RADISH AND OTHER BRASSICA COVER CROP EFFECTS ON NITROGEN AVAILABILITY AND WEED MANAGEMENT

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Dedication

To my grandparents, Bussie and Loretta Gieske and Myer and Evelyn Horowitz. You are my inspiration.

Abstract

Use of radish (*Raphanus sativus* L.) and other brassica species as cover crops has increased in the US Midwest in recent years, as farmers seek new ways to reduce nitrogen losses and manage weeds. Brassicas can take up large amounts of nitrogen quickly, but their effects on nitrogen available to subsequent crop are mixed. Fall-seeded radish cover crops suppress fall weed growth. Little is known about the ability of spring-seeded radish to suppress weeds.

The first objective of this research was to determine the effects of radish seeding date (mid-August [Date 1], late August [Date 2], mid-September [Date 3], late September [Date 4]), accession, and seeding rate (4.1 to 22.4 kg ha^{-1}) on canopy cover, biomass, and nitrogen accumulation of a fall-seeded radish cover crop. To accomplish this objective, two-year field experiments were established at St. Paul and Lamberton, MN in 2010 and 2011. The effect of seeding date was larger and more consistent than the effects of accession and seeding rate. At St. Paul, radish cover was ≥ 79% for all rates and accessions at seeding dates 1-3, but ≤ 59% at Date 4. Delaying seeding decreased radish biomass by 143 kg ha^{-1} day^{-1}. Total nitrogen accumulation averaged 96-225 kg ha^{-1} at Date 1 and 57-132 kg ha^{-1} at Date 3. At Lamberton, severe drought resulted in poor radish growth at Dates 2-4. In Minnesota, radish cover crops should be planted by mid-September at 5 kg ha^{-1}.

The second objective of this research was to determine the effect of fall-seeded brassica cover crops on nitrogen availability in the subsequent growing season. Two-year field experiments were established at St. Paul, Rosemount, and Lamberton, MN in 2010 and 2011. Brassica cover crops accumulated large amounts of nitrogen, up to 151 kg ha^{-1}. In 2010-2011, a wet year, they had little effect on nitrogen availability in the subsequent growing season, but in 2011-2012, a dry year, they reduced nitrogen availability. Brassica cover crops have the potential to reduce nitrogen leaching, but their failure to increase later nitrogen availability suggests that nitrogen taken up by the cover crops is not available when the subsequent crop needs it.

The third objective of this research was to determine the effect of fall- and spring-seeded radish cover crops on the density, cover, and biomass of weeds in organically-managed corn. Again, two-year field experiments were established at Rosemount and Lamberton, MN. Spring-seeded radish does not appear feasible as a cover crop in Minnesota. Shoot biomass of spring-seeded radish averaged 385 kg ha^{-1}, compared to 3057 kg ha^{-1} for fall-seeded radish in the same fields. Effects of radish cover crops on weed density, cover, and biomass were inconsistent. The effect of fall-seeded radish ranged from a 44% decrease in August weed cover to an 88% increase in June weed density in the reduced tillage treatment relative to plots without fall-seeded radish. The effect of spring-seeded radish ranged from a 46% decrease in June weed density to a 94% increase in August non-crop biomass. Radish cover crops are unlikely to improve management of summer annual weeds in organic systems over the short term.

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Literature review

Characteristics of radish and other brassica cover crop species

A member of the family Brassicaceae, radish (*Raphanus sativus* L.) is a fast-growing, cool season plant with a large, fleshy taproot which often protrudes from the ground. Radish is frost-tolerant, but winterkills when the temperature drops to -5°C or below for several nights in a row (Weil et al., 2009). Decomposition over the fall, winter, and spring results in little residue remaining at the beginning of the next cropping season (Lawley et al., 2011; Stivers-Young, 1998). Radish taproots can grow up to 2.4 m deep in just 11 weeks, which allows radish to scavenge nitrogen from deep in the soil profile (Dean and Weil, 2009; Kristensen and Thorup-Kristensen, 2004). Its deep taproot also relieves soil compaction by creating root channels that subsequent crops can use to access subsoil moisture and nutrients (Chen and Weil, 2011; Williams and Weil, 2004). Radish cover crops quickly form a closed canopy, which suppresses winter annual weeds (Lawley et al., 2011) and reduces soil erosion. Research has also shown that some radish varieties are useful for control of plant-parasitic nematodes (Smith et al., 2004; Wang et al., 2010).

Other brassica species used as cover crops include *Brassica juncea* (L.) Czern. (brown or Oriental mustard), *B. rapa* L. (turnip, rapeseed, canola), *B. napus* L. (rapeseed, canola), and *Sinapis alba* L. (white or yellow mustard). Chen et al. (2007) describe these species in the publication *Managing Cover Crops Profitably.* Like radish, other brassicas are fast-growing, cool-season annuals with some frost tolerance. Turnip, rapeseed, and canola have long taproots, while mustards have shallower, more fibrous root systems.

Like radish, mustards are generally not winter hardy in northern climates. Winter-hardiness varies between accessions of rapeseed and canola.

When planted by mid-September, radish can produce over 8000 kg ha^{-1} total biomass and take up over 300 kg ha^{-1} nitrogen (Dean and Weil, 2009; Wang et al., 2008), though values of 3000-5000 kg ha^{-1} for biomass production and 50 - 100 kg ha^{-1} for nitrogen accumulation are more typical (Dean and Weil, 2009; Isse et al., 1999). About 70% of the nitrogen accumulated is contained in the shoot biomass (Dean and Weil, 2009). Other brassica species have similar biomass production and nitrogen accumulation (Stivers-Young, 1998; Wang et al., 2010).

Effect of seeding date and rate on brassica and other cover crops

Date of planting strongly influences biomass production and nitrogen accumulation of cover crops. In general, seeding later in the fall decreases the biomass and nitrogen accumulation of cover crops, as temperature and light levels decline (Gselman and Kramberger, 2008; Vos and van der Putten, 1997). Stivers-Young found aboveground radish biomass declined from 3947 to 2694 kg ha^{-1} when seeding was delayed from 3 to 16 September, a decrease of 96 kg ha^{-1} day^{-1}. Sheldrick et al. (1981), on the other hand, found radish biomass decreased by 17 kg ha^{-1} day^{-1} when seeding was delayed from mid-July to mid-August. For kale (*Brassica oleracea* L.), the effect of a delay in seeding increases later in the season; delaying seeding from 20 May to 17 June reduced biomass by approximately 1000 kg ha^{-1}, while delaying seeding from 25 July to 24 August reduced biomass by approximately 6000 kg ha^{-1} (Kunelius et al., 1987). The same may be true for radish, although the difference between the findings of Stivers-Young and Sheldrick et al. could also be due to other differences between their experiments. Keogh et al. (2012) reported a 108 to 124 kg ha^{-1} day^{-1} reduction in biomass of rape when seeding was delayed from 1 to 31 August. Stivers-Young (1998) reported that radish seeded 3 September accumulated 128 kg ha^{-1} nitrogen in its aboveground biomass, while radish seeded 16 September accumulated only 91 kg ha^{-1}, a decrease of 2.8 kg ha^{-1} day^{-1}. In comparison, Vos and van der Putten (1997) reported an average reduction in total (root and shoot) nitrogen accumulation of 3.4 kg ha^{-1} day^{-1} for rapeseed, rye (*Secale cereale* L.), and radish cover crops. Current extension publications from Michigan (Ngouajio and Mutch, 2004) and Maryland (Weil et al., 2009) recommend seeding radish in late summer to early fall, but published information is lacking concerning the effect of seeding date on radish biomass and nitrogen accumulation in the US Midwest.

Research on the effect of seeding rate on radish cover crop biomass and nitrogen accumulation is also lacking, and current recommended seeding rates for drilled radish cover crops vary widely, from 6.7 to 22.4 kg ha^{-1} (Gruver et al., 2012; Ngouajio and Mutch, 2004). The effect of seeding rate on biomass and nitrogen accumulation of other cover crop species varies. In experiments with a mustard mix [*Brassica juncea* (L.) Czern. and *Sinapis alba* L.], increasing the seeding rate to three times the level typically used by farmers did not affect mustard biomass or nitrogen accumulation (Brennan and Boyd, 2012a,b). However, increasing the seeding rate of canola (*Brassica napus* L.) increased early season biomass production (McCormick et al., 2012). Seeding rate can also affect residual soil nitrate after cover crop growth: increasing the seeding rate of an Italian ryegrass (*Lolium multiflorum* Lam.) cover crop drilled into pea (*Pisum sativum* L.) stubble increased biomass production and nitrogen accumulation and reduced residual soil nitrate (Kramberger et al., 2007). The effect of seeding rate may depend on seeding date; increasing the seeding rate of a simulated rye cover crop decreased nitrate leaching, but the effect of seeding rate was only important at the later of two seeding dates (van Dam, 2006).

Effect of cover crops on nitrogen availability

Managing nitrogen 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). Soil mineral nitrogen can be lost to the environment through multiple pathways, including leaching, denitrification, and ammonia volatilization (Robertson and Vitousek, 2009). One strategy for reducing agricultural nitrogen losses is the use of a cover crop to scavenge residual nitrogen 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 nitrogen is mineralized again. Assuming nitrogen mineralization occurs in synchrony with nitrogen demand by the subsequent crop, the increase in nitrogen availability can offset the cost of establishing the cover crop.

Although brassica cover crops can scavenge large amounts of nitrogen rapidly, their effects on the subsequent crop are mixed. In some cases, a radish cover crop increased the nitrogen accumulation, biomass production, or yield of the subsequent crop (Thorup-Kristensen, 1994; Vyn et al., 1999), while in others, the cover crop provided no benefit to the subsequent crop, even though radish nitrogen accumulation was high (Isse et al., 1999). Rapeseed and white mustard cover crops have also been shown to increase the nitrogen accumulation and biomass production or yield of the subsequent crop in some cases (Thorup-Kristensen, 1994; Weinert et al., 2002).

The lack of benefit seen in some studies may occur either because the nitrogen taken up by the cover crop mineralizes from the residue too slowly, or because it mineralizes too quickly. A nitrogen-scavenging cover crop initially reduces nitrogen availability by removing nitrate and ammonium from the soil. After the cover crop is killed, this nitrogen becomes available gradually as the cover crop residue decomposes. If mineralization of nitrogen from the residue occurs too slowly, the nitrogen scavenged by the cover crop may not be available when the subsequent crop needs it for growth and development. On the other hand, if mineralization occurs too quickly, the nitrogen 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 (Engel et al., 2011; Magid et al., 2004; Wagner-Riddle and Thurtell, 1998).

Both winterhardiness and C:N ratio of the cover crop affect the dynamics of nitrogen mineralization from the residue (Thorup-Kristensen, 1994; Trinsoutrot et al., 2000). The likelihood of nitrogen loss over the winter is highest with radish, which typically winterkills and has a low C:N ratio (Thorup-Kristensen, 1994). Winterkilled radish residue decomposes rapidly; 69-78% of the nitrogen content of radish biomass can be mineralized over the winter (Thorup-Kristensen, 1994; Vos and van der Putten, 2001). 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, nitrogen leached from the residue may travel below the rooting zone before the subsequent crop can take it up (Dean and Weil, 2009). By the same measure, though, too-slow mineralization of nitrogen is less likely to be a problem with radish than with other brassica cover crops. The higher C:N ratio and lignin content of mustards as compared to radish (Thorup-Kristensen, 1994) may result in slower release of nitrogen from mustard residue. 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 nitrogen to be released too slowly.

Effect of radish cover crops on weed control

Organic field crop producers in Minnesota and throughout the US consistently cite weed management as a major concern (Moynihan, 2010; Minnesota Department of Agriculture, 2007; Walz, 1999). Organic farmers manage weeds through a combination of mechanical tillage and ecological weed management strategies (Bond and Grundy, 2001). Ecological weed management focuses on redesigning cropping systems to reduce weed recruitment, increase crop competitiveness, and reduce the size of the weed seedbank (Bastiaans *et al*., 2008). Reliance on mechanical tillage for weed control is inherently risky, since effective mechanical weed control requires multiple precisely-timed cultivations, which can easily be disrupted by wet weather (Mohler, 2001; Posner et al., 2008; Porter et al., 2003; Cavigelli et al., 2008). By reducing weed populations and competitiveness, ecological weed management can mitigate this risk. One of the ecological weed management strategies available to organic farmers is cover cropping. Liebman and Davis (2000) suggest two ways cover crops can improve weed management in low external input systems: by reducing off-season weed seed production through competition, and by reducing weed recruitment during the cropping season through allelopathy or stimulation of plant pathogens that attack weed seeds and seedlings.

Radish cover crops may be useful as part of an ecological weed management system. Fall-seeded radish cover crops grow quickly but die over the winter, leaving a low-residue seedbed in the spring (Lawley et al., 2011). In small grain crops, post-harvest seed production accounts for a large portion of the seed rain (Kegode *et al.*, 2003). Fall-seeded radish consistently suppresses weed growth in the fall and early spring (Charles et al., 2006; Kruidhof et al., 2008; Lawley et al., 2011; O'Reilly et al., 2011, Stivers-Young, 1998) and has been shown to reduce weed seedbank size (Wang et al., 2008). However, weed suppression by fall-seeded radish generally does not persist into the following summer (Charles et al., 2006; Lawley et al., 2011, O'Reilly et al., 2011). Indeed, fall-seeded radish sometimes increases weed emergence during the following summer, perhaps due to its effect on soil nitrate levels (Charles et al., 2006; Lawley et al., 2011, 2012).

The potential of spring-seeded radish for weed control has not been studied.

Spring-seeded radish evidently has allelopathic or pathogen-promoting effects; emergence of direct-seeded muskmelon was reduced to zero where a radish cover crop was incorporated 7 to 8 days before muskmelon seeding (Ackroyd and Ngouajio, 2011). However, effects on weed emergence were not reported in this study. Other brassica cover crops seeded in spring have been reported to reduce weed emergence. A spring-seeded mustard mixture (*Brassica juncea* L. and *Sinapis alba* L.) incorporated into the soil reduced densities of annual grasses by 58-73% relative to a weedy check, but generally did not affect densities of broadleaf weeds (Norsworthy et al., 2005). In a field bioassay, incorporation of spring-seeded brassica cover crops (*Brassica napus* L. and *S. alba*) reduced average emergence of 16 bioassay species by 23 to 34% and delayed emergence by about 2 days, compared to a fallow control (Haramoto and Gallandt, 2005).

The mechanism of weed suppression may differ between fall- and spring-seeded radish cover crops. Like other members of the brassica family, radish contains glucosinolates in its tissues (Brown and Morra, 1997; Sang et al., 1984). The main degradation products of glucosinolates are isothiocyanates, several of which inhibit weed seed germination and seedling growth (Brown and Morra, 1997; Haramoto and Gallandt, 2004). In laboratory bioassays, extracts of fresh radish tissue reduced germination and radicle length of muskmelon, honeydew, and cucumber (Ackroyd and Ngouajio, 2011), while extracts of dried tissue inhibited germination and root growth of lettuce (Lawley et al., 2012). However, field trials of a fall-seeded radish cover crop and laboratory bioassays with extracts of decomposing radish residue and soil provided little evidence for allelopathy; thus, Lawley et al. (2012) attributed weed suppression by fall-seeded radish cover crops to competition during the fall growing season rather than allelopathic effects. The lack of allelopathic effect seen in trials with fall-seeded radish may be due to rapid loss of isothiocyanates from the soil (Brown and Morra, 1997; Petersen et al., 2001); by the time weed seeds begin germinating in the spring, any allelochemicals from the radish biomass may be gone. Incorporation of spring-seeded radish immediately before crop planting may be more effective for allelopathic suppression of weeds, though the risk of allelopathy towards the crop must be studied.

Chapter 1

Radish Cover Crop Effects on Nitrogen Availability and Corn (*Zea mays* L.) Yield

Radish Cover Crop Effects on Nitrogen Availability and Corn (*Zea mays* L.) Yield

SUMMARY

Cover crops can scavenge residual soil nitrate and recycle it, reducing nitrogen losses from agricultural fields and increasing nitrogen availability for the next crop. Radish (*Raphanus sativus* L.) can take up large amounts of nitrogen rapidly. Effects of fall-planted radish on soil nitrate levels, corn (*Zea mays* L.) nitrogen accumulation, and corn grain yield and response to nitrogen in an oat (*Avena sativa* L.)-corn rotation were evaluated in 2010 and 2011 at two southern Minnesota locations. Radish was planted into tilled oat stubble in mid-August. Where residual nitrate-nitrogen was less than 67 kg ha^{-1}, urea was applied before radish planting to simulate high residual nitrate conditions. To determine the fertilizer replacement value of the cover crop, urea was applied at five rates before corn planting. The radish cover crop reduced soil nitrate by 65% in late fall and 42% at corn planting, but did not increase later nitrogen availability. In 2011, a wet year, the cover crop did not affect soil nitrate and corn nitrogen accumulation at the V8 growth stage, while in 2012, a dry year, the cover crop reduced V8 soil nitrate by 27% across sites and reduced corn nitrogen accumulation by 24% at one site. Corn grain yield and response to nitrogen fertilizer were not affected by the cover crop. A radish cover crop has the potential to reduce nitrate leaching, but its failure to increase later nitrogen availability suggests nitrogen taken up by the cover crop is not available when the subsequent crop needs it.

INTRODUCTION

Managing nitrogen 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 nitrogen 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 nitrogen losses is the use of a cover crop to scavenge residual nitrogen 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 nitrogen is mineralized again. Assuming nitrogen mineralization occurs in synchrony with nitrogen demand by the subsequent crop, the increase in nitrogen availability could offset the cost of establishing the cover crop.

Forage and oilseed radish (*Raphanus sativus* L.) are currently being promoted in the US as nitrogen-scavenging cover crops. Their fast-growing taproots allow them to take up nitrogen from deep in the soil profile (Kristensen and Thorup-Kristensen, 2004). When planted by mid-September, they can produce over 8000 kg ha^{-1} total biomass and accumulate over 300 kg ha^{-1} nitrogen (Dean and Weil, 2009; Wang et al., 2008), though values of 3000-5000 kg ha^{-1} for biomass production and 50-100 kg ha^{-1} for nitrogen accumulation are more typical (Dean and Weil, 2009; Isse et al., 1999). About 70% of the nitrogen accumulated is contained in the shoot biomass (Dean and Weil, 2009). Despite the ability of radish cover crops to scavenge large amounts of nitrogen rapidly, their effects on the subsequent crop are mixed. In some cases, a radish cover crop increased the nitrogen accumulation, biomass production, or yield of the subsequent crop (Thorup-Kristensen, 1994; Vyn et al., 1999), while in others, the cover crop provided no benefit to the subsequent crop, even though radish nitrogen accumulation was high (Isse et al., 1999).

The lack of benefit seen in some studies may occur either because the nitrogen taken up by the cover crop mineralizes from the residue too slowly, or because it mineralizes too quickly. A nitrogen-scavenging cover crop initially reduces nitrogen availability by removing nitrate and ammonium from the soil. After the cover crop is killed, this nitrogen becomes available gradually as the cover crop residue decomposes. If mineralization of nitrogen from the residue occurs too slowly, the nitrogen scavenged by the cover crop may not be available when the subsequent crop needs it for growth and development. On the other hand, if mineralization occurs too quickly, the nitrogen 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 (Engel et al., 2011; Magid et al., 2004; Wagner-Riddle and Thurtell, 1998).

Radish typically winterkills, and the residue decomposes rapidly, even at low temperatures (Thorup-Kristensen, 1994; Vos and van der Putten, 2001). In these studies, only 22-31% of the nitrogen 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 nitrogen in radish biomass remained in the decomposing residue after 35 days 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, nitrogen leached from the residue may travel below the rooting zone before the subsequent crop can use it (Dean and Weil, 2009). Thus, it seems unlikely that nitrogen taken up by a radish cover crop would be released too slowly to benefit the subsequent crop, but it might be released too quickly.

Processes involved in nitrogen losses from soil and residue, including decomposition, volatilization, denitrification, and leaching, are strongly influenced by soil and climate conditions (Agehara and Warncke, 2005; Di and Cameron, 2002; Li, 2000; Li et al., 2006). Thus, the effect of a radish cover crop on nitrogen availability is likely to vary between regions. Furthermore, even basic knowledge about radish cover crops, such as their potential biomass production over the short fall growing season, is lacking for the Upper Midwest. Given this lack of basic knowledge, the mixed effects of radish cover crops in other regions, and the sensitivity of nitrogen cycling processes to climate and soil conditions, research is needed to understand nitrogen cycling in radish cover crop systems. The objectives of this research were to determine the effect of a fall-planted radish cover crop in a small grain-corn rotation on (i) nitrogen availability to the subsequent year's corn crop, (ii) corn yield, and (iii) corn response to applied nitrogen fertilizer.

MATERIALS AND METHODS

Site characteristics and experimental design

To determine the effect of a radish cover crop planted into oat (*Avena sativa* L.) stubble on nitrogen availability to a subsequent corn crop, 2-yr field experiments were established in August 2010 and 2011 at the University of Minnesota Rosemount Research and Outreach Center (Rosemount, MN, 44.72 N, 93.11 W) and Southwest Research and Outreach Center (Lamberton, MN, 44.25 N, 95.31W), for a total of four environments. At Rosemount, the soil was a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludoll). At Lamberton, the soil was a Ves loam (fine-loamy, mixed, superactive, mesic, Calcic Hapludoll) in 2010, and Ves loam and Normania loam (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) in 2011.

The experimental design was a randomized complete block (RCB) 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 nitrogen fertilizer (0, 45, 90, 135, and 179 kg N ha^{-1}) applied as urea prior to corn planting. Subplots were 4.6 m (six corn rows) wide by 7.6 m long at Rosemount in 2010, and 4.6 m wide by 9.1 m long in all other locations and years.

Field management

The oat crop 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 5 cores. At Rosemount, cores were collected by hand using a standard 1.9 cm diameter 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 cadmium 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 some years, the target level of residual soil nitrate-nitrogen was set at 67 kg ha^{-1}. Where measured soil nitrate-nitrogen was below this level, supplemental urea was broadcast and incorporated (Table 1). The field was prepared within 2 d of cover crop planting using a field cultivator, harrow, and/or packer as necessary to create a smooth seedbed.

Radish (GroundHog brand) was planted 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. Dates of planting and other field operations are presented in Table 2. 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, phosphorus and potassium were broadcast applied to the entire plot area in late April to mid-May on the basis of soil tests, at rates recommended for corn by University of Minnesota Extension (Rehm et al., 2006). Nitrogen rate treatments were applied by hand-broadcasting urea. Urea was incorporated with a field cultivator within four hours of application. Glyphosate-resistant corn was planted within 5 d of urea application. Corn was planted 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 DeKalb 50-47 at Rosemount in 2011, Pioneer 36V51 at Rosemount in 2012, DeKalb 48-12 at Lamberton in 2011, and 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 ha^{-1} a.e. with 2.2 kg ha^{-1} AMS and 2.3 L ha^{-1} crop oil. The glyphosate application failed to kill all weeds. Therefore, the field was resprayed 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 ha^{-1} a.e. 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 ha^{-1} a.e. At Lamberton in 2012, acetochlor [2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6-methylphenyl)acetamide] was applied on 16 May at 2.5 kg ha^{-1} a.i. for pre-emergence weed control, followed by glyphosate on 21 May at 0.84 kg ha^{-1} a.e. and on 18 June at 0.68 kg ha^{-1} a.e.

Data collection

Radish biomass production, radish nitrogen accumulation, soil nitrate levels, and corn biomass and nitrogen accumulation were measured in the zero nitrogen subplots, while corn grain yield was measured in all subplots. Data collection dates are presented in Table 2. Corn grain yield data were used to create nitrogen response curves for both the radish and no cover treatments and to determine the effect of the radish cover crop on grain yield. Radish root and shoot biomass were collected in mid to late October of the establishment year, before severe frost damage occurred, by digging plants in a single 0.25 m^2 quadrat in each subplot. This method allowed collection of the swollen, fleshy portion of the taproot, though fine roots were not collected. 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. 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) was stored in plastic bags at 6°C for up to 2 d before washing, while root biomass was stored for up to 2 wk. Both root and shoot biomass were dried in a forced-air dryer at 60°C before weighing.

Dried biomass 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 near infrared reflectance spectroscopy (NIR) with a Perten DA 7250 NIR analyzer (Perten Instruments, Inc., Springfield, IL). Because standard NIR equations for nitrogen concentration in brassica biomass were not available, a subset of samples from this experiment and several other concurrent brassica cover crop experiments was also analyzed by combustion with a Carlo Erba 1500 nitrogen/carbon analyzer (CE Elantech, Inc., Lakewood, NJ) at Brookside Laboratories, New Knoxville, OH. 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). In some cases, not enough tissue was available to analyze a sample using NIR. These samples were analyzed by combustion instead. Nitrogen accumulation was calculated as biomass multiplied by nitrogen concentration.

Soil nitrate-nitrogen 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-nitrogen subplots only, except at Rosemount in fall of 2010, when a single composite sample was taken from each main plot. At Rosemount, soil cores were taken by hand using a standard 1.9-cm diameter soil probe and divided into 30-cm increments. At least 3 cores were taken per plot. At Lamberton, 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. 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 cadmium reduction and colorimetry at Agvise Laboratories, Benson, MN.

Corn biomass and nitrogen concentration were determined by collecting above-ground biomass of 10 plants per plot from the zero-nitrogen subplots on the same date as the summer soil sampling. Plants were selected randomly from the second and fifth rows of each six-row plot. Biomass was dried and ground as for radish biomass. Nitrogen concentration was determined by combustion using a ThermoFinnigan FlashEA organic elemental analyzer (Thermo Fisher Scientific Inc., Waltham, MA) in 2011 and a Carlo Erba 1500 nitrogen/carbon analyzer in 2012. Nitrogen accumulation was determined as for radish biomass. In 2012, corn stand counts were also made on the same date in the same plots by counting plants in three randomly selected 1 m sections of the second and fifth rows. 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.

Air temperature and precipitation data were obtained from weather stations located at the experiment stations. Soil temperature data 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.

Statistical analysis

Fall, spring, and V8 soil nitrate, V8 corn nitrogen accumulation, 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 by year and treatment by location interactions for corn grain yield, and treatment by year or treatment by location by 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 nitrogen. 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 by treatment interaction within a year, and by location within year where there was a location by treatment interaction.

RESULTS AND DISCUSSION

Temperature and precipitation data for the study sites are presented in Fig. 1. 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-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-year 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 the 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 -2ºC. After 1 April, however, soil temperature often exceeded 10ºC. 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 -11ºC to 7ºC at Lamberton and from -12ºC to 3ºC at Rosemount until the last snowfall of the season melted in early March, after which soil temperatures rose rapidly, often exceeding 10ºC.

The radish cover crop was established successfully at both locations in both years, grew vegetatively over the fall, and winterkilled. Radish biomass production ranged from 1160 to 3536 kg ha^{-1}, while nitrogen accumulation ranged from 31 to 92 kg ha^{-1} (Table 3). These results are 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). In 2010, biomass production and nitrogen accumulation did not differ between locations, but in 2011 both were lower at Rosemount than at Lamberton. 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 nitrogen accumulation were therefore reduced in this environment, but may also have been underestimated, as shed leaves were not included in the collected biomass samples. Of the nitrogen accumulated by the radish cover crop and recovered by sampling, the majority (71% or more) was in the shoot tissue. This result agrees with observations by Axelsen and Thorup-Kristensen (2000), Dean and Weil (2009), and Isse et al. (1999). Nitrogen concentration of the radish shoot tissue ranged from 2.23 to 3.61%, while nitrogen concentration of the root tissue ranged from 1.36 to 2.39% (Table 3).

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 4). Averaged across locations, the radish cover crop reduced late fall soil nitrate-nitrogen by 49 kg ha^{-1} in 2010 and 53 kg ha^{-1} in 2011. These results confirm the ability of the radish cover crop to remove available nitrogen 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 nitrogen accumulated by the radish cover crop was available at corn planting. In 2010-2011, there was a net loss of 21 kg nitrate-nitrogen 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 ($p = 0.0099$ for the difference between cover crop treatments). However, soil nitrate-nitrogen 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 4). In 2011-2012, the change in soil nitrate-nitrogen between the fall and spring sampling dates did not differ between the radish treatment and the control ($p = 0.8848$), with a net gain of 34 kg nitrate-nitrogen 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-nitrogen at planting averaged 54 kg ha^{-1} lower in the radish treatment than in the no-cover control. The difference between the two 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. 1).

In 2011, the radish cover crop had no effect on V8 soil nitrate level or corn nitrogen accumulation (Table 4). In 2012, however, the radish cover crop reduced V8 soil nitrate-nitrogen by an average of 31 kg ha^{-1} (Table 4). There was a significant cover by location interaction for V8 corn nitrogen accumulation: the radish cover crop had no effect on nitrogen accumulation at Lamberton, but it reduced nitrogen accumulation at Rosemount (Table 4).

The radish cover crop did not affect corn grain yield, nor was there an interaction between cover crop treatment and nitrogen fertilizer rate. At Lamberton in 2012, nitrogen rate did not affect grain yield, which averaged 6.26 Mg ha^{-1} across treatments, due to drought. In the other locations and years, polynomial contrasts showed that the response to nitrogen was quadratic (Fig. 2).

While either too-early or too-late mineralization of nitrogen from the radish residue could account for the negative effect of the radish cover crop on nitrogen availability at planting and V8, it seems unlikely that most of the nitrogen taken up by the radish cover crop mineralized too late, given the extent to which the residue had decomposed by spring. It also seems unlikely that nitrate leaching losses were high in either the radish treatment or the no-cover control during the dry winter of 2011-2012. However, 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 nitrogen upward and depositing it at the soil surface, the radish cover crop could have increased the risk of ammonia volatilization as well. De Ruijter et al. (2010) reported that under freeze-thaw conditions, radish shoot biomass lost 4-6% of its total nitrogen as ammonia after 37 days and 7-11% after 119 days.

In this research, a radish cover crop planted to scavenge nitrogen did not increase nitrogen availability in the following cropping season. 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 nitrogen losses from cover crops also need additional investigation.

ACKNOWLEDGEMENTS

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Table 1. Soil nitrogen levels prior to radish cover crop planting in August 2010 and 2011 at Lamberton and Rosemount, MN.

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

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

	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 3. Radish biomass, nitrogen concentration, and nitrogen accumulation in 2010 and 2011 at Lamberton and Rosemount, MN.

	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)
	Nitrogen concentration			
	---------- % ----------			
Root	1.36 (0.45)	2.39 (0.68)	1.96 (0.67)	1.95 (0.47)
Shoot	2.23 (0.28)	3.35 (0.87)	3.61 (0.35)	3.52 (0.74)
	Nitrogen 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)

All data are from the zero-nitrogen treatment. Means are followed by standard deviations in parentheses.

Table 4. Effect of a radish cover crop on late fall, spring, and V8 soil nitrate-nitrogen and V8 corn nitrogen accumulation at Lamberton and Rosemount, MN.

	2010-2011			2011-2012		
	Lamberton	Rosemount	Mean	Lamberton	Rosemount	Mean
	Late fall soil nitrate-nitrogen (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-nitrogen (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-nitrogen (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 nitrogen accumulation					
	g N plant^{-1}					
No cover	0.25	0.29	0.27	0.12	0.33	0.22
Radish	0.21	0.33	0.27	0.12	0.25	0.19
P > F	0.4813	0.0750	0.9537	0.9697	0.0344	-

† P-value not shown because the cover crop by location interaction was significant.
All data are from the zero-nitrogen treatment, except at Rosemount in fall of 2010, when a single composite soil sample was taken from each main plot.

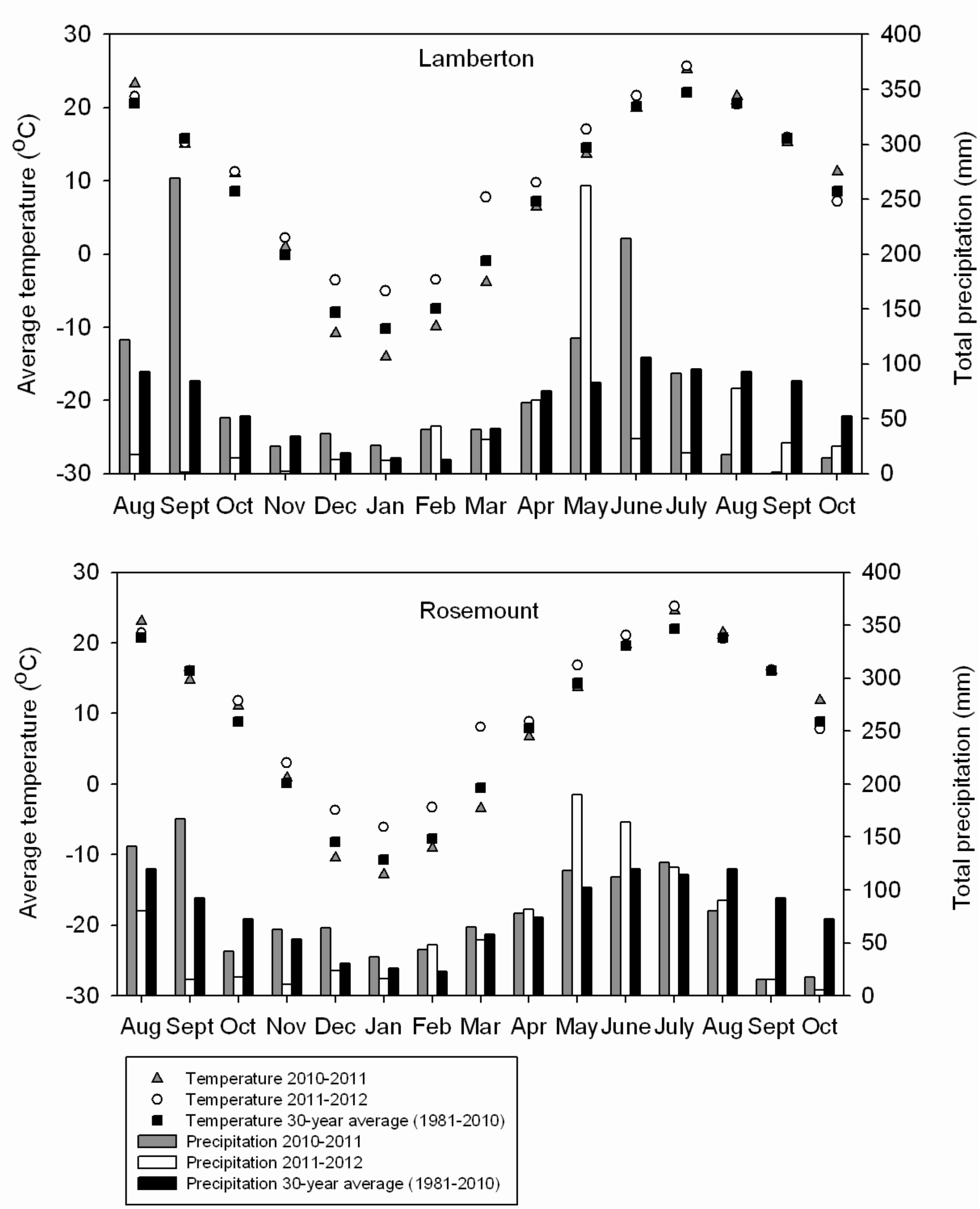

Fig. 1. Monthly average temperature and total precipitation at Lamberton and Rosemount, MN.

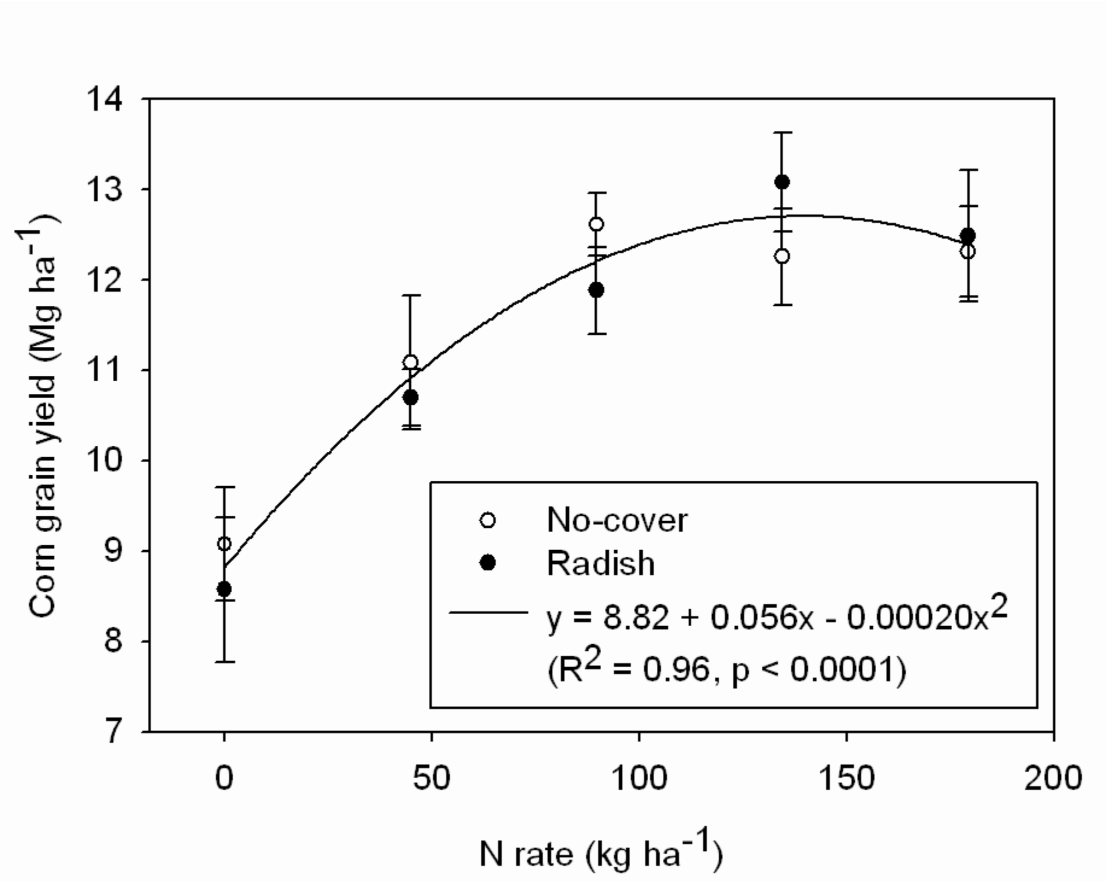

Fig. 2. Effect of nitrogen rate on corn grain yield. Means presented are averaged over three environments (Lamberton 2011, Rosemount 2011, and Rosemount 2012). Error bars denote standard error of the mean.

Chapter 2

Brassica Cover Crop Effects on Nitrogen Availability and Oat (*Avena sativa* L.) Yield

Brassica Cover Crop Effects on Nitrogen Availability and Oat (*Avena sativa* L.) Yield

SUMMARY

Brassica species have recently gained popularity as cover crops to scavenge residual nitrogen following row crops and release it in the following cropping season. However, their effects on nitrogen available to the subsequent crop are mixed. The objectives of this research were to determine the effect of fall-planted brassica cover crop species and accessions on nitrogen availability for the subsequent year's oat crop (*Avena sativa* L.). Five brassica species (*Brassica juncea* [L.] Czern., *B. napus* L., *B. rapa* L. x *B. napus* L., *Raphanus sativus* L., and *Sinapis alba* L.) were evaluated at St. Paul, MN from 2010 to 2012. End-of-season brassica biomass did not differ between species, averaging 6170 kg ha^{-1} in 2010 and 4838 kg ha^{-1} in 2011. Brassica nitrogen accumulation averaged 136 kg ha^{-1} in 2010, with no differences between species. In 2010-2011, brassicas had little effect on soil nitrate. *R. sativus* increased grain yield by 593 kg ha^{-1}, while *B. juncea* and *S. alba* reduced grain yield by 489 and 521 kg ha^{-1}, respectively. In 2011, *R. sativus* accumulated more nitrogen (122 kg ha^{-1}) than *B. juncea* or *B. rapa* x *napus* (97 to 99 kg ha^{-1}). In 2011-2012, all brassicas reduced soil nitrate by at least 124 kg ha^{-1} at oat planting and at least 90 kg ha^{-1} 4 wk after planting, relative to the control. Brassicas also reduced June oat nitrogen accumulation by an average of 83 kg ha^{-1}, but three species (*B. napus, R. sativus,* and *S. alba*) increased oat grain yield.

INTRODUCTION

Several species in the family Brassicaceae have recently gained popularity as cover crops in the US Midwest due to their ability to scavenge residual soil mineral nitrogen after a row crop is harvested. Nitrogen-scavenging cover crops are used to reduce the loss of nitrogen from agricultural fields to the environment (Thorup-Kristensen et al., 2003). The nitrogen scavenged by the cover crop may also offset the cost of cover crop establishment, assuming it is released from the cover crop residue in synchrony with nitrogen demand by the subsequent crop.

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 nitrogen from deep in the soil, while mustards have shallower, more fibrous root systems.

Although brassica cover crops can scavenge large amounts of nitrogen rapidly, their effects on the amount of nitrogen available to the subsequent crop are mixed. When planted by mid-September, brassicas typically produce 3000-5000 kg ha^{-1} total biomass and take up 50-100 kg ha^{-1} nitrogen (Dean and Weil, 2009; Isse et al., 1999; Stivers-Young, 1998; Wang et al., 2010). In some cases, radish, rapeseed, and white mustard cover crops increase the nitrogen 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, a brassica cover crop has no effect on the following crop (Isse et al., 1999). Thus, it appears that the nitrogen taken up by brassica cover crops is not always released when the following crop needs it to support plant development.

The lack of benefit seen in some studies may occur either because the nitrogen taken up by the cover crop mineralizes from the residue too slowly, or because it mineralizes too quickly. A nitrogen-scavenging cover crop initially reduces nitrogen availability by removing nitrate and ammonium from the soil. After the cover crop is killed, this nitrogen becomes available gradually as the cover crop residue decomposes. If mineralization of nitrogen from the residue occurs too slowly, the nitrogen scavenged by the cover crop may not be available when the subsequent crop needs it for growth and development. On the other hand, if mineralization occurs too quickly, the nitrogen 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 (Engel et al., 2011; Magid et al., 2004; Wagner-Riddle and Thurtell, 1998).

Both winterhardiness and C:N ratio of the cover crop affect the dynamics of nitrogen mineralization from the residue (Thorup-Kristensen, 1994; Trinsoutrot et al., 2000). The likelihood of nitrogen loss over the winter is highest with radish, which typically winterkills and has a low C:N ratio (Thorup-Kristensen, 1994). Winterkilled radish residue decomposes rapidly; 69-78% of the nitrogen content of radish biomass can be mineralized over the winter (Thorup-Kristensen, 1994; Vos and van der Putten, 2001). 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, nitrogen leached from the residue may travel below the rooting zone before the subsequent crop can take it up (Dean and Weil, 2009). By the same measure, though, too-slow mineralization of nitrogen is less likely to be a problem with radish than with other brassica cover crops. 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 nitrogen from mustard residue. Winter-hardiness varies between accessions of rapeseed and canola (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.

Processes involved in nitrogen losses from soil and plant residue, including decomposition, volatilization, denitrification, and leaching, are strongly influenced by soil and climate conditions (Agehara and Warncke, 2005; Di and Cameron, 2002; Li, 2000; Li et al., 2006). Thus, the effect of brassica cover crops on nitrogen availability is likely to vary between regions. Furthermore, estimates of brassica cover crop biomass production and nitrogen accumulation vary widely and may differ between species and accessions. More comprehensive research is needed in order to make recommendations about use of brassica cover crops for nitrogen scavenging to farmers in the upper Midwest. The objectives of this research were to determine the effect of fall-planted brassica cover crops on nitrogen availability to the subsequent year's oat crop and oat biomass and grain yield.

MATERIALS AND METHODS

Site characteristics and experimental design

Trials of five brassica cover crop species were initiated at the University of Minnesota campus in St. Paul, MN (44.99^o N, 93.19^o W) in August of 2010 and 2011 and continued with the establishment of an oat crop (*Avena sativa* L.) in the spring of 2011 and 2012. The soil was a well-drained Waukegan silt-loam. The species evaluated were brown mustard (*Brassica juncea* [L.] Czern.), hybrid turnip (*Brassica rapa* L. x *B. napus* L.), radish (*Raphanus sativus* L.), rapeseed (*Brassica napus* L.), and white mustard (*Sinapis alba* L.). A total of 12 accessions were tested: *B. juncea* cv. Pacific Gold and a variety not stated (VNS) accession; *B. rapa* x *napus* cv. Pasja; *B. napus* cv. Dwarf Essex; *S. alba* cvs. Accent and IdaGold; and *R. sativus* cv. Defender, commercial selections Driller, GroundHog, and Tillage, and two VNS accessions. A no cover control was also included. The experimental design was a randomized complete block with four replications. Plot size was 1.8 x 6.1 m in 2010 and 4.6 x 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.

Cover crop and oat management

Dates of field operations and sampling events are presented in Table 1. The brassicas followed a soybean green manure, which was chopped and disked 2-3 wk prior to planting. On 17 August 2010 and 22 August 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 Wintersteiger cone-drill seeder, 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 seven days after planting. On 25 April 2010 and 12 April 2011, brassica residues and surviving plants were flail-mowed and rototilled, and oat (cv. '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 month after planting. A vigorous oat stand kept weed density very low in both years. No fertilizer or herbicides were applied.

Data collection

Radish 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 (Table 1). Sample size was two 0.25 m^2 quadrats per plot in 2010 and three 0.25 m^2 quadrats in 2011. This method allowed collection of the upper 15-30 cm of the taproot, though fine roots were not collected. Roots were separated from shoots at or shortly after harvest. Root biomass was washed to remove clinging soil. Due to the amount of biomass collected, root biomass was stored in plastic bags at 6 °C for up to 3 wk before washing. Both root and shoot biomass were dried in paper bags 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 in 2010 ('Pacific Gold,' 'Pasja,' 'GroundHog,' and 'Dwarf Essex'). For all other accessions, nitrogen concentration was determined by near infrared reflectance spectroscopy (NIR) with a Perten DA 7250 NIR analyzer (Perten Instruments, Inc., Springfield, IL). Because standard NIR equations for nitrogen concentration in brassica biomass were not available, a subset of samples from this experiment and several other concurrent brassica cover crop experiments was also analyzed by combustion with a Carlo Erba 1500 nitrogen/carbon analyzer (CE Elantech, Inc., Lakewood, NJ) at Brookside Laboratories, New Knoxville, OH. 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 ($R^2 = 0.96$, $SE_{prediction} = 0.28$). Nitrogen accumulation was calculated as biomass multiplied by nitrogen concentration.

Brassica winterkill data were collected in spring of each year (Table 1). In 2011, the number of surviving plants in each plot was counted. In 2012, hybrid turnip plants were counted in the whole plot, while rapeseed plants were counted in three 0.25 m^2 quadrats per plot due to their higher survival rate.

Soil samples were collected 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. Samples were collected before oat planting and again in May when the oat crop was at Feekes stage 1-2 in both years. Samples were also collected in June at Feekes stage 10.1-10.54 in 2012. A standard 1.9 cm diameter hand probe was used to take a 0-30 cm core. A second probe was then inserted into the same hole to take a 30-60 cm core. Three to five cores were collected per plot. Cores were bulked by depth. Samples were dried in a forced-air dryer at 35 ºC and analyzed for nitrate concentration via KCl extraction followed by cadmium reduction and colorimetry.

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 ºC. In 2012, oat biomass from the treatments selected for soil analysis was ground and analyzed for nitrogen content by combustion with a Carlo Erba 1500 nitrogen/carbon analyzer. 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 1). Grain was dried at 60 ºC in 2011 and 49 ºC in 2012.

Temperature and precipitation data were obtained from the weather station on the St. Paul campus via the Minnesota Climatology Working Group (http://climate.umn.edu/HIDradius/radius.asp). The 1981-2010 climate normals for St. Paul were used as the baseline.

Statistical analysis

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. An initial analysis of variance showed significant year by 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).

RESULTS AND DISCUSSION

Temperature and precipitation data 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 are 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.

Average end-of-season cover crop biomass was 6170 kg ha^{-1} in 2010 and 4838 kg ha^{-1} in 2011 (Table 2). Biomass did not differ between species in either year. Average nitrogen 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 nitrogen accumulation than brown mustard or hybrid turnip (Table 2). These biomass and nitrogen accumulation results fall in the upper end of the range reported in the literature (Dean and Weil, 2009; Isse et al., 1999; Stivers-Young, 1998; Wang et al., 2010).

Cold winter temperatures completely killed all accessions of brown mustard, white mustard, and radish. Winter survival of rapeseed ranged from 5.8 to 35.3 plants m^{-2}, while winter survival of hybrid turnip ranged from 0.3 to 5.3 plants m^{-2}.

At oat planting in April, cover crops had little effect on soil nitrate levels in 2011, but reduced soil nitrate substantially in 2012 (Table 3). Soil nitrate-nitrogen 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 the two 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. In April 2011, brown mustard reduced soil nitrate nitrogen 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 nitrogen levels relative to the control by at least 124 kg ha^{-1}.

These patterns persisted into May and June. In May 2011, white mustard reduced soil nitrate nitrogen by 15 kg ha^{-1} relative to the control, while other species had no effect on soil nitrate (Table 3). In 2012, all cover crops reduced May soil nitrate nitrogen by 90 kg ha^{-1} or more relative to the control (Table 3). Additional data collected in 2012 showed that oat nitrogen accumulation in May 2012 was low (9-10 kg ha^{-1}) and was not affected by cover crop treatment, despite the large effect of the cover crops on soil nitrate (Table 3). Therefore, soil nitrate provides a reasonable measure of the effects of cover crops on nitrogen availability at this stage in oat development. May 2012 oat biomass also was not affected by cover crops (Table 4). In 2012, additional soil and biomass sampling showed that the negative effect of the cover crops on nitrogen availability continued through June (Tables 3 and 4). Soil nitrate nitrogen was 7 kg ha^{-1} or less in all treatments at the June sampling date. All cover crop species reduced oat biomass and nitrogen accumulation in June 2012, consistent with their effects on April and May soil nitrate. Interestingly, plant-available nitrogen, estimated as the sum of 0-60 cm soil nitrate and aboveground biomass nitrogen, was constant from April to June of 2012 in the control, but increased over the same time period in all of the cover crop treatments. The greater increase in plant-available nitrogen in the cover crop treatments relative to the control suggests that a portion of the nitrogen taken up by the cover crops was released between planting and heading, though not enough to raise nitrogen 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 4). 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 nitrogen 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 is likely due to extensive lodging which occurred in the control and may have reduced its yield.

In summary, mustard cover crops reduced nitrogen availability in 2011, as did all cover crops in 2012. It is not clear whether these negative effects were due to too-early or too-late release of nitrogen from the decomposing biomass. In 2011, nitrogen availability was higher following the radish cover crops, which decomposed quickly, than following the mustards, which decomposed more slowly. This suggests that reduced nitrogen availability in the mustard treatments relative to the control was due to slow mineralization of nitrogen from the mustard residue, rather than to losses over the winter. In 2012, the high soil nitrate level at oat planting (Table 3) suggests that nitrogen losses were low due to the dry fall (Fig. 1). Under these circumstances, it is not surprising that the cover crops reduced nitrogen availability relative to the control, though the magnitude of their effect is surprising. While the effect of the mustard cover crops may have been due to too-late mineralization of the scavenged nitrogen, it seems unlikely that too-late mineralization would have been the cause for all of the cover crops, given how quickly the radish residue decomposed. It also seems unlikely that high nitrate leaching losses would have occurred in the cover crop treatments under the dry conditions that occurred in the fall and winter of this year. However, it is possible that by removing available nitrogen from the soil and depositing it on the surface in association with easily-degradable carbon, the cover crops may have increased ammonia volatilization or denitrification (Parkin, 1987; Petersen et al., 2011; de Ruijter et al., 2010). The possibility that brassica cover crops increase gaseous nitrogen losses should be investigated.

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Table 1. Dates of data collection and field operations at St. Paul, MN in 2010-2012.

	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
Winterkill data	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

Table 2. Total biomass production and nitrogen accumulation of brassica cover crop species at St. Paul, MN in 2010 and 2011.

	Biomass production		Nitrogen 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 ($\alpha_{family} = 0.05$, Šidàk correction).

Table 3. Effect of brassica cover crop species on spring and summer soil nitrate-nitrogen (0-60 cm) and oat nitrogen accumulation at St. Paul, MN in 2011 and 2012.

	Soil nitrate					Oat nitrogen 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 4. Effect of brassica cover crop species on oat biomass and grain yield at St. Paul, MN in 2011 and 2012.

	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.

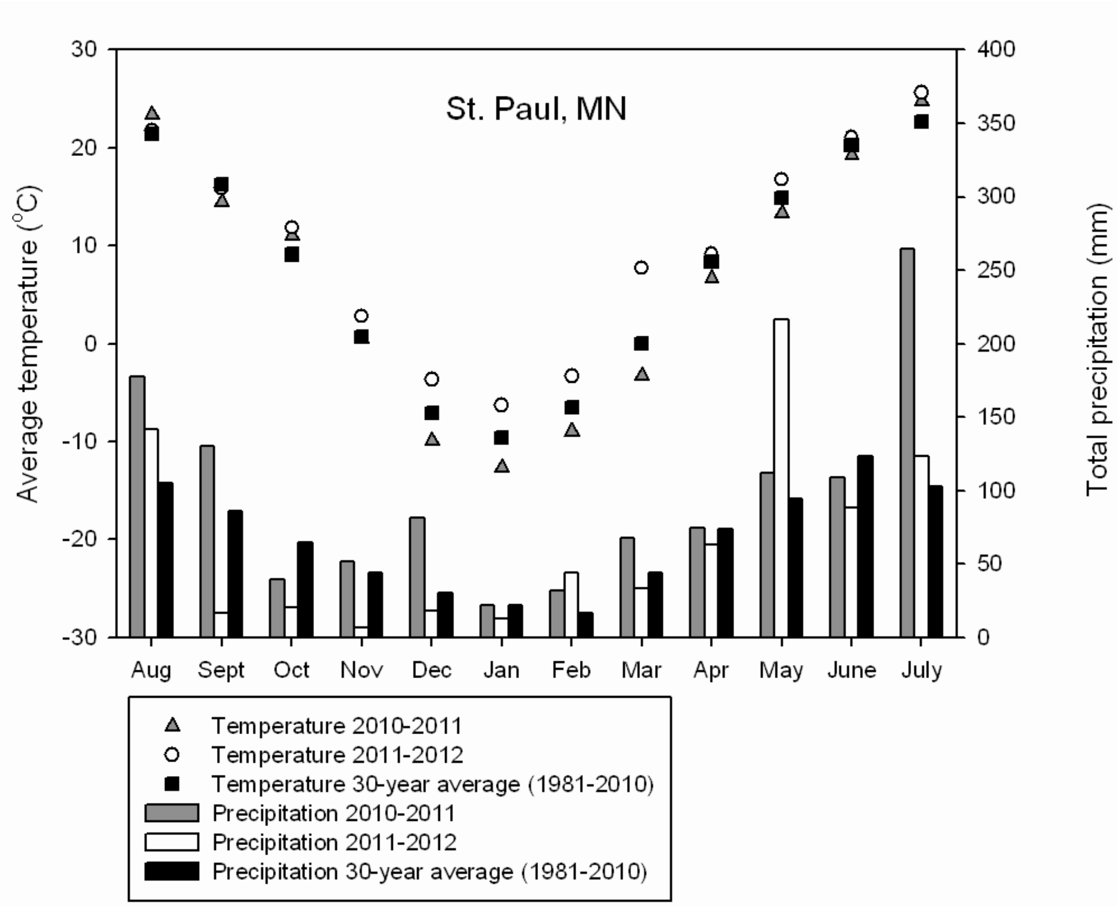

Fig. 1. Monthly average temperature and total precipitation at St. Paul, MN.

Chapter 3

Seeding Date and Seeding Rate Effects on Radish Cover Crop Growth and Nitrogen Accumulation

Seeding Date and Seeding Rate Effects on Radish Cover Crop Growth and Nitrogen Accumulation

SUMMARY

Use of radish (*Raphanus sativus* L.) cover crops has increased in the US Midwest in recent years. Trials were established at two sites in Minnesota in 2010 and 2011 to evaluate the effects of radish seeding date (mid-August [Date 1], late August [Date 2], mid-September [Date 3], late September [Date 4]) and rate (4.1 to 22.4 kg ha^{-1}) on radish canopy cover, biomass, and nitrogen accumulation. Two accessions were used each year to evaluate whether the effects of seeding date and rate varied between accessions. At St. Paul, radish cover was ≥ 79% for all rates and accessions at seeding dates 1-3, but ≤ 59% at Date 4. The seeding rate effect was greatest at Date 4, when each additional kg ha^{-1} of seed increased cover by two percentage points. Delaying seeding decreased radish biomass by 143 kg ha^{-1} day^{-1}. Total nitrogen accumulation averaged 96-225 kg ha^{-1} at Date 1 and 57-132 kg ha^{-1} at Date 3. Effects of seeding rate and accession on radish biomass and nitrogen accumulation were small and inconsistent. At Lamberton, severe drought resulted in poor radish growth at Dates 2-4. At Date 1, across accessions, increasing the seeding rate from 5.4 to 10.8 kg ha^{-1} increased biomass by 49% and nearly doubled cover. Increasing the seeding rate to 21.6 kg ha^{-1} did not further increase cover or biomass. In Minnesota, radish cover crops should be planted by mid-September at 5 kg ha^{-1}, though under adverse environmental conditions, increasing the seeding rate may improve performance.

INTRODUCTION

Use of radish (*Raphanus sativus* L.) as a cover crop has increased dramatically in the north-central US in recent years—for example, one Minnesota seed company saw a 1000% increase in sales of radish seed from 2009 to 2012 (Matt Leavitt, personal communication, 2013). Research is needed to determine appropriate seeding dates and rates for this region. A member of the family Brassicaceae, radish is a fast-growing, cool season plant with a large, fleshy taproot which often protrudes from the ground. Radish is frost-tolerant, but winterkills when the temperature drops to -5°C or below for several nights in a row (Weil et al., 2009). Its rapid, deep root growth makes it an excellent nitrogen scavenger (Dean and Weil, 2009; Kristensen and Thorup-Kristensen, 2004). Its deep taproot also relieves soil compaction by creating root channels that subsequent crops can use to access subsoil moisture and nutrients (Chen and Weil, 2011; Williams and Weil, 2004). Radish cover crops quickly form a closed canopy, which suppresses winter annual weeds (Lawley et al., 2011) and reduces soil erosion. Research has also shown that some radish varieties are useful for control of plant-parasitic nematodes (Smith et al., 2004; Wang et al., 2010).

Despite recent efforts to increase use of cover crops, cover crop adoption remains low in the US Midwest (Singer et al., 2007; Arbuckle and Ferrell, 2012). Two of the main barriers to cover crop use are the short growing window between crop harvest and winter, and producers' lack of knowledge about cover crops (Arbuckle and Ferrell, 2012). To address these concerns, research is needed to determine how late in the growing season a radish cover crop can be planted in this region. Current extension publications from Michigan (Ngouajio and Mutch, 2004) and Maryland (Weil et al., 2009) recommend seeding radish in late summer to early fall. Delaying seeding into September may make it easier to fit a radish cover crop into midwestern cropping systems. However, published information on the effect of seeding date on biomass and nitrogen accumulation of fall-seeded radish is lacking in this region. In general, seeding later in the fall decreases the biomass and nitrogen accumulation of cover crops, as temperature and light levels decline (Gselman and Kramberger, 2008; Vos and van der Putten, 1997). In New York, Stivers-Young (1998) found that radish biomass production and nitrogen accumulation were lower when a radish cover crop was planted in mid-September than when it was planted in late August to early September, but did not test the effect of seeding date statistically. With regard to summer (mid-July to mid-August) seeding dates, later seeding decreases radish biomass accumulation, but increases the nitrogen concentration of the biomass (Sheldrick et al., 1981). Similarly, delaying seeding from 1 to 31 August decreases biomass accumulation of turnip (*Brassica rapa* L.) and rape (*Brassica napus* L.) (Keogh et al., 2012). For kale (*Brassica oleracea* L.), the effect of a delay in seeding increases later in the season; delaying seeding from 20 May to 17 June reduced biomass by approximately 1 Mg ha^{-1}, while delaying seeding from 25 July to 24 August reduced biomass by approximately 6 Mg ha^{-1} (Kunelius et al., 1987).

Current recommended seeding rates for drilled radish cover crops vary widely, from 6.7 to 22.4 kg ha^{-1} (Gruver et al., 2012; Ngouajio and Mutch, 2004), and research on the effect of seeding rate on radish cover crop biomass and nitrogen accumulation is lacking. More precise recommendations will allow producers to minimize cover crop costs, which may increase adoption. The effect of seeding rate on biomass and nitrogen accumulation of other cover crop species varies. In experiments with a mustard mix [*Brassica juncea* (L.) Czern. and *Sinapis alba* L.], increasing the seeding rate to three times the level typically used by farmers did not affect mustard biomass or nitrogen accumulation (Brennan and Boyd, 2012a,b). However, increasing the seeding rate of canola (*Brassica napus* L.) increased early season biomass production (McCormick et al., 2012). Seeding rate can also affect residual soil nitrate after cover crop growth: increasing the seeding rate of an Italian ryegrass (*Lolium multiflorum* Lam.) cover crop drilled into pea (*Pisum sativum* L.) stubble increased biomass production and nitrogen accumulation and reduced residual soil nitrate (Kramberger et al., 2007). The effect of seeding rate may depend on seeding date; increasing the seeding rate of a simulated rye (*Secale cereale* L.) cover crop decreased nitrogen leaching, but the effect of seeding rate was only important at the later of two seeding dates (van Dam, 2006). Finally, increasing the seeding rate of a cover crop may compensate for the effect of delayed seeding, but this hypothesis has not been tested.

The objectives of this research were to evaluate the effects of seeding rate and seeding date on basic aspects of cover crop performance (percent ground cover, biomass production, biomass nitrogen concentration, nitrogen accumulation, and effect on the subsequent year’s cash crop), determine whether increased seeding rate can compensate for a later seeding date, and determine whether the effects of seeding rate and date are consistent across radish accessions.

MATERIALS AND METHODS

Site characteristics and experimental design

To evaluate the effects of seeding date, seeding rate, and accession on establishment and growth of a fall-planted radish (*Raphanus sativus* L.) cover crop, as well as the effects of that cover crop on the following year's corn (*Zea mays* L.) crop, 2-yr field experiments were initiated in August 2010 at University of Minnesota campus in St. Paul, MN (44.99 N, 93.19 W) and in August 2011 at St. Paul and at the University of Minnesota Southwest Research and Outreach Center at Lamberton, MN (44.25 N, 95.31W). At St. Paul, the soil was a well-drained Waukegan silt-loam (fine-silty over sandy or sandy-skeletal, mixed, mesic, Typic Hapludoll) with a history of heavy manure application. At Lamberton, the soil was mainly well-drained Ves loam (fine-loamy, mixed, superactive, mesic, Calcic Hapludoll), with some well-drained Ves-Storden loams (Storden: fine-loamy, mixed, superactive, mesic, Typic Eutrudept) and poorly-drained Delft-Webster complex (fine-loamy, mixed, superactive, mesic, Cumulic and Typic Endoaquolls).

The experimental design was a randomized complete block with four replications and a split-split-plot layout. Seeding date was the main plot treatment, radish accession was the subplot treatment, and seeding rate was the sub-subplot treatment. The four seeding dates were mid-August (Date 1), late August (Date 2), mid-September (Date 3), and late September (Date 4). Two radish accessions were used each year: Defender and GroundHog in 2010, and Graza and GroundHog in 2011. Defender is an oilseed cultivar developed for nematode control, GroundHog is a large-rooted selection marketed for use as a cover crop, and Graza is a recently developed forage cultivar. Three seeding rates (1x, 2x, and 4x) were used. The 2x rate was twice the 1x rate, and the 4x rate was twice the 2x rate. The target seeding rates were 5.6, 11.2, and 22.4 kg ha^{-1} pure live seed (PLS), but due to how germination rates were calculated, actual PLS seeding rates varied somewhat. Seeding rates for each year and accession are presented in Table 1. Sub-subplot size was 3.0 by 6.1 m at St. Paul and 3.0 by 9.1 m at Lamberton.

Field management and data collection

Dates of data collection and field operations are presented in Table 2. At each site, prior to establishment of the experimental treatments, a buckwheat cover crop (*Fagopyrum esculentum* Moench) was planted over the entire field in early summer. The buckwheat cover crop was chopped in late July of each year. The buckwheat residue remained in the field. The field was tilled 2-3 times after terminating the buckwheat and before seeding the first radish treatments. At subsequent seeding dates, plots for that date were tilled again with a tractor-mounted rototiller before seeding. At St. Paul, plots were packed with a roller before planting, while at Lamberton they were packed after planting.

Radish treatments were seeded at a depth of about 2.5 cm using a cone-drill seeder. The row spacing was 15 cm at St. Paul and 19 cm at Lamberton. At St. Paul, plots for the mid-August and late September seeding dates in 2010 and the late August and mid-September seeding dates in 2011 were irrigated using sprinklers to ensure that sufficient moisture was available for germination. Other seeding dates received rain before or after planting and were not irrigated. Irrigation was not available at Lamberton. Volunteer buckwheat was removed by hand at St. Paul, but not at Lamberton, where few volunteer buckwheat seedlings were present.

Radish percent cover was visually rated (0-100%, rounded to the nearest 5%) and root and shoot biomass were collected between mid-October and early November of the establishment year, before severe frost damage occurred. Biomass samples were collected by digging or pulling plants in three 0.25 m^2 quadrats in each subplot. This method allowed collection of the swollen, fleshy portion of the taproot, though fine roots were not collected. Roots were separated from shoots at or shortly after harvest. At Lamberton, all biomass sampling was completed within a 24-hr period. At St. Paul, sampling could not be completed within 24 hours. However, plots were sampled by replication. Biomass was brushed off or washed to remove clinging soil. Due to the large amount of biomass collected, shoot biomass was stored in plastic bags at 6°C for up to 2 d before washing, while root biomass was stored for up to 3 wk. Both root and shoot biomass were dried in paper bags in a forced-air dryer at 60°C before weighing. After weighing, biomass from the 1x and 4x rate sub-subplots for each accession from the mid-August seeding date was ground and analyzed to determine its nitrogen concentration. Root and shoot biomass were ground and analyzed separately. Biomass from each sub-subplot was coarsely ground, mixed thoroughly, and a subsample was finely ground. Nitrogen concentration of ground biomass was determined by near infrared reflectance spectroscopy (NIR) with a Perten DA 7250 NIRS analyzer (Perten Instruments, Inc., Springfield, IL). Because standard NIR equations for nitrogen concentration in brassica biomass were not available, a subset of samples from this experiment and several other concurrent brassica cover crop experiments was also analyzed by combustion with a Carlo Erba 1500 nitrogen/carbon analyzer (CE Elantech, Inc., Lakewood, NJ) at Brookside Laboratories, New Knoxville, OH. 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 ($R^2 = 0.96$, $SE_{prediction} = 0.28$). Nitrogen accumulation was calculated as biomass multiplied by nitrogen concentration.

In the second year of each 2-yr trial, glyphosate resistant corn was planted in late April to mid-May in 76-cm rows at a seeding rate of 79,000 seeds ha^{-1} at St. Paul and 86,000 seeds ha^{-1} at Lamberton. The corn hybrid was DeKalb 50-47 at St. Paul in 2011, Pioneer 36V51 at St. Paul in 2012, and DeKalb 48-12 at Lamberton in 2012. At St. Paul, the entire plot area was tilled with a tractor-mounted rototiller 0-1 d before planting. At Lamberton, the field was disked and field cultivated 10 d before planting, then field cultivated again 1 d before planting. Soil P and K levels were measured each spring before corn was planted by collecting five 15 cm cores per rep from the center alley with a hand probe. On the basis of these soil tests and University of Minnesota Extension recommendations (Rehm et al., 2006), 24 kg ha^{-1} K in the form of KCl was broadcast across all plots before planting at Lamberton. No K was applied at St. Paul and no P was applied at either location, due to very high soil test levels. To ensure that any effect the radish cover crop treatments might have had on nitrogen availability would be reflected in corn yield, no additional nitrogen was applied.

Methods of weed control in the corn crop varied between environments, depending on weed species present. At St. Paul in 2011, glyphosate [N-(phosphonomethyl) glycine, isopropylamine salt] was applied on 13 June at 0.77 kg ha^{-1} a.e. Because the glyphosate application failed to kill all weeds, the field was resprayed by hand with dicamba (3,6-dichloro-2-methoxybenzoic acid) on 17 and 19 June. At St. Paul in 2012, glyphosate was applied on 22 May at 1.1 kg ha^{-1} a.e. with 2.3 L ha^{-1} non-ionic surfactant. On 31 May, the field was row cultivated. Escapes were removed by hand-weeding and hoeing on 31 May and 4 June. At Lamberton in 2012, acetochlor [2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6-methylphenyl)acetamide] was applied on 16 May at 2.5 kg ha^{-1} a.i. and glyphosate was applied on 18 June at 0.68 kg ha^{-1} a.e.

Corn grain yield was measured in mid-September to early October. At St. Paul, 3.0 to 9.2 m of row in each sub-subplot were harvested by hand. The grain was mechanically shelled and percent moisture was determined by drying a subsample at 60°C for 6-7 days. At Lamberton, 13 to 16 m of row were harvested with a plot combine. Percent moisture was determined using the sensor in the combine. All yields were adjusted to 15.5% moisture.

Temperature and precipitation data were obtained from weather stations located at the experiment sites. Growing degree days (GDD) were calculated using the standard equation $GDD = (T_{max} – T_{min})/2 – T_{base}$, where T_{max} is the daily maximum temperature, T_{min} is the daily minimum temperature, and T_{base} is the base temperature (McMaster and Wilhelm, 1997). The base temperature for radish was set at 5°C, on the basis of estimates for other brassicaceous species (Adams et al., 2005; Huang et al., 2001). T_{max} and T_{min} values less than 5°C were set equal to 5°C before calculating GDD.

Statistical analysis

Data were analyzed in SAS Proc Glimmix (Version 9.3, SAS Institute, Cary, NC) using an analysis of variance appropriate for a split-split-plot in randomized complete block design. Because accessions and seeding rates differed between environments, each environment was analyzed separately. Replication effects were treated as random variables, while all other effects were fixed. Seeding date and seeding rate effects were partitioned using polynomial contrasts, after which Proc Reg was used to fit linear or quadratic equations.

RESULTS AND DISCUSSION

Weather conditions

Temperature and precipitation data for the study sites are presented in Fig. 1. At St. Paul, precipitation during the cover crop growing season (August-October) in 2010 was 347 mm (135% of the 1981-2010 normal), while in 2011 it was 179 mm (70% of normal). Irrigation ensured that cover crops had sufficient moisture to germinate at every seeding date. At Lamberton in 2011, August-October precipitation was only 33 mm (14% of normal). The fall of 2011 was the driest on record at this location, with 7 mm of rain 5 days before the first radish planting date and 2 mm 2 days before the second planting date, but only 1 mm total during the month of September. Irrigation was not available, and radish germination and growth at the later seeding dates were greatly reduced by these severe drought conditions. Thus, these two locations presented the opportunity to study radish cover crop performance under contrasting environmental conditions. Results for St. Paul show the effect of radish seeding date, accession, and seeding rate on radish cover crop performance under near-optimum conditions, while results for Lamberton show radish performance under conditions of severe drought stress, but do not provide information about the typical relationship between seeding date and radish performance.

At both locations, average air temperature was normal to cooler than normal in September, but warmer than normal in October. Precipitation during the corn growing season (May-September) was 125% of normal at St. Paul in 2011, while in 2012 it was 92% of normal at St. Paul and 91% of normal at Lamberton. Average air temperature was cooler than normal in May and June 2011, but warmer than normal in July 2011 and May-July 2012. Air temperature in August and September was normal.

Canopy cover

At St. Paul, radish seeding date, accession, and seeding rate all affected end-of-season radish canopy cover (Table 3). All two- and three-way interactions also affected radish canopy cover. At seeding dates 1-3 (mid-August to mid-September), canopy cover was 79% or greater for all accessions and seeding rates in both years. Although there were differences in percent cover between accessions and seeding rates at Dates 1-3, they were relatively small, and all accessions and seeding rates resulted in reasonably good cover. At Date 4, in late September, canopy cover was affected by both accession and seeding rate, but the effect of accession was small relative to the effect of seeding rate (Fig. 2). There was a linear relationship between seeding rate and canopy cover (Fig. 2). Each additional kg ha^{-1} of seed increased canopy cover by 2 percentage points. This result suggests that increasing the seeding rate at later seeding dates can compensate to some extent for the effect of delayed seeding on radish canopy cover. However, even at the highest seeding rate, canopy cover at Date 4 was lower than canopy cover at any seeding rate at Dates 1-3. Furthermore, October was warmer than normal in both years of this study, which suggests that the results presented here represent the upper end of the range for canopy cover of radish cover crops planted in late September in Minnesota. Thus, seeding a radish cover crop by mid-September at the latest is preferable to reduce the risk of low canopy cover.

At Lamberton, seeding date and seeding rate affected canopy cover (Table 3). The effect of seeding rate was greatest at Date 1, when radish canopy cover was greater at the 2x and 4x rates than at the 1x rate (Tukey-Kramer test, $\alpha = 0.05$). Canopy cover was 49% at the 1x seeding rate, 89% at the 2x rate, and 96% at the 4x rate. At later seeding dates, the radish cover crop grew poorly at all seeding rates, due to drought. Canopy cover averaged 35% at Date 2, 12% at Date 3, and 1% at Date 4. Accession did not affect canopy cover. These results suggest that increasing the seeding rate improves radish canopy cover under adverse environmental conditions.

Radish biomass

At St. Paul, end-of-season radish biomass was affected by seeding date in both years (Table 3). Accession and the interaction between date and accession also affected biomass in 2010, while seeding rate affected biomass in 2011. The effects of accession and seeding rate were small relative to the effect of seeding date. In 2010, averaged across seeding rates, Defender's biomass production exceeded GroundHog's by 766 kg ha^{-1} when planted in mid-August and 686 kg ha^{-1} when planted in late August. Biomass production did not differ between accessions at the mid-September and late September seeding dates. In 2011, polynomial contrasts showed a linear relationship between seeding rate and biomass, but the effect was small: each additional kg ha^{-1} of pure live seed increased biomass production by only 19 kg ha^{-1} ($R^2 = 0.9113$, $p = 0.1925$). For all accessions and seeding rates, radish biomass declined as seeding date was delayed. The relationship between seeding date and end-of-season biomass was approximately linear over the range of dates used (Fig. 3). Each day's delay in seeding reduced radish biomass production by 143 kg ha^{-1}. This is an order of magnitude larger than the 17 kg ha^{-1} day^{-1} reduction in biomass with delayed seeding reported by Sheldrick et al. (1981) for radish seeded in mid-July to mid-August, but similar to the 96 kg ha^{-1} day^{-1} reduction in radish biomass reported by Stivers-Young when seeding was delayed from 3 to 16 September and the 108 to 124 kg ha^{-1} day^{-1} reduction in biomass of rape reported by Keogh et al. (2012) for 1 to 31 August seeding dates. The relationship between biomass production and growing degree days (base 5ºC) between planting and biomass harvest was also linear ($R^2 = 0.86$, $p < 0.0001$). For each additional growing degree day accumulated, biomass increased by 12 kg ha^{-1}, averaged over years and accessions. Brennan and Boyd (2012a) likewise found that cover crop biomass production was correlated with growing degree day accumulation, although they investigated differences in growing degree days between years rather than between seeding dates in a single year. These results suggest that when the primary goal of planting a radish cover crop is to produce biomass, seeding date is the most important consideration, although accession can also affect performance. Increasing the seeding rate is not a feasible way of compensating for the effect of delayed seeding on biomass production.

At Lamberton, biomass production was affected by seeding date and seeding rate, but not by accession (Table 3). Increasing the seeding rate increased biomass production at Date 1, though not at the later dates. Across accessions, biomass production at Date 1 averaged 2493 kg ha^{-1} at the 1x seeding rate, 3725 kg ha^{-1} at the 2x rate, and 3622 kg ha^{-1} at the 4x rate. The 1x seeding rate differed from the other two rates, while the 2x and 4x rates did not differ from each other (Tukey-Kramer test, $\alpha = 0.05$). At the later seeding dates, biomass was low due to drought, averaging 951 kg ha^{-1} at Date 2, 167 kg ha^{-1} at Date 3, and 8 kg ha^{-1} at Date 4. Like the results for canopy cover, these results suggest that there is some benefit to increasing the seeding rate under adverse environmental conditions.

Nitrogen concentration of radish biomass

At St. Paul, both seeding date (mid-August versus mid-September) and seeding rate (1x versus 4x) affected the nitrogen concentration of radish shoot biomass (Table 4). Shoot nitrogen concentration was greater at Date 3 than at Date 1, and greater at the 1x seeding rate than the 4x rate (Table 5). Radish accessions differed in shoot nitrogen concentration at St. Paul in 2011 (Table 4). Across seeding dates and rates, shoot nitrogen concentration averaged 4.2% for Graza and 3.8% for GroundHog. There were no interactions between seeding date, accession, and seeding rate. At Lamberton, the effect of seeding date on radish biomass nitrogen concentration was not measured due to very low biomass production at the last three seeding dates. At Date 1, shoot nitrogen concentration was greater at the 1x rate than the 4x rate, just as at St. Paul (Table 5).

Accession did not affect shoot nitrogen concentration.

At St. Paul, the effect of seeding date on root nitrogen concentration was qualitatively similar to its effect on shoot nitrogen concentration, although bulking of samples for analysis made it impossible to analyze statistically the effect of seeding date on root nitrogen concentration. At seeding date 1, accession affected root nitrogen concentration in both years. Averaged across seeding rates, GroundHog's root nitrogen concentration was 0.4 percentage points lower than Defender's in 2010, and 0.5 percentage points lower than Graza's in 2011. Seeding rate affected Date 1 root nitrogen concentration in 2011: increasing the seeding rate reduced root nitrogen concentration (Table 5). At Lamberton, Date 1 root nitrogen concentration was not affected by accession or seeding rate (Table 4). The effect of seeding date on biomass nitrogen concentration in this experiment is in agreement with previous research (Sheldrick et al., 1981; Vos and van der Putten, 1997).

Radish nitrogen accumulation

At St. Paul, nitrogen accumulation in radish shoot biomass was affected only by seeding date in 2010, while in 2011 it was affected by accession and by two-way interactions between accession and seeding date and between seeding rate and seeding date (Table 4). Shoot nitrogen accumulation was greater at Date 1 than Date 3 in 2010 and at the 1x seeding rate in 2011, but did not differ between seeding dates at the 4x rate in 2011 (Table 6). Shoot nitrogen accumulation was affected by accession only at Date 1 in 2011. Averaged across seeding rates at Date 1, Graza's shoot nitrogen accumulation was 80 kg ha^{-1} while GroundHog's was 53 kg ha^{-1}. At Date 3 in 2011, shoot nitrogen accumulation was greater at the 4x rate than the 1x rate (Table 6). At St. Paul, root nitrogen accumulation was greater at Date 1 than Date 3, similar to shoot nitrogen accumulation (Table 6). At Date 1, root nitrogen accumulation was greater at the 1x seeding rate than the 4x rate. At Date 3, root nitrogen accumulation was nearly identical across seeding rates. Averaged across accessions and seeding rates, total nitrogen accumulation in the radish cover crop biomass (shoot + root) declined by 3.3 kg N ha^{-1} day^{-1} between the mid-August and mid-September seeding dates. Vos and van der Putten (1997) similarly reported a 3.4 kg N ha^{-1} day^{-1} reduction in nitrogen accumulation of rape, rye, and radish cover crops as seeding was delayed in the fall.

At Lamberton, shoot nitrogen accumulation at Date 1 was affected only by seeding rate (Table 4). Shoot nitrogen accumulation was greater at the higher seeding rate (Table 6). Root nitrogen accumulation was not affected by accession or seeding rate (Table 4). Nitrogen accumulation in biomass from Date 3 was not measured. Like the canopy cover and biomass results, these results suggest it is advantageous to increase seeding rate under adverse environmental conditions.

Corn grain yield

At St. Paul, corn grain yield was affected by radish seeding date in 2010-2011, and by radish seeding rate and an interaction between radish accession and seeding date in 2011-2012 (Table 7). In 2010-2011, corn yield was greater in the mid-August radish seeding date treatment than in the mid-September and late September radish seeding date treatments (Table 8). The positive effect of earlier radish seeding on corn yield may be related to the greater radish biomass production at the earlier seeding dates, although within each seeding date, radish biomass and corn yield were uncorrelated (Dates 2-4, $R^2 \leq 0.0768$, $p \geq 0.1897$) or negatively correlated (Date 1, $R^2 = 0.2913$, $p = 0.0079$). Overall, corn yield was extraordinarily high at St. Paul in 2010-2011, due to a combination of an extremely fertile site with a history of heavy manure application, favorable weather, and hand-harvesting, which reduced harvest losses. In 2011-2012, increasing the radish seeding rate had a negative effect on corn yield: each additional kg ha^{-1} of radish seed decreased corn yield by 23 kg ha^{-1} ($R^2 = 0.9943$, $p = 0.0483$). The cause of this relationship between radish seeding rate and corn yield is unclear. Radish accession affected corn yield only in the mid-August radish seeding date treatment at St. Paul in 2011-2012, where corn following Graza out-yielded corn following GroundHog by 1.8 Mg ha^{-1}. The reason for this interaction is unclear, but it may be related to spatial effects. The overall average yield at St. Paul in 2011-2012 was 8.6 Mg ha^{-1}. At Lamberton, corn yield was not affected by radish seeding date, accession, or seeding rate (Table 7). The average yield at this site was 7.7 Mg ha^{-1}.

CONCLUSIONS

The effects of seeding date and rate were consistent across accessions. Seeding date strongly affected radish biomass and percent cover. Delaying radish planting until late September reduced both cover and biomass, and often reduced nitrogen accumulation. In Minnesota, as in other regions with similar environmental conditions, radish cover crops should be planted in mid-August to early September for best results. The effects of seeding rate were smaller and less consistent than the effects of seeding date. These results suggest that a seeding rate of 5 kg ha^{-1} is suitable under good conditions, but increasing the seeding rate may improve cover crop performance under adverse conditions. The effects of radish cover crop treatments on corn grain yield were inconsistent and need to be clarified by further research.

ACKNOWLEDGEMENTS

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Table 1. Radish seeding rates (pure live seed) by accession and environment at St. Paul and Lamberton, MN in 2010-2012.

Accession	Seeding rate	St. Paul		Lamberton
		2010	2011	2011
		kg ha^{-1}		
GroundHog	1x	5.5	5.6	5.6
	2x	11.0	11.2	11.2
	4x	22.0	22.4	22.4
Defender	1x	4.1	-	-
	2x	8.1	-	-
	4x	16.2	-	-
Graza	1x	-	5.6	5.2
	2x	-	11.2	10.4
	4x	-	22.4	20.7

Table 2. Dates of data collection and field operations at St. Paul and Lamberton, MN in 2010-2012.

	St. Paul		Lamberton
	2010 – 2011	2011 – 2012	2011 – 2012
Buckwheat chopped	26 Jul	21 Jul	20 Jul
Entire field disked	26 Jul	9 Aug	5 Aug
Secondary tillage†	16 Aug	19 Aug	15 and 22 Aug
Radish planting date 1	16 Aug	22 Aug	23 Aug
Radish planting date 2	30 Aug	29 Aug	31 Aug
Radish planting date 3	13 Sept	12 Sept	15 Sept
Radish planting date 4	29 Sept	26 Sept	30 Sept
Percent cover visually rated	25 Oct	8 Nov	25 Oct
Radish biomass sampled	22 and 28 Oct	17-18 Oct	25-26 Oct
Soil sampled	8 Apr	21 Mar	20 Mar
Corn planted	4 May	27 Apr	11 May
Corn grain harvested	5 Oct	18 Sept	27 Sept

† Secondary tillage was performed with a tractor-mounted rototiller at St. Paul in 2010, a field finisher at St. Paul in 2011, and a field cultivator at Lamberton in 2011.

Table 3. Fixed effects of radish seeding date (D), accession (A), and seeding rate (R) on radish cover and biomass at St. Paul and Lamberton, MN in 2010 and 2011.

	Radish cover			Radish biomass		
	St. Paul		Lamberton‡	St. Paul		Lamberton
Effect	2010	2011	2011	2010	2011	2011
	p > F					
D	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
A	<0.0001	0.0317	1.0000	0.0117	0.1875	0.4083
D x A	<0.0001	0.0006	0.8465	0.0014	0.4136	0.5812
R	<0.0001	<0.0001	<0.0001	0.7999	0.0107	<0.0001
D x R	<0.0001	<0.0001	<0.0001	0.4114	0.3233	<0.0001
A x R	0.0024	0.0070	0.2094	0.9861	0.4277	0.4473
D x A x R	<0.0001	0.0074	0.4436	0.7204	0.5782	0.4243

‡At Lamberton, only data from the mid-August seeding date were analyzed due to the effect of severe drought conditions on radish germination at later seeding dates.

Table 4. Fixed effects of radish seeding date (D), accession (A), and seeding rate (R) on radish shoot and root nitrogen concentration and accumulation at St. Paul and Lamberton, MN in 2010 and 2011.

	St. Paul		Lamberton†	St. Paul		Lamberton
	2010	2011	2011	2010	2011	2011
Effect	Shoot nitrogen concentration			Shoot nitrogen accumulation		
	-- p > F			--------------------------------------		
D	0.0051	0.0002	-	0.0286	0.0942	-
A	0.8065	0.0054	0.7055	0.2436	0.0023	0.5493
D x A	0.1317	0.0746	-	0.0507	0.0009	-
R	0.0030	<0.0001	0.0206	0.8582	0.1089	0.0126
D x R	0.9818	0.2165	-	0.0620	0.0009	-
A x R	0.5818	0.7628	0.8019	0.2361	0.9051	0.5357
D x A x R	0.5320	0.0653	-	0.0921	0.2229	-
	Root nitrogen concentration			Root nitrogen accumulation		
	-- p > F			--------------------------------------		
A	0.0135	0.0078	0.0801	0.6299	0.9849	0.7574
R	0.1164	0.0040	0.1099	0.0036	0.0098	0.8401
A x R	0.8113	0.5261	0.2531	0.1377	0.1954	0.8281

Shoot nitrogen concentration and accumulation: mid-August and mid-September seeding dates, 1x and 4x seeding rates. Root nitrogen concentration and accumulation: mid-August seeding date only, 1x and 4x seeding rates. Root biomass for the mid-September seeding date was bulked over reps for analysis; thus, statistical analyses of the effect of seeding date on root nitrogen concentration and accumulation could not be performed.

† At Lamberton, only biomass from the mid-August seeding date was analyzed due to the effect of severe drought conditions on radish biomass at later seeding dates.

Table 5. Effect of radish cover crop seeding date and seeding rate on end-of-season radish shoot and root nitrogen concentration at St. Paul and Lamberton, MN in 2010 and 2011. Means presented are averaged across radish accessions.

		Shoot nitrogen concentration			Root nitrogen concentration		
		St. Paul		Lamberton†	St. Paul		Lamberton
Seeding date	Seeding rate	2010	2011	2011	2010	2011	2011
		------------------------------ % ------------------------------					
Mid-August	1x	3.7 a‡	2.9 a	4.7 a	2.5 a	2.0 a	3.5 a
	4x	3.2 b	2.2 b	4.4 b	2.2 a	1.5 b	3.3 a
Mid-September	1x	6.2 a	6.0 a	-	4.0§	3.7	-
	4x	5.8 b	5.1 b	-	3.7	2.9	-
				Mean over seeding rates			
Mid-August		3.5 b¶	2.5 b	4.5	2.3	1.8	3.4
Mid-September		6.0 a	5.5 a	-	3.8	3.3	-
				Mean over seeding dates			
	1x	5.0 a¶	4.4 a	-	3.2	2.8	-
	4x	4.5 b	3.6 b	-	3.0	2.2	-

† At Lamberton, only biomass from the mid-August seeding date was analyzed due to the effect of severe drought conditions on radish biomass at later seeding dates.

‡ Within a column and seeding date, means followed by the same letter are not significantly different at α = 0.05 (ANOVA F-test).

§ Root biomass for the mid-September seeding date was bulked over reps for analysis; thus, statistical analyses could not be performed for comparisons involving root nitrogen concentration at this seeding date.

¶ Within a column, means followed by the same letter are not significantly different at α = 0.05 (ANOVA F-test).

Table 6. Effect of radish cover crop seeding date and seeding rate on end-of-season radish shoot and root nitrogen accumulation at St. Paul and Lamberton, MN in 2010 and 2011. Means presented are averaged across radish accessions.

		Shoot nitrogen concentration			Root nitrogen concentration		
		St. Paul		Lamberton†	St. Paul		Lamberton
Seeding date	Seeding rate	2010	2011	2011	2010	2011	2011
		------------------------------ % ------------------------------					
Mid-August	1x	191 a‡	71 a	83 b	54 a	32 a	24 a
	4x	169 a	62 a	125 a	36 b	26 b	25 a
Mid-September	1x	99 a	43 b	-	10§	4	-
	4x	125 a	63 a	-	10	5	-
				Mean over seeding rates			
Mid-August		180 a¶	67 a	104	45	29	24
Mid-September		112 b	53 a	-	10	4	-
				Mean over seeding dates			
	1x	145 a¶	57 a	-	33	18	-
	4x	147 a	63 a	-	23	15	-

† At Lamberton, only biomass from the mid-August seeding date was analyzed due to the effect of severe drought conditions on radish biomass at later seeding dates.

‡ Within a column and seeding date, means followed by the same letter are not significantly different at α = 0.05 (ANOVA F-test).

§ Root biomass for the mid-September seeding date was bulked over reps for analysis; thus, statistical analyses could not be performed for comparisons involving root nitrogen concentration at this seeding date.

¶ Within a column, means followed by the same letter are not significantly different at α = 0.05 (ANOVA F-test).

Table 7. Fixed effects of radish seeding date (D), accession (A), and seeding rate (R) on corn grain yield at St. Paul and Lamberton, MN in 2011 and 2012.

	Corn grain yield		
	St. Paul		Lamberton
Effect	2010-2011	2011-2012	2011-2012
	------------------------------------ p > F ----------------------------------		
D	0.0073	0.2057	0.1007
A	0.2012	0.9984	0.0935
D x A	0.0605	0.0288	0.1936
R	0.8412	0.0445	0.3371
D x R	0.6037	0.6763	0.1974
A x R	0.4660	0.6779	0.0646
D x A x R	0.4671	0.6981	0.4715

‡At Lamberton, only data from the mid-August seeding date were analyzed due to the effect of severe drought conditions on radish germination at later seeding dates.

Table 8. Effect of radish cover crop seeding date on grain yield of a subsequent corn crop at St. Paul, MN in 2011. Means presented are averaged across radish accessions and seeding rates.

Radish seeding date	Corn grain yield
	------------------ Mg ha^{-1} --------------------
Mid-August	17.0 a†
Late August	16.5 ab
Mid-September	14.8 b
Late September	15.0 b

† Means followed by the same letter are not significantly different at $\alpha = 0.05$ (Tukey-Kramer test).

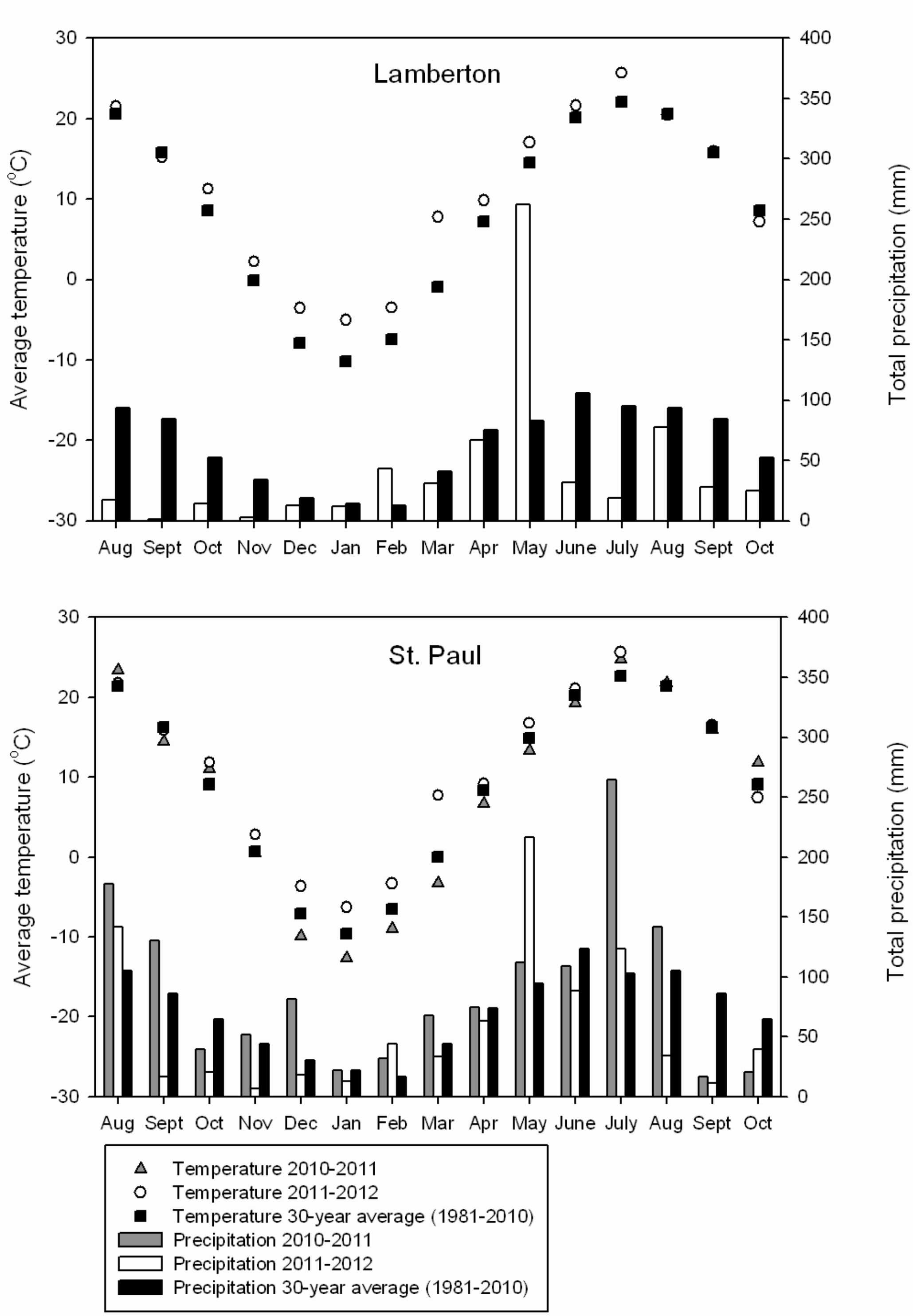

Fig. 1. Monthly average temperature and total precipitation at Lamberton and St. Paul, MN.

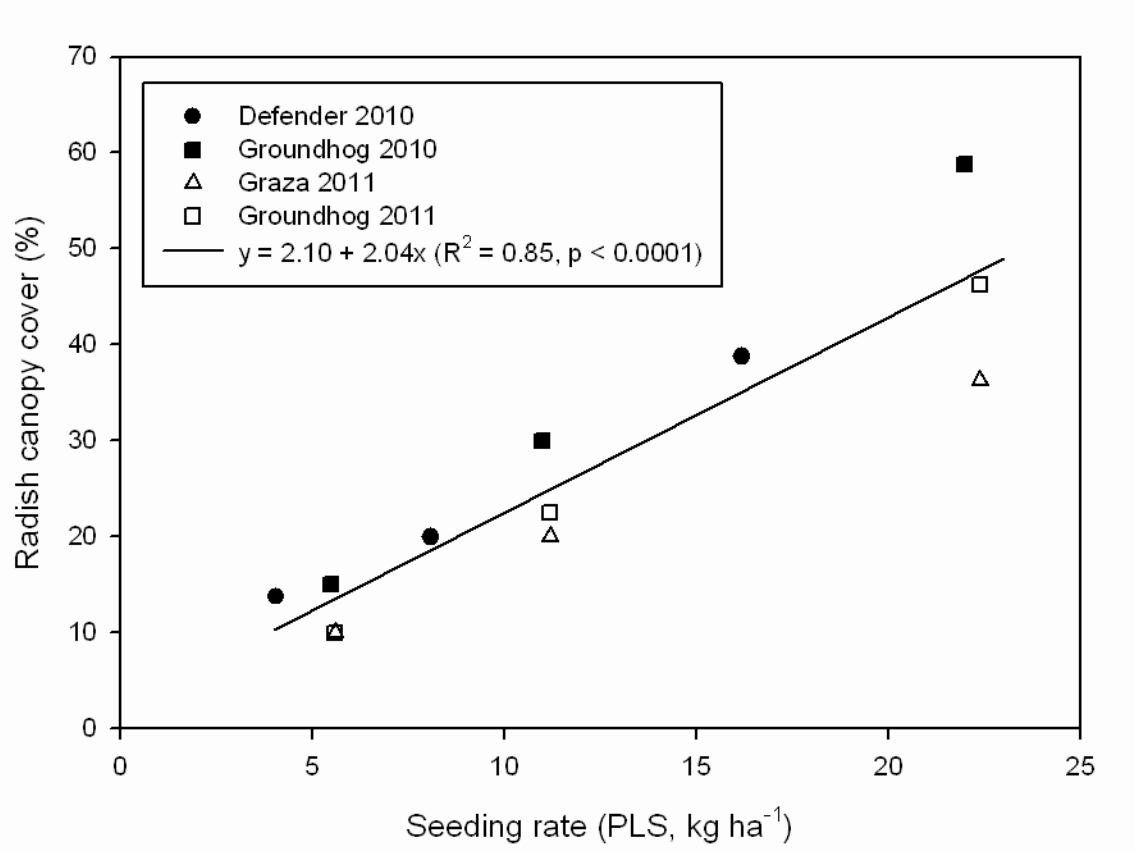

Fig. 2. Effect of seeding rate on end-of season canopy cover for radish cover crops seeded in late September at St. Paul, MN.

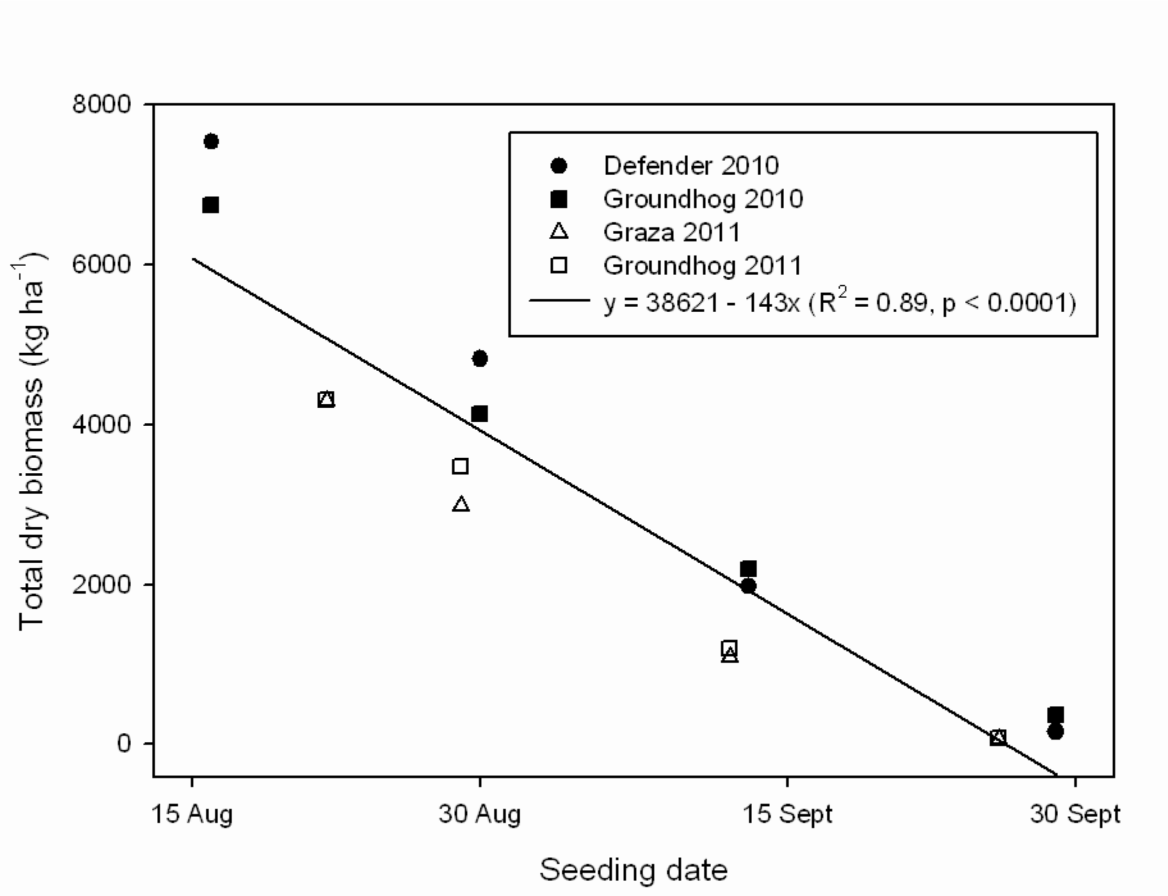

Fig. 3. Effect of seeding date on end-of-season radish biomass at St. Paul, MN in 2010 and 2011. Biomass is averaged over seeding rates. Day of year was used as the x variable in the regression analysis.

Chapter 4

Spring and Fall-Seeded Radish Cover Crop Effects on Weed Management in Corn (*Zea mays* L.)

Spring and Fall-Seeded Radish Cover Crop Effects on Weed Management in Corn (*Zea mays* L.)

SUMMARY

Weed management is a major factor limiting productivity of organic cropping systems. Fall-seeded radish (*Raphanus sativus* L.) cover crops suppress fall weed growth and may be useful for weed management in organic cropping systems. Spring-seeded radish may be allelopathic, but little is known about its ability to suppress weeds. Two-year field experiments were established at Lamberton and Rosemount, MN in August 2010 and 2011 to evaluate the effect of radish cover crops and tillage intensity on density, cover, and biomass of weeds in organically-managed corn. The experimental design was a factorial with four radish cover crop treatments (fall-only, spring-only, fall+spring, and no-cover) and three cultivation treatments ("standard" [one to two rotary hoeings and two row cultivations], "false seedbed" [standard plus an additional tillage pass 20-50 d before corn planting], and "reduced" [one rotary hoeing and one row cultivation]). All plots were tilled immediately before planting. Shoot biomass averaged 3057 kg ha^{-1} for fall-seeded radish and 385 kg ha^{-1} for spring-seeded radish with no false seedbed. Effects of radish cover crops on weed responses were inconsistent. The effect of fall-seeded radish ranged from a 44% decrease in August weed cover to an 88% increase in June weed density in the reduced tillage treatment relative to plots without fall-seeded radish. The effect of spring-seeded radish ranged from a 46% decrease in June weed density to a 94% increase in August non-crop biomass. Radish cover crops are unlikely to improve management of summer annual weeds in organic systems over the short term.

INTRODUCTION

Organic field crop producers in Minnesota and throughout the US consistently cite weed management as a major concern (Moynihan, 2010; Minnesota Department of Agriculture, 2007; Walz, 1999). Organic farmers manage weeds through a combination of mechanical tillage and ecological weed management strategies (Bond and Grundy, 2001). Ecological weed management focuses on redesigning cropping systems to reduce weed recruitment, increase crop competitiveness, and reduce the size of the weed seedbank (Bastiaans *et al*., 2008). Reliance on mechanical tillage for weed control is inherently risky, since effective mechanical weed control requires multiple precisely-timed cultivations, which can easily be disrupted by wet weather (Mohler, 2001; Posner et al., 2008; Porter et al., 2003; Cavigelli et al., 2008). By reducing weed populations and competitiveness, ecological weed management can mitigate this risk. One of the ecological weed management strategies available to organic farmers is cover cropping. Liebman and Davis (2000) suggest two ways cover crops can improve weed management in organic systems: byreducing off-season weed seed production through competition, and by reducing weed recruitment during the cropping season through allelopathy or stimulation of plant pathogens that attack weed seeds and seedlings.

Radish (*Raphanus sativus* L.) is a relatively new cover crop with potential usefulness as part of an ecological weed management system. Fall-seeded radish cover crops grow quickly but winterkill in northern climates, leaving a low-residue seedbed in the spring (Lawley et al., 2011). Fall-seeded radish consistently suppresses weed growth in the fall and early spring (Charles et al., 2006; Kruidhof et al., 2008; Lawley et al., 2011; O'Reilly et al., 2011, Stivers-Young, 1998). In addition, Wang et al. (2008) reported that fall-seeded radish reduced weed seed bank size in a vegetable rotation where the major weed species were yellow nutsedge (*Cyperus esculentus* L.), common purslane (*Portulaca oleracea* L.), redroot pigweed (*Amaranthus retroflexus* L.), and wild mustard (*Sinapis arvensis* L.). The low-residue, nearly weed-free seedbed produced by radish may allow organic farmers to reduce the number or intensity of tillage passes used for seedbed preparation (Lawley et al., 2011). However, weed suppression by fall-seeded radish generally does not persist into the following summer (Charles et al., 2006; Lawley et al., 2011, O'Reilly et al., 2011). Indeed, fall-seeded radish sometimes increases weed emergence during the following summer, perhaps due to its effect on soil nitrate levels (Charles et al., 2006; Lawley et al., 2011, 2012). Thus, fall-seeded radish cover crops must be combined with other measures to maintain season-long weed control.

The potential of spring-seeded radish for weed control has not been studied. Spring-seeded radish evidently has allelopathic or pathogen-promoting effects; emergence of direct-seeded muskmelon was reduced to zero where a radish cover crop was incorporated 7 to 8 days before muskmelon seeding (Ackroyd and Ngouajio, 2011). However, effects on weed emergence were not reported in this study. Other brassica cover crops seeded in spring have been reported to reduce weed emergence. A spring-seeded mustard mixture (*Brassica juncea* L. and *Sinapis alba* L.) incorporated into the soil reduced densities of annual grasses by 58-73% relative to a weedy check, but generally did not affect densities of broadleaf weeds (Norsworthy et al., 2005). In a field bioassay, incorporation of spring-seeded brassica cover crops (*Brassica napus* L. and *S.*

alba) reduced average emergence of 16 bioassay species by 23 to 34% and delayed emergence by about 2 days, compared to a fallow control (Haramoto and Gallandt, 2005).

The mechanism of weed suppression may differ between fall- and spring-seeded radish cover crops. Like other members of the brassica family, radish contains glucosinolates in its tissues (Brown and Morra, 1997; Sang et al., 1984). The main degradation products of glucosinolates are isothiocyanates, several of which inhibit weed seed germination and seedling growth (Brown and Morra, 1997; Haramoto and Gallandt, 2004). In laboratory bioassays, extracts of fresh radish tissue reduced germination and radicle length of muskmelon, honeydew, and cucumber (Ackroyd and Ngouajio, 2011), while extracts of dried tissue inhibited germination and root growth of lettuce (Lawley et al., 2012). However, field trials of a fall-seeded radish cover crop and laboratory bioassays with extracts of decomposing radish residue and soil provided little or no evidence for allelopathy; thus, Lawley et al. (2012) attributed weed suppression by fall-seeded radish cover crops to competition during the fall growing season rather than allelopathic effects. The lack of allelopathic effect seen in trials with fall-seeded radish may be due to rapid loss of isothiocyanates from the soil (Brown and Morra, 1997; Petersen et al., 2001); by the time weed seeds begin germinating in the spring, any allelochemicals from the radish biomass may have degraded. Incorporation of spring-seeded radish immediately before crop planting may be more effective for allelopathic suppression of weeds, though the risk of allelopathy towards the crop must be studied.

The compatibility of radish cover crops with weed management methods typically used by organic farmers requires study before radish cover crops can be recommended for use in organic systems. Organic farmers typically use an integrated system of mechanical and cultural tactics to control weeds. They often delay planting of corn and soybean to allow early flushes of weeds to be removed by preplanting tillage. Many also use the “false seedbed” or “stale seedbed” technique, tilling the soil one or more times a week or more before planting in order to stimulate emergence of weed seedlings which will then be killed by the next tillage pass (Bond and Grundy, 2001). After planting, they use blind cultivation and row cultivation to control weeds that germinate after the crop is planted. Radish cover crops may not be compatible with some of these techniques. For example, Lawley et al. (2011) suggest seeding the following crop earlier than normal when using a fall-seeded radish cover crop, in order to take advantage of the early spring weed suppression provided by the cover crop. If seeding is delayed, as it typically is in an organic system, the benefits of a fall-seeded radish cover crop may be limited. The stimulation of weed emergence by fall-planted radish cover crops reported by Lawley et al. (2011, 2012) might improve the ability of the false seedbed technique to remove viable weed seeds from the seedbank. However, the effectiveness of post-planting cultivation depends in part on weed density—the greater the initial weed density, the greater the number of escapes that will go on to compete with the crop (Mohler, 2001). Stimulation of weed emergence after planting would likely reduce the success of post-planting cultivation techniques. Finally, delayed seeding may make it possible to add a spring-seeded radish cover crop to an organic system, but if a false seedbed is used, the spring-seeded radish may be killed by tillage along with the weeds.

The objectives of this study were to (i) quantify the biomass production of fall-and spring-seeded radish cover crops in an organically-managed corn rotation, (ii) evaluate the effect of radish cover crops on weed density, cover, and biomass in the subsequent corn crop, and (iii) examine the compatibility of radish cover crops with weed management methods typically used by organic farmers.

MATERIALS AND METHODS

Site characteristics and experimental design

Two-year field experiments were established in August 2010 and 2011 at the University of Minnesota Rosemount Research and Outreach Center (Rosemount, MN, 44.72 N, 93.11 W) and Southwest Research and Outreach Center (Lamberton, MN, 44.25 N, 95.31W), for a total of four sites. At Rosemount, the soil was a well-drained Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls). At Lamberton, the soil was a mixture of poorly-drained Webster clay loam (fine-loamy, mixed, superactive mesic Typic Endoaquolls) and somewhat poorly-drained Normania loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). Study sites at Lamberton were on certified organic land, while sites at Rosemount were not certified organic but were managed with organic practices during the corn growing season.

The experimental design was a factorial in randomized complete block (RCB) with four replications and a split-plot layout. Tillage treatment was the main plot, and cover crop treatment was the subplot. Subplots were 4.6 m (six corn rows) wide by 7.6 m long at Rosemount in 2010-2011, 3.0 m (4 corn rows) wide by 9.1 m long at Lamberton in 2010-2011, and 4.6 m wide by 9.1 m long at both sites in 2011-2012. Cover crop treatments were fall-seeded radish (“fall-only”), spring-seeded radish (“spring-only”), both fall- and spring-seeded radish (“fall+spring”), and a no cover crop control (“no-cover”). To establish a range of weed pressures and test the compatibility of cover crop treatments with tillage practices commonly used for weed control by organic farmers, three tillage treatments were imposed. In all tillage treatments, the seedbed was prepared immediately before corn planting with a disk (Lamberton) or field cultivator (Rosemount). In the “false seedbed” treatment, plots were tilled with a disk (Lamberton) or field cultivator (Rosemount) 20-50 d before corn planting, retilled immediately before planting, and cultivated 1-2 times with a rotary hoe and 1-2 times with a row cultivator between planting and the V8 growth stage of the corn crop. In the “standard tillage” treatment, plots were tilled before planting and cultivated 1-2 times with a rotary hoe and 2 times with a row cultivator. In the “reduced tillage” treatment, plots were tilled before planting and cultivated 1 time with a rotary hoe and 1 time with a row cultivator. Dates of all tillage operations are presented in Table 1. In 2011, due to weather and management constraints, the standard and reduced tillage treatments were treated identically through June at Lamberton and through the end of the season at Rosemount. Where this occurred, the standard tillage plots were treated as an additional replication of the reduced tillage treatment in statistical analyses.

Field management and data collection

Dates of data collection and field operations are presented in Table 1. At Rosemount in 2010, radish cover crops were established following an oat crop which was harvested for grain, with the straw baled and removed. At all other locations and years, the preceding crop was a soybean green manure. Aboveground soybean biomass was sampled shortly before mowing to determine its nitrogen content. Preplanting soil nitrate levels were determined by analysis of two to four bulk 0-60 cm soil samples per field. Each sample was a composite of at least four cores. At Rosemount, cores were collected with a standard 1.9 cm diameter hand probe and dried in a forced air dryer at 35°C. At Lamberton, cores with 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 cadmium reduction and colorimetry. Prior to establishing the radish cover crop, liquid swine manure (Rosemount) or solid beef manure (Lamberton) was broadcast and incorporated. Soil nitrate levels, soybean biomass nitrogen, and manure nitrogen, phosphorus, and potassium are presented in Table 2. The field was prepared for planting using a disk, field cultivator, harrow, and/or packer as necessary to create a smooth seedbed.

In the fall-only and fall+spring cover crop treatments, radish was seeded with a cone-drill seeder at 19 kg ha^{-1} between 18 and 23 Aug of each year. Seeding depth was about 2.5 cm, and row spacing was 15 cm at Rosemount and 19 cm at Lamberton. At Lamberton in 2010, radish was seeded in the spring-only and no-cover treatments as well, but removed with a field cultivator 12 d after planting. At Rosemount in 2010, volunteer oats were 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 0.12 kg a.i. ha^{-1} 20 d after planting. In the spring-only and fall+spring cover crop treatments, radish seed was broadcast by hand at 19 kg ha^{-1} as soon as it was possible to enter the field in the spring, between 19 Mar and 8 Apr.

Between 16 May and 7 June, following preplanting tillage operations, corn was planted across the entire plot area in 76-cm rows at a seeding rate of 79,000 seeds ha^{-1} at Rosemount and 84,000 seeds ha^{-1} at Lamberton. The corn hybrid used was certified organic 42A32 from Blue River Hybrids, Kelley, IA. Post-planting tillage treatments were imposed as described above and in Table 1.

Root and shoot biomass of fall-seeded radish were collected in mid to late October of the establishment year, before severe frost damage occurred, by digging or pulling plants in a single 0.25 m^2 quadrat in each subplot in the fall-only and fall+spring treatments. This method allowed collection of the swollen, fleshy portion of the taproot, though fine roots were not collected. 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. Due to the amount of biomass collected, shoot biomass was stored in plastic bags at 6 °C for up to 2 d before washing, while root biomass was stored for up to 3 wk. Both root and shoot biomass were dried in paper bags in a forced-air dryer at 60°C before weighing. In 2011, weed cover was visually rated (0-100%, to the nearest 1%) in all plots in mid to late October, around the time of radish biomass sampling.

Dried biomass from the fall-seeded radish cover crop was ground and analyzed to determine its nitrogen concentration. Root and shoot biomass were ground and analyzed separately. Biomass was coarsely ground, mixed thoroughly, and a subsample was finely ground. In each rep, the biomass from the fall-only, standard tillage treatment was analyzed separately, while biomass from the other treatments was bulked. Nitrogen content of ground biomass was determined by near infrared reflectance spectroscopy (NIR) with a Perten DA 7250 NIRS analyzer (Perten Instruments, Inc., Springfield, IL). Because standard NIR equations for nitrogen concentration in brassica biomass were not available, a subset of samples from this experiment and several other concurrent brassica cover crop experiments was also analyzed by combustion with a Carlo Erba 1500 nitrogen/carbon analyzer (CE Elantech, Inc., Lakewood, NJ) at Brookside Laboratories, New Knoxville, OH. 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 ($R^2 = 0.96$, $SE_{prediction} = 0.28$). In some cases, not enough tissue was available to analyze a sample using NIR. These samples were analyzed by combustion instead. Nitrogen accumulation was calculated as biomass multiplied by nitrogen concentration.

Stand density and shoot biomass of spring-seeded radish were determined by counting and harvesting radish plants in two 0.25 m^2 quadrats in each plot in mid-May of each year, prior to corn planting. Nitrogen accumulation and root biomass of spring-seeded radish were not measured.

Weed density was determined before corn planting by counting plants in two 0.25 m^2 quadrats per plot. In treatments with spring-seeded radish, weed density counts occurred in the same quadrats used for radish sampling. Weed density was also determined when the corn was at the V3-V4 stage, between rotary hoeing and row cultivation. At this sampling date, weeds were counted in one (Lamberton 2011) to two (all other locations and years) quadrats per plot. Quadrats were 0.44 m by 0.76 m (0.33 m^2) and were centered on a row of corn, making it possible to obtain a representative sample of the in-row and inter-row space. Some weed seedlings were pulled to aid in identification. Weed and radish cover were visually rated in late August. At the same time, non-crop (weed and radish) biomass was determined by clipping all aboveground non-crop material in three 0.33 m^2 quadrats centered on one of the middle two rows of corn. Corn grain yield was measured in October by harvesting 9.2 to 16.0 m of row from each subplot with a combine. All yields were adjusted to 15.5% moisture.

Temperature and precipitation data were obtained from weather stations located at the experiment sites. Growing degree days (GDD) were calculated using the standard equation GDD = $(T_{max} – T_{min})/2 – T_{base}$, where T_{max} is the daily maximum temperature, T_{min} is the daily minimum temperature, and T_{base} is the base temperature (McMaster and Wilhelm, 1997). The base temperature for radish was set at 5°C, on the basis of estimates for other brassicaceous species (Adams et al., 2005; Huang et al., 2001). T_{max} and T_{min} values less than 5°C were set equal to 5°C before calculating GDD.

Statistical analysis

All data were analyzed with SAS software (Version 9.3, SAS Institute, Cary, NC). Due to treatment by site interactions for several variables, each study site was analyzed separately. The high level of weed suppression achieved in the false seedbed and standard tillage treatments at some sites made it difficult to test the effect of the radish cover crop treatments. Therefore, effects of cover crop treatments on weed density, biomass, and cover were tested within tillage treatments rather than across tillage treatments. Where the standard and reduced tillage treatments were treated identically, a single degree of freedom contrast was used to test the effect of tillage treatment. Otherwise, tillage effects were tested using an ANOVA appropriate for a split-plot in RCB design followed by means separation (Tukey-Kramer, $\alpha = 0.05$). Cover crop effects were tested using single degree of freedom contrasts to test the effect of fall-seeded radish (fall-only and fall+spring vs. spring-only and no-cover) and spring-seeded radish (spring-only and fall+spring vs. fall-only and no-cover).

RESULTS AND DISCUSSION

Weather conditions

Temperature and precipitation data for the study sites are presented in Fig. 1. Precipitation during the fall 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-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 fall cover crop growing season until spring cover crop seeding (November-March) was colder than normal in 2010-2011, but warmer than normal in 2011-2012. In 2010-2011, snow cover was present continuously 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, on the other hand, snow cover was sparse and sporadic, and snow depth never exceeded 10 cm. The spring cover crop growing season (15 Mar-15 May) was cooler than normal in 2011, but warmer than normal in 2012 (Fig. 1; Table 3). Spring growing degree day accumulation was greater in 2012 than in any of the previous 30 years. May-July precipitation was normal to greater than normal at both locations in 2011 and at Rosemount in 2012. At Lamberton in 2011, precipitation ≥ 5 mm occurred on 14 d out of 46 from May 16 to June 30. These frequent precipitation events interfered with field work and promoted weed growth. At Lamberton in 2012, precipitation during the corn growing season was unevenly distributed, with greater than average May precipitation giving way to very dry conditions 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 was normal in August and September.

Radish cover crop

Fall-seeded radish cover crops established and grew well at all four sites (Table 4). Averaged across sites, radish root biomass was 1340 kg ha^{-1}, shoot biomass was 3057 kg ha^{-1}, and total nitrogen accumulation was 115 kg ha^{-1}. Shoot biomass of spring-seeded radish cover crops was much lower than shoot biomass of fall-seeded radish, even in the unusually warm spring of 2012 (Table 5). Nitrogen accumulation and root biomass of spring-seeded radish were not measured. Neither tillage treatment nor fall-seeded radish affected biomass of spring-seeded radish in the colder than normal spring of 2011, when biomass averaged across locations and treatments was only 18 kg ha^{-1}. In 2012, the false seedbed treatment consistently reduced radish biomass compared to no false seedbed. There was also an interaction between fall-seeded radish and tillage treatment at Rosemount: fall-seeded radish reduced the biomass of spring-seeded radish only where there was no false seedbed. Use of a false seedbed increased stand count of spring-seeded radish at Rosemount in 2011, but decreased stand count in 2012 (Table 5). The difference between years is probably due to weather-related differences in timing of radish germination relative to tillage. Stand count of spring-seeded radish was not affected by presence or absence of fall-seeded radish. Spring radish stand counts were similar to those necessary to maximize biomass production of fall-seeded radish in a field experiment testing the effect of seeding rate on radish biomass (unpublished data, 2011). Thus, low spring biomass production is due to the short growing season available between snowmelt and corn planting, rather than poor establishment.

Weed density, cover, and biomass

At Rosemount in 2011, fall-seeded radish reduced October weed cover from 4% to 0%. The dominant weeds at this site were *Amaranthus* species, common lambsquarters (*Chenopodium album* L.), and eastern black nightshade (*Solanum physalifolium* Rusby), all of which are summer annuals. Both *Amaranthus* and lambsquarters flowered during the fall season. At Lamberton in 2012, October weed cover was 0% both with and without fall-seeded radish. The effect of fall-seeded radish on fall weed cover was not measured in 2010. In small grain crops, post-harvest seed production accounts for a large portion of yearly seed rain (Kegode *et al*., 2003). Liebman and Davis (2000) propose the use of cover crops as a way to reduce weed seed production between cash crops. The results of this experiment suggest that fall-seeded radish cover crops may be useful for this purpose. However, further research is needed to determine whether fall seed rain is affected by radish cover crops.

In mid-May, when organic corn is typically planted in Minnesota, the most common weeds included common lambsquarters and summer annual grasses at all sites, as well as *Amaranthus* species and eastern black nightshade at Rosemount in 2012. Use of a false seedbed reduced weed density (Table 6). The effect of a false seedbed on weed density was consistent across cover crop treatments. In the false seedbed treatment, neither fall nor spring-seeded radish affected weed density (Table 6). In treatments with no false seedbed, spring-seeded radish did not affect May weed density, but fall-seeded radish reduced weed density at Rosemount in 2012. The reduction in May weed density at this site is consistent with the idea that fall-seeded radish cover crops may aid in weed management over the long term by reducing seed rain. However, at 256 plants m^{-2}, weed density in plots with fall-seeded radish remained far too high to permit reduced use of other weed management methods over the short term.

Fall-seeded radish also showed promise for control of winter annual weeds. While densities of winter annual species were low, field pennycress (*Thlaspi arvense* L.) accounted for the majority of May weed cover at Lamberton in 2011 due to the large size of the plants. At this site, in treatments with no false seedbed, fall-seeded radish reduced pennycress density from 9 plants m^{-2} to less than 1 plant m^{-2} ($p = 0.0006$). Fall-seeded radish also reduced the density of horseweed (*Conyza canadensis* [L.] Cronq.) at Rosemount in 2011 from 6 to 2 plants m^{-2} ($p = 0.0038$) in treatments with no false seedbed. At other sites, densities of winter annual weeds were too low to permit measurement of the effect of radish cover crops. In agreement with the observations of Lawley et al. (2011), these results suggest that fall-seeded radish cover crops may be useful for management of winter annuals. The effect of fall-seeded radish on horseweed density may be of particular interest to conventional farmers, since herbicide-resistant horseweed is a problem in conventional no-till systems (Davis and Johnson, 2008). It should be noted that horseweed does not always behave as a winter annual (Davis and Johnson, 2008). Buhler and Owen (1997) found that 28 to 32% of total horseweed emergence at Rosemount occurred in the spring, beginning in mid-May. While it is likely that the majority of the horseweed plants observed in this study emerged in the fall, further research is needed to clarify the effect of fall-seeded radish on fall- and spring-emerging horseweed.

The effect of tillage treatments on weed growth during the corn growing season was greatest at Rosemount in 2012, where August weed cover and non-crop (weed plus radish) biomass were greater in the reduced tillage treatment than the other treatments (Table 7). June weed density was also greatest in the reduced tillage treatment, although there was an interaction between tillage treatment and cover crop—the size of the difference between tillage treatments was smaller in the spring-only treatment than in the other cover crop treatments. There were no interactions between tillage and cover crop treatments at the other sites. As at Rosemount in 2012, the reduced tillage treatment had greater weed cover than the other treatments at Rosemount in 2011 and greater non-crop biomass at Lamberton in 2012. At Lamberton in 2011, weed density, cover, and biomass were very high compared to the other sites, and were not affected by tillage treatments. The most common weeds in both June and August were summer annual grasses, *Amaranthus* species, and common lambsquarters.

Within the reduced tillage treatment, fall-seeded radish increased June weed density at Rosemount in 2011 and Lamberton in 2012 (Table 8). This increase in weed density may have been due to stimulation of nitrophile species such as lambsquarters, as reported by Lawley et al. (2011, 2012). However, higher weed density with fall-seeded radish did not result in higher weed cover or non-crop biomass in August: fall-seeded radish reduced weed cover at Rosemount in 2011 and had no effect on non-crop biomass at any site (Table 8). The effect of fall-seeded radish on weed cover at Rosemount in 2011 appeared to be related to its effect on horseweed density; a few large horseweed plants accounted for a significant proportion of the weed cover at this site. Spring-seeded radish reduced June weed density at Rosemount in 2012, but as with fall-seeded radish, this effect on weed density did not translate into an effect on weed cover or non-crop biomass later in the growing season (Table 8). Spring-seeded radish did not affect weed density or cover at the other sites. This lack of effect may be due to poor spring radish growth in 2011 (Table 5) and low weed pressure at Lamberton in 2012 (Tables 7 and 8). Spring-seeded radish increased non-crop biomass at Lamberton in 2012. The effect of spring-seeded radish at this site may have been due to the presence of volunteer radish plants, which were included in non-crop biomass.

The potential of a cover crop to escape control and compete with the crop must be considered when evaluating cover crop species and management techniques (Snapp et al., 2005). Fall-seeded radish was uniformly killed by cold winter temperatures while still in the vegetative stage. Averaged across tillage treatments, June radish density was ≤ 0.1 plants m^{-2} and August radish cover was ≤ 0.2% in the fall-only cover crop treatment.

Spring-seeded radish, however, sometimes escaped control, especially in treatments without a false seedbed. Where radish was seeded in spring and a false seedbed was not used, June radish density averaged 10 plants m^{-2} at Rosemount in 2011 and 2 plants m^{-2} at Lamberton in 2012. The false seedbed reduced radish density in treatments with spring-seeded radish to 2 plants m^{-2} at Rosemount and 0 plants m^{-2} at Lamberton. August radish cover in treatments with spring-seeded radish and no false seedbed averaged 4% at Rosemount in 2011 and 1% at Lamberton in 2012.

Corn yield

Averaged across treatments, corn grain yield measured 4.7 Mg ha^{-1} at Lamberton in 2011, 11.1 Mg ha^{-1} at Lamberton in 2012, 8.8 Mg ha^{-1} at Rosemount in 2011, and 10.7 Mg ha^{-1} at Rosemount in 2012. The unusually low yield at Lamberton in 2011 is attributable to a combination of late planting, unsuccessful weed control, and a frost in September that killed the corn before it reached physiological maturity. There was an interaction between cover crop and tillage treatments at Lamberton in 2012: the reduced tillage treatment reduced corn yield in the spring-only treatment but not in the other cover crop treatments. At the other sites, there was no interaction between cover crop and tillage treatments. Averaged across cover crop treatments, tillage treatments affected corn yield only at Rosemount in 2011, where corn yield was higher with a false seedbed (Table 9). Averaged across tillage treatments, radish cover crop treatments had no effect on corn yield (Table 9).

CONCLUSIONS

Radish can be established successfully as a cover crop when seeded in mid-

August. Although fall-seeded radish sometimes increased weed emergence the following year, it did not increase weed cover or non-crop biomass. Thus, organic farmers should not need to increase their use of tillage if they use fall-seeded radish as a cover crop. The effect of fall-seeded radish on weed seed rain during the fall deserves further study. If fall-seeded radish can be shown to reduce weed seed rain, it could play an important role in integrated weed management systems. Likewise, the effect of fall-seeded radish on horseweed establishment should be studied further, with attention to the phenology of the local horseweed population.

Spring-seeded radish had low biomass production due to the short growing window before corn planting. It was not compatible with the false seedbed method, and it sometimes escaped control. While spring-seeded radish sometimes reduced weed emergence during the corn growing season, it did not reduce weed cover or non-crop biomass. Thus, the use of a spring-seeded radish cover crop for weed management in organic field crop systems in Minnesota does not appear feasible.

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Table 1. Dates of data collection and field operations at Lamberton and Rosemount, MN in 2010-2012.

	Lamberton		Rosemount	
	2010-2011	2011-2012	2010-2011	2011-2012
Fall radish seeding	18 Aug	23 Aug	19 Aug	19 Aug
Weed percent cover rating	-	26 Oct	-	11 Oct
Radish biomass sampling	19 Oct	25 Oct	28 Oct	22 Oct
Spring radish seeding	25 Mar	20 Mar	8 Apr	19 Mar
Early preplanting tillage (false seedbed treatment)	5 May	1 May	6 May	27 Mar
Preplanting weed and radish counts, radish biomass sampling	17 May	17 May	18 May	15-16 May
Preplanting tillage (all treatments)	6 June	18 and 22 May	26 May	16 May
Corn planting	7 June	22 May	26 May	16 May
First rotary hoeing (all treatments)	16 June	4 June	1 June	22 May
Second rotary hoeing (false seedbed and standard tillage treatments)	-	8 June	-	1 June
Post-planting weed counts	30 June	11 June	20 June	8 June
First row cultivation (all treatments)	30 June	18 June	27 June	14 June
Second row cultivation (false seedbed and standard tillage treatments)	18 July	27 June	-	25 June
Weed percent cover rating	30 Aug	24 Aug	25 Aug	22 Aug
Weed biomass sampling	30 Aug	24 Aug	26 Aug	22 Aug
Corn grain harvest	25 Oct	12 Oct	21 Oct	10 Oct

Table 2. Soil nitrate-nitrogen, nitrogen content of soybean green manure, and nutrient content of manure applied prior to radish cover crop planting at Lamberton and Rosemount, MN in 2010 and 2011.

Site	Year	Soil (0-60 cm) Nitrate-nitrogen	Soybean biomass Total nitrogen	Manure Total nitrogen	Manure P_2O_5	Manure K_2O
		----------------------------------	kg ha^{-1}	--------------------------------		
Lamberton	2010	34	117	126	133	78
	2011	41	--†	215	202	202
Rosemount	2010	18	--‡	151	139	61
	2011	50	61	110	33	72

† Data not available.

‡ Soybean not present.

Table 3. Growing degree day (GDD) accumulation from 15 March to 15 May at Lamberton and Rosemount, MN in 2011 and 2012.

Site	Year	GDD	Deviation from 1981-2010 mean
Lamberton	2011	169	-77
	2012	453	207
Rosemount	2011	175	-92
	2012	431	164

Table 4. Biomass and nitrogen accumulation of a fall-seeded radish cover crop at Lamberton and Rosemount, MN in 2010 and 2011.

	Lamberton		Rosemount	
	2010	2011	2010	2011
	---------- kg ha^{-1} ----------			
Biomass				
Root	1308	1360	1302	1390
Shoot	3831	3019	2612	2767
Total	5139	4379	3913	4157
Nitrogen accumulation				
Root	18	32	27	28
Shoot	81	106	84	86
Total	98	138	111	114

Table 5. Effect of tillage and fall cover crop treatments on stand count and biomass production of a spring-seeded radish cover crop in mid-May at Lamberton and Rosemount, MN in 2011 and 2012.

	Stand count				Shoot biomass			
Tillage	Lamberton		Rosemount		Lamberton		Rosemount	
Cover crop	2011	2012	2011	2012	2011	2012	2011	2012
	------------ plants m^{-2} ------------				-------------- kg ha^{-1} --------------			
False seedbed								
Fall present	34	66	57	53	0	50	20	20
absent	30	91	50	25	0	115	25	15
P > F (contrast)	0.6447	0.1822	0.6215	0.3008	-	0.3039	0.6376	0.8361
No false seedbed								
Fall present	26	100	28	122	20	458	23	883
absent	32	76	32	99	28	340	15	1313
P > F (contrast)	0.4193	0.2742	0.3762	0.3433	0.6537	0.5230	0.2849	0.0223
Mean (over cover crops)								
False seedbed	32	79	53	39	0	83	23	18
No false seedbed	29	88	30	110	24	399	19	1098
P > F (contrast)	0.6756	0.4613	0.0136	0.0154	0.0996	0.0030	0.5336	0.0008

Table 6. Effect of tillage and cover crop treatments on weed density in mid-May at Lamberton and Rosemount, MN in 2011 and 2012.

		May weed density			
Tillage		Lamberton		Rosemount	
Cover crop		2011	2012	2011	2012
		plants m^{-2}			
False seedbed					
Fall	present	18	21	48	64
	absent	9	23	38	56
	P > F (contrast)	0.2386	0.7498	0.3968	0.6072
Spring	present	13	21	46	62
	absent	14	22	40	58
	P > F (contrast)	0.9720	0.9363	0.5772	0.7713
No false seedbed					
Fall	present	122	105	123	256
	absent	135	128	149	368
	P > F (contrast)	0.6093	0.1142	0.0539	0.0193
Spring	present	131	110	149	293
	absent	126	123	123	331
	P > F (contrast)	0.8495	0.3978	0.0560	0.3973
Mean (over cover crops)					
False seedbed		13	22	43	60
No false seedbed		128	116	136	312
	P > F (contrast)	0.0038	0.0001	0.0017	0.0002

Table 7. Effect of tillage treatments on June weed density, August weed cover, and August non-crop biomass at Lamberton and Rosemount, MN in 2011 and 2012. Effects of tillage treatments are averaged across cover crop treatments.

	Lamberton		Rosemount	
Tillage treatment	2011	2012	2011	2012
	June weed density			
	plants m^{-2}			
False seedbed	142a†	5a	12a	5a
Standard tillage	-	5a	-	8a
Reduced tillage	103a	12a	10a	75b
	August weed cover			
	%			
False seedbed	18a	3a	5a	1a
Standard tillage	16a	3a	-	1a
Reduced tillage	18a	5a	7b	10b
	August non-crop biomass			
	kg ha^{-1}			
False seedbed	1608a	203a	85a	9a
Standard tillage	1343a	199a	-	7a
Reduced tillage	1413a	369b	211a	241b

†Within a column, means followed by the same letter are not statistically different at $\alpha = 0.05$. Where only two treatments were present, a single degree of freedom contrast was used to test for a difference between means. Otherwise, the Tukey-Kramer test was used for means separation.

Table 8. Effect of cover crop treatments on June weed density, August weed cover, and August non-crop biomass in reduced-tillage plots at Lamberton and Rosemount, MN in 2011 and 2012.

		Lamberton		Rosemount	
Cover crop		2011	2012	2011	2012
		June weed density			
		plants m^{-2}			
Fall	present	107	15	13	84
	absent	99	8	7	65
	P > F (contrast)	0.6818	0.0442	0.0185	0.2530
Spring	present	100	11	11	52
	absent	105	12	9	97
	P > F (contrast)	0.7844	0.8456	0.3319	0.0161
		August weed cover			
		%			
Fall	present	18	5	5	11
	absent	17	6	9	9
	P > F (contrast)	0.2594	0.2632	0.0258	0.1649
Spring	present	16	5	7	9
	absent	19	6	7	11
	P > F (contrast)	0.0544	0.6445	0.6560	0.1649
		August non-crop biomass			
		kg ha^{-1}			
Fall	present	1723	301	191	252
	absent	1104	437	231	230
	P > F (contrast)	0.0894	0.1244	0.5174	0.8242
Spring	present	1316	487	267	183
	absent	1510	251	155	299
	P > F (contrast)	0.5655	0.0160	0.0837	0.2628

Table 9. Effect of cover crop and tillage treatments on corn yield at Lamberton and Rosemount, MN in 2011 and 2012.

		Corn grain yield			
		Lamberton		Rosemount	
		2011	2012	2011	2012
		---------------------------- Mg ha^{-1}	----------------------------	----------------------------	----------------------------
Cover crops					
Fall	present	4.6	11.0	8.6	10.7
	absent	4.8	11.3	9.0	10.7
	P > F (contrast)	0.2634	0.1526	0.4761	0.7924
Spring	present	4.8	11.1	8.5	10.8
	absent	4.7	11.2	9.1	10.6
	P > F (contrast)	0.5525	0.6536	0.3111	0.6197
Tillage treatment					
False seedbed		5.0a†	11.3a	9.3a	10.9a
Standard tillage		4.3a	11.1a	-	10.5a
Reduced tillage		4.7a	10.9a	8.5b	10.7a

†Within a column, means followed by the same letter are not statistically different at $\alpha = 0.05$. Where only two treatments were present, a single degree of freedom contrast was used to test for a difference between means. Otherwise, the Tukey-Kramer test was used for means separation.

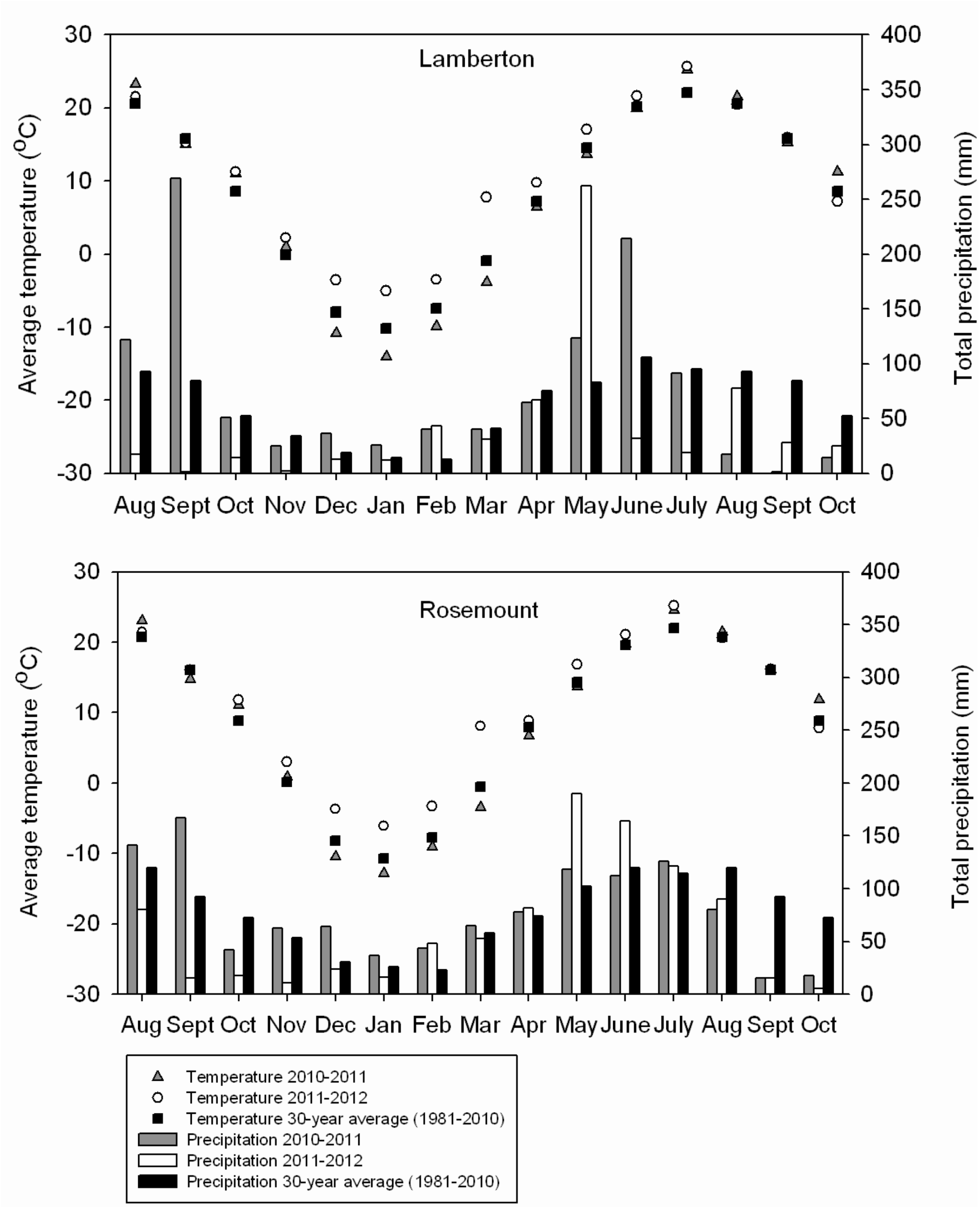

Fig. 1. Monthly average temperature and total precipitation at Lamberton and Rosemount, MN.

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