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Biomass production of 12 winter cereal cover crop cultivars and their effect on subsequent no-till corn yield

T.C. Kaspar and M.G. Bakker

Abstract: Cover crops can improve the sustainability and resilience of corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) production systems. At present, the most widely used cover crops in corn–soybean systems in the upper Midwest United States have been winter cereals. However, there have been isolated reports of corn yield reductions following winter rye (*Secale cereale* L.) cover crops, and the risk of corn yield reductions will reduce the likelihood of farmers adopting cover crops. Although the exact mechanism is unknown and there are many possible causes of corn yield reductions following winter cereal cover crops, we hypothesize that there may be differences among winter cereal species or cultivars in their effect on corn yield. Additionally, there have been no evaluations of shoot growth and nitrogen (N) uptake of winter cereal cultivars used as cover crops in the upper Midwest. Seven winter rye cultivars, 2 winter triticale (× *Triticosecale* Wittmack) cultivars, and 3 winter wheat (*Triticum aestivum* L.) cultivars were planted following soybean harvest and grown as a winter cover crops preceding corn in four years to determine whether the 12 cultivars differed in (1) biomass production and N uptake, and (2) impact on corn yield, harvest population, and other yield parameters. The 12 cover crop cultivars differed in each of the four years for shoot dry weight, shoot N concentration, and total shoot N content. In general, the winter rye cultivars had greater shoot biomass, lower shoot N concentrations, and higher total shoot N contents than the winter triticale and winter wheat cultivars. The winter cereal cultivars decreased corn yield in two of the four years, and the yield effect varied among cultivars. Some cultivars of all three species caused corn yield decreases, with no indication that winter rye had a greater effect than did winter wheat or winter triticale. Four winter rye cultivars did not significantly reduce corn yield in either of the two years in which yield was reduced. In general, the decreases in corn yield following the winter cereal cover crops were related to decreases in harvest population and increases in the number of barren plants, but were not strongly related to cover crop shoot dry weight within years. Our study shows that there are genotypic differences among winter cereal cultivars for their performance as cover crops and their effect on corn yields.

Key words: corn—cover crops—population—rye—triticale—wheat

Cover crops are known to provide many environmental and crop production benefits and can improve the sustainability and resilience of corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) production systems in the upper Midwest United States (Kaspar and Singer 2011). The principal idea behind winter cover crops in these cropping systems is to insert a living plant into the five to seven month fallow period between harvest and planting of corn and soybean. In general, it is easier to integrate cover crops into corn–soybean rotations that use no-till or strip till rather than full width tillage because there is more time for cover crop management and growth (Kladivko et al. 2014). Additionally, incorporating cover crop residues into the soil with tillage eliminates most of the erosion prevention benefits of cover crops. In contrast, cover crops in no-till corn–soybean rotations can reduce erosion by over 50% (Kaspar et al. 2001). In no-till corn–soybean rotations with artificial drainage systems, winter cover crops can substantially reduce nitrate (NO_3^-) concentrations and load in drainage water (Kladivko et al. 2004; Kaspar et al. 2007, 2012), which can improve surface water quality. Kladivko et al. (2014) projected that with changes to no-till or late spring tillage practices, cover crops could potentially be grown on nearly 7.7 million ha (19 million ac) of artificially drained land in the upper Midwest with corn or soybean crops and estimated a 19% reduction in the amount of nitrogen (N) transported to the Gulf of Mexico. Additionally, cover crops can improve soil quality by increasing soil organic matter, improving soil aggregation, reducing bulk density, and increasing infiltration, rooting depth, N storage, and N availability (Benoit et al. 1962; Hansen et al. 2000; Williams and Weil 2004; Kaspar and Singer 2011; Moore et al. 2014). Thus, cover crops have the potential to prevent off-farm environmental degradation, while improving soil quality.

In much of the upper Midwest, which is dominated by the corn–soybean rotation, the potential winter cover crop growing season is limited by cold temperatures and short days. For cover crops to provide both environmental and soil quality benefits, they must be able to grow enough during this time to provide measureable impacts. Although it is difficult to determine exactly how much growth is needed, more growth usually provides more benefits. Cover crops that grow in the fall, overwinter, and grow again in the spring have more potential for growth than cover crops that only grow in the fall before being winter-killed. In general, winter cereal grains, like winter rye (*Secale cereale* L.), winter wheat (*Triticum aestivum* L.), and winter triticale (× *Triticosecale* Wittmack) can survive the winters in the upper Midwest and have been the most consistently successful winter cover crops for corn–soybean cropping systems in this region. For example, Johnson et al. (1998) showed that winter rye produced four times more shoot growth (1,872 kg ha^{-1} dry weight [1,670 lb ac^{-1}]) than spring oats (*Avena sativa* L.) that were grown in the fall and then winter-killed (461 kg ha^{-1} [411 lb ac^{-1}]). In another study over four years,

Thomas C. Kaspar and **Matthew G. Bakker** are research scientists at the USDA Agricultural Research Service National Laboratory for Agriculture and the Environment, Ames, Iowa, United States.

Kaspar et al. (2007) measured an average of 1,726 kg ha^{-1} (1,540 lb ac^{-1}) of winter rye cover crop shoot dry weight. Other potential cover crops, such as legumes or *Brassica* species, even when overseeded before corn or soybean harvest, are often not winter-hardy, have had inconsistent results, or do not produce appreciable amounts of biomass (PFI 2013). Thus, at the present time winter cereal grains seem to have the best potential as cover crops in full-season corn–soybean rotations in the upper Midwest.

In spite of the environmental and soil quality benefits, the adoption of winter cereal cover crops by farmers in the upper Midwest has been minimal (Singer et al. 2007; NASS 2014). Concerns about possible corn yield decreases following winter cereal cover crops are one of the reasons for this limited adoption of cover cropping in corn–soybean rotations (Dinnes et al. 2002). For example, Tollenaar et al. (1992, 1993) observed reductions in corn silage yields when a winter rye cover crop was killed immediately before corn planting. In Iowa, Johnson et al. (1998) reported a 1.57 Mg ha^{-1} (25 bu ac^{-1}) corn grain yield reduction following a rye cover crop killed at corn planting, but no yield reduction following oats that winter killed. Other studies, however, have not shown consistent corn yield decreases following winter cereal cover crops. In Nebraska, Kessavalou and Walters (1997) measured lower corn yields following a rye cover crop in only one of three years. Kaspar et al. (2007) saw lower corn yields following a rye cover crop in one of two years in one study and no effect on corn yield in three years at the same site in a subsequent study (Kaspar et al. 2012). In Iowa, corn yield was decreased following a winter rye cover crop in only 3 of 22 on-farm replicated strip trials (ILF and PFI 2014). Miguez and Bollero (2005) conducted a review of corn yield response to cover crops and reported that grass winter cover crops, including small grains, did not consistently decrease corn yields in the midwestern Corn Belt and that many studies reported no effect on yield. Thus, although the effect is inconsistent and not well understood, there is potential for corn yield decreases following a winter cereal cover crop in some fields and in some years. This increased risk is likely a serious impediment to adoption of winter cereal cover crops by farmers. Thus, research is needed to improve our understanding of corn yield responses to winter cereal cover crops and to devise management strategies to improve corn performance following winter cereals.

Corn yield decreases following a winter cereal cover crop have been difficult to study because of the apparent inconsistency of the effect. Several studies have reported that yield reductions are more likely to occur when a winter rye cover crop is killed less than two weeks before corn planting (Munawar et al. 1990; Raimbault et al. 1991; Ball Coelho et al. 2005). Several mechanisms have been proposed to explain this effect. A number of studies (Karlen and Doran 1991; Tollenaar et al. 1993; Wagger and Mengel 1993) have proposed that a rye cover crop may reduce corn yields by reducing inorganic N levels in the spring, either through uptake while the cover crops are growing or through immobilization of N during decomposition of their residues. Additionally, cover crop water use may reduce subsequent crop yield if soil water is not replenished before it is needed by the following grain crop (Eckert 1988; Munawar et al. 1990). Alternately, cover crops may reduce yield because of allelopathy or a rotation effect (Tollenaar et al. 1993; Kessavalou and Walters 1997). Other possibilities are interference with planter performance (Eckert 1988), increased insect or nematode pressure, cooler soil temperatures, and increased population size or activity of plant pathogens. As a result of the many potential contributing mechanisms, it has been difficult to devise management strategies to overcome this problem.

Interestingly, winter cereal cover crops rarely decrease, and sometimes increase, soybean yields (Ruffo et al. 2004; De Bruin et al. 2005; Kaspar et al. 2007, 2012; ILF and PFI 2014). Compared with corn in the upper Midwest, soybeans are normally planted later when air and soil temperatures are warmer, they are not as sensitive to reductions in population, they may share fewer pathogens and insect pests with grass cover crops, and they fix N.

One approach to reducing the occasional corn yield reductions following winter cereal cover crops may lie in breeding or selecting winter cereals explicitly for traits that will maximize the benefits of cover cropping, while reducing risks to the subsequent grain crop. To the best of our knowledge, very little selection of winter cereals for use as cover crops has been done in the United States. One exception is Aroostook winter rye, which was selected as a cover crop plant for northern Maine, United States (USDA NRCS 1999). Additionally, we are not aware of any comparisons of winter cereal cultivars used as cover crops that have been made in the upper Midwest. We hypothesized that there would be differences among winter rye, winter wheat, and winter triticale cultivars in their growth when used as a cover crop and in their effects on the yield of a following corn crop. To test this, we conducted a study with 7 winter rye cultivars, 2 winter triticale cultivars, and 3 winter wheat cultivars planted following soybean harvest and grown as winter cover crops preceding corn in four years to determine whether the 12 cultivars differed in (1) biomass production and N uptake and (2) impact on corn yield, harvest population, and other yield parameters.

Materials and Methods

Site Description and Management. This experiment was conducted in three fields (0.8 to 1.6 ha [2 to 4 ac]) that are part of Iowa State University's Agricultural Engineering and Agronomy Research Farms (AEARF), located in Boone County, Iowa, United States (42°1′15″ N, 93°46′26″ W) with measurements taken in four years, from 2006 to 2009. The fields were in a corn–soybean rotation and soybeans were grown in each field in the year prior to measurements. A different field was used in each of the first three years, and in 2009 the same field that was used in 2007 was used again. The predominant soils series in the three fields used in this experiment were: Clarion loam, Nicollet clay loam, and Webster silty clay loam (Andrews and Diderikson 1981), and slopes within the fields were generally less than 2%. Average monthly air temperatures, cumulative precipitation, and growing degree days (tables 1 and 2) were calculated using daily values from a National Weather Service Cooperative Observer Program site (site ID IA0200; Iowa Environmental Mesonet 2014) located near the main buildings for the AEARF and less than 6 km (3.7 mi) from the three fields

The experimental design was a randomized complete block design with 12 winter cereal cultivars randomly assigned to plots in three blocks in each field in the fall prior to year of measurement. Check plots without cover crops were also included in each block. In 2006, there were two check plots per block, and in the other three years, eight check plots were included in each block. Plots in all four years were 3.8 m wide (12.5 ft) and consisted of five main crop rows

Table 1
Average monthly air temperature and total precipitation from 2005 to 2009.

	Average air temperature (°C)						Total precipitation (mm)					
Month	2005	2006	2007	2008	2009	1951 to 2010 Avg.	2005	2006	2007	2008	2009	1951 to 2010 Avg.
Jan.	−7.8	1.1	−5.6	−8.3	−10.0	−7.4	26	16	14	9	25	19
Feb.	0.0	−2.8	−8.9	−7.8	−2.2	−4.2	47	6	45	18	7	22
Mar.	3.3	3.3	6.1	1.1	3.3	2.1	35	74	81	71	103	53
Apr.	12.8	13.3	8.9	8.3	8.9	10.0	82	109	153	130	116	90
May	15.6	16.7	18.9	15.6	15.6	16.2	111	55	169	216	102	115
June	23.3	22.2	22.2	21.1	21.1	21.3	124	21	52	271	104	128
July	24.4	24.4	23.3	23.3	20.6	23.3	104	141	75	234	70	105
Aug.	22.2	22.2	24.4	21.1	21.1	22.0	172	156	200	53	123	111
Sept.	20.6	16.1	20.0	17.8	17.8	17.8	111	191	48	78	24	82
Oct.	12.2	10.0	13.9	11.7	7.8	11.4	9	63	137	92	186	62
Nov.	5.0	4.4	3.3	3.3	6.7	2.9	49	40	4	66	34	43
Dec.	−6.6	1.1	−6.7	−7.8	−6.7	−4.5	24	68	49	35	50	25
Jan. to Dec.*	10.6	11.1	10.0	8.3	8.9	9.3	894	940	1,028	1,273	945	856

*Values for the Jan. through Dec. periods are averages for the period for air temperature and totals for the period for precipitation.

spaced 0.76 m (2.5 ft) apart. Plot length varied among the three fields from 22.9 to 38.1 m (75 to 125 ft) long. The 12 winter cereal cultivars compared in this experiment were seven winter rye cultivars (Aroostook, Dacold, Elbon, Maton, Oklon, Rymin, and Wheeler), two winter triticale cultivars (Boreal and NE-422t), and three winter wheat cultivars (Nekota, Pronghorn, and Wesley).

Soybeans were harvested in early to mid-October and then the winter cereal cover crop cultivars were planted in mid to late October (table 2) using a no-till grain drill in rows spaced 0.19 m (7.5 in) apart and at a rate of 3.0×10^6 seeds ha^{-1} (1.2×10^6 seeds ac^{-1}). Cover crop seed lots were tested for germination and weight per hundred seeds, and the grain drill was calibrated for different size classes of seed to achieve the targeted seeding rate. From cover crop planting to corn harvest each year, the experimental fields were managed as no-till. The winter cereal cover crops were terminated with glyphosate (N-[phosphonomethyl] glycine) applied at 1.12 kg of active ingredient ha^{-1} (1 lb ac^{-1}) from 0 to 9 days prior to planting the main crop (table 2). The variation in the interval between termination and planting the main crop was in part caused by variable field and weather conditions in the spring and equipment logistics. Weeds were suppressed in corn using preemergence herbicides and postemergence applications of glyphosate. Corn (Pioneer 35P17; relative maturity 105 days) was planted in early May (table 2) with a five-row, 0.76 m (2.5 ft) row width no-till planter without residue clearing attachments at 79,000 seeds ha^{-1} (32,000 seeds ac^{-1}). Nitrogen fertilizer was applied for corn in split applications at planting and in late May or early June for a total rate of 202 kg N ha^{-1} (180 lb N ac^{-1}). Phosphorus (P) and potassium (K) fertilizer were surface applied in the fall or winter prior to corn planting, at rates as indicated by soil tests. Some P and K fertilizer was applied with an in-furrow starter at planting (4.9 kg P ha^{-1} and 4.6 kg K ha^{-1} [4.3 lb P ac^{-1} and 4.1 lb K ac^{-1}]).

Table 2
Dates of management operations for experimental plots from 2006 to 2009.

Management operation	2006	2007	2008	2009
Rye cover crop planting date (Previous fall)	13 Oct.	25 Oct.	11 Oct.	20 Oct.
Rye cover crop termination date	27 Apr.	10 May	5 May	8 May
Growing degree days for rye cover crop base 4°C	692	717	531	590
Corn planting date	5 May	14 May	14 May	8 May
Corn harvest date	20 Oct.	26 Oct.	4 Nov.	4 Nov.
Growing degree days for corn base 10°C	1,694	1,827	1,624	1,469

Cover Crop Shoot Biomass and Nitrogen Concentration Measurements. Cover crop shoot biomass samples were collected in the spring of each year within one or two days of glyphosate application (table 2). Two samples were taken from each plot by clipping at the soil surface all the rye plants found within a sampling frame (0.76 m wide by 0.50 m long [30 in wide by 19.7 in long]). For each sample, the 0.76 m side of the frame was oriented perpendicular to the stubble of the previous year's soybean row so that the frame spanned an entire inter row. Biomass samples were dried at 60°C (140°F) to constant weight and weights recorded. Subsamples from each plot (n = 2) were averaged and cover crop shoot dry weights were calculated on an area basis. Combined subsamples were then finely ground and analyzed for N concentration using the dry combustion-gas chromatograph method (Schepers et al. 1989) with an EA1112 Flash NC Elemental analyzer (Thermo Electron Corp., Waltham, Massachusetts). Nitrogen contents were calculated by multiplying cover crop shoot biomass on an area basis by tissue N concentration.

Corn Grain Yields, Ear Samples, Plant Population, and Number of Barren Plants Measurements. Corn population and barren plants were determined by counting all plants and all plants without ears for the entire length of the center three rows of each plot less than seven days before harvest. Barren plants were not counted in 2006. Ears were harvested from five consecutive plants from one of the center three rows of each plot to determine ear, cob, and grain characteristics. The ears were dried at 60°C (140°F), and total ear weight determined. Ears were shelled by hand, and grain and cob weights were determined. The number of kernels was determined using an automated seed counter, and weight per kernel was calculated using the grain weight and kernel number. Subsamples of corn kernels were then finely ground with a flour mill and analyzed for N concentration using the dry combustion-gas chromatograph method (Schepers et al. 1989). At the plot scale, corn grain yields were determined using a modified combine with an internally mounted weigh tank and grain moisture meter. The entire length of the center three rows of each five-row plot were harvested in late October or early November (table 2). Yields were calculated based on harvested plot area and were adjusted to a moisture content of 0.155 g water g^{-1} grain (0.005 oz water oz^{-1} grain; 15.5% grain moisture).

Statistical Analysis. Because treatments were randomly assigned each year, the experimental design for the combined analysis over years could be considered as a split plot design with "years" as main plots and "treatments" as subplots (Gomez and Gomez 1984) and analyzed using PROC GLM procedure (SAS 2010). For variables where the year by treatment interactions were significant, the analysis of data from individual years is more relevant and the combined analysis will be discussed only briefly. Data from individual years were analyzed separately for block and treatment effects as a randomized complete block design using the PROC GLM procedure. When the analysis of variance indicated significant effects at the 0.05 probability level, the least significant difference (LSD) test at the 0.05 probability level was used to compare treatment means. Data collected from the multiple check plots without cover crops within each block (n = 2 for 2006, n = 8 for 2007 to 2009) were averaged before analysis.

Regression analysis (PROC REG; SAS 2010) was used to examine the linear relationships between cover crop shoot dry weight, corn harvest population, and corn yield across all four years and within individual years. These variables were chosen because there were significant differences among the cultivar treatments for these variables. Quadratic regression equations were also examined, but they did not show substantial improvements in the r^2 compared with the linear regression.

Results and Discussion

Cover Crop Shoot Biomass and Nitrogen Concentration Measurements. Cover crop shoot biomass varied significantly among cultivars in each year and averaged across years (table 3). Additionally, the year by cultivar interaction was significant and there were significant differences among years. In general, three winter rye cultivars (Aroostook, Elbon, and Maton) had greater shoot biomass than many of the other winter rye, winter wheat, or winter triticale cultivars averaged across years or within individual years. Boreal and NE-422t, winter triticale cultivars, and Nekota and Wesley, winter wheat cultivars, had relatively poor shoot biomass production averaged over the four years. From our visual observations, we hypothesized that low biomass production for some cultivars in some years was due to a combination of poor winter survival, reduced tillering, and slow growth in the spring. For example, Oklon (winter rye) had above average growth in 2006 and 2008, but had very poor growth in 2007 due to poor winter survival and a reduced stand (visual observations) in the spring of 2007. In general, winter rye usually has better winter survival and growth at cold temperatures than winter wheat or winter triticale (Clark 2007; Fowler 2008; Peltonen-Sainio et al. 2011). This was largely confirmed in our study as the winter rye cultivar (Wheeler) with the lowest four-year average shoot biomass production of all rye cultivars still had significantly more shoot growth than the two winter triticale cultivars and was greater than or equal to the three winter wheat cultivars (table 3).

There were significant differences among years for cover crop biomass with 2006 having the greatest biomass and 2008 the least biomass (table 3). The 2008 cover crops had significantly less shoot biomass than the 2006 cover crops even though they were planted two days earlier in the fall and terminated eight days later in the spring (table 2). One noticeable difference between the two years is the warmer average temperature in April of 2006 (13.3°C [55.9°F]) than in April of 2008 (8.3°C [46.9°F]; table 1). This is also reflected in the greater number of growing degree days (GDD) available to rye in 2005 through 2006 (692 GDD) compared to 2007 through 2008 (531 GDD; table 2). Additionally, other weather, soil, and cropping systems affected factors such as winter survival, stand density, or soil N levels. They also could have influenced shoot biomass production.

Higher levels of cover crop biomass production are important because to a large extent biomass production of cover crops determines their beneficial effects. Although this study was not intended to rank or select the cultivars with the greatest biomass production, our results indicated that there is genetic variation among winter cereal cultivars for how well they grow when managed as a cover crop at a particular location over four years. If the weather, management, or location had been different, it is probable that the ranking of cultivars for biomass production would have been different. Nonetheless, there would seem to be opportunities for selection and breeding of winter cereals as cover crops for the upper Midwest corn and soybean cropping systems.

As with cover crop shoot biomass, there were significant differences in cover crop shoot N concentration among cultivars and among years (table 4), but the year by cultivar interaction was not significant. Linear regression analysis indicated that within years the shoot N concentrations generally decreased as biomass increased except for 2006 (r^2 = 0.02, 0.44, 0.12, and 0.22 for 2006, 2007, 2008, and 2009, respectively). Decreasing N concentration with shoot growth and maturity of winter cereals has been observed in other studies (Muldoon 1986). Thus, the two winter triticale cultivars, Boreal and NE-422t, with the greatest four-year average shoot N concentrations also had the lowest four-year average shoot biomass (table 3). The greatest cover crop shoot N concentrations were measured in 2007 (table 4). Shoot biomass in 2007 was significantly greater than biomass in 2008, indicating that low biomass production and slow development were not completely responsible for the higher N concentration in 2007. Although soil N levels were not measured, it is possible that higher shoot N concentrations in 2007 were due to higher N availability during cover crop growth in

Table 3
Cover crop shoot dry weights (Mg ha⁻¹) for four years (n = 3).

Cover crop species	Cultivar	2006	2007	2008	2009	Average
Winter rye	Aroostook	4.01a*	1.40bc	1.33a	1.77a	2.13a
Winter rye	Dacold	2.57bc	2.08a	1.25a	1.42abc	1.83bc
Winter rye	Elbon	3.63a	1.90ab	1.60a	1.18bcd	2.08ab
Winter rye	Maton	4.10a	1.59abc	1.31a	1.45ab	2.11a
Winter rye	Oklon	3.80a	0.75d	1.30a	0.92cd	1.69cde
Winter rye	Rymin	2.80b	1.45bc	1.33a	1.46ab	1.76cd
Winter rye	Wheeler	2.49bc	1.44bc	1.46a	1.25bc	1.66cde
Winter triticale	Boreal	1.97c	1.08cd	0.43b	0.30e	0.94f
Winter triticale	NE-422t	1.99c	1.42bc	0.47b	0.74d	1.15f
Winter wheat	Nekota	2.54bc	1.75ab	0.47b	1.20bcd	1.49e
Winter wheat	Pronghorn	3.01b	1.69ab	0.49b	1.10bcd	1.57de
Winter wheat	Wesley	2.62b	1.83ab	0.37b	1.00bcd	1.46e
	Average	2.96A	1.53B	0.98C	1.15BC	1.66
	Pr > F†	0.01	0.01	0.01	0.01	0.01
	LSD (0.05)	0.60	0.56	0.44	0.51	0.25
	CV (%)	12.1	21.5	26.2	26.1	18.9

*Numbers within a column followed by the same lowercase letter and numbers within a row followed by the same uppercase letter are not significantly different, as indicated by least significant difference (LSD) test at the 0.05 probability level.

†Pr > F indicates the significance of an analysis of variance test for differences across all cultivars within a given year.

2007 than in 2008. This may have occurred because of more residual N remaining after the 2006 soybean crop or more N mineralization occurring during cover crop growth.

Total cover crop shoot N content (shoot N concentration × shoot dry weight) differed significantly among cultivars, years, and the year by cultivar interaction (table 5). Averaged over four years, the rye cultivars Aroostook, Elbon, and Maton had the greatest shoot N content. However, differences among cultivars in total shoot N content were not as pronounced as for shoot biomass, likely because shoot N concentration tended to decrease with increasing shoot biomass within years. Similarly, the winter triticale cultivars, Boreal and NE-422t, and the winter wheat cultivars, Nekota, Pronghorn, and Wesley, had relatively low total shoot N contents compared to the other cultivars, but the relative differences were smaller than for shoot biomass. As for shoot biomass, total shoot N contents were relatively higher in 2006 than in 2008 and 2009 due mostly to greater shoot growth in 2006.

Nitrogen uptake by winter cover crops is important for two reasons. First, a portion of the N taken up by cover crops will be recycled to the soil organic matter and eventually will be mineralized and made available in the soil for plant uptake (Magdoff and van Es 2010). This is controlled in part by the N concentration and the C:N ratio of the cover crop residues (Magdoff and van Es 2010). Second, cover crop N uptake between harvest and planting of soybean and corn could potentially reduce the amount of NO_3^- moving downward with soil water to depths below the rooting depth of subsequent crops. In humid areas of the Midwest, NO_3^- below the crop rooting depth can continue to move downward to groundwater or move laterally to surface water sources through subsurface flow paths or agricultural drainage tiles (Tomer and Burkhart 2003; Schilling et al. 2007; David et al. 2010). There may be advantages to selecting cover crops with relatively higher shoot N concentrations at a specific developmental stage or plant size to maximize total N uptake and to reduce the C:N ratio of cover crop residues, which should increase the decomposition rate of cover crop residues and release the residue N more quickly to the following crop.

Corn Grain Yield. Corn yield was significantly affected by cover crop cultivars, years, and the year by cultivar interaction (table 6). There were relatively large differences in yield across the four years with 2009 having the greatest yield and the other three years being considerably lower. The cultivar by year interaction was especially important because the treatment effect of the cover crop cultivars on corn yield was highly significant in 2006 and 2007, but was not significant in 2008 or 2009, which were also the highest yielding years (table 6).

In 2006 and 2007 the cover crop cultivar treatments caused significant decreases in corn yield and there were significant differences among cultivars. In 2006 the average corn grain yield following cover crops was 0.86 Mg ha⁻¹ (13.7 bu ac⁻¹) less than the no cover crop check, with corn yields significantly less than the check for 7 of the 12 cultivars. Four winter rye cultivars, Elbon, Oklon, Rymin, and Wheeler, and one winter wheat cultivar, Pronghorn, were not significantly different from the check. Four cultivars, Aroostook, Boreal, Nekota, and Wesley had the lowest corn yields, which were significantly lower than the check (> 1.14 Mg ha⁻¹ [18.2 bu ac⁻¹]) and the winter rye cultivar, Wheeler.

In 2007 the corn yield difference between the average of the cover crop cultivars and the no cover crop check (–0.37 Mg ha⁻¹ [–5.9 bu ac⁻¹]) was smaller than in 2006. Additionally, corn yields following seven cultivars (Elbon, Maton, Oklon, Rymin, Wheeler, Boreal, and Wesley) were not significantly different from the check, whereas corn yields following five others (Aroostook, Dacold, NE-422t, Nekota, and Pronghorn) were significantly lower than the check. Corn yields following Maton, Oklon, Wheeler, and Boreal were significantly greater than corn yields following Aroostook, Dacold, NE-422t, Nekota, and Pronghorn.

In 2008 the greatest numerical difference between the no cover crop check and one of the cover crop treatments was –0.69 Mg ha⁻¹ (–11.0 bu ac⁻¹) and the mean yield across all cover crop treatments was 11.89 Mg ha⁻¹ (189 bu ac⁻¹), which was 0.31 Mg ha⁻¹ (4.9 bu ac⁻¹) less than the no cover crop check. In 2008, it is possible that some cover crop cultivars had real negative impacts on yield that we were unable to detect statistically because of the overall experimental variability. However, that was likely not true for most cultivars and especially for the two cultivars that had numerically greater yields than the check.

The evidence for no negative yield effect was stronger in 2009 than in 2008. The average across the cover crop cultivar treatments in 2009 was almost exactly the same as the mean of the no cover crop check, and the greatest differences between individual cover crop cultivar treatments and the no cover crop check were −0.33 Mg ha^{-1} (−5.2 bu ac^{-1}; Wesley winter wheat) and +0.34 Mg ha^{-1} (5.4 bu ac^{-1}; Aroostook winter rye). Additionally, six cultivars had numerically greater corn yields than the check. This suggests that there was a low probability of negative impacts on corn yield in 2009. This absence of negative impacts by the cover crops occurred even though the cover crops were terminated on the same day as corn planting and the same field was used as the one used in 2007, when the cover crops did cause yield reductions. Previous studies have reported that yield reductions were more likely to occur when the cover crop was terminated closer to the time of corn planting (Munawar et al. 1990; Raimbault et al. 1991; Ball Coelho et al. 2005).

Because of the significant cultivar by year interaction, the averages across all four years cannot be easily interpreted and it may be more informative to look at the response across the two years (2006 and 2007) in which corn yields were negatively impacted. Elbon, Oklon, Rymin, and Wheeler did not significantly reduce corn yield in either 2006 or 2007. Alternately, Aroostook, Dacold, NE-422t, and Nekota negatively affected corn yield in both years. One cultivar, Pronghorn, had no effect on yield in 2006 and a negative effect in 2007. The remaining cultivars had a negative effect on yield in 2006 and no effect in 2007 with Boreal and Wesley having the biggest relative changes between the two years. It is important to note that the four cultivars that did not affect corn yield in these two years were winter rye cultivars and that specific winter rye, winter wheat, and winter triticale cultivars were all represented in the cultivar treatments that decreased corn yield in both 2006 and 2007 (table 6). Because some studies have reported that rye had greater allelopathic effects on weeds than wheat or other cereals (Pérez and Ormeno-Numez 1993; Shilling et al. 1986), it has sometimes been assumed that rye used as a cover crop would also have greater negative effects on corn than other winter cereals. Regardless of whether allelopathy contributed to corn yield reductions, in our study cultivars of all three winter cereals species were capable of causing similar negative effects on corn yields.

Grain Moisture. Corn grain moisture at harvest was significantly affected by cover crop cultivar, year, and the year by cultivar

Table 4
Cover crop shoot nitrogen concentrations (g kg^{-1}) for four years (n = 3).

Cover crop species	Cultivar	2006	2007	2008	2009	Average
Winter rye	Aroostook	22.5de*	31.2cde	23.8b	22.6cd	25.1de
Winter rye	Dacold	25.8cde	29.0e	23.9b	21.6d	25.1cde
Winter rye	Elbon	19.7e	30.4e	22.4bcd	23.0cd	23.9e
Winter rye	Maton	23.5cde	35.0ab	21.2cd	25.3bcd	26.3bcd
Winter rye	Oklon	23.4cde	36.9a	21.1d	25.6abcd	26.8bcd
Winter rye	Rymin	25.8bcd	32.4bcde	24.2b	22.7cd	26.3bcd
Winter rye	Wheeler	25.9bcd	34.8abc	23.6bc	25.9abcd	27.5b
Winter triticale	Boreal	29.4ab	37.9a	24.1b	31.2a	30.7a
Winter triticale	NE-422t	30.4a	34.2abcd	29.7a	29.9ab	31.0a
Winter wheat	Nekota	27.0abc	31.6bcde	21.4cd	28.3abc	27.1bc
Winter wheat	Pronghorn	26.5abcd	29.2e	22.7bcd	23.6cd	25.5cde
Winter wheat	Wesley	28.3ab	30.6de	23.1bcd	25.7abcd	26.9bcd
	Average	25.7B	32.8A	23.5C	25.5B	26.8
	Pr > F†	0.01	0.01	0.01	0.04	0.01
	LSD (0.05)	4.0	3.7	2.3	5.7	2.0
	CV (%)	9.3	6.8	5.8	13.2	9.1

*Numbers within a column followed by the same lowercase letter and numbers within a row followed by the same uppercase letter are not significantly different, as indicated by a least significant difference (LSD) test at the 0.05 probability level.

†Pr > F indicates the significance of an analysis of variance test for differences across all cultivars within a given year.

Table 5
Cover crop total shoot nitrogen content (kg ha^{-1}) for four years (n = 3).

Cover crop species	Cultivar	2006	2007	2008	2009	Average
Winter rye	Aroostook	90.3ab*	43.2abc	31.9a	40.3a	51.4ab
Winter rye	Dacold	63.8de	59.0a	29.4a	30.9abc	45.8bcd
Winter rye	Elbon	71.3cde	56.5ab	35.4a	27.8abc	47.7bc
Winter rye	Maton	96.5a	56.5ab	27.6a	36.8ab	54.3a
Winter rye	Oklon	89.1ab	27.6c	27.1a	23.4bc	41.8cde
Winter rye	Rymin	71.9cde	47.1ab	32.3a	33.1abc	46.1bcd
Winter rye	Wheeler	62.3de	50.1ab	33.4a	33.7abc	44.9cd
Winter triticale	Boreal	57.6e	40.8bc	10.5b	9.3d	29.6f
Winter triticale	NE-422t	60.1e	48.7ab	13.9b	22.3cd	36.3e
Winter wheat	Nekota	68.3cde	55.3ab	10.1b	32.2abc	41.5cde
Winter wheat	Pronghorn	80.5bc	49.4ab	11.1b	25.7bc	41.7cde
Winter wheat	Wesley	74.7cd	56.0ab	8.5b	25.4bc	41.1de
	Average	73.9A	49.2B	22.6C	28.4C	43.5
	Pr > F†	0.01	0.03	0.01	0.01	0.01
	LSD (0.05)	14.3	16.3	8.8	13.5	6.5
	CV (%)	11.5	19.6	22.9	28.1	18.4

*Numbers within a column followed by the same lowercase letter and numbers within a row followed by the same uppercase letter are not significantly different, as indicated by a least significant difference (LSD) test at the 0.05 probability level.

†Pr > F indicates the significance of an analysis of variance test for differences across all cultivars within a given year.

Table 6
Corn grain yield (Mg ha^{-1}) following 12 cover crop small grain cultivars and a no cover crop check in four years (n = 3).

Cover crop species	Cultivar	2006	2007	2008	2009	Average
None	No cover crop check	12.21a*	11.90a	12.20ns	13.19ns	12.38a
Winter rye	Aroostook	11.07c	11.25bcd	11.65	13.53	11.88bc
Winter rye	Dacold	11.36bc	11.12d	11.51	12.98	11.74c
Winter rye	Elbon	11.56abc	11.66abc	11.92	12.91	12.01bc
Winter rye	Maton	11.18bc	11.87a	11.60	13.44	12.02bc
Winter rye	Oklon	11.51abc	11.96a	11.90	13.33	12.18ab
Winter rye	Rymin	11.67abc	11.53abcd	11.73	13.34	12.07ab
Winter rye	Wheeler	11.89ab	11.91a	11.76	13.04	12.15ab
Winter triticale	Boreal	11.05c	11.80a	12.19	13.14	12.04bc
Winter triticale	NE-422t	11.39bc	11.09d	12.47	13.25	12.05abc
Winter wheat	Nekota	10.97c	11.18cd	12.09	13.46	11.93bc
Winter wheat	Pronghorn	11.51abc	11.28bcd	11.66	13.09	11.89bc
Winter wheat	Wesley	11.06c	11.70ab	12.23	12.86	11.97bc
	Average	11.42B	11.56B	11.92B	13.20A	12.02
	Cover crop average	11.35B	11.53B	11.89B	13.20A	11.99
	Pr > F†	0.05	0.01	0.30	0.55	0.05
	LSD (0.05)	0.72	0.51	0.77	0.66	0.32
	CV (%)	3.7	2.6	3.8	3.0	3.3

*Numbers within a column followed by the same lowercase letter and numbers within a row followed by the same uppercase letter are not significantly different, as indicated by a least significant difference (LSD) test at the 0.05 probability level. 'ns' indicates that there were no significant differences among treatments in that year.

†Pr > F indicates the significance of an analysis of variance test for differences across all treatments within a given year.

interaction (table 7). There was a relatively large effect of year on grain moisture. Grain moisture is affected by many factors including the rate of corn development and the length of time and drying conditions between physiological maturity and harvest (Elmore and Roeth 1999; Abendroth et al. 2011). The highest grain moistures at harvest occurred in 2009. The next highest grain moisture at harvest was in 2006, which had a relatively early harvest date. The lowest grain moistures were measured in 2007 and 2008. In general, the cover crop treatments increased grain moisture relative to the no cover crop check in 2006 and 2009 (table 7). In 2006, a year in which some cover crop cultivars reduced grain yield, all cover crop cultivars had greater grain moistures than the check, but there were no significant differences among cultivars. In 2009, a year in which there were no yield differences among cultivars, seven entries had grain moistures that were similar to that of the check, whereas the other five were significantly wetter than the check (table 7). We hypothesize that the higher grain moisture contents indicate that the cover crop treatments delayed or slowed early development of the corn plants, which then delayed the date of physiological maturity in those years and shortened the time for drying before harvest. Perhaps the increased surface residue from the cover crop treatments kept the soil colder and wetter in the spring and this or some other cause may have delayed emergence and early development (Kaspar et al. 1990; Kravchenko and Thelen 2007). It is possible that the same slowing of early development could have occurred in 2007 and 2008, but that favorable drying conditions or sufficient time between maturity and harvest allowed the grain of later maturing plants to dry down to the same level as early maturing plants.

Plant Population at Harvest. Corn plant population at harvest was significantly affected by cover crop cultivars, years, and the year by cultivar interaction (table 8). The lowest average plant population at harvest occurred in 2006. Harvest population in 2007, 2008, and 2009 were all greater than in 2006, but not significantly different from each other. However, the harvest population of the no cover crop check was highest in 2008 and lowest in 2009 and did not vary as much (73,887 to 75,832 plants ha^{-1} [29,900 to 30,690 plants ac^{-1}]) over the four years as the average across the cover crop cultivar treatments. Similar to the corn yield data, the year by cultivar interaction was significant with cover crops decreasing plant population in 2006 and 2007, but not in 2008 and 2009. Also, the cover crops on average caused a greater decrease in corn population relative to the check in 2006 (10,013 plants ha^{-1} [4,052 plants ac^{-1}]) than in 2007 (2,367 plants ha^{-1} [958 plants ac^{-1}]).

In 2006, only one cultivar (Elbon) did not cause a decrease in plant population. The cultivars Aroostook, Boreal, Nekota, and Wesley caused the greatest decrease in corn population in 2006, and these same cultivars also caused the greatest reduction in corn yield in that year (table 6). In 2007, six cultivars (Dacold, Elbon, Oklon, Wheeler, Boreal, and Pronghorn) did not reduce plant population at harvest relative to the check. Alternately, Aroostook, Rymin, NE-422t, and Nekota caused the greatest decreases in population in 2007 and Aroostook, NE-422t, and Nekota were also among the four lowest ranked cultivars for yield in 2007. Interestingly, Rymin did not significantly reduce corn grain yields in 2007 (table 6) despite the reduction in corn population. Six cultivars (Aroostook, Maton, Rymin, NE-422t, Nekota, and Wesley) reduced plant population in both 2006 and 2007, and of those, Aroostook, NE-422t, and Nekota also reduced yield relative to the check in both years. Also noted was Dacold, which reduced population a little in 2006 and not at all in 2007, yet significantly reduced yield in both years. This data suggests that impacts on population are not the only mechanism by which winter cereal cover crops may impact corn grain yield.

Number of Barren Plants. The number of barren plants (i.e., plants without ears) was measured in the last three years of the study. This measurement was added when we observed the strong effect of cover crop cultivars on plant population in 2006. However, we speculate that the number of barren plants was probably minimal in 2006 because of the low harvest plant populations, which should have reduced competition between corn plants and the resulting barrenness (Ford and Hicks 1992). The number of barren plants was significantly affected by cover crop cultivar, year, and the year by cultivar interaction (table 9). The most

Table 7
Corn grain moisture contents (g kg^{-1}) at harvest in four years (n = 3).

Cover crop species	Cultivar	2006	2007	2008	2009	Average
None	No cover crop check	172b*	169ns	172ns	206e	180b
Winter rye	Aroostook	185a	169	177	209cde	185a
Winter rye	Dacold	184a	169	172	216ab	185a
Winter rye	Elbon	184a	169	172	211abcde	184a
Winter rye	Maton	184a	169	175	206de	183a
Winter rye	Oklon	184a	169	176	210bcde	185a
Winter rye	Rymin	185a	170	174	216abcd	186a
Winter rye	Wheeler	182a	169	175	209cde	184a
Winter triticale	Boreal	184a	168	173	208cde	183a
Winter triticale	NE-422t	182a	170	174	214abc	185a
Winter wheat	Nekota	187a	169	172	213abc	185a
Winter wheat	Pronghorn	187a	169	172	209cde	184a
Winter wheat	Wesley	186a	168	171	218a	186a
	Average	184B	169D	173C	211A	184
	Cover crop average	185B	169D	174C	212A	185
	Pr > F†	0.01	0.99	0.46	0.03	0.01
	LSD (0.05)	5	4	6	7	3
	CV (%)	1.5	1.5	1.9	2.0	1.8

*Numbers within a column followed by the same lowercase letter and numbers within a row followed by the same uppercase letter are not significantly different, as indicated by a least significant difference (LSD) test at the 0.05 probability level. 'ns' indicates that there were no significant differences among treatments in that year.

†Pr > F indicates the significance of an analysis of variance test for differences across all treatments within a given year.

barren plants were observed in 2007 with about half as many present in 2008 and 2009. The cover crops increased the number of barren plants only in 2007 when the average number of barren plants for the cover crop treatments was 2,678 plants ha^{-1} (1,083 plants ac^{-1}) greater than the no cover crop check. Elbon, Maton, Wheeler, and Boreal had a similar number of barren plants as the no cover crop check and the corn yield of these four cultivars did not differ from the check in 2007. Alternately, Rymin, NE-422t, Nekota, and Wesley produced the most barren corn plants, and of these, Nekota and NE-422t also significantly reduced yields in 2007. Rymin and Wesley did not reduce yields even though both their plant populations and barren plants differed from the check.

Other Yield Parameters. Ears collected immediately before harvest showed that ear weight, grain weight, cob weight, grain N, number of kernels, and weight per kernel were not significantly affected by the cover crop cultivars or the cultivar by year interaction. There were significant differences among years for some yield components or grain parameters, but that is not unusual.

Table 8
Corn plant population (plants ha^{-1}) at harvest in four years (n = 3).

Cover crop species	Cultivar	2006	2007	2008	2009	Average
None	No cover crop check	74,822a*	74,309ab	75,832ns	73,887ns	74,713a
Winter rye	Aroostook	59,003f	70,498de	72,767	74,056	69,081d
Winter rye	Dacold	68,698bc	74,478a	74,747	74,324	73,062ab
Winter rye	Elbon	70,548ab	71,876bcd	71,927	72,984	71,834bc
Winter rye	Maton	66,594bcd	71,455cde	72,047	73,941	71,009bcd
Winter rye	Oklon	64,552cdef	73,215abc	71,328	75,127	71,056bcd
Winter rye	Rymin	68,337bc	71,212cde	74,747	74,387	72,171bc
Winter rye	Wheeler	66,019bcde	73,560abc	72,887	74,592	71,764bc
Winter triticale	Boreal	63,596cdef	73,368abc	72,167	73,596	70,682cd
Winter triticale	NE-422t	63,787cdef	69,273e	76,007	74,592	70,915cd
Winter wheat	Nekota	60,598ef	70,230de	75,587	75,548	70,491cd
Winter wheat	Pronghorn	64,361cdef	72,794abcd	75,827	73,635	71,654bc
Winter wheat	Wesley	61,618def	71,340cde	76,247	71,645	70,212cd
	Average	65,579B	72,124A	74,009A	74,024A	71,434
	Cover crop average	64,809B	71,942A	73,857A	74,036A	71,161
	Pr > F†	0.01	0.01	0.29	0.72	0.01
	LSD (0.05)	5,784	2,577	4,733	3,385	2,068
	CV (%)	5.2	2.1	3.8	2.7	3.6

*Numbers within a column followed by the same lowercase letter and numbers within a row followed by the same uppercase letter are not significantly different, as indicated by a least significant difference (LSD) test at the 0.05 probability level. 'ns' indicates that there were no significant differences among treatments in that year.

†Pr > F indicates the significance of an analysis of variance test for differences across all treatments within a given year.

We also used harvest population or distance between the five consecutive plants that we sampled as covariates to adjust the means for these yield parameters, but that did not result in the detection of significant treatment differences for any of the parameters. It is possible that any negative effect of the cover crop cultivar treatments on these plant yield parameters may have been compensated for by the decrease in plant populations in 2006 and 2007, which would have had a positive effect on individual plant yield because of reduced plant-to-plant competition.

Relationship of Corn Yield to Cover Crop Shoot Biomass and Plant Population. Because we were primarily interested in understanding the effect of cover crops on corn yield and harvest population, we calculated the difference in yield or population between each cultivar treatment and the no cover crop check for each replication within each year. A negative difference indicated that the cover crop treatment had lower populations or yield than the check. Then we used regression analysis to look at the relationships between yield difference, population difference, and cover crop shoot dry weight for all four years together and for each year separately. The relationship between the difference in harvest population and the difference in corn yield was the strongest and most consistent of the three relationships (figure 1). Across all four years when the difference in population between the cover crop cultivar treatments and the check became less negative, the corn yield difference also became less negative and approached zero (r^2 = 0.43; slope = 0.00008). Additionally, when the harvest population difference was positive (i.e., cover crop population was greater than the check population) as often occurred in 2009, then the yield difference was positive and increased as the population difference increased.

The relationships for each of the four years individually were also significant and followed the same trend as the combined analysis with positive and similar slopes (figure 1). This indicates that differences in harvest population between the cover crop cultivars and the check may explain part of the treatment differences in yield. We also examined this relationship for two cultivars that caused significant yield reductions (Dacold and Nekota) and two cultivars that did not cause significant yield reductions (Rymin and Wheeler) in both 2006 and 2007. Dacold reduced harvest population relative to the check in 2006, but not in 2007, and the relationship between population difference and yield difference across years for this cultivar was not significant (r^2 = 0.08; slope = 0.00003). This indicates that a decrease in harvest population is not entirely responsible for reduced yield following Dacold, especially in 2007. The number of barren plants also impacted yield and in 2007 barren plants for Dacold were significantly greater than the check, but they were slightly less than the average for all cover crop cultivars. So although barren plants contributed to the yield decrease for Dacold, we hypothesize that corn plants following Dacold must also have been stressed in some other way that affected yield even though our measurements of ear yield parameters did not reveal any significant differences from the check. In contrast, Nekota reduced harvest population in both 2006 and 2007 relative to the check and had a strong relationship between harvest population difference and yield difference (r^2 = 0.79, slope = 0.00009). Rymin and Wheeler, which did not reduce yield in 2006 and 2007, both reduced harvest population relative to the check in 2006 and Rymin also reduced it in 2007. Neither Rymin nor Wheeler, however, had a significant relationship between harvest population difference and yield difference (Rymin, r^2 = 0.09, slope = 0.00003; Wheeler, r^2 = 0.09, slope = 0.00003).

Cover crop shoot residues have the potential to reduce corn population in several ways. Plant residues can interfere with planter performance (Eckert 1988; Kaspar and Erbach 1998) resulting in variable planting depth, improper seed furrow closure, poor seed to soil contact, and reduced plant stands. Cover crop and previous crop residues also can reduce soil temperatures (Kaspar et al. 1990), slowing emergence and reducing plant stand. Also, cover crop residues may contain allelochemicals that can inhibit germination or emergence (Reberg-Horton et al. 2005). For each of these potential mechanisms, the negative impacts on corn population should be greater with increasing cover crop biomass. The relationship between cover crop shoot dry weight and the difference in harvest corn population was significant (r^2 = 0.39, slope = –3,125) when data were com-

Table 9
The population (plants ha^{-1}) of corn plants without ears (barren plants) at harvest in three years (n = 3).

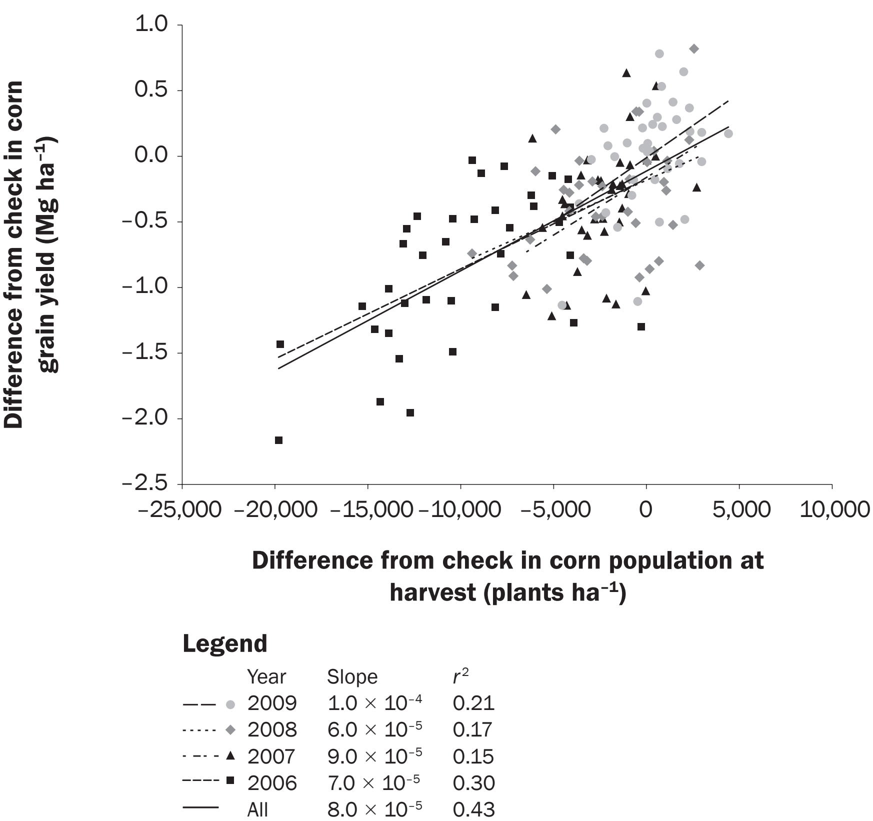
Cover crop species	Cultivar	2006	2007	2008	2009	Average
None	No cover crop check	—	2,266f*	2,453ns	2,423ns	2,381d
Winter rye	Aroostook	—	5,090cde	2,691	1,952	3,244bc
Winter rye	Dacold	—	4,899cde	3,110	1,531	3,180bcd
Winter rye	Elbon	—	3,598def	2,093	2,181	2,624cd
Winter rye	Maton	—	4,019cdef	2,332	1,416	2,589cd
Winter rye	Oklon	—	4,287cde	3,110	2,602	3,333abc
Winter rye	Rymin	—	5,326bcd	2,960	2,175	3,487ab
Winter rye	Wheeler	—	3,406ef	2,033	3,253	2,898bcd
Winter triticale	Boreal	—	3,942def	2,930	2,947	3,273bc
Winter triticale	NE-422t	—	7,616a	2,272	2,526	4,138a
Winter wheat	Nekota	—	6,966ab	3,349	2,181	4,165a
Winter wheat	Pronghorn	—	4,401cde	2,571	2,717	3,230bcd
Winter wheat	Wesley	—	5,779bc	2,571	2,717	3,689ab
	Average	—	4,738A	2,652B	2,356B	3,249
	Cover crop average	—	4,944A	2,669B	2,350B	3,321
	Pr > F†	—	0.01	0.71	0.26	0.01
	LSD (0.05)	—	1,804	1,415	1,329	853
	CV (%)	—	22.6	31.7	33.5	27.9

*Numbers within a column followed by the same lowercase letter and numbers within a row followed by the same uppercase letter are not significantly different, as indicated by a least significant difference (LSD) test at the 0.05 probability level. 'ns' indicates that there were no significant differences among treatments in that year.

†Pr > F indicates the significance of an analysis of variance test for differences across all treatments within a given year.

Figure 1

Relationship between the difference (treatment – check) in corn population at harvest and the difference in corn grain yield for corn following 12 winter cereal cover crop cultivars.



bined over years (figure 2). However, when examined within each of the four years the relationship was only significant in 2008. This indicates that the relationship for the combined data is the result of a year effect with the small differences in harvest populations coinciding with low cover crop shoot dry weights in 2008 and 2009 and large population differences coinciding with large cover crop shoot dry weights in 2006. The significant relationship for 2008 seems to be an anomaly. The range of cover crop shoot dry weights and population differences in 2008 was relatively small and cover crop cultivars did not cause significant reductions in yield or population in 2008. In contrast, in 2006 there was no significant relationship across a much larger range in population differences and cover crop shoot dry weights and yet the cover crop treatments did cause significant reductions in corn harvest populations in that year. Thus, at least in three years of this experiment, there was not a strong relationship between variations in cover crop shoot dry weight and reductions in corn population by cover crops.

Cover crop residues may also affect corn yield through effects on corn growth and development through reduced soil temperatures, allelopathy, plant diseases, and N availability. Although we did not measure cover crop root biomass in this study, we would expect that root biomass could also have contributed to some of the potential effects on corn seedling growth and development. Similar to the relationship between cover crop shoot dry weight and harvest population difference, the relationship between cover crop shoot dry weights and yield differences was significant for the data combined over four years (r^2 = 0.16, slope = 0.23), but not consistent for the individual years. In 2006 and 2009, the relationships were not significant and had positive slopes (2006, r^2 = 0.07, slope = 0.17; 2009, r^2 = 0.06, slope = 0.22). In 2007 and 2008, the relationships were significant with negative slopes (2007, r^2 = 0.19, slope = –0.44; 2008, r^2 = 0.16, slope = –0.36). Some cover crop cultivar treatments caused significant yield decreases in 2007, but not in 2008 (table 6). Thus, there may be some relationship between cover crop shoot weight and the effect of cover crop cultivars on yield in 2007, but the effect was not consistent across all four years or even in the two years where the cultivar effect on yield was significant.

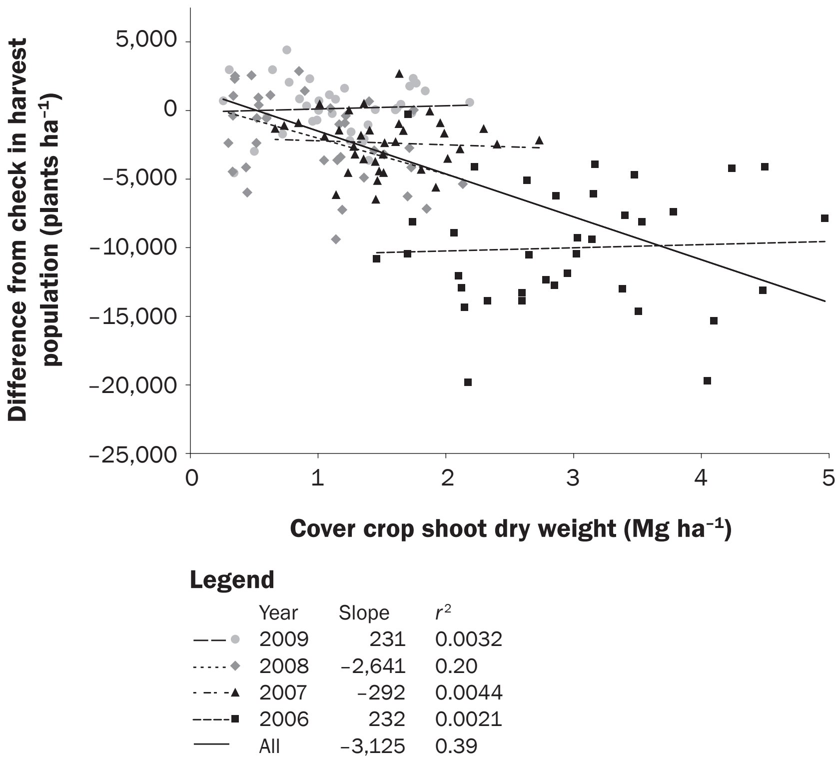
Summary and Conclusions

Cover crops have enormous potential to improve the soil conservation and sustainability of corn and soybean cropping systems in the upper Midwest. However, farmers may be reluctant to adopt cover crops if they perceive that cover crops increase risk for main crop yields. Additionally, we are not aware of any published evaluation of different winter cereal cultivars for use as cover crops in corn–soybean production systems in the upper Midwest. In this study, 12 winter rye, winter triticale, and winter wheat cultivars were grown as cover crops over four years to evaluate their growth and their effects on corn yield. The 12 cover crop cultivars differed in each of the four years for shoot dry weight, shoot N concentration, and total shoot N content. In general, the winter rye cultivars had greater shoot biomass, lower shoot N concentrations, and higher total shoot N contents than the winter triticale and winter wheat cultivars. The cover crop treatments significantly decreased corn yield in two of the four years and the yield effect varied among winter cereal cultivars. Some cultivars of all three species caused corn yield decreases, with no indication that winter rye had a greater effect on corn yield than did winter wheat or winter triticale. In fact, four winter rye cultivars did not significantly reduce corn yield in either of the two years in which yield was affected.

In general, the decreases in corn yield following the winter cereal cover crops were related to decreases in harvest population and increases in the number of barren plants, but were not strongly related to cover crop shoot dry weight within years. However, corn yield following some cultivars was reduced without accompanying decreases in plant population. This may indicate that in some cases corn following winter cereal cover crops is being stressed after the seedling stage. Additionally, it seems that weather or other environmental factors are important because corn yield was negatively affected following the winter cereal cover crops in only two of the four years.

Our study shows that there are genotypic differences among winter cereal cultivars for

Figure 2
Relationship between cover crop shoot dry weight and the difference (treatment – check) in corn population at harvest following 12 winter cereal cover crop cultivars.



their performance as cover crops and their effect on corn yields. The results of our study, however, should not be used to recommend one winter cereal cultivar over another at this time. Evaluations of more cultivars at multiple locations, along with a better understanding of the characteristics that affect cover crop performance are needed before reasonable recommendations can be developed. Although an evaluation of different corn hybrids was not included in this study, we would speculate that corn hybrids will vary in their response to winter cereal cover crop genotypes. Second, if the genetic, weather, and management factors that cause occasional corn yield deceases following winter cereal cover crops are understood and managed, then we may be able to realize the potential for cover crops to increase corn yields through improvements to soil quality. Lastly, to reach the full potential of cover crops to improve the conservation and sustainability of corn–soybean production systems in the upper Midwest, dedicated cover crop selection and breeding programs should be initiated.

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