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Wheat improves nitrogen use efficiency of maize and soybean-based cropping systems

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ABSTRACT

Integrated nitrogen (N) management strategies could make significant contributions to improving the efficiency of N use in the northern Corn Belt, particularly for maize, which has high N requirements. Using legume cover crops has been shown to increase both the soil's capacity to supply N and nitrogen use efficiency (NUE), through the reduction in the amount of N fertilizer that must be applied to the following crops. However, the impact of non-legume crops such as winter wheat (*Triticum aestivum* L.) on the diminishing return function between crop yield and N supply and its influence on N fertilizer use remains unclear. We hypothesized that maintaining wheat in short maize and soybean- based rotations is instrumental to improve cropping system performance and increase N fertilizer use efficiency while decreasing N requirements for maize. Seven maize and soybean rotations with different frequency of winter wheat with or without underseeded red clover (*Trifolium pratense L.*) were grown in two tillage systems (conventional and zone-tillage) and four long-term N regimes in Ridgetown, ON, Canada (2009–2013). Wheat in the rotation increased maize and soybean yields, negated crop yield lags due to zone-tillage, and decreased maximum economic rates of fertilizer N (MERN). The benefits of wheat in the rotation on maize yield were negated by high N rates; however, similar yields were obtained with lower N levels in rotationally grown maize, resulting in a 17% (conventional till) to 21% (zone-till) increase in partial factor productivity for N fertilizer at MERN (PFP_{MERN}). While N benefits to crops following wheat alone may be attributed to a higher indigenous plant available soil N, underseeding red clover further increased the agronomic efficiency (AE) of N fertilizer (AE_{MERN}) up to 32%. Maize yields were also less limited by N supply and less responsive to N fertilization when grown in rotation with wheat, especially in the zone-till system. These results highlight the value of wheat as a system component of dominant maize/soybean short rotations of Ontario and its potential to increase both maize and soybean productivity using less N input.

1. Introduction

Over the past several decades, crop diversity in the northern Corn Belt (Ontario and North Central US) has substantially declined and rotations consisting solely of maize and/or soybean increasingly dominate the landscape (Fig. 1). Increases in maize and soybean acreage has corresponded with reductions in acreages of grasslands, forages and other small cereal grains (Fig. 1) (Liebman et al., 2013; Nickerson et al., 2007; Wright and Wimberly, 2013).

Agronomic and environmental consequences of declining rotation diversity have been well documented. Loss of rotation diversity has been associated with reductions in soil organic matter, aggregate stability and soil quality (Dapaah and Vyn, 1998; Havlin et al., 1990; Katsvairo et al., 2002; McDaniel et al., 2014a,b; Munkholm et al., 2013; Raimbault and Vyn 1991; Van Eerd et al., 2014; Varvel, 1994), increased soil erosion (Langdale et al., 1991; Rachman et al., 2003; Tisdall and Oades, 1982), increased greenhouse gas emissions (Drury et al., 2008; Liebig et al., 2005; Meyer-Aurich et al., 2006a), decrease in yield potential and increased yield instability (Grover et al., 2009; Katsvairo and Cox, 2000; Lund et al., 1993; Meyer-Aurich et al., 2006a,b; Singer

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and Cox, 1998; Smith et al., 2008; Stanger and Lauer, 2008; Varvel, 2000; Yamoah et al., 1998a).

Many of the agronomic and environmental consequences associated with losses of crop rotation diversity also influence soil nitrogen (N) processes, N losses and crop response to N (Culman et al., 2013; Havlin et al., 1990; McDaniel et al., 2014a,b; Shipitalo et al., 2013; Stecker et al., 1995; Varvel and Peterson, 1990). For instance, there is considerable evidence that removal of legumes, such as alfalfa (*Medicago sativa* L.), red clover (*Trifolium pratense* L.) or soybean (*Glycine max* (L.) Merr.) from a maize (*Zea mays* L.) based rotation increase optimum N fertilization rates and have a significant impact on N dynamics (Bruulsema and Christie, 1987; Gentry et al., 2013; Henry et al., 2010; Hesterman et al., 1992; Liebman et al., 2012; Stecker et al., 1995; Stute and Posner, 1995; Wivstad, 1999). Furthermore, increasing N fertilization has also been shown to decrease rotational benefits of legumes on maize yields in various studies (Adams et al., 1970; Copeland and Crookston, 1992; Crookston et al., 1991; Nevens and Reheul, 2001; Peterson and Varvel, 1989; Porter et al., 1997; Riedell et al., 1998; Singer and Cox, 1998; Stecker et al., 1995). However, much less is known when non-legume species, such as winter wheat (*Triticum aestivum* L.), are removed from common maize-based rotations in the northern Corn Belt.

The potential effect of rotation diversity on crop response to N fertilization is of interest given escalating N fertilizer costs (USDA-NASS, 2014a) and continuing concerns about the negative impact of fertilizer N production and potential losses on environmental quality (Lebender et al., 2014; Peoples et al., 2004; Syswerda et al., 2012). Increasing N use efficiency (NUE) has also been a long-lasting research goal, particularly for maize, which is a major user of N. Although the amount of maize grain produced per unit of N applied (PFP_N) in the United States has increased linearly by 36% in the last 21 years (from 42 kg kg^{-1} in 1980 to 57 kg kg^{-1} in 2000), due to a combination of high yielding hybrids and improvement in crop management, the amount of N fertilizer recovered in aboveground plant biomass during the growing season (RE_N) remains relatively low (~37% across various rotations in the North-Central USA) (Cassman et al., 2002), and significant opportunities remain to improve N fertilizer use practices in maize. For instance, the impact of wheat in maize–soybean rotations on the diminishing return function between maize yield and N supply and NUE is not well understood.

We hypothesized that maintaining crop rotation diversity is instrumental to increase productivity, maize N fertilizer use efficiency and decrease crop N requirements. We used yield data (2009–2013) gathered at a long-term N regime and rotation trial to quantify benefits of maintaining wheat in short maize- and soybean-based rotations on: (1) cropping system's productivity, (2) crop N requirements, (3) NUE, and (4) whether the temporal niche provided by winter wheat for red clover or tillage system influences these responses.

2. Material and methods

2.1. Study site

Research was conducted from 2009 to 2013 on a field trial that was established at the University of Guelph Ridgetown Campus,

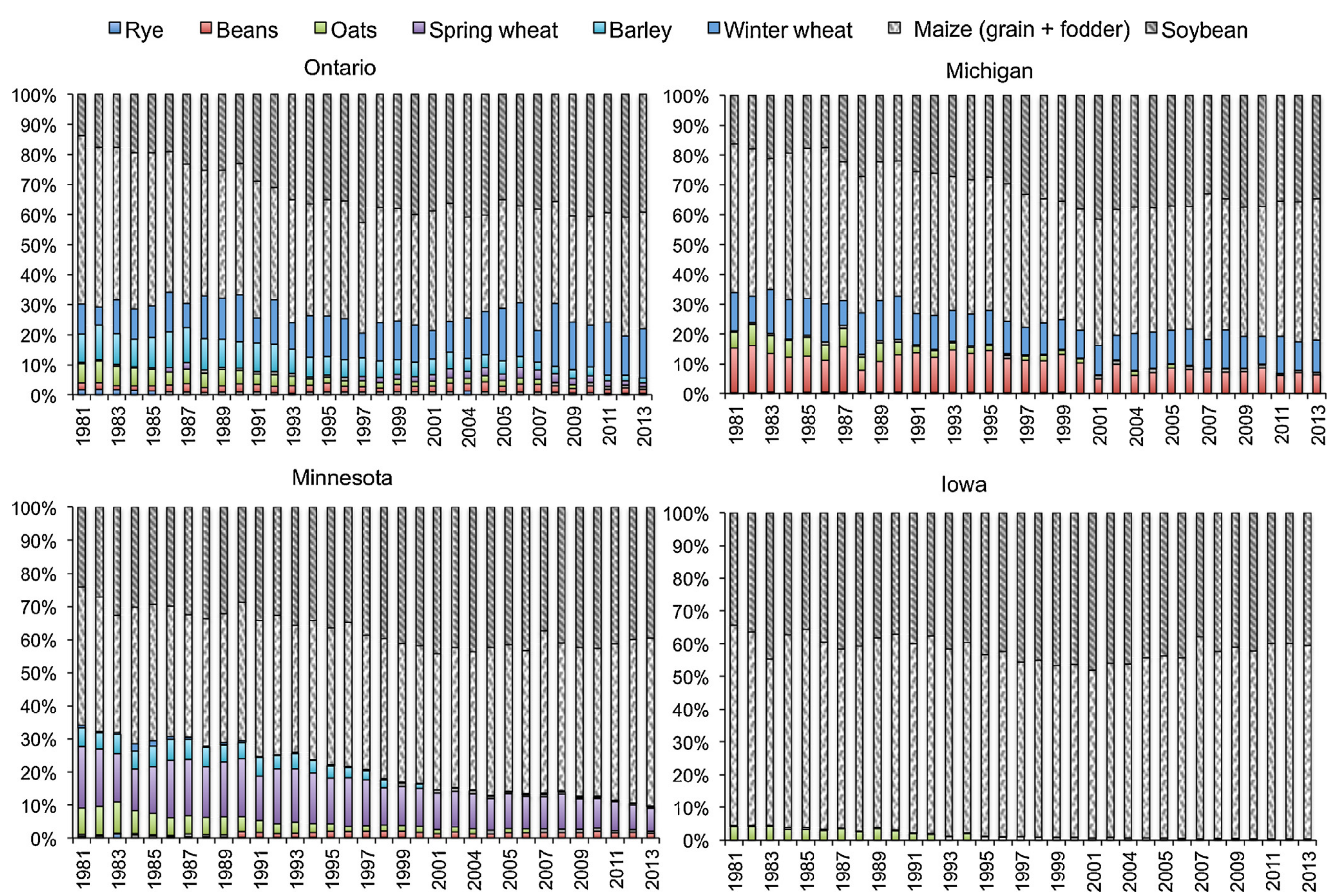

Fig. 1. Harvested areas of field crops grown in four states/provinces of the northern Corn Belt from 1981–2013. Harvested areas (hectares) of major field crops are shown as % of total harvested area from 1981 to 2013 for Ontario (OMAFRA, 2014), Michigan, Minnesota and Iowa (USDA-NASS, 2014b). Surface areas harvested in canola and hay were not included for clarity.

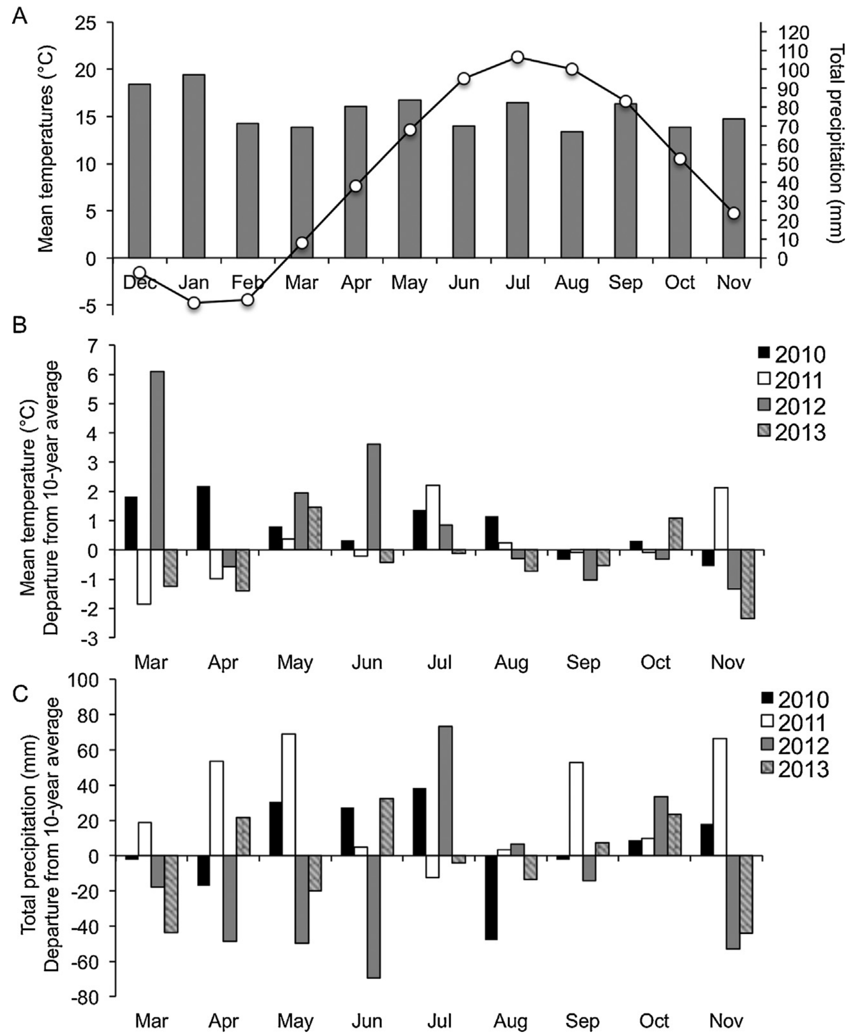

Fig. 2. Weather conditions at the experimental site. (A) Monthly 10-year average temperature (bars) and precipitation (line) pattern (2003–2013). Mean temperature (A) and total precipitation (B) deviation from 10-year average during crop growth (March–November) for each study year (2010–2013). Weather data was collected daily by Environment Canada at the site.

Ridgetown, ON (42°26′N, 81°53′W) in 1995. The soil was an Orthic Humic Gleysol clay loam with 1.6% to 2.3% organic carbon in the top 15 cm in 2009 (Van Eerd et al., 2014). Weather data were recorded on-site at ~200 m from the experiment; data included hourly air temperature at 1.25 m above the soil surface and daily rainfall. Average monthly temperature and precipitation for the last decade (2003–2013) are shown in Fig. 2A. Deviations from monthly long-term averages for both temperature and precipitation during the study are presented in Fig. 2B and C.

2.2. Experimental design and treatments

Since 1995, treatments were established annually on the same plots and were arranged as a split-split plot design with four replications. The treatments were tillage system on the main plot, crop rotation on the split-plot and N rates on the split-split-plot.

The main-plot treatment consisted of two tillage systems: conventional and zone-till for maize. For maize and soybean, conventional tillage consisted of moldboard plowing in the fall at a depth of 0.20 m, followed by two or three passes with a field cultivator in the spring at a depth between 0.07 to 0.08 m. Prior to 2012, the zone-till treatment for maize consisted of two planter-mounted coulters per row. In 2012, the zone-till maize treatment was modified by tilling zones in the fall using a Trans-Till (Row-tech, Snover, MI, USA) since very few local maize growers use no-till practices on similar fine-textured soils because of unfavorable seedbeds or delays in maize planting (Vyn and Hooker, 2002). Maize was then planted into these tilled zones in the spring with the same planter equipped with two coulters per row. In all years of the long-term trial for maize, the inter-row spaces where left undisturbed.

From 1995 to 2008, the split-plot consisted of five crop rotation regimes: continuous maize (MM), continuous soybean (SS), maize–soybean (MS), soybean–winter wheat (SW) and maize–soybean–winter wheat (MSW). In 2009, a red clover treatment was introduced by frost seeding into the wheat stand in March of every year in all wheat plots by splitting across the width. This resulted in two additional rotation treatments from 2009 to 2013: SW with the wheat underseeded to red clover (SWrc) and MSW with the wheat underseeded to red cover (MSWrc). Crop rotations with more than one crop were duplicated or triplicated so that all crops within each rotation were present in every year. Impact of the red clover split implemented in 2009 on crop yields could be first measured in 2011 for soybean (SW vs SWrc) and 2012 for maize

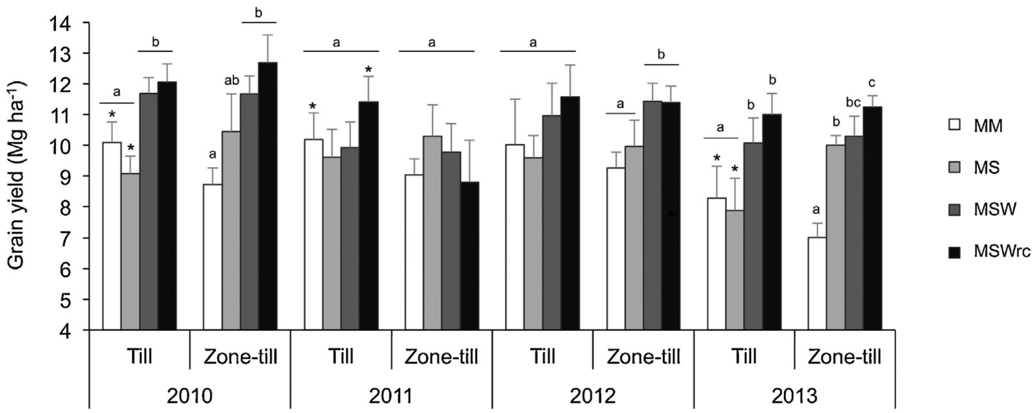

Fig. 3. Yearly variation in maize yields response to rotation and tillage. LS means ± SE across N treatment are shown. Letters indicate statistical differences among rotations within tillage treatment for each year and (*) indicate significant tillage effect for each rotation at $p = 0.05$. Crop abbreviation: S = soybean, M = maize, W = winter wheat, Wrc = winter wheat underseeded with red clover.

(MSW vs MSWrc). Since no significant effects of red clover history could be detected in 2010 or across study years (Fig. 3), yield data from 2010 and onward were used for all rotations.

The split-split-plot treatment consisted of four N rates in the maize and wheat. No N fertilizer was applied to soybean. Each maize and wheat split-plot (6.1-m wide × 24-m long) was divided along the length to represent the four N rate treatments, which were kept consistent across the whole duration of the rotation since the experiment was established in 1995. From 2009 to 2013, total N rates for maize were 12, 72, 132, and 192 kg N ha^{-1}, and 0, 50, 100, and 150 kg ha^{-1} for wheat. In maize, N treatments consisted of 12 kg N ha^{-1} applied as a starter fertilizer (150 kg ha^{-1}of 8-32-16) on all treatments, with the balance of N sidedress-applied as urea ammonium nitrate (28-0-0) at about the V3 developmental stage. The UAN was knifed-in or injected at 10 cm deep between crop rows. In winter wheat, 100 kg ha^{-1} of monoammonium phosphate (11-52-0 or MAP) was applied at planting, followed by urea (46-0-0) or ammonium nitrate (33-0-0) at Zadoks 21 up to the target N rate. All N rates used in the analysis include the total N applied in both the starter and in-crop applications and were not adjusted when red clover was included in the rotation. From 1995 to 2008, N rates ranged from 0 to 150 kg N ha^{-1} and 0 to 120 kg N ha^{-1} in maize and wheat respectively.

2.3. Crop management

The cultivars planted along with planting and harvesting dates are presented for each crop in Table A.1. From 2009 to 2013, maize was seeded at 84,000 seeds ha^{-1} in 0.76 m-wide rows with a 4-row no-till planter (John Deere 7000, Moline, IL). Soybean was seeded at 400,000 seeds ha^{-1} in 0.38 m-wide rows with an eight-row-unit no-till planter (Kearney Planters Inc., Thamesville, ON). Wheat was seeded at 400,0000 seeds ha^{-1} and single-cut red clover was frost-seeded at 10 kg ha^{-1} in early March. The same maize, soybean, and wheat cultivars were never planted for more than two successive years throughout the study (Table A.1), and they were chosen according to their popularity among local growers. Weeds were controlled in maize and soybean with both pre- and post-emergent herbicides. In wheat, post-emergent herbicides were applied when needed. Plots were maintained so that pests and weed pressure did not differ between treatments and that productivity was not adversely affected by those factors.

The middle two rows of each four-row-plot were harvested for yield determinations in maize, and a 1.5-m wide swath was harvested from the middle rows of each soybean and wheat plot. In all years of the experiment, crop residues were returned to the plot area after the grain was harvested. Grain yields, grain moistures, and test weights were measured on plot combines equipped with HarvestMaster GrainGage Classic grain measurement systems (Juniper Systems, Inc., Logan, UT). Red clover plant population densities were estimated visually in September between 2009 and 2013.

2.4. Crop response to nitrogen

Regression analyses were performed using treatment means across years to estimate maize and winter wheat grain yields at increasing N rates from 2010 to 2013. Grain yields were not estimated beyond 192 kg N ha^{-1} in maize and 150 kg N ha^{-1} in wheat.

The impact of N fertilization on crop-specific rotational benefits to maize yields was measured by fitting regression models to the estimated delta (Δ) yield between two treatments (Table 2). Nmax was calculated from regression equations, and was defined as the N rate at which grain yields ($Nmax_Y$) or rotational effects ($Nmax_r$) was maximized for each treatment.

Table 2
Effects of N fertilization on crop-specific rotational benefits to maize yields.

Rotation benefits	Δ yield	$Nmax_r$ (kg N ha^{-1})		Y_r at $Nmax_r$ (kg ha^{-1})		Regression models (capped at 0 and 192 kg N ha^{-1})	
		Till	Zone till	Till	Zone till	Till	Zone till
Soybean (S)	MS–MM	71	90	−426	2416	$Y_b = -702 + 7.77N - 0.0548N^2$	$Y_b = 1227 + 28.63N - 0.1591N^2$
Wheat (W)	MSW–MS	40	0	2038	2176	$Y_b = 1976 + 3.04N - 0.0377N^2$	$Y_b = 2175 - 23.32N + 0.0557N^2$
Red clover (RC)	MSWrc–MSW	47	8	1653	429	$Y_b = 1262 + 16.77N - 0.1804N^2$	$Y_b = 427 + 0.41N - 0.0269N^2$
S + W	MSW–MM	58	26	1591	3371	$Y_b = 1274 + 10.81N - 0.0926N^2$	$Y_b = 3303 + 5.31N - 0.1033N^2$
W + RC	MSWrc–MS	45	0	3689	2603	$Y_b = 3239 + 19.81N - 0.2182N^2$	$Y_b = 2603 - 22.91N + 0.0289N^2$
S + W + RC	MSWrc–MM	50	22	3234	3793	$Y_b = 2537 + 27.58N - 0.2730N^2$	$Y_b = 3730 + 5.72N - 0.1302N^2$

Nitrogen rates maximizing rotation effect ($Nmax_r$) were calculated based on the regression models. Corresponding regression curves are shown in Fig. A.3. Abbreviations: Y_r = yield gain from rotation crops; S = soybean, M = maize, W = winter wheat, Wrc = winter wheat underseeded with red clover.

The maximum economic rate of nitrogen (MERN, kg N ha^{-1}) was defined as the N rate that produced maximum return to N investments and maximum economic yield (MEY, kg grain yield ha^{-1}). MERN was calculated from quadratic regression equations describing the maize yield responses to fertilizer N (Gaudin et al., 2014; Rajsic and Weersink, 2008; Vyn et al., 2000):

$$\mathrm{MERN} = \frac{[b - (F/P)]}{2c} \quad (1)$$

where b and c are linear and quadratic coefficients from the yield response equations (yield = $a + b\mathrm{N} + c\mathrm{N}^2$), F is the cost of fertilizer N (CAN\$ kg^{-1}) and P is the price of maize (CAN\$ kg^{-1}). The average farm value of maize and cost of urea fertilizer in Ontario from 08/2009 to 08/2013 were used (CAN\$0.22 kg^{-1} of maize at farm value and CAN\$1.54 kg^{-1} of N as urea, OMAFRA, 2014).

Partial factor productivity for N fertilizer at economic optimums (PFP_{MERN}, Cassman et al., 2002) represents yields obtained per unit of N applied at MERN for each rotation and tillage treatments (PFP_{MERN} = MEY/MERN). Agronomic efficiencies of N fertilizer at MERN (AE_{MERN}, Cassman et al., 2003) account for differential plant available soil N of the different treatments in NUE calculation:

$$AE_{MERN}\left(\mathrm{kg\ kgN}^{-1}\right) = \left(\frac{(\mathrm{MEY} - Y_{N=0})}{\mathrm{MERN}}\right) \quad (2)$$

where $Y_{N=0}$ is the yield intercept (a) of the N response curves. Incremental agronomic efficiencies of N fertilizer (AE_i, Cassman et al., 2003) estimate yield gains obtained per unit of incremental N rate:

$$AE_i(\mathrm{kg\ kgN}^{-1}) = \frac{dY}{df} = \frac{(\mathrm{Yield}_N - \mathrm{Yield}_{N-1})}{(\mathrm{Nrate}_N - \mathrm{Nrate}_{N-1})} \quad (3)$$

2.5. Statistical methods

Statistical analyses were performed using SAS statistical software (Statistical Analysis System, version 9.3, SAS institute, NC, USA). Residuals were found homogeneous, normal-distributed using the Shapiro–Wilk W test ($P = 0.98$) and no significant outliers were detected by Lund's test. Mixed models were used for analysis of variance, with crop rotation, tillage system and N as fixed effects, and year and replication as random effects. PROC NLIN with Marquardt iterative method was used to fit crop yield response to N rate to quadratic plateau models. Models were constrained such that the linear regression coefficient was greater than or equal to 0, and the quadratic coefficient was less or equal to 0 (Gaudin et al., 2014). Comparison of predicted values from regression curves were based on a t-test using standard errors obtained from the Mixed model. Type I error rate was set at 0.05 for all tests.

3. Results

3.1. Winter wheat in rotation increases maize and soybean yields

Inclusion of winter wheat in the crop rotation increased maize and soybean yields, but the magnitude of impact depended on the tillage system in both crops (Table 1). Crop rotation with winter wheat increased soybean yields by 0.61 and 0.32 Mg ha^{-1} in tilled and zone-tilled systems, respectively ($P < 0.05$; Fig. 4). Inclusion of wheat also eliminated the 6% soybean yield lag in the tilled treatments compared to zone-till observed in the SS and MS rotations (Fig. 4).

Compared to soybean, the maize yield response to crop rotation and tillage system was dependent on the year ($P < 0.001$; Table 1) and variations in monthly precipitation and temperature among growing seasons (Fig. 2). Abnormally wet and cool spring conditions in 2011 (Fig. 2) delayed planting, which probably was the main reason for lower maize yields and the lack of crop rotation effects in both tillage treatments compared to other years (Fig. 3). In 2012, abnormally dry conditions and above normal temperatures during vegetative growth (Fig. 1) appeared to negate crop rotation effects in the tilled systems (Fig. 3). However, in the zone-till system, the inclusion of winter wheat increased maize yields by 18.8% in the dry year (Fig. 3). In the two other years of the study (2010 and 2013),

Table 1
Long term rotation, tillage and nitrogen effects on maize, soybean and wheat yields grown from 2010 to 2013.

	Maize yield			Soybean yield			Wheat yield		
	df	Pr (>F)		df	Pr (>F)		df	Pr (>F)	
Year	3	<0.001	**	2	< 0.001	**	1	0.021	*
Tillage	1	0.801		1	0.713		1	0.286	
Rotation	3	<0.001	**	5	<0.001	**	3	0.090	
Nitrogen[a]	3	<0.001	**	3	0.477		3	<0.001	**
Year × Tillage	3	0.044	*	2	0.079		1	0.773	
Year × Rotation	9	<0.001	**	10	0.004	*	3	<0.001	**
Year × Nitrogen	9	<0.001	**	6	0.068		3	<0.001	**
Tillage × Rotation	3	0.016	*	5	0.008	*	3	0.731	
Rotation × Nitrogen	9	<0.001	**	15	0.387		9	0.555	
Nitrogen × Tillage	3	<0.001	**	3	0.345		3	0.071	
Year × Tillage × Rotation	9	0.105		10	0.539		3	0.184	
Year × Rotation × Nitrogen	27	0.301		30	0.614		9	0.324	
Year × Nitrogen × Tillage	9	0.119		6	0.499		3	0.278	
Tillage × Nitrogen × Rotation	9	0.535		15	0.338		9	0.594	
Maize: 0 kg N ha^{-1}	7	<0.001	**	N/A		N/A			
72 kg N ha^{-1}	7	<0.001	**	N/A		N/A			
132 kg N ha^{-1}	7	<0.001	**	N/A		N/A			
192 kg N ha^{-1}	7	0.089		N/A		N/A			
Wheat: 0 kg N ha^{-1}	N/A		N/A		7	0.830			
50 kg N ha^{-1}	N/A		N/A		7	0.112			
100 kg N ha^{-1}	N/A		N/A		7	0.582			
150 kg N ha^{-1}	N/A		N/A		7	0.124			
Year × Tillage × Rotation × Nitrogen	27	0.528		30	0.522		9	0.209	

N/A: non applicable.
[a] Nitrogen rates directly applied to maize and wheat or as part of the rotation history for soybean.
* Significant at 0.05 probability level.
** Significant at <0.001 probability level.

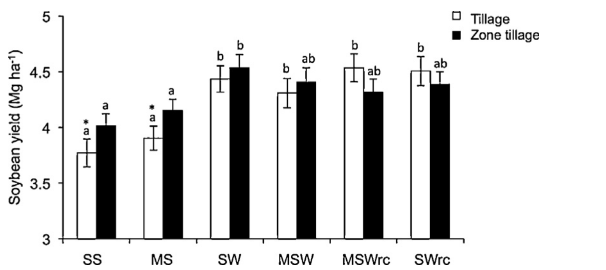

Fig. 4. Soybean yields response to rotation and tillage. LS means (2010–2013) ± SE across N treatments are shown. Letters indicate statistical differences among rotations within tillage treatment and (*) indicate significant tillage effect for each rotation at $p = 0.05$. Crop abbreviation: S = soybean, M = maize, W = winter wheat, Wrc = winter wheat underseeded with red clover.

maize yielded the lowest in the MM and MS crop rotations in the tilled system (Fig. 3). Despite different year environments, maize response to treatment did not interact with year (Table 1, Fig. 3). On average, winter wheat improved maize performance by 16.6% and 18.8% in the zone-till and till systems, respectively, and negated yield reductions due to MM in the zone-till system (Fig. 3). Our results show no significant rotation and tillage effects on wheat yields, which remained stable across both treatments (Table 1).

3.2. Wheat rotation benefits are N dependent

Maize yields were highly responsive to N fertilizer across crop rotation, but N response interacted with crop rotation (Table 1, Fig. 5A and B). In both tillage systems, grain maize yield differences across rotations were the greatest at low to mid-N rates, and increasing the N rate to 192 kg N ha^{-1} resulted in similar yields across all crop rotations. (Fig. 5A and B). Including wheat in the MS rotation increased maize yields at the lowest N rate, while maize yields were similar at the two highest rates in both tillage systems (MS vs MSW, Fig. 5A and B). Similarly, maize yields were higher in the MSW rotation than MM only at the two lowest rates in both tillage systems (Fig. 5A and B). No statistically significant maize yield gains were obtained from winter wheat with red clover (MSWrc vs MS) at N rates above or equal to 72 kg total N ha^{-1} in zone-till (Fig. 5B).

Increasing N rates did not alter rotation responses to tillage (Table 1); however, tillage practice altered the magnitude of the crop rotation effects obtained at various N rates (Fig. 5A and B). Except for yield benefits obtained from the inclusion of red clover into rotation, higher or similar crop rotation benefits were found at lower maximum N rates in zone-till compared to tilled systems (Table 2). Crop rotation benefits attributed to soybean (MS vs MM) were only significant in zone-tilled systems (Fig. 5, Table 2) and were maximized at 90 kg N ha^{-1} (+2416 kg ha^{-1}, Table 2). Similarly, maximum crop rotation benefits obtained from the inclusion of soybean and wheat (MSW vs MM) were 2.1-fold higher (+1780 kg ha^{-1}) at $Nmax_r$ rates which were 56% lower in zone-till compared to tilled systems (Table 2).

The highest yield gains (+2037 kg ha^{-1}) at the lowest $Nmax_r$ (40 kg N ha^{-1}) were found when wheat was included into rotations of the tilled systems. The effect of wheat on the crop was further enhanced when red clover was underseeded into the wheat (Table 2). However, benefits from wheat, with or without red

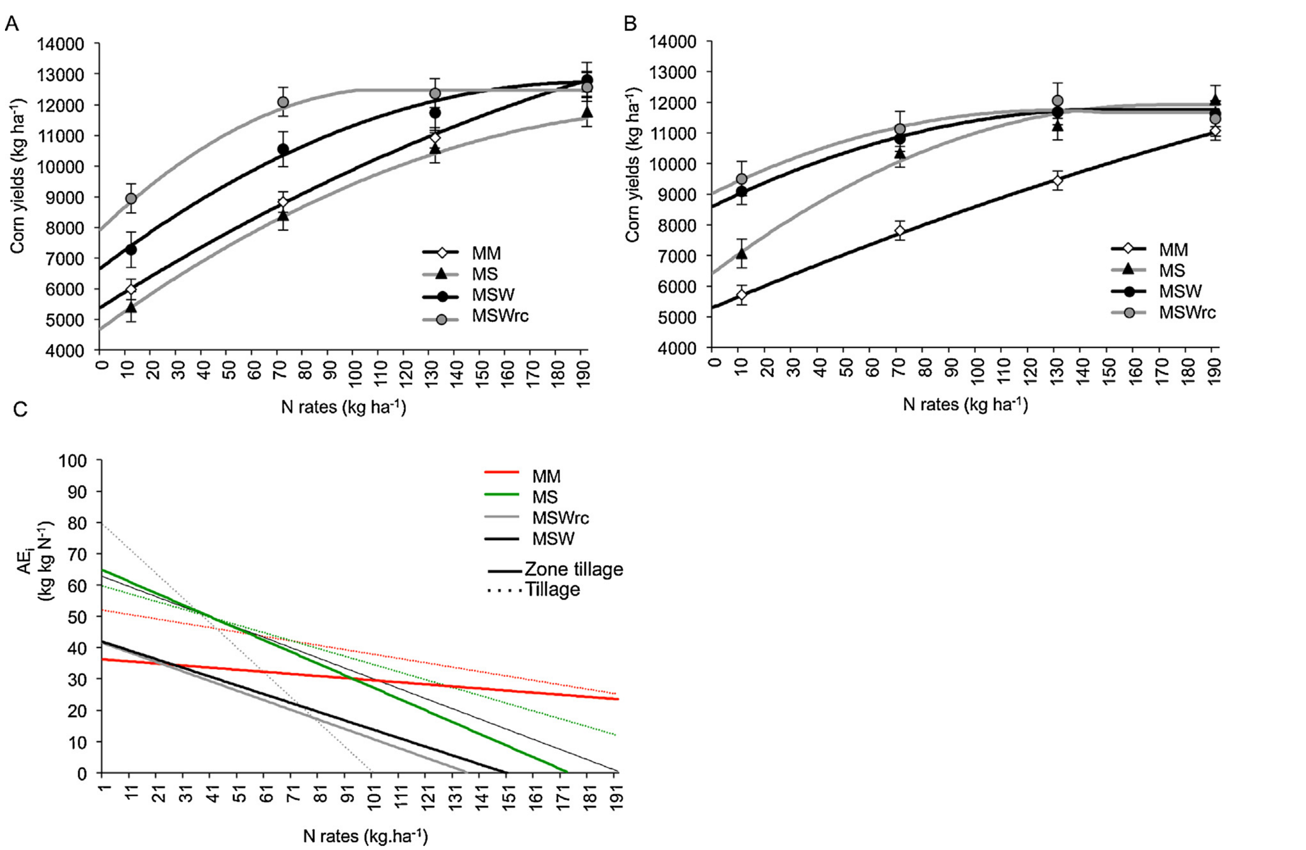

Fig. 5. Impact of crop rotation and tillage on maize yields response to N fertilization. Regression analysis of the effects of N rate treatments on maize yields under (A) conventional tillage and (B) zone tillage systems. Maize yield response to N rates (2010–2013) was fitted using quadratic plateau models capped at 192 kg N ha^{-1}. Nitrogen rates maximizing yields for each rotation and tillage treatments are presented in Table 3. Markers show treatment LS means used for regression analysis ± SE. (C) Agronomic efficiency of N fertilization (AE_i). Agronomic efficiencies are estimated yield gain per unit of increasing N fertilization based on N response equations (A and B). Crop abbreviation: S = soybean, M = maize, W = winter wheat, Wrc = winter wheat underseeded with red clover.

Table 3
Effect of crop rotation on maize N use and economic optimums.

	$Nmax_Y$ (kg N ha^{-1})		Y_{Nmax} (kg ha^{-1})		MERN (kg N ha^{-1})		MEY (kg ha^{-1})		PFP_{MERN} (kg grain kg N^{-1})		$Y_{N=0}$ (kg ha^{-1})		AE_{MERN} (kg grain kg N^{-1})	
Rotation	Till	Zone till	Till	Zone till	Till	Zone till	Till	Zone till	Till	Zone till	Till	Zone till	Till	Zone till
MM	192a	192	12730*	11039	192a	192a	12730*	11039	66	57	5386a	5299a	38	30
MS	192a	174	11786	11920	192a	154a	11786	11853	61	77	4684a	6427b	37	35
MSW	192a	150	12710	11660	176ab	124ab	12638	11570	72	93	6661b	8603c	34	24
MSWrc	101b	136	12465	11749	93b	112b	12437	11666	133	104	7924c	9030c	48	23

The effects of crop rotation on maize nitrogen use and economic optimums were calculated based on the regression models shown in Fig. 3 and not extrapolated beyond 192 kg N ha^{-1}. Estimates within each variable followed by similar letter or no letters were not significantly different at $p = 0.05$.
* Indicates significant tillage effect at $p = 0.05$. Abbreviations: $Nmax_Y$ = Nitrogen rates at maximum grain yield; Y_{Nmax} = grain yields at $Nmax_Y$; MERN = maximum economic rate of nitrogen; MEY = maximum economic yield (estimated grain yield at MERN), PFP_{MERN} = partial factor productivity for N fertilizer at MERN (MEY/MERN); $Y_{N=0}$ = Yield at $N = 0$, AE_{MERN} = agronomic efficiency of N fertilizer at MERN (($MEY - Y_{N=0}$)/MERN); M = maize; S = soybean; W = winter wheat; Wrc = winter wheat underseeded with red clover.

clover, decreased sharply with increasing N rates in zone-till systems (Fig. 5B).

3.3. Wheat decreases maize N requirement and improves NUE

The rate of N that maximized grain maize yields ($Nmax_y$) and economic returns of N fertilization (MERN) tended to decrease with wheat in the crop rotations, especially in the zone-till system (Table 3). Crop rotations including wheat and red clover also reached $Nmax_y$ and MERN values below 192 kg N ha^{-1} in both tillage systems (Table 3). Such reductions of maize N requirements are likely underestimates because regression models were not extrapolated beyond 192 kg N ha^{-1}, and maximum yields were often estimated at higher N rates (Fig. 5A and B). However, grain yields at optimum N rates (Y_{Nmax}) were maintained, resulting in 17% (till) to 21% (zone-till) increase in PFP_{MERN} associated with inclusion of wheat into rotations (Table 3, MSW vs MS). The inclusion of wheat underseeded with red clover into tilled MS rotations significantly lowered N rates required to maximize maize yields and economic returns from N fertilizer ($P < 0.05$) and significantly increased PFP_{MERN} (Table 3). Estimated grain maize yields obtained at zero-N (intercept, $Y_{N=0}$) are function of the plant available soil N from net mineralization. Grain yields were significantly higher when wheat, with or without red clover, was included into rotations in both tillage systems (Table 3). The AE_{MERN} included differential plant available soil N into NUE calculations and corrected for the bias caused by the linear inverse correlation between MERN and $Y_{N=0}$ ($R^2 = 0.81$, $P = 0.032$). The AE_{MERN} shows that the effects of wheat alone were likely attributed to an increase in plant available soil N, rather than an increase in efficiency of N fertilizer in both tillage systems. However, by providing a niche for red clover into the crop rotation, wheat significantly increased yield obtained per unit of N applied at MERN by 14 kg, on average, in tilled systems (AE_{MERN} MSW vs MSWrc Table 3). Incremental N fertilization had the largest impact on maize yields in rotations with wheat and red clover in the tilled system, especially at low N rates (AE_i, Fig. 5C). Maize yields were less responsive to N fertilization when grown in rotation with wheat in the zone-till system (Fig. 5C). The AE_i showed that wheat decreases fertilizer N requirements in maize: AE_i decreased sharply with increasing N rates when wheat was in rotation, while yields of simple rotations were constrained by the maximum N rate applied, especially in tilled systems (Fig. 5C, Table 3). Wheat yield responses to increasing N rate were not different across rotation and tillage treatments (Table 1, Fig. 6). Soybean yields were not responsive to the long-term N regimes applied in previous years to maize and/or wheat in the rotation (Table 1).

4. Discussion

The objective of this study was to quantify the long-term N benefits of maintaining wheat in maize and soybean rotations under different tillage practices. Seven maize and soybean-based rotations were grown under two tillage systems and four long-term N regimes in Ridgetown (ON, Canada). We show 4 years of crop performance data (2010–2013) in systems established in 1995 and at, or close-to, steady state across tillage, crop rotation, and N treatments. Steady state conditions of soil organic matter are achieved in 15–20 years of continuous practice (West and Post, 2002; Alvarez, 2005) and a meta-analysis of various long-term sites in Ontario has shown that treatments established for less than 10 years provide valuable insight into the long-term impact of crop production practices on soil properties (Congreves et al., 2014). Our results demonstrate that the value of wheat in a crop rotation with maize and soybean is much more than its market price: maintaining rotation diversity in the northern Corn Belt is

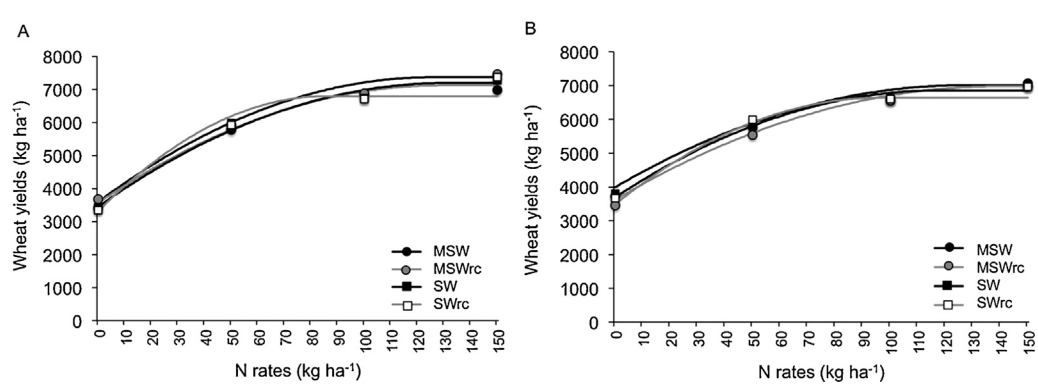

Fig. 6. Impact of crop rotation and tillage on wheat yields response to N fertilization. (A and B) Regression analysis of the effects of N rate treatments on wheat yields (2010–2013) under (A) conventional tillage and (B) zone tillage systems. Wheat yield response to N rates was fitted using quadratic plateau models capped at 150 kg N ha^{-1}. Markers show treatment LS means used for regression analysis ± SE. Crop abbreviation: S = soybean, M = maize, W = winter wheat, Wrc = winter wheat underseeded with red clover.

instrumental to increase soybean productivity and maize yields using less N input. We found that wheat: (1) produced higher maize and soybean yields in both tillage systems (Figs. 3 and 4); (2) acted synergistically with conservation tillage practices to reduce the crop yield lag due to long-term zone-tillage (Figs. 3 and 4) and (3) decreased fertilizer N requirements for maximum maize yield (Fig. 5, Table 3).

4.1. Wheat contribution to maize N use efficiency

4.1.1. Increase in plant available soil N

Wheat decreased optimal N fertilizer rates and PFP_{MERN} both directly and by providing a temporal niche for underseeding red clover (Table 3).

In our study, wheat N benefits could be attributed to a higher plant available soil N rather than an increase in efficiency of N fertilizer used (Table 3). Mineralization of wheat root biomass and stubble likely provided the N credit from 16 kg ha^{-1} in the tilled system to 30 kg ha^{-1} in the zone-till system based on MERN (MS vs MSW, Table 3). Including red clover likely increased plant available soil N further (12 kg ha^{-1} in zone-till, 83 kg ha^{-1} in tilled system), and decreased maize N requirements (Table 3). We found similar results using a compilation of maize N responses over a range of soil type and F/P ratios for the past 40 years in Ontario (Gaudin et al., 2013). It was estimated that MERN decreased by 41–64 kg N ha^{-1} when maize was preceded by red clover, with up to 7.11% positive rotational benefits of red clover on maize yields in conventional tillage systems (Gaudin et al., 2013).

Large differences in N credit obtained across the tillage treatments (Table 3) may be due to differential rates and timings of N release from above and below-ground residues (Dou et al., 1995; Groffman et al., 1987; Sarrantonio and Scott, 1988). Soil nitrate levels have been reported to be higher in conventional tillage compared to zone-till throughout the growing season and incorporation of clover residue may lead to higher N release in tilled compared to zone-till systems (Dou et al., 1995; Drinkwater et al., 1998; Varco et al., 1989; Wilson and Hargrove, 1986). Moreover, other studies have shown red clover to enhance wheat straw decomposition in zone-till systems, which might have alleviated some of the negative effects of wheat residues and zone-tillage on maize emergence and yield (Drury et al., 2003, 1999; Kravchenko and Thelen, 2009). However, to extract the benefits of wheat/red clover on system NUE, the release of N from above and below-ground residues must be synchronous with maize N uptake.

4.1.2. Increase in N fertilizer use efficiency

Along with higher indigenous plant available soil N, red clover increased the efficiency of maize N fertilizer use (AE_{MERN} = +14 kg grain kg N^{-1} applied, Table 3). This may be partially explained by maize preferably recovering N from fertilizer instead of legume residue decomposition, as shown in several studies evaluating N transfer from red clover to maize using N^{15} isotopes (Gardner and Drinkwater, 2009; Harris et al., 1994).

Direct and indirect benefits of wheat on soil properties at this trial (Van Eerd et al., 2014) may also improve recovery of N fertilizer. More diverse rotations and improvement of soil structure, aggregation and health help foster root growth (Goldstein, 2000; Nickel et al., 1995; Tisdall and Oades, 1979), which in turn may improve fertilizer N uptake (Durieux et al., 1994; Eghball and Maranville, 1993). Longer periods without tillage and abundant living plant roots in diverse rotations can also host mycorrhizea over a greater duration of time within the crop rotation (Brito et al., 2012; Curaqueo et al., 2010; Deguchi et al., 2007; Lehman et al., 2012). This may enhance the services they provide such as increase N uptake (George et al., 1995), especially in water-stress environments (Tobar et al., 1994).

As a result of both increase in indigenous soil N and higher use of N fertilizer, maize yields were less limited by N supply and less responsive to N fertilization when grown in rotation with wheat, especially in the zone-till system (Fig. 5B). Restrictions of N application due to regulation or weather constraints would have a smaller impact on maize yields when grown in zone-till rotations with wheat compared to MS or MM rotations. In the event of higher N fertilizer prices relative to grain maize (i.e., higher F/P ratio), $NMax_y$ would also be significantly reduced but MEY would likely remain comparable in crop rotations with wheat. Wheat may therefore help mitigate the effects of lower N supply and high market volatility of N fertilizer and grain.

4.2. Positive feedback of lower N requirements

We observed higher benefits of wheat and greater differences in maize yields across rotations at low to mid-N rates (Table 2). Various researchers have reported lower beneficial effect of crop rotation on maize yield with increasing N fertilization, especially when legumes were included (Adams et al., 1970; Copeland and Crookston, 1992; Crookston et al., 1991; Nevens and Reheul, 2001; Peterson and Varvel, 1989; Porter et al., 1997; Riedell et al., 1998; Singer and Cox, 1998; Stecker et al., 1995). In our study, red clover plant population densities significantly decreased with increasing wheat N rates (from 165 plants m^{-2} at zero-N to 18 plants m^{-2} at 150 kg N ha^{-1} across tillage systems and years, data not shown). Lower rates of N fertilizer in wheat have been shown to increase red clover biomass and stand count and decrease clover patchiness (Gaudin et al., 2014). As a result, lower N rates maximize economic returns from wheat-red clover intercropping with higher partial profits (Gaudin et al., 2014). Yet wheat rotation benefits on maize yield were masked by high N rates (Fig. 5A and B), implying that higher N applications could offset the negative impact of monoculture or short rotation. However, we show that similar yields can be obtained with lower N levels in rotationally grown maize and that soybean yields, which were not responsive to increasing N rates, significantly benefited from any rotation with wheat (Figs. 4 and 5). If N requirements are lower when crops are grown in rotation, the potential risk of nitrate losses through leaching or denitrification may also be reduced (Varvel and Peterson, 1990; Yamoah et al., 1998b). These results highlight the value of wheat as a system component and its potential to increase both maize and soybean productivity using less N input. It also suggests that fertilizer N levels should be taken into account when comparing crop rotation benefits across studies and environments.

4.3. Additional value of wheat on soybean yields

Our study also supports the hypothesis that crop productivity is increased with crop rotation diversity. The inclusion of wheat in a MS or SS rotations significantly increased soybean yields by an average of 0.47 Mg ha^{-1} across tillage systems (Fig. 4). Higher soybean yields may be attributed to the benefits of small grain cereal on soil structure. Soil quality parameter such as aggregate stability, penetrometer resistance and other parameters used for the Cornell Soil Health Assessment, were found higher with a higher frequency of winter wheat in the rotation at this trial (Van Eerd et al., 2014). Lowest soybean yields were produced with continuous soybean in the tilled system (Fig. 4), which corresponded with the treatment with the lowest soil quality (Van Eerd et al., 2014). Others have reported higher soybean yields in systems that retain soil moisture (Pedersen and Lauer, 2004), which may have occurred with wheat in this study because of improved soil structure. Wheat might also help break pest cycles and decrease the incidence of soil-borne pathogens and soybean cyst nematodes, which can negatively impact on soybean yields (Zhang et al., 2012).

4.4. Conclusions and significance for northern Corn Belt cropping systems

Crop diversity regulates various bioprocesses such as residue decomposition and microbial dynamics with large effects on nutrient cycling (McDaniel et al., 2014a,b). Given the large production areas of maize and soybean in the northern Corn Belt (Fig. 1), diversifying continuous or short maize and soybean rotations with wheat has potential to increase NUE of agricultural systems and alleviate N environmental footprint at a large scale. However, more research and economic analysis is needed to quantify opportunity costs, wheat winter survival in other states of the Corn Belt and confirm potential at the Corn Belt scale. Nonetheless, wheat provides a valuable temporal niche to include late-season legumes, such as red clover, into northern cropping systems and obtain numerous non-N benefits (Gaudin et al., 2013). For instance, it has been shown recently that forages, wheat and other small grain cereals help mitigate weather variations and improve maize and soybean yield stability in Ontario, especially when hot and dry conditions occur (Gaudin et al., 2015). This is highly significant to maintain yields as springs may become wetter, summers drier and hotter, with greater frequencies of abnormally low precipitation or high temperature extremes (Hatfield et al., 2013; IPCC, 2013). Finally, advances in crop breeding will be realized more efficiently when higher crop yields are produced in diverse crop rotations, especially in the general context of decreased N inputs and higher environmental stresses.

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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.agee.2015.04.034.

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