.01.016.

Thornton, P., Thornton, M.M., Mayer, B.W., Wilhelmi, N., Wei, Y., Devarakonda, R., Cook, R., 2014. Daymet: Daily surface weather data on a 1-km grid for North America; Version 2. 10.3334/ORNLDAAC/1219.

Thorup-Kristensen, K., Magid, J., Jensen, L.S., 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv. Agron. 79, 227–300, http://dx.doi.org/10.1016/S0065-2113(02)79005-6.

Tollenaar, M., Mihajlovic, M., Vyn, T.J., 1993. Corn growth following cover crops: Influence of cereal cultivar, cereal removal, and nitrogen rate. Agron. J. 85, 251–255, http://dx.doi.org/10.2134/agronj1993.00021962008500020017x.

Unger, P.W., Vigil, M.F., 1998. Cover crop effects on soil water relationships. J. Soil Water Conserv. 53, 200–207.

Vigil, M.F., Kissel, D.E., 1991. Equations for estimating the amount of nitrogen mineralized from crop Residues. Soil Sci. Soc. Am. J. 55, 757, http://dx.doi.org/10.2136/sssaj1991.03615995005500030020x.

Wiles, L.J., Barlin, D.H., Schweizer, E.E., Duke, H.R., Whitt, D.E., 1996. A new soil sampler and elutriator for collecting and extracting weed seeds from soil. Weed Technol. 10, 35–41.

Zadoks, J.C., Chang, T.T., Konzak, C.F., 1974. A decimal code for the growth stages of cereals. Weed Res. 14, 415–421, http://dx.doi.org/10.1111/j.1365-3180.1974.tb01084.x.

Ziadi, N., Bélanger, G., Claessens, A., Lefebvre, L., Cambouris, A.N., Tremblay, N., Nolin, M.C., Parent, L.É., 2010. Determination of a critical nitrogen dilution curve for spring wheat. Agron. J. 102, 241–250, http://dx.doi.org/10.2134/agronj2009.0266.