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Brassica Cover Crop Effects on Nitrogen Availability and Oat and Corn Yield

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ABSTRACT

Cover crops are used to scavenge residual soil nitrate, with the goal of reducing N losses from agricultural fields and increasing subsequent N availability. Two experiments were conducted to determine fall-planted brassica cover crops' effect on N availability for rotational crops. The first evaluated five species—brown mustard [*Brassica juncea* (L.) Czern], hybrid turnip (*Brassica rapa* L. × *B. napus* L.), radish (*Raphanus sativus* L.), rapeseed (*Brassica napus* L.), and white mustard (*Sinapis alba* L.)—in rotation with oat (*Avena sativa* L.). The second evaluated radish in rotation with corn (*Zea mays* L.). End of season cover crop biomass averaged 1160 to 6170 kg ha^{-1} across experiments, locations, and years. Biomass did not differ by species. Nitrogen accumulation was generally greater than 70 kg ha^{-1} (range 31–136 kg ha^{-1}). In the subsequent spring and summer, brassica cover crops reduced soil nitrate N levels relative to a no-cover control by 0 to 132 kg ha^{-1}. In Exp. 1, all brassicas reduced oat N accumulation by $\geq$77 kg ha^{-1} and oat biomass by $\geq$1255 kg ha^{-1} in June 2012, relative to the control. Mustards reduced oat grain yield by 505 kg ha^{-1} in 2011, while radish increased oat yield by $\geq$578 kg ha^{-1} in each year. In Exp. 2, radish did not affect corn V8 biomass N concentration, grain yield, or response to N fertilizer. Nitrogen taken up by brassica cover crops often is not available when the subsequent crop needs it.

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Managing N to provide for crop growth and development while preventing losses to the environment has been identified as a "fundamental challenge" for agriculture today (Robertson and Vitousek, 2009). Nitrogen losses from agricultural fields reduce profitability and can contribute to groundwater contamination, eutrophication of surface waters, greenhouse gas emissions, and acid rain (Robertson and Vitousek, 2009). Available N in the soil can be lost to the environment through multiple pathways, including leaching, denitrification, and ammonia volatilization (Robertson and Vitousek, 2009). One strategy for reducing agricultural N losses is the use of a cover crop to scavenge residual N during periods when no cash crop is present (Thorup-Kristensen et al., 2003). After the cover crop is killed, the residue decomposes and the scavenged N is mineralized again. Assuming N mineralization occurs in synchrony with N demand by the subsequent crop, the increase in N availability could offset the cost of establishing the cover crop.

Several species in the family Brassicaceae have recently gained popularity as cover crops in the U.S. Midwest due to their ability to scavenge residual soil mineral N after a row crop is harvested. Brassica species used as cover crops include *Brassica juncea* (L.) Czern. (brown or Oriental mustard), *B. nigra* L. (black mustard), *B. rapa* L. (turnip, rapeseed, canola), *B. napus* L. (rapeseed, canola), *Raphanus sativus* L. (forage, oilseed, or daikon radish), and *Sinapis alba* L. (white or yellow mustard). Common names are based on functional characteristics; for example, "rapeseed" is used for oilseed varieties of *B. rapa* and *B. napus* with high glucosinolate and erucic acid content, while "canola" is used for varieties of the same species that have been selected for edible oil. As noted by Chen et al. (2007), brassica species used as cover crops are fast-growing, cool-season annuals with some frost tolerance. Turnip, radish, rapeseed, and canola have long taproots that can scavenge N from deep in the soil, while mustards have shallower, more fibrous root systems. When planted by mid-September, brassicas typically produce 3000 to 5000 kg ha^{-1} total biomass and take up 50 to 100 kg N ha^{-1} (Stivers-Young, 1998; Isse et al., 1999; Dean and Weil, 2009; Wang et al., 2010).

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Although brassica cover crops can scavenge large amounts of N rapidly, their effects on the amount of N available to the subsequent crop are mixed. In some cases, radish, rapeseed, and white mustard cover crops increased the N accumulation and biomass production or yield of the subsequent crop (Thorup-Kristensen, 1994; Vyn et al., 1999; Weinert et al., 2002). However, in other cases, the cover crop provided no benefit to the subsequent crop, even though radish N accumulation was high (Isse et al., 1999).

A N-scavenging cover crop will increase N availability for subsequent crops only if N taken up by the cover crop is released when the following crop needs it to support plant development. A cover crop initially reduces N availability by removing nitrate and ammonium from the soil. After the cover crop is killed, this N becomes available gradually as the cover crop residue decomposes. If mineralization of N from the residue occurs too slowly, the N scavenged by the cover crop may not be available when the subsequent crop needs it. If mineralization occurs too quickly, the N scavenged by the cover crop may be lost before the subsequent crop is able to use it. Nitrogen mineralization, denitrification, and ammonia volatilization can occur even at temperatures near 0°C (Wagner-Riddle and Thurtell, 1998; Magid et al., 2004; Engel et al., 2011). Both winterhardiness and C/N ratio of the cover crop affect the dynamics of N mineralization from the residue (Thorup-Kristensen, 1994; Trinsoutrot et al., 2000).

The likelihood of winter N losses is highest with radish, which has a low C/N ratio and typically does not overwinter (Thorup-Kristensen, 1994). Radish residue decomposes rapidly even at low temperatures (Thorup-Kristensen, 1994; Vos and van der Putten, 2001). In these studies, only 22 to 31% of the N accumulated by a radish cover crop in the fall was recovered in the residue the following spring. Likewise, Magid et al. (2004) found that only about 30% of the N in radish biomass remained in the decomposing residue after a 35 d incubation at 3°C. Nitrogen can be lost from decomposing radish residue through ammonia volatilization (de Ruijter et al., 2010), denitrification (Petersen et al., 2011), or leaching (Miller et al., 1994). Especially on sandy soils, N leached from the residue may travel below the rooting zone before the subsequent crop can take it up (Dean and Weil, 2009). However, too-slow mineralization of N is unlikely to be a problem with radish.

Other brassica cover crops may be less likely to lose N over the winter. Like radish, mustards are generally not winter hardy in northern climates (Chen et al., 2007). However, the higher C/N ratio and lignin content of mustards as compared to radish (Thorup-Kristensen, 1994) may result in slower release of N from mustard residue. Rapeseed has a lower C/N ratio than radish (Thorup-Kristensen, 1994), but unlike radish, many rapeseed accessions are winter-hardy (Chen et al., 2007). Nitrogen released from the biomass of winter-hardy accessions over the winter may be taken up again in the spring before the cover crop is killed, reducing the potential for early spring losses but increasing the potential for too-slow mineralization (Thorup-Kristensen, 1994).

The effect of brassica cover crops on N availability is likely to vary between regions, since processes involved in N losses from soil and plant residue are strongly influenced by soil and climate conditions (Li, 2000; Di and Cameron, 2002; Agehara and Warncke, 2005; Li et al., 2006). Furthermore, estimates of brassica cover crop biomass production and N accumulation vary widely and may differ between species and accessions. More comprehensive research on N cycling in brassica cover crop systems is needed to make recommendations about use of brassica cover crops for N scavenging to farmers in the upper Midwest. The objectives of this research were to determine the effect of fall-planted brassica cover crops on (i) N availability to the subsequent year's crop of oat (*Avena sativa* L.) or corn (*Zea mays* L.), (ii) oat and corn biomass, N accumulation, and grain yield, and (iii) corn response to applied N fertilizer.

MATERIALS AND METHODS

Site Characteristics and Experimental Design

Experiment 1: Effect of Five Brassica Species on a Rotational Oat Crop

Field studies of five brassica cover crop species were initiated at the University of Minnesota campus in St. Paul, MN (44.99° N, 93.19° W, elevation 299 m) in August of 2010 and in a neighboring field in August of 2011. They continued with the establishment of an oat crop in the spring of 2011 and 2012. Thus, potential accumulative effects were excluded. Soil characteristics are presented in Table 1. The species evaluated were brown mustard, hybrid turnip, radish, rapeseed, and white mustard. A total of 12 accessions were tested: brown mustard cultivar Pacific Gold and a variety not stated (VNS) accession; hybrid turnip cultivar Pasja; rapeseed cultivar Dwarf Essex; white mustard cultivars Accent and IdaGold; and radish cultivar Defender, commercial selections Driller, GroundHog, and Tillage, and two VNS accessions. A no-cover control was also included. Neither the cover crop treatments nor the control were fertilized. The experimental design was a randomized complete block with four replications. Plot size was 1.8 by 6.1 m in 2010 and 4.6 by 6.1 m in 2011. The seeding rate was 2 kg ha^{-1} for hybrid turnip, 6 kg ha^{-1} for rapeseed, 9 kg ha^{-1} for brown and white mustard, and 11 kg ha^{-1} for radish. In 2011, seeding rates were adjusted to pure live seed based on germination tests.

Experiment 2: Effect of Radish on a Rotational Corn Crop

Field studies were initiated in neighboring fields in August 2010 and 2011 at the University of Minnesota Rosemount Research and Outreach Center (Rosemount, MN, 44.72° N, 93.11° W, elevation 292 m) and Southwest Research and Outreach Center (Lamberton, MN, 44.25° N, 95.31° W, elevation 346 m). They continued with the establishment of a corn crop in the spring of 2011 and 2012. Soil characteristics are presented in Table 1. The experimental design was a randomized complete block with four replications and a split-plot layout. Main plot treatments were a radish cover crop and a no-cover control. Subplot treatments were five levels of N fertilizer (0, 45, 90, 135, and 179 kg N ha^{-1}) applied as urea before corn planting. Subplots were 4.6 m (six corn rows) by 7.6 m at Rosemount in 2010, and 4.6 by 9.1 m in all other locations and years.

Table 1. Background soil characteristics for brassica cover crop experiments in 2010–2011 and 2011–2012 at St. Paul, MN (Exp. 1) and at Lamberton and Rosemount, MN (Exp. 2).

Year	Location	Soil series (classification)	Soil pH†	P‡	K§
				— mg kg^{-1} —	
		Experiment 1¶			
2010–2011	St. Paul	Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludoll)	–	91	148
2011–2012	St. Paul	Waukegan silt loam	6.2	205	320
		Experiment 2#			
2010–2011	Lamberton	Ves loam (fine-loamy, mixed, superactive, mesic, Calcic Hapludoll)	5.9	14	132
	Rosemount	Waukegan silt loam	6.4	10	128
2011–2012	Lamberton	Ves loam and Normania loam (fine-loamy, mixed, superactive, mesic Aquic Hapludoll)	4.9	32	156
	Rosemount	Waukegan silt loam	5.8	14	146

† Average soil pH for the surface 0 to 15 cm of soil.

‡ Average Bray-P for the surface 0 to 15 cm of soil.

§ Average NH_4Oac-exchangable K for the surface 0 to 15 cm of soil.

¶ The field used in 2010–2011 was sampled in 2013. No pH data are available, but pH of soil at this location is typically 6.1 to 6.7. The field used in 2011–2012 was sampled in spring 2012, before oat planting. All samples were collected from alleys, which had not been planted to brassicas the previous fall. This field had extremely high soil fertility due to a history of frequent application of liquid swine manure (every 3–4 yr since 1991).

All soil samples were collected in spring, before corn planting, from the no-cover control plots.

Field Management

Experiment 1

Dates of field operations and sampling events for Exp. 1 are presented in Table 2. The brassicas followed a soybean [*Glycine max* (L.) Merr.] green manure, which was chopped and disked 2 to 3 wk before planting. On 17 Aug. 2010 and 22 Aug. 2011, the field was rototilled and brassica cover crops were seeded in 15 cm rows with a seeding depth of about 2.5 cm, using a cone-drill seeder (Wintersteiger AG, Ried im Innkreis, Austria), with the exception of Defender radish in 2011, which was broadcast seeded, raked in, and irrigated on 29 August. The field was packed with a roller immediately after planting in 2010 and immediately before planting in 2011. In 2010, plots were hand-weeded 7 d after planting. On 25 Apr. 2011 and 12 Apr. 2012, brassica residues and surviving plants were flail-mowed and rototilled, and oat (cultivar Souris) was drilled in 18 cm rows at 90 kg ha^{-1}. Some rapeseed and hybrid turnip plants survived field preparation and were removed by hand 1 mo after planting. A vigorous oat stand kept weed density very low in both years. No fertilizer or herbicides were applied to any treatment at any time during this experiment.

Experiment 2

Dates of field operations and sampling events for Exp. 2 are presented in Table 3. Radish cover crops followed an oat crop, which was harvested for grain in late July to early August, with straw baled and removed. Before the radish cover crop was planted, 60 cm soil samples were collected to determine the residual soil nitrate level. Four samples were collected from the entire field. Each sample was a composite of at least five cores. At Rosemount, cores were collected by hand using a standard 1.9 cm diam. hand probe and dried in a forced air dryer at 35°C. At Lamberton, cores were collected with a tractor-mounted hydraulic probe and dried in a forced air dryer at ambient temperature. Soil samples were analyzed by CaCl extraction (Lamberton) or $CaSO_4$ extraction (Rosemount) followed by Cd reduction and colorimetry. To test the effect of the radish cover crop under residual nitrate conditions similar to what might be seen after a small grain crop in years of high leaching risk, the target level of residual soil nitrate N was set at 67 kg ha^{-1}. Where measured soil nitrate N was below this level, supplemental urea was broadcast and incorporated (Table 4). The field was prepared within 2 d of cover crop planting using

Table 2. Dates of data collection and field operations for brassica cover crop experiments in 2010–2011 and 2011–2012 at St. Paul, MN (Exp. 1).

Operation	2010– 2011	2011– 2012
Soybean chopped and disked	26 July	9 Aug.
Field rototilled and packed	17 Aug.	22 Aug.
Brassicas planted	17 Aug.	22 Aug.
Brassica biomass sampling	20–22 Oct.	17 Oct.
Brassica winter survival	6 Apr.	29 Mar.
Pre-planting soil sampling	12–14 Apr.	9–11 Apr.
Brassicas flail-mowed	25 Apr.	12 Apr.
Field rototilled	25 Apr.	12 Apr.
Oat crop planted	25 Apr.	12 Apr.
Post-planting soil sampling	16 May	9–10 May, 21–22 June
Oat biomass sampling	na†	9–10 May, 21–22 June
Surviving brassicas removed	26 May	11 May
Oat grain harvest	25 July	12 July

† na, not applicable.

Table 3. Dates of data collection and field operations for radish cover crop experiments in 2010–2011 and 2011–2012 at Lamberton and Rosemount, MN (Exp. 2).

Operation	2010–2011		2011–2012	
	Lamberton	Rosemount	Lamberton	Rosemount
Cover crop planting	17 Aug.	19 Aug.	24 Aug.	19 Aug.
Cover crop biomass harvest	19 Oct.	28 Oct.	25 Oct.	22 Oct.
Late fall soil sampling	20–21 Oct.	9 Nov.	27 Oct.	11 Nov.
Spring soil sampling	4 May	19 Apr.	26 Apr.	20 Apr.
Urea application	10 May	6 May	26 Apr.	27 Apr.
Corn planting	11 May	6 May	1 May	27 Apr.
Summer soil and corn biomass sampling	30 June	29 June	11 June	12 June
Corn grain harvest	14 Oct.	21 Oct.	27 Sept.	25 Sept.

Table 4. Soil N levels before radish cover crop planting in August 2010 and 2011 at Lamberton and Rosemount, MN (Exp. 2).

Year	Location	Soil nitrate N (0–60 cm)	Applied urea
		kg N ha^{-1}	
2010	Lamberton	101	0
	Rosemount	18	73
2011	Lamberton	52	17
	Rosemount	21	46

a field cultivator, harrow, and/or packer as necessary to create a smooth seedbed.

Radish (cultivar GroundHog) was planted between 17 and 24 August with a cone-drill seeder at 19 kg ha^{-1}, with a seeding depth of about 2.5 cm. Row spacing was 15 cm at Rosemount and 19 cm at Lamberton. Volunteer oat was controlled in all treatments with clethodim [(E-2-[1[[(3-chloro-2-propenyl)oxy]imino]propyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one] at 0.079 to 0.12 kg a.i. ha^{-1} within 22 d after planting.

In the second year of each 2-yr trial, P and K were broadcast applied to the entire plot area in late April to mid-May when needed on the basis of soil tests, with the aim of providing enough P and K that these nutrients would not limit growth of the corn crop. Rates were based on University of Minnesota Extension recommendations for corn (Rehm et al., 2006). Amounts applied, in kg ha^{-1} elemental P and K, were as follows: Lamberton 2011, none; Rosemount 2011, 38 kg ha^{-1} P and 140 kg ha^{-1} K; Lamberton 2012, 0 kg ha^{-1} P and 23 kg ha^{-1} K; and Rosemount 2012, 22 kg ha^{-1} P and 23 kg ha^{-1} K. Nitrogen rate treatments were applied by hand-broadcasting urea. Urea was incorporated with a field cultivator within 4 h of application. Glyphosate-resistant corn was planted within 5 d of urea application. Corn was planted between 27 April and 11 May in 76-cm rows at a seeding rate of 79,000 seeds ha^{-1} at Rosemount and 89,000 seeds ha^{-1} at Lamberton. The corn hybrid used was cultivar DeKalb 50-47 at Rosemount in 2011, cultivar Pioneer 36V51 at Rosemount in 2012, cultivar DeKalb 48-12 at Lamberton in 2011, and cultivar DeKalb 53-78 at Lamberton in 2012.

Weed control in the corn crop varied between locations and years, depending on weed species present. At Rosemount in 2011, glyphosate [N-(phosphonomethyl) glycine] was applied on 13 June at 1.3 kg a.e. ha^{-1} with 2.2 kg ammonium sulfate ha^{-1} and 2.3 L crop oil ha^{-1}. The glyphosate application failed to kill all weeds. Therefore, the field was sprayed with a mixture of glyphosate and dicamba (3,6-dichloro-2-methoxybenzoic acid, diglycolamine salt) on 28 June. At Rosemount in 2012, glyphosate was applied on 22 May at 1.1 kg a.e. ha^{-1}. On 6 June, the field was row cultivated. Dandelion (*Taraxacum officinale* Weber), Canada thistle [*Cirsium arvense* (L.) Scop.], and perennial sowthistle (*Sonchus arvensis* L.) were removed by hand hoeing on 21 May and 25 June. At Lamberton in 2011, glyphosate [isopropylamine salt] was applied on 9 June and 5 July at 0.84 kg a.e. ha^{-1}. At Lamberton in 2012, acetochlor [2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6-methylphenyl)acetamide] was applied on 16 May at 2.5 kg a.i. ha^{-1} for pre-emergence weed control, followed by glyphosate on 21 May at 0.84 kg a.e. ha^{-1} and on 18 June at 0.68 kg a.e. ha^{-1}.

Data Collection

In Exp. 1, brassica biomass production, brassica N accumulation, brassica winter survival, and oat grain yield were measured in all plots in both years. Oat biomass production was also measured in all plots in 2012. Soil nitrate levels (both years) and oat N accumulation (2012 only) were measured in the following treatments: VNS brown mustard, Pasja hybrid turnip, GroundHog and Tillage radish, Dwarf Essex rapeseed, IdaGold white mustard, and the no-cover control. In Exp. 2, radish biomass production, radish N accumulation, soil nitrate levels, and corn biomass and N accumulation were measured in the zero N subplots, while corn grain yield was measured in all subplots.

In both experiments, brassica root and shoot biomass were collected in mid- to late October of the establishment year, after plants had achieved maximum percent ground cover, but before severe frost damage occurred, by digging or pulling plants (Tables 2 and 3). This method allowed collection of the swollen, fleshy upper 15 to 30 cm of the taproot, though fine roots were not collected. In Exp. 1, sample size was two 0.25 m^2 quadrats per plot in 2010 and three 0.25 m^2 quadrats in 2011. In Exp. 2, sample size was one 0.25 m^2 quadrat per plot. Roots were separated from shoots at or shortly after harvest. Root biomass was washed to remove clinging soil. Shoot biomass was also washed at Rosemount in 2010 (Exp. 2). At other locations and years, shoot biomass was clean and did not require washing. Due to the amount of biomass collected, shoot biomass (Rosemount 2010 only) was stored in plastic bags at 6°C for up to 2 d before washing, while root biomass (both experiments) was stored for up to 3 wk. Both root and shoot biomass were dried in a forced-air dryer at 60°C before weighing.

Dried biomass from each plot was coarsely ground, mixed thoroughly, and a subsample was finely ground. Root and shoot biomass were ground and analyzed separately. Nitrogen concentration of ground biomass was determined by combustion for four accessions from Exp. 1 in 2010 (Pacific Gold, Pasja, GroundHog, and Dwarf Essex). For all other accessions from this experiment and all samples from Exp. 2, N concentration was determined by near infrared reflectance spectroscopy (NIR) with an automated analyzer (DA 7250 NIR analyzer, Perten Instruments, Inc., Springfield, IL). In some cases, not enough tissue was available to analyze a sample using NIR. These samples were instead analyzed by combustion with a N/C analyzer (Carlo Erba 1500, CE Elantech, Inc., Lakewood, NJ) at Brookside Laboratories, New Knoxville, OH. Nitrogen accumulation was calculated as biomass multiplied by N concentration.

Standard NIR equations for N concentration in brassica biomass were not available. Therefore, a subset of samples from this experiment and other concurrent brassica cover crop experiments was also analyzed by combustion, as described above. The NIR and combustion data were sent to Perten Instruments, Inc., where they were used to develop NIR prediction equations (Neuhausen et al., 1988). Separate equations were developed for brassica root tissue ($R^2 = 0.96$, $SE_{prediction} = 0.15$) and shoot tissue ($R^2 = 0.96$, $SE_{prediction} = 0.28$).

Brassica winter survival data were collected in Exp. 1 each year (Table 2). In 2010–2011, stand counts were made in replicates 2 to 4 at the fall biomass sampling date and in the spring before the field was tilled. In 2011–2012, winter survival was visually rated in the spring before the field was tilled. Cold winter temperatures completely killed all accessions of brown mustard, white mustard, and radish in both years. Winter survival of rapeseed was 7% in 2010–2011 and 88% in 2011–2012, while winter survival of hybrid turnip was 12% in 2010–2011 and 1% in 2011–2012.

In Exp. 1, soil nitrate N to 60 cm was measured before oat planting and again in May when the oat crop was at Feekes stage 1 to 2 in both years, and also in June at Feekes stage 10.1 to 10.54 in 2012. In Exp. 2, soil nitrate N to 60 cm was measured at three sampling dates: in late fall after cover crop biomass harvest, in spring immediately before corn planting, and in summer when the corn was at the V7–V8 growth stage. Soil was sampled from the zero-N subplots only, except at Rosemount in the fall of 2010, when a single composite sample was taken from each main plot.

At St. Paul (Exp. 1) and Rosemount (Exp. 2), soil cores were taken by hand in 30-cm increments using a standard 1.9-cm diam. soil probe. At least three cores were taken per plot. At Lamberton (Exp. 2), fall and spring soil samples were taken using a tractor-mounted hydraulic soil corer and divided into 30-cm increments. One core was collected per subplot in fall 2010, and two cores per subplot at all other sampling dates. The V7–V8 soil samples were taken by hand, following the same procedures used at Rosemount.

Soil samples were dried in a forced-air dryer at 35°C and then stored at room temperature until they were processed, with two exceptions. Samples from the fall sampling date at Rosemount in 2010 were dried on a greenhouse bench at ambient temperature, and samples from the spring sampling date at Rosemount in 2012 were frozen before drying due to a dryer malfunction. Dried samples were ground or sieved to pass a 2 mm screen, then analyzed for nitrate concentration on a volumetric basis via KCl extraction followed by Cd reduction and colorimetry at Agvise Laboratories, Benson, MN.

In Exp. 1, oat biomass samples were collected concurrent with May and June soil samples in 2012. A single 0.25 m^2 quadrat was clipped within 5 cm of the ground. Biomass was dried at 60°C. In 2012, oat biomass from the treatments selected for soil analysis was ground and analyzed for N content by combustion as described above. To determine oat grain yield, a 4.1 to 7.4 m^2 section of each plot was harvested in mid- to late July using a plot combine (Table 2). Grain was dried at 60°C in 2011 and 49°C in 2012.

In Exp. 2, corn biomass N concentration was determined by collecting aboveground biomass of 10 plants per plot from the zero-N subplots concurrent with the summer soil sampling (Table 3). Plants were selected randomly from the second and fifth rows of each six-row plot. Biomass was dried at 60°C and ground in the same way as brassica biomass. Nitrogen concentration was determined by combustion using an organic elemental analyzer (ThermoFinnigan FlashEA, Thermo Fisher Scientific Inc., Waltham, MA) in 2011 and a N/C analyzer (Carlo Erba 1500) in 2012. Corn grain yield was measured in October by harvesting a 4.6 to 12.2 m^2 section of each plot by combine. All yields were adjusted to 15.5% moisture. Corn grain yield data were used to create N response curves for both the radish and no-cover treatments and to determine the effect of the radish cover crop on grain yield.

Weather Conditions

Air temperature and precipitation data were obtained from weather stations located at the experiment stations via an interactive online tool (Minnesota Department of Natural Resources Staff, 2015). For each site, the 1981 to 2010 climate normals were used as the baseline. Soil temperature data for Exp. 2 were obtained from temperature probes (Onset Computer Corporation, Bourne, MA) installed at the experiment stations within 1 km of the fields used in this research. Probes were installed 2.5 cm below the soil surface under radish cover in November of each year and removed the following May.

Experiment 1

Temperature and precipitation data for Exp. 1 are presented in Fig. 1. Fall precipitation was 347 mm (135% of the 1981–2010 average) in 2010 and 179 mm (70% of normal) in 2011. Average air temperature was normal to cooler than normal in September, but warmer than normal in October. The winter of 2010–2011 was colder than normal, while the winter of 2011–2012 was warmer than normal. There was continuous snow cover from 4 Dec. 2010 to 19 Mar. 2011, with an average snow depth of 320 mm over that period. In 2011–2012, by contrast, snow cover was sparse and sporadic. April–July precipitation was 560 mm (142% of normal) in 2011 and 491 mm (124% of normal) in 2012. These high precipitation totals were attributable mostly to a few large storms in July 2011 and May 2012. April–June temperatures were cooler than normal in 2011 and slightly warmer than normal in 2012, while July was warmer than normal in both years.

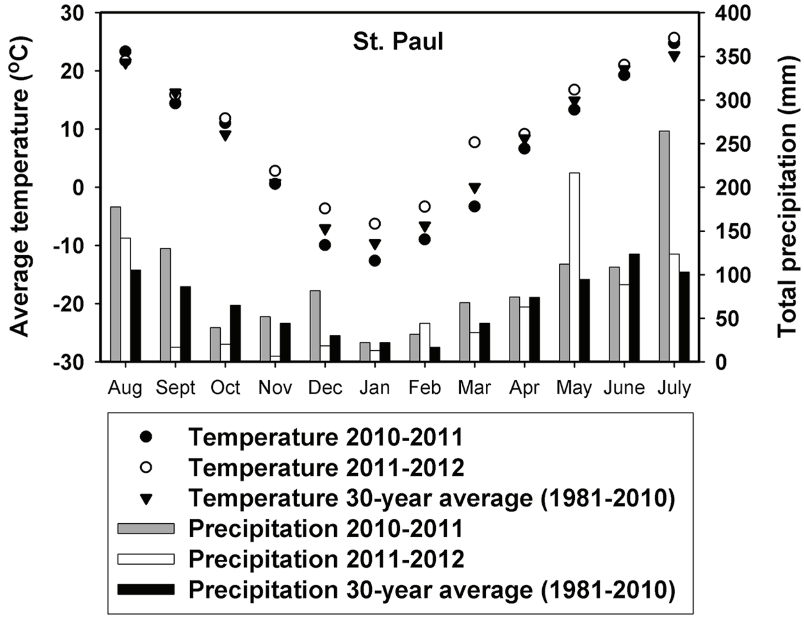

Fig. 1. Monthly average temperature and total precipitation at St. Paul, MN (Exp. 1).

Experiment 2

Temperature and precipitation data for Exp. 2 are presented in Fig. 2. Precipitation during the cover crop growing season (August–October) was greater than normal in 2010 but less than normal in 2011. At Lamberton, the fall of 2011 was the driest on record, with August to October precipitation measuring only 33 mm (14% of normal). Average air temperature was normal to cooler than normal in September and warmer than normal in October.

The period from the end of the cover crop growing season until corn planting (November–April) was colder than normal in 2010–2011, but warmer than normal in 2011–2012. In 2010–2011, snow cover was present from 30 November to 28 March at Lamberton and from 1 December to 17 March at Rosemount, with snow depth generally exceeding 20 cm. In 2011–2012, snow cover was sparse and sporadic, and snow depth did not exceed 10 cm. May–July precipitation was normal to greater than normal at both locations in 2011 and at Rosemount in 2012. At Lamberton in 2012, precipitation during the corn growing season was unevenly distributed. May 2012 precipitation at Lamberton was more than three times the 30-yr average, but soil moisture levels did not reach the historic (1966–2011) average, and dry conditions occurred in June and July. Average air temperature was normal to slightly cooler than normal in May and June 2011, but warmer than normal in July 2011 and May–July 2012. Air temperature returned to normal in August and September.

In 2010–2011, data from soil temperature probes showed that the soil in radish plots at both locations froze between 20 and 23 November and remained frozen until mid- to late March. During this period, the soil temperature generally remained between 0 and –2°C. After 1 April, however, soil temperature often exceeded 10°C. In 2011–2012, the soil at both locations froze for the first time between 16 and 17 November, but did not remain frozen. Soil temperatures fluctuated from –11°C to 7°C at Lamberton and from –12°C to 3°C at Rosemount until the last snowfall of the season melted in early March, after which soil temperatures rose rapidly, often exceeding 10°C.

Statistical Analysis

Experiment 1

All variables were analyzed in SAS Proc Glimmix (SAS Version 9.3, SAS Institute, Cary, NC) using an analysis of variance appropriate for a randomized complete block design. Replication effects were random, while all other effects were fixed. An initial analysis of variance showed significant year × treatment interactions for several variables. Therefore, results were analyzed by year. Differences between accessions within a species were not statistically significant. Differences between species or between each species and the control were tested using single degree of freedom contrasts. The Šidàk correction was applied to control family-wise error rate at the stated level (0.05, 0.01, or 0.001). Changes in PAN were analyzed using a repeated measures ANOVA followed by slice statements.

Experiment 2

Fall, spring, and V8 soil nitrate, V8 corn biomass N concentration, and corn grain yield were analyzed using SAS Proc Mixed (Version 9.3, SAS Institute, Cary, NC). Replication effects were random, while all other effects were fixed. Initial analyses showed treatment × year and treatment × location interactions for corn grain yield, and treatment × year or treatment × location × year interactions for several other variables. For corn grain yield, these interactions were due to severe drought conditions at Lamberton in 2012, which resulted in low and variable yields with no response to N. Therefore, yield data from Lamberton in 2012 were analyzed separately, while yield data from the other three environments were pooled for analysis. For other variables, data were analyzed by year where there was no location × treatment interaction within a year, and by location within year where there was a location × treatment interaction. Corn grain yield response to N fertilizer was analyzed by fitting linear, quadratic, linear-plateau, quadratic-plateau, and exponential models. Linear and quadratic models were fitted with SAS Proc Reg, while the other models were fitted with SAS Proc Nlin. The quadratic model was chosen because it had the lowest mean

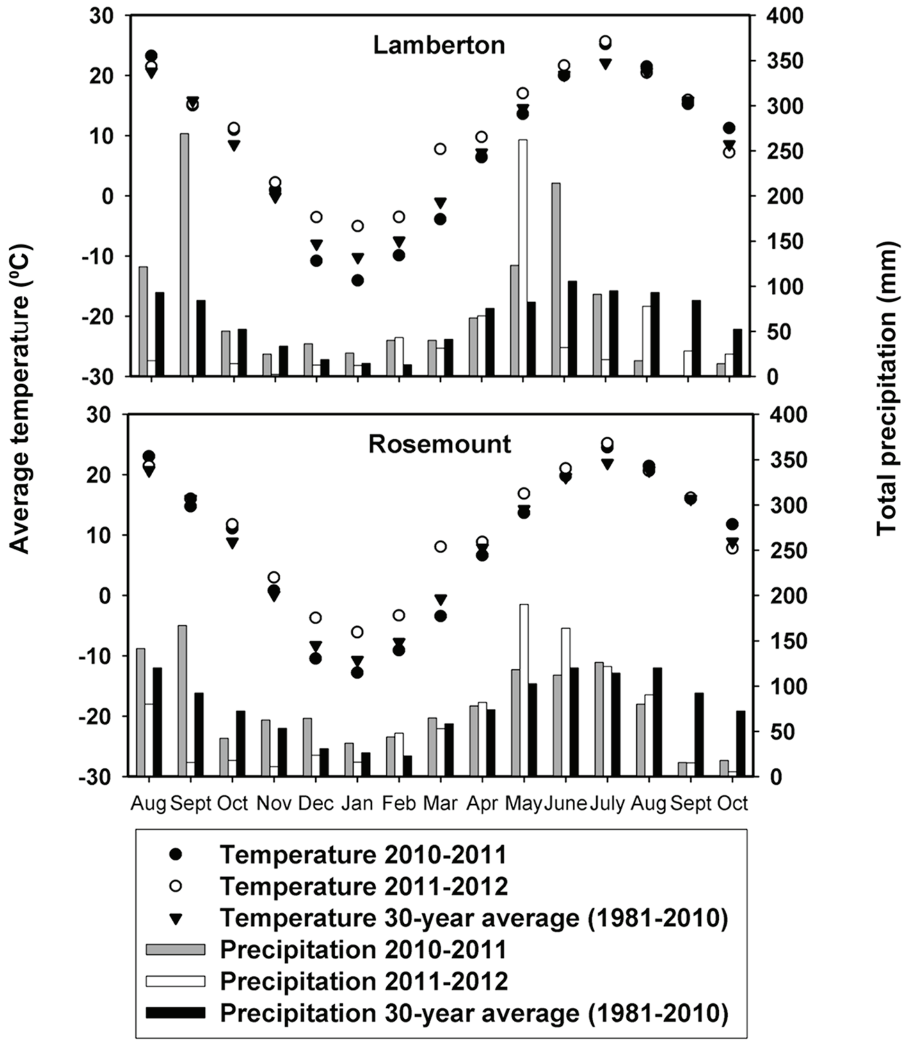

Fig. 2. Monthly average temperature and total precipitation at Lamberton and Rosemount, MN (Exp. 2).

square error of the five models and residuals were randomly and approximately normally distributed.

RESULTS AND DISCUSSION

Cover Crop Performance

Experiment 1

Average end-of-season cover crop biomass was 6170 kg ha^{-1} in 2010 and 4838 kg ha^{-1} in 2011 (Table 5). Biomass did not differ between species in either year. Average N accumulation was 136 kg ha^{-1} in 2010 and 130 kg ha^{-1} in 2011. Nitrogen accumulation differed between species only in 2011, when radish had greater N accumulation than brown mustard or hybrid turnip (Table 5). These biomass and N accumulation results fell in the upper end of the range reported in the literature (Stivers-Young, 1998; Isse et al., 1999; Dean and Weil, 2009; Wang et al., 2010).

Experiment 2

The radish cover crop was established successfully at both locations in both years, grew vegetatively over the fall, and was killed by cold winter temperatures. Radish biomass production ranged from 1160 to 3536 kg ha^{-1}, while N accumulation ranged from 31 to 92 kg ha^{-1} (Table 6). These results were similar to values reported for New York (Stivers-Young, 1998), Ontario (Vyn et al., 1999, 2000), and Quebec (Isse et al., 1999), but lower than some values reported for Maryland (Weil and Kremen, 2007; Dean and Weil, 2009) and Denmark (Thorup-Kristensen, 1994). Of the N accumulated by the radish cover crop and recovered by sampling, the majority (71% or more) was in the shoot tissue. This result agreed with observations by Isse et al. (1999), Axelsen and Thorup-Kristensen (2000), and Dean and Weil (2009).

In 2010, biomass production and N accumulation did not differ between locations (biomass: $F_{1,5} = 1.22$, $P = 0.3192$; N: $F_{1,5} = 0.46$, $P = 0.5261$), but in 2011 both were lower at Rosemount than at Lamberton (biomass: $F_{1,6} = 20.98$, $P = 0.0038$; N: $F_{1,6} = 31.03$, $P = 0.0014$). This difference may have been due to the effects of drought and soil type. The fall of 2011 was very dry at both sites, but the clay soil at Lamberton has a greater water-holding capacity than the soil at Rosemount, which is a silt loam over coarse gravel. The radish cover crop at Rosemount in 2011 showed the effects of drought stress in poor growth and early senescence of the older leaves. Biomass production and N accumulation were therefore reduced in this environment, but may also have been underestimated, as it was not possible to include shed leaves in the collected biomass samples.

Table 5. Total biomass production and N accumulation of brassica cover crop species at St. Paul, MN, in 2010 and 2011 (Exp. 1).

Cover crop	Biomass production		N accumulation	
	2010	2011	2010	2011
	kg ha^{-1}			
Brown mustard	6850a†	4531a	122a	97b
Rapeseed	6460a	4513a	151a	122ab
Hybrid turnip	5105a	4473a	121a	99b
Radish	5822a	4993a	145a	143a
White mustard	6920a	5025a	123a	135ab

† Within a column, means followed by the same letter do not differ according to single degree of freedom contrasts (α_{family} = 0.05, Šidàk correction).

Table 6. Radish biomass and nitrogen accumulation in 2010 and 2011 at Lamberton and Rosemount, MN (Exp. 2). All data are from the zero-N treatment.

Plant part	2010–2011		2011–2012	
	Lamberton	Rosemount	Lamberton	Rosemount
	Dry biomass, kg ha^{-1}			
Root	933 (326)†	1010 (305)	1130 (148)	490 (218)
Shoot	2602 (653)	1860 (254)	1940 (618)	670 (285)
Total	3536 (939)	2870 (490)	3070 (572)	1160 (502)
	N accumulation, kg N ha^{-1}			
Root	13 (7)	23 (2)	23 (9)	9 (4)
Shoot	59 (22)	61 (12)	69 (20)	22 (9)
Total	72 (29)	84 (10)	92 (15)	31 (12)

† Means are followed by standard deviations in parentheses.

Table 7. Effect of brassica cover crop species on spring and summer soil nitrate N (0–60 cm) and oat N accumulation at St. Paul, MN, in 2011 and 2012 (Exp. 1).

Cover crop	Soil nitrate					Oat N accumulation	
	2011		2012			2012	
	Apr.	May	Apr.	May	June	May	June
	kg N ha^{-1}						
Brown mustard	21*	34	43***	55***	4*	9	67***
Rapeseed	25	35	20***	59***	5	10	82***
Hybrid turnip	28	43	36***	49***	4*	9	71***
Radish	26	49	40***	61***	4**	10	84***
White mustard	22	28*	45***	65***	4*	9	81***
Control	29	43	169	155	7	10	161

* Significantly different from the control at the 0.05 probability level.
** Significantly different from the control at the 0.01 probability level.
*** Significantly different from the control at the 0.001 probability level.

Table 8. Effect of brassica cover crop species on oat biomass and grain yield at St. Paul, MN, in 2011 and 2012 (Exp. 1).

Cover crop	Oat biomass		Oat grain yield	
	2012		2011	2012
	May	June	July	July
	kg ha^{-1}			
Brown mustard	205	6234***	2407*	1986
Rapeseed	200	6514**	3041	2089*
Hybrid turnip	200	6771**	3054	1886
Radish	217	7459*	3489**	2094**
White mustard	210	7149**	2375*	2237**
Control	210	8714	2896	1516

* Significantly different from the control at the 0.05 probability level.
** Significantly different from the control at the 0.01 probability level.
*** Significantly different from the control at the 0.001 probability level.

Soil Nitrate and Biomass, Nitrogen Accumulation, and Yield of the Rotational Crop

Experiment 1

At oat planting in April, cover crops had little effect on soil nitrate levels in 2011, but reduced soil nitrate substantially in 2012 (Table 7). Soil nitrate N level (0–60 cm) in the control at oat planting was relatively low in 2011 at 29 kg ha^{-1}, but very high in 2012 at 169 kg ha^{-1}. The difference between years may be due to differing weather conditions: the period from August to April was wetter than normal in 2010–2011, but drier than normal in 2011–2012 (Fig. 1). Thus, the potential for nitrate leaching would have been higher in 2010–2011 than in 2011–2012. The high soil nitrate level in the control in April 2012 also reflected the high soil fertility of this site, which had a history of frequent (every 3–4 yr) manure application. In April 2011, brown mustard reduced soil nitrate N by 8 kg ha^{-1}, while other cover crop species did not affect soil nitrate. In 2012, in contrast, every cover crop species reduced soil nitrate N levels relative to the control by at least 124 kg ha^{-1}. This result suggests that the brassica cover crops effectively removed N from the soil during the fall growing season, but this N was not released from the brassica biomass at the time of planting. The N accumulated by the brassicas may have been lost from the system over the winter, or it may have been retained in the decomposing biomass until after oat planting.

These effects on soil nitrate persisted in May. In 2011, white mustard reduced May soil nitrate N by 15 kg ha^{-1} relative to the control, while other species had no effect on soil nitrate (Table 7). In 2012, all cover crops reduced May soil nitrate N by 90 kg ha^{-1} or more relative to the control (Table 7). Since the oat crop was at Feekes stage 1 to 2 at the time of soil sampling, oat N accumulation was expected to be minimal. In accordance with this expectation, data collected in May 2012 showed that oat N accumulation was only 9 to 10 kg ha^{-1} and did not differ between cover crop treatments (Table 7). Therefore, soil nitrate provides a reasonable measure of the effect of cover crops on N availability at this stage in oat development. May 2012 oat biomass was not affected by cover crops (Table 8).

In 2012, additional soil and biomass sampling showed that the negative effect of the cover crops on N availability continued through June (Tables 7 and 8). Soil nitrate N was 7 kg ha^{-1} or less in all treatments at the June sampling date. All cover crop species reduced oat biomass and N accumulation in June 2012, consistent with their effects on April and May soil nitrate. Interestingly, plant-available N, estimated as the sum of 0 to 60 cm soil nitrate and aboveground biomass N, was constant from April to June of 2012 in the control ($F_{2,40} = 0.07$, $P = 0.9349$), but increased over the same time period in each of the cover crop treatments ($F_{2,40} \geq 5.13$, $P \leq 0.0104$). The greater increase in plant-available N in the cover crop treatments relative to the control suggests that a portion of the N taken up by the cover crops was released between planting and heading, though not enough to raise N availability to the level seen in the control.

The effect of the cover crops on oat grain yield differed between years. In 2011, both mustard species reduced oat yield relative to the control, while radish increased yield (Table 8). Although differences in soil nitrate levels between the cover crop treatments and the control generally were not statistically significant, trends suggest that the effects of the cover crops on oat yield may have been related to N availability. In 2012, radish, rapeseed, and white mustard increased oat yield, despite their negative effects on soil nitrate and oat biomass earlier in the growing season. This unexpected result may have been due to extensive lodging which occurred in the control and may have reduced its yield.

Experiment 2

Soil nitrate level at the end of the fall cover crop growing season was lower in the radish treatment than in the no-cover control in both years (Table 9). Averaged across locations, the radish cover crop reduced late fall soil nitrate N by 49 kg ha^{-1} in

Table 9. Effect of a radish cover crop on late fall, spring, and V8 soil nitrate-N and V8 corn N accumulation at Lamberton and Rosemount, MN (Exp. 2). All data are from the zero-N treatment, except at Rosemount in fall of 2010, when a single composite soil sample was taken from each main plot.

	2010–2011			2011–2012		
Treatment	Lamberton	Rosemount	Mean	Lamberton	Rosemount	Mean
			Late fall soil nitrate N (60 cm), kg N ha^{-1}			
No cover	67	66	66	99	82	91
Radish	10	25	17	62	15	38
P > *F*	0.0003	0.0990	0.0014	0.2029	0.0007	0.0043
			Spring soil nitrate N (60 cm), kg N ha^{-1}			
No cover	48	43	46	147	105	126
Radish	22	33	27	90	53	72
P > *F*	0.0057	0.0864	–†	0.0148	0.0039	0.0002
			V8 soil nitrate N (60 cm), kg N ha^{-1}			
No cover	34	19	27	152	78	115
Radish	31	20	25	112	57	84
P > *F*	0.6124	0.6376	0.7358	0.1425	0.1608	0.0396
			V8 corn biomass N concentration, %			
No cover	2.0	2.5	2.2	3.5	3.5	3.5
Radish	2.2	2.7	2.4	3.6	3.1	3.4
P > *F*	0.1746	0.0974	0.0512	0.3561	0.1094	–

† *P* value not shown because the cover crop × location interaction was significant (*P* = 0.0487).

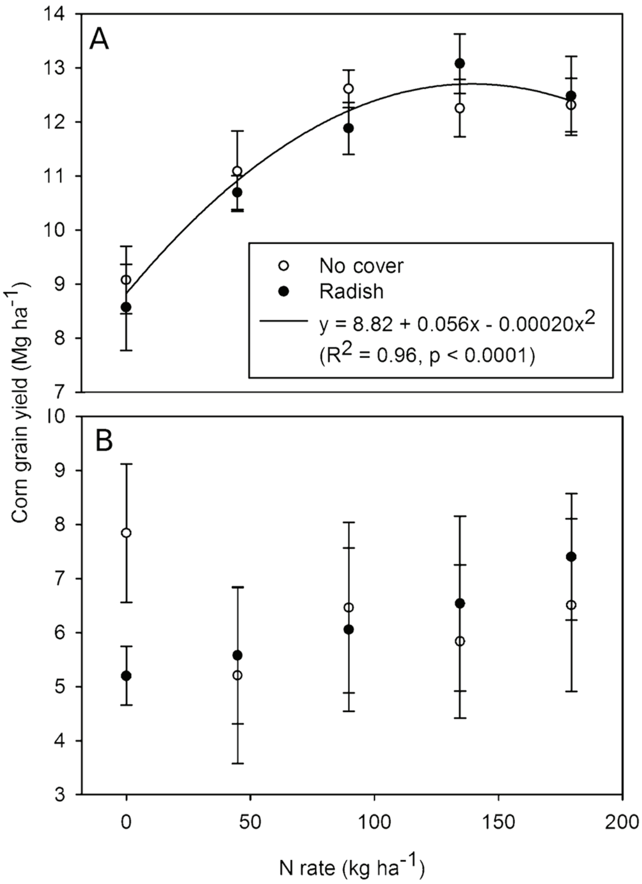

Fig. 3. Effect of nitrogen rate on corn grain yield (Exp. 2). (A) Means presented are averaged over three environments (Lamberton 2011, Rosemount 2011, and Rosemount 2012). (B) Means at Lamberton in 2012. Due to drought, there was no response to N. Error bars denote standard error of the mean.

2010 and 53 kg ha^{-1} in 2011. These results confirm the ability of the radish cover crop to remove available N from the soil.

The radish cover crop winterkilled in both years. At the time of corn planting in April or May, the radish residue had largely decomposed. However, soil nitrate results show that little of the N accumulated by the radish cover crop was available at corn planting.

In 2010–2011, there was a net loss of 21 kg nitrate N ha^{-1} between the fall and spring sampling dates in the control, but a net gain of 10 kg ha^{-1} in the radish treatment (Difference between cover crop treatments: $F_{1,6} = 13.80$, $P = 0.0099$). However, soil nitrate N at planting was still lower in the radish treatment than in the control, with a difference of 26 kg ha^{-1} at Lamberton and 11 kg ha^{-1} at Rosemount (Table 9).

In 2011–2012, the change in soil nitrate N between the fall and spring sampling dates did not differ between the radish treatment and the control ($F_{1,6} = 0.02$, $P = 0.8848$), with a net gain of 34 kg nitrate N ha^{-1} averaged across treatments and locations. This lack of difference suggests that the gain in soil nitrate in the radish treatment over this time period was entirely due to mineralization from the soil organic matter. Soil nitrate N at planting averaged 54 kg ha^{-1} lower in the radish treatment than in the no-cover control. The difference between years is probably related to differing weather conditions; the winter of 2010–2011 began with a moisture surplus, while the winter of 2011–2012 began with a moisture deficit due to the extremely dry fall (Fig. 2).

In 2011, the radish cover crop had no effect on V8 soil nitrate level (Table 9). In 2012, however, the radish cover crop reduced V8 soil nitrate N by an average of 31 kg ha^{-1} (Table 9). The radish cover crop did not affect V8 corn biomass N concentration in either year of the study (Table 9).

Yield data from the three site years with adequate moisture (Lamberton 2011, Rosemount 2011, and Rosemount 2012) showed that the radish cover crop did not affect corn grain yield ($F_{1,9} = 0.13$, $P = 0.7290$), nor was there an interaction between cover crop treatment and N fertilizer rate ($F_{4,68} = 0.61$, $P = 0.6565$). In these site-years, the response to N was quadratic (Fig. 3). At Lamberton in 2012, where corn yield was affected by severe drought conditions, neither cover crop nor N rate nor the interaction between them affected corn grain yield (cover: $F_{1,3} = 0.06$, $P = 0.8156$; N rate: $F_{4,24} = 0.86$, $P = 0.5034$; interaction: $F_{4,24} = 1.37$, $P = 0.2751$). Yield in this site-year averaged 6.26 Mg ha^{-1} across treatments (Fig. 3).

In 2011, with its relatively wet fall and winter, brassicas had no effect or a negative effect on N availability and crop N accumulation. In Exp. 1, N availability was higher following the radish cover crops, which decomposed quickly, than following the mustards, which decomposed more slowly. This suggests that reduced N availability in the mustard treatments relative to the control was due to slow mineralization of N from the mustard residue, rather than to increased losses over the winter.

In 2012, high soil nitrate levels at planting in both experiments (Tables 7 and 9) suggest that N leaching losses were low due to the dry fall (Fig. 1 and 2). Under these circumstances, it is not surprising that all cover crops reduced N availability and crop N accumulation relative to the control, though the magnitude of their effect is larger than expected. While the effect of the mustard, turnip, and rapeseed cover crops could have been due to too-late mineralization of the scavenged N, it seems unlikely that most of the N taken up by the radish cover crops mineralized too late, given the extent to which the residue had decomposed by spring.

It is possible that the radish cover crop increased denitrification or volatilization losses. Petersen et al. (2011) found that under winter freeze–thaw conditions, a radish cover crop decomposing on the soil surface caused a small but consistent increase in nitrous oxide emissions. Even under aerobic conditions, decaying organic matter can create hotspots for denitrification (Parkin 1987). By moving N upward and depositing it at the soil surface, the radish cover crop could have increased the risk of ammonia volatilization as well. Research by de Ruijter et al. (2010) showed that under freeze–thaw conditions, radish shoot biomass lost 4 to 6% of its total N as ammonia after 37 d and 7 to 11% after 119 d.

In this research, brassica cover crops planted to scavenge N did not increase N availability or crop biomass or N accumulation in the following cropping season, nor did they affect crop response to applied N fertilizer. While the use of these cover crops did sometimes increase crop grain yield, yield increases were not linked to increased N availability. Thus, although brassica cover crops can accumulate impressive amounts of N, it cannot be assumed that the N they accumulate will be saved from losses or will be available to the following year's crop. The interaction between environment and cover crop effect should be studied further so that cover crops can be incorporated into cropping systems where they are most likely to provide a net benefit. The pathways and timing of N losses from cover crops, including the possibility that brassica cover crops increase gaseous N losses, should also be investigated.

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