Rolled Winter Rye and Hairy Vetch Cover Crops Lower Weed Density But Reduce Vegetable Yields in No-Tillage Organic Production

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Dedication

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Abstract

Winter annual cover crops, winter rye (*Secale cereale*) and hairy vetch *(Vicia villosa* roth.), can reduce weed density and build soil health in organic production systems. There is considerable interest in integrating cover crops and reduced tillage with organic vegetable production; but few studies have been conducted in regions with short growing seasons and cool soils such as the upper Midwest. We evaluated no-tillage production of tomato, zucchini, cauliflower, and bell pepper planted into winter rye, hairy vetch, and a winter rye-hairy vetch mixture that were mechanically suppressed with a roller-crimper at two locations in Minnesota. Average marketable yields of tomato, zucchini, and bell pepper in the cover crops were reduced 58-87%, 27-75% and 62-92%, respectively, compared to a no-cover control. Winter rye and the mixture reduced average annual weed density at St. Paul by 96% for 8-10 weeks after rolling (WAR) and hairy vetch mulch had 80% control for 2-8 WAR; while at Lamberton, there was no consistent effect of cover treatments on weed populations. Winter rye and the mixture had higher average residue biomass (5.3 and 5.7 $Mg \cdot ha^{-1}$) than hairy vetch (3.0 $Mg \cdot ha^{-1}$) throughout the season in addition to higher biomass N content in most cases. Cover crop mulches reduced soil temperature by 2.9° to 5.7° C compared to a no-cover control for 4-5 weeks after planting which delayed vegetable growth and could have contributed to reduced yields in the cover crop mulches. In addition, low levels of soil N (<10 mg $N \bullet kg^{-1}$) in the top 15 cm under all cover crop mulches likely resulted in nutrient deficiency symptoms and reduced vegetable yields. Rolled winter annual cover crops show promise for controlling annual weeds in organic no-tillage systems, but there is a need to reduce the impact of the rolled cover crops on the yield of organic vegetables in the upper Midwest.

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Introduction

Fruit and vegetable production, valued at $23 billion, continue to dominate the organic market in the United States (ERS/USDA, 2009). With continued double-digit increases in the percent growth of the organic market since 1990, there is enormous potential for growers to reap the benefits of this enduring trend (Dimitri and Greene, 2002). However, there remain significant production limitations to profitable organic production in some regions. Weed management is often identified as a key challenge of growing crops organically (Clark et al., 1998; Reimens, 2007). A comprehensive survey of organic producers from around the United States found that weed management and associated labor costs were the top problems experienced by respondents (MDA, 2007, Organic Farming Research Foundation, 2004). Weed management in organic systems often relies heavily on mechanical cultivation and tillage that can be detrimental to soil health and quality (Kuratomi et al., 2004). These concerns are even more acute for organic vegetable production where there is greater reliance on cultural methods for adequate weed control.

Among organic producers, there is growing interest in utilizing winter annual cover crops with no-tillage systems to manage weeds and reduce reliance on mechanical cultivation. Organic systems, with no-tillage, need to integrate cover crops to replace the use of herbicides, which are widely used in conventional reduced tillage (Triplett and Dick, 2008; Singer 2008; Yenish et al., 1996). These cover crop systems can reduce weed populations (Clark and Panciera, 2002), preserve soil structure, soil quality, and soil moisture (Lamarca, 1996; Dabney, 1998; Villamil et al., 2006; Schonbeck and Evanylo, 1998) and have potential to produce yields which are equivalent to traditional production methods (Hoyt, 1999). Improvements and developments in no-tillage seeders, vegetable transplanters and machinery to control high-residue cover crops have increased the efficacy of this system in recent years (Morse, 1999; Hoyt et al., 1994). However, mechanical weed control remains a challenge in a no-tillage, high-residue system (Teasdale et al., 2007). In addition, high-residue cover crops can affect growth of some crops by lowering soil temperatures (Hoyt, 1999; Teasdale and Daughtry, 1993; Teasdale and Mohler, 1993) and immobilizing soil N (Hoyt and Mikkelson, 1991), two major concerns in upper-Midwestern states with short growing seasons and cooler climates. Low soil temperatures slow the maturity rate of vegetable crops and delay the timing of harvest, a key financial consideration in a fresh-market operation. Choosing appropriate cover crops for northern climates can depend heavily on rotations, machinery, and desired cash crops, but much research has been focused on the use of winter rye (*Secale cereal* L.*)* (Snapp et al., 2005; Singer 2008) and hairy vetch (*Vicia villosa* Roth.) (Sustainable Agriculture Network, 1998).

Winter rye accumulates significant biomass in varied climates, can scavenge residual soil nitrogen and reduce nitrate leaching (Ranells and Wagger, 1997; Feyereisen et al., 2006; Wyland et al., 1996), and provides both physical (Teasdale and Mohler, 1993) and allelopathic (Barnes and Putnam, 1983) impediments to weed emergence. Walters and Young (2008) found that a dense stand of winter rye residues controlled about 80% of common annual weeds; similar results were reported elsewhere (Teasdale et al., 1991; Liebl et al., 1992; Masiunas, 2006). Vegetable yield responses to winter rye residues varied depending on the amount of mulch biomass and the vegetable species. NeSmith et al. (1994) found similar yields of summer squash (*Cucurbita pepo* L.) when grown with no-tillage and significant winter rye residues compared to a conventional, no-cover control; but Walters and Young (2008) observed significant zucchini (*Cucurbita Pepo* L.) stunting and reduced yields of 20-50% when planted into winter rye residues. Some researchers have reported positive or equivalent responses with tomatoes (*Solanum lycopersicum* L.*)* (Abdul-Baki et al., 1996; Smeda and Weller 1996; Madden et al., 2004), cabbage (*Brassica oleracea* L.) (Borowy, 2004), and broccoli (*Brassica* *oleracea var. botrytis*) (Morse, 1995) transplanted into winter rye and other grass covers. Others have reported reduced yields of bell pepper, (*Capsicum annuum* L.) (Diaz-Perez et al. 2008), broccoli, cabbage, sweet corn (*Zea mays* convar. *saccharata* var. *rugosa)*, and tomato (Roberts and Cartwright, 1991; Madden et al., 2004) when vegetables were planted into no-tillage, winter rye plots compared to no-cover controls.

Hairy vetch has superior winter hardiness compared to other winter annual legumes (Brandsæter and Netland, 1999), suppresses weeds (Hoffman et al., 1993, Teasdale et al., 1991), produces rapid spring biomass and fixes an average of 123.3 kg N ha^{-1} under ideal soil conditions (Sustainable Agriculture Network, 1998; Sarrantonio, 1994). Yield responses to hairy vetch residues have generally been positive. In a 6-year study, tomatoes transplanted into killed hairy vetch mulch yielded more than when planted into black polyethylene mulch and bare soil (Teasdale and Abdul-Baki, 1995; Abdul-Baki et al., 1996a). Mills et al. (2002) corroborated those results, but under drought conditions tomato yields with black plastic were superior to those with hairy vetch.

The many mechanical methods explored for controlling cover crops in no-tillage, high residue systems have been well reviewed (Creamer and Dabney, 2002). Roller-crimpers, used extensively in Latin America, have begun to be tested in the United States and have shown promise as an effective tool for no-tillage, cover crop systems. The roller-crimper is a drum roller with horizontal or chevron welded blunt metal strips that crushes and crimps the stems of the cover crop without chopping (Ashford and Reeves, 2003). Creamer and Dabney (2002) found that rolling was more efficient, faster, and left more persistent mulch than mowing, thereby controlling weeds for a longer period of time. A roller-crimper leaves uniformly distributed residue, concurrently lowering weed density by increasing layering in the mulch and reducing the available space between those layers (Teasdale and Mohler, 2000). Moreover, the roller-crimper lays mulch down in a flat, uniform direction, which facilitates better soil contact for planting machinery. High-residue, no-tillage vegetable systems controlled with a roller-crimper respond well to the use of transplants as opposed to direct seeding of vegetable crops (Morse, 1999). No-tillage, high residue systems need more evaluation for organic vegetable production in cool, northern climates (Phatak et al., 2002). Our objective was to determine the effect of hairy vetch, winter rye and a winter rye-hairy vetch mixture that have been rolled and crimped, on establishment and yield of tomato, bell pepper, zucchini, and cauliflower (*Brassica oleracea var. botrytis)*. In addition, we evaluated the impact of roller-crimped winter annual cover crops on soil properties, weed management, and mulch characteristics.

Methods and Materials

A rolled cover crop experiment was conducted on the University of Minnesota, St. Paul campus (UMN) and the Southwest Research and Outreach Center (SWROC) near Lamberton, Minnesota in 2008 and 2009. Air temperature and precipitation data for each site (Minnesota Climatology Working Group, 2009) is presented in Table 1 and 2. The soil at UMN is a well-drained Waukegan silt loam (fine-silty over sandy, mixed mesic Typic Hapludoll) and the soil at SWROC is a Normania-Ves complex loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). The experiment at SWROC was established on certified organic land in 2008 and on first-year transitional land in 2009. High populations of perennial weeds on the SWROC organic plots in 2008 prompted relocation of the experiment to sites with no perennial weed populations. The UMN site was established on first-year transitional organic land in both study years. Prior to seeding the experiments, the land was planted to small grains and mustard at UMN and an oat/alfalfa mixture at SWROC.

The experimental design at each location was a randomized complete block with nested arrangement of treatments with four replications (32 total plots). Four whole-plot mulch treatments were the cover crops of winter rye 'Rymin', hairy vetch 'local ecotype, variety not stated', a winter rye-hairy vetch mixture (mixture), and a no-cover control. The subplot vegetable treatments were 'Celebrity' tomato, 'California Wonder' bell pepper, 'Anton' and 'Raven' zucchini, and 'Snowball' cauliflower. These species and cultivars were chosen in consultation with organic growers, to represent important vegetable families and simulate a diverse, organic vegetable operation. Whole plot size was 38.7 x 48.8 m at UMN and SWROC.

The vegetable subplots were 2.4 x 9.1 m. Between each treatment replication there was a 1.5 m wide alley planted with winter rye at UMN and tilled bare soil at SWROC.

Winter rye, hairy vetch, and mixture were drilled in 0.2 m row spacing at a depth of 2.5 cm into a seedbed prepared with a chisel plow and field cultivator. Cover crops for the 2008 study year were planted on 10 September, 2007 and on 11 September, 2008 for the 2009 study. Winter rye was seeded at 50.8 $kg \cdot ha^{-1}$ and hairy vetch at 11.3 $kg \cdot ha^{-1}$. The mixture of the two species was seeded together at the full rates described above. Nitrogen was knifed in, in the form of liquefied pig manure (at 112 $kg\ N \cdot ha^{-1}$), at UMN prior to cover crop planting in 2007. Due to high levels of residual nitrogen at UMN in 2008, cover crop plots were not fertilized before planting. Composted beef manure (1.2N-0.5P-0.9K) at 9.0 $Mg \cdot ha^{-1}$ was applied on 5 September, 2007 at SWROC prior to tillage and cover crop planting. The 2009 study site at SWROC was fertilized prior to cover crop establishment with the identical amount of beef manure used previously.

The cover crops were roller-crimped when rye was at anthesis on 16 June, 2008 and 1 June, 2009 using a roller-crimper designed by the Rodale Institute (I & J Manufacturing, PA). Growth stage of winter rye was determined by the Feekes' scale (1941). In instances where mechanical control was not adequate to kill the cover crops, cover crop control and weed management were done by hand as needed throughout the growing season. The no-cover control plots were rototilled before rolling the cover crops. No-cover control plots were maintained weed-free throughout the growing season by hand weeding.

Vegetable sub-plots consisted of three rows of 9.1 m length at spacing of 0.9 m between rows. Tomato and zucchini were planted 0.9 m apart within the rows, cauliflower and pepper were planted 0.5 m apart within rows. Plugs of tomatoes, cauliflower, and bell pepper were purchased to minimize experimental error due to variation in growth stage and size of plants (Plug Connection, CA). The plugs were potted in 60-cell flats (cell size 4 X 5 X 5.5 cm) filled with an organic potting mixture (33.5% peat : 33.5% compost : 16% sand : 16% perlite : 1% fertilizer) about 3 weeks before transplanting into the field. Potted plants were grown in a greenhouse at 21.1° C (day), 15.5° C (night) and hardened off outside for about 4 days before field planting. Zucchini seed was planted in 60-cell flats in the organic potting mix about 3 weeks prior to planting. Immediately after rolling the mulch, the transplants were manually planted by parting the cover crop residue, hand digging, inserting the plant, and then replacing the mulch. The transplants were manually watered after planting and then three times weekly in 2008. A drip irrigation system was installed in 2009 with drip lines laid on the mulches and bare soil next to the plants. Plots were irrigated every other day to avoid water stress. Initial soil nitrate and ammonium concentrations at St. Paul measured 80.9 and 30.8 mg N/kg in 2008 and 2009, respectively, from a 0 to 61 cm depth; soil N concentrations at the same depth at Lamberton was approximately 29.2 mg N/kg in 2008 and 2009. Liquid fish emulsion fertilizer (4N-1.7P-0.4K), was applied at a rate of 0.86 $L \cdot m^{-2}$ in 2008 and 2009. Fish emulsion fertilizer was applied two times throughout the growing season in 2008. Composted, dry turkey manure (8N-0.9P-3.3K) was also applied in mid-July 2009, in addition to two applications of fish emulsion. Turkey manure application in tomato, pepper and cauliflower rows was 10.2 $g \cdot m^{-2}$ and each zucchini row received 4.9 $g \cdot m^{-2}$. Fertilizer applications exceeded the normal rates recommended for the respective vegetables because of observed deficiency symptoms in the cover crop treatments (Rosen and Eliason, 2005). Total amount of applied N in manure and sidedressed fertilizer at St. Paul totaled about 112.0 kg $N \cdot ha^{-1}$ and 70.9 kg $N \cdot ha^{-1}$ in 2008 and 2009, respectively. Total amount of added N at Lamberton, in 2008 and 2009, measured approximately 108.0 kg $N \cdot ha^{-1}$ and 178.9 kg $N \cdot ha^{-1}$. Vegetable transplants that did not survive were replaced at two weeks and again at four weeks after planting. Organic pest control was employed at both UMN and SWROC as pests became visible in routine field scouting. In 2008, squash bugs (*Anasa tristis*) and cucumber beetles (*Acalymma vittatum*) were abundant at UMN and SWROC. Pyrethrum insecticides (Pyganic) were applied at 0.18 $l \cdot ha^{-1}$ to control these pests. Both pests were less abundant in 2009 and pesticide application occurred after field scouting. Cabbage loopers (*Trichoplusia ni*) and cabbageworm larvae (*Pieris rapae*) were abundant in 2008 and 2009 and flowable *Bacillus thuringiensis* (Dipel) was applied at 0.60 $g \cdot L^{-1}$ on an as needed basis.

Plant Data Collection

Harvest of vegetables commenced with the maturity of the first ripe fruit in the field and continued until plants died from frost damage in the fall. The middle row of the three rows present in each cover crop treatment was harvested. Tomatoes were harvested weekly, weighed, and separated by size and marketability using the United States Standards for Grades (USDA, 1997a). Tomatoes in grades 0 and 1 were accepted as marketable and tomatoes in grades 2 and 3 were labeled as cull. Zucchini was harvested three times weekly and visually rated for overall appearance (Walters and Young, 2008; USDA, 1997b). The fruit was separated into marketable (10.2 to 20.3 cm in length) and oversized/cull (>20.3 cm, misshapen, off-color, or damaged fruit). Peppers were harvested once at the end of the season and were separated into marketable (≥6.4 cm in diameter and length) and non-marketable (<6.4 cm in diameter and length, decaying, misshapen, or discolored fruit) (USDA, 2005). Due to inconsistent growth over both study years, all cauliflower heads were harvested as they matured. Marketability was determined by United States Standards for Grades for head appearance and not on head size (USDA, 1997c). Vegetable stand establishment was determined in the center row of each vegetable subplot by counting dead or dying plants and survivors at two and four weeks after cover crop rolling.

Cover crop control resulting from the roller-crimper, was assessed visually at two-week intervals on a scale of 0% (no cover crop killed) to 100% (cover crop completely killed) (Frans et al., 1986; Ashford and Reeves, 2003). The dry weight of the rolled winter rye, hairy vetch, and mixture treatments were determined by cutting four 0.10 m^2 randomly distributed quadrants to the soil surface 4 to 7 days prior to rolling and at two-week intervals post-rolling. Bare spots left after sample collection were replaced with mulch from border areas to maintain the integrity of the treatments and were not sampled further. Samples were dried in a forced air oven at 150°C for 4 days, weighed, and ground for further analysis. Mulch biomass nitrogen was determined in a combustion N analyzer (Finnigan FlashEA 1112 N/Protein Analyzer, Thermo Scientific).

Weed density was determined by counting and identifying weeds in two randomly distributed 0.25 m^2 quadrants within each subplot. Weeds were identified and separated into perennial and annual categories.

Soil sampling

Sixteen soil cores were taken at all locations in the fall of 2007 and 2008 at 0-15 cm, 15-30.5 cm and 30.5-61 cm. Samples were combined according to depth then sub-sampled. Soil was analyzed for extractable P, K, and organic matter in the top 15 cm and extractable nitrate and ammonium at all depths. Initial soil test levels at St. Paul in the top 15 cm measured 586 mg P/kg, 910 mg K/kg, and 5% organic matter in 2008 and 555 mg P/kg, 758 mg K/kg and 4.5% organic matter in 2009. Initial nutrient levels at Lamberton were considerably less, measuring 20 mg P/kg, 212 mg K/kg, and 4.2% orgamic matter in 2008 and 24 mg P/kg, 180 mg K/kg and 3.8% organic matter in 2009. Soil temperatures were monitored beginning in mid-May for both study years by burying one data logger (HOBO Pendant Onset Corporation, MA) at a depth of 5.1 cm in a random location within each cover crop treatment plot. Data loggers recorded soil temperature at one-hour intervals until they were removed in early November. Gravimetric soil moisture was measured each week after planting by taking four cores per cover crop treatment to a 15-cm depth (Reynolds 1970). Samples were weighed wet, dried at 105°C in a forced air oven for 24 to 48 hours and weighed dry. The moisture content of the soil on a dry weight basis was determined from the following formula: θ_d = [((wt of wet soil) – (wt of dry soil soil)) / (wt of dry soil)].

Extractable NO_3-N and NH_4^+ were determined from the same samples used for gravimetric soil moisture and were prepared according to the extraction procedures described by Gelderman and Beegle (1997). Sub-samples were air dried in paper bags at 20-25°C for 3 weeks then used in the extraction procedure. Soil samples from SWROC in 2008 were not available for analysis.

An analysis of total labor hours was compiled by recording the amount of hours required to adequately kill the cover crops, keep the no-cover plots weeded, and to perform periodic weeding within the cover crop treatments.

Statistical Analysis

Data were subjected to ANOVA using the PROC Mixed models procedure of SAS (version 9.2, 2009 (SAS Institute Inc., NC, 2009)) to determine the effects of cover crop treatment, location, and study year on vegetable yield, weed density, cover crop biomass, and soil N. Means were separated using Fisher's protected LSD ($P \leq 0.05$). Due to large differences inherent in comparing yields of varying vegetable crops, each vegetable species was analyzed with ANOVA separately. Data transformations were used as necessary to achieve statistical normality prior to utilizing SAS. When data were distributed non-normally and could not be amended with normal transformation, data were analyzed with non-parametric ranked ANOVA procedure.

Results

Air temperature and precipitation.

At St. Paul in 2008 and 2009, total season precipitation was 29% lower than the 30-year average (Table 1). Monthly precipitation was below normal from May to September in 2008 and from May to July in 2009. Total season precipitation at Lamberton in 2008 and 2009 was 10% lower than the 30-year average. Precipitation was also deficient in August 2008 and April, May, and July 2009. At the time of cover crop rolling and vegetable transplanting in June, precipitation was below normal at St. Paul in 2008 and 2009 and at Lamberton in 2009. Monthly air temperatures were 1-2° C below the 30-year average March to May at St. Paul and Lamberton in 2008 (Table 2). Lower early season temperatures in 2008 likely accounted for the later onset of anthesis and blooming of the winter rye and hairy vetch cover crops. Roller-crimping and vegetable planting was two weeks later in 2008 compared to 2009 because of delayed maturity of the cover crops.

Vegetable yield.

Cover crop treatments consistently reduced marketable yield of all vegetable crops except for cauliflower (Table 3-6). When tomato, zucchini, and pepper were grown with no-tillage in winter cover crop residue, average marketable yields for 2008 and 2009 were 58-87%, 27-75% and 62-92% lower, respectively, compared to the no-cover control. Yields of all vegetables were consistently higher in 2009 than 2008; however, significant ($P \leq 0.05$) year x location x cover or location x cover interactions occurred for yield of all vegetables due to variation in cover crop effects on yields among years and locations. Therefore, cover crop effects on yield data are presented by year and location.

Replacement of all vegetables was not affected by treatments at St. Paul and Lamberton in 2009 and never exceeded 29% for cauliflower and 10% for all other vegetables. However, at St. Paul in 2008, treatment effects were observed for zucchini where the no-cover control (0%) had less replacement than all other cover crops (14-35%). At Lamberton in 2008, bell peppers had the highest replacement rate in the hairy vetch (64%) compared to winter rye (9%), mixture (9%) and the no-cover control (20%). Likewise, replacement rates of tomato in the hairy vetch (61%) and the mixture (37%) were larger than winter rye (18%) and the no-cover control (13%).

Tomato. No-cover control plots yielded 18.7 and 58.6 $Mg \cdot ha^{-1}$ marketable fruit in 2008 and 2009 at Lamberton and 17.4 and 44.0 $Mg \cdot ha^{-1}$ in 2008 and 2009 at Saint Paul, respectively (Table 3). Averaged for 2008 and 2009, winter rye, hairy vetch, and the winter rye-hairy vetch mixture (mixture) cover crops reduced yields by 87%, 78%, and 81% at Lamberton, and by 58%, 64%, and 67% at St. Paul. At Lamberton in 2008 and 2009 and St. Paul in 2008, yield of marketable tomatoes was similar for the rye, vetch and mixture treatments each year; but at St. Paul in 2009, yields for the rye treatment were similar to the control. Tomato yields at Lamberton in 2008 for all treatments were lower than at St. Paul and were particularly depressed by use of cover crops. In contrast, yields at Lamberton in 2009 were higher than at St. Paul.

Zucchini. Yield for the no-cover control consistently exceeded those of all cover crop treatments and were 18.7 and 58.6 $Mg \cdot ha^{-1}$ at Lamberton in 2008 and 2009 and 17.4 and 44.0 $Mg \cdot ha^{-1}$ at St. Paul in 2008 and 2009, respectively (Table 4). Winter rye, hairy vetch, and mixture cover crop treatments lowered average yields by 75%, 57%, and 55% at Lamberton in 2008 and 2009 and 40%, 27% and 45% at St. Paul in 2008 and 2009. While all cover crop treatments reduced yields relative to the no-cover control, cover crop effects on yield differed with location and year. Zucchini yields were greater in the hairy vetch and mixture covers than in the winter rye at Lamberton in 2009, while zucchini yields in the hairy vetch were greater than the mixture but similar to the winter rye at St. Paul in 2009. Hairy vetch had similar yields as the no-cover control at St. Paul in 2008.

Cauliflower. Cauliflower yields were very low in all years in all treatments, being 94 to 77 % less than average yields described by Maynard and Hochmuth (2006). Average marketable yield of cauliflower in the no-cover control were 0.9 and 0.4 $Mg{\cdot}ha^{-1}$ at Lamberton and 0.3 and 5.0 $Mg{\cdot}ha^{-1}$ at St. Paul in 2008 and 2009, respectively (Table 5). Treatment effects differed over years and locations and the no-cover control was not consistently greater than the cover crop treatments. Average marketable cauliflower yield at Lamberton in 2008 was reduced by 86% in the winter rye and mixture treatments and 43% in the hairy vetch compared to the no-cover control in 2008. In 2009, however, hairy vetch had similar yields to the no-cover control and yields for the hairy vetch and no-cover control exceeded those of the winter rye and mixture treatments. At St. Paul in 2008 all treatments had similar yields, while in 2009; yields in the no-cover control were larger than the winter rye and mixture but were similar to those in hairy vetch.

Bell Pepper. Average pepper yield for the no-cover control treatment was 11.6 and 18.1 $Mg{\cdot}ha^{-1}$ at Lamberton in 2008 and 2009 and only 2.6 and 7.4 $Mg{\cdot}ha^{-1}$ at St. Paul in 2008 and 2009. However, a year x cover x location interaction occurred because the no-cover control had greater yields than the cover crop treatments at Lamberton in both years but similar yields to the winter rye at St. Paul (Table 6). Cover crop treatments reduced average marketable yield at Lamberton by about 90% in both years while at St. Paul yields were lowered on average by 92% and 74% for the hairy vetch and mixture cover crop plots.

Weed populations.

Weeds at St. Paul were primarily shepherd's purse (*Capsella bursa-pastoris* L.*),* foxtail spp. (*Setaria spp.),* common lambsquarter (*Chenopodium album*), and redroot pigweed (*Amaranthus retroflexus)*. In both years at St. Paul, winter rye and the mixture reduced weed population by at least 96% at all sampling times compared to the no-cover control except at 16 WAR in 2009 (Table 7). Hairy vetch, while less effective for weed control than winter rye and mixture cover crops, also reduced weed density by a minimum of 80% compared to the no-cover control at 2-8 WAR in both years, but the effectiveness of hairy vetch for weed control declined at 16 WAR. Annual weed populations were less at Lamberton than at St. Paul each year and were mainly foxtail spp., pigweed, and common purslane (*Portulaca oleracea).* At Lamberton in 2008, there was no consistent effect of cover treatments on weed populations. In contrast, in 2009 at Lamberton, all cover crop treatments reduced weed density by 100% at 2 WAR compared to the no-cover control but at subsequent samplings, weeds in the cover crops did not consistently differ from the no-cover control.

Due to previous cropping and weed control patterns at Lamberton, perennial weeds were present in 2008 and 2009, but did not appear at St. Paul. In 2008, Canada thistle (*Cirsium arvense* L.) and alfalfa (*Medicago sativa* L.) were evenly distributed in all cover crop treatments and may have competed with growing cover crops and vegetables (Table 8). Perennial weed density was not affected by any of the cover crop treatments but did exceed those of the no-cover control at 8 and 16 WAR in 2008. Perennial weeds, primarily alfalfa, were less evenly distributed in 2009 and were not present in sizeable numbers in the no-cover control due to mechanical tillage. Hairy vetch had the lowest perennial weed populations at 2, 4, and 8 WAR whereas winter rye had the highest density. Poor initial cover of the winter rye and re-growth of alfalfa played a role in high perennial weed density. Control of perennial weeds also contributed to high labor hours in 2008 and 2009 where re-growth of alfalfa and Canada thistle needed to be controlled by hand at least once weekly.

Cover Crop Residue.

The roller-crimper was generally effective at controlling the winter rye and mixture treatments (percent control > 85%) at 2, 4 and 8 WAR in both environments and study years (Table 9). At the time of roller-crimping, winter rye alone and in the mixture was uniformly past anthesis, a stage that is recommended for effective killing (Mirsky et al., 2009). However, at this time the hairy vetch was only in 5-10% bloom, less mature than the flowering stage when mechanical control is recommended (Mischler et al., 2010). Consequently, hairy vetch treatments were not controlled and had significant re-growth following rolling, which necessitated additional labor inputs for adequate control (Table 10). The mixture plots at Lamberton in 2009 had poor kill percentages due to the hairy vetch in the mix not being terminated by rolling. Though seeding rates were the same at both environments, there was lower abundance of hairy vetch in the mixture treatment at St. Paul due to vigorous growth of the winter rye, resulting in adequate mechanical kill.

There was a significant ($P \leq 0.05$) three-way interaction of year x location x cover for biomass yield in both environments when residue weights at 2-4 WAR in 2009 and 3-6 WAR in 2008 were combined and analyzed. In addition, the year x cover interaction was also significant. These interactions justified the presentation of residue biomass by year, location and sampling time.

Cover crop biomass at the time of rolling and throughout out the growing season at St. Paul was greater for the winter rye and the mixture than for the hairy vetch at nearly all sampling dates in 2008 and 2009. Pre-roll mixture and winter rye yields averaged 6.6 and 5.3 $Mg \cdot ha^{-1}$ and 8.0 and 8.1 $Mg \cdot ha^{-1}$, while hairy vetch yields were 1.2 and 2.2 $Mg \cdot ha^{-1}$ in 2008 and 2009, respectively (Fig. 1). The low biomass accumulation for the hairy vetch treatment in 2008 and 2009 was related to high incidence of winterkill each year. There was a significant change ($P \leq 0.05$) in biomass over time for all treatments in 2008 and the winter rye and the mixture in 2009. The hairy vetch biomass did not change over time due to continued re-growth.

Like St. Paul, cover crop biomass at Lamberton in 2008 was greatest for winter rye and the mixture and least for hairy vetch at all sampling dates. Winter rye and mixture yields at 3-6 WAR in 2008 averaged 6.3 and 6.7 $Mg \cdot ha^{-1}$ while hairy vetch yielded 1.4 $Mg \cdot ha^{-1}$. All yields were notably lower in 2009 where winter rye, hairy vetch and mixture prior to rolling measured 3.0, 3.3, and 3.4 $Mg \cdot ha^{-1}$. All cover crops initially had similar biomass in 2009 with the exception of winter rye, which had greater biomass residue at 2-4 and 6-8 WAR, but was not different from the mixture or hairy vetch at other sampling dates (Fig. 2). In 2008, winter rye and hairy vetch residue biomass changed over time while the mixture remained fairly constant. Only the mixture treatment had a significant change in biomass over the growing season in 2009. The hairy vetch experienced extensive (60-90%) winterkill in 2008 but far less in 2009.

Treatment differences in tissue N content, on a residue weight basis, were detected at all locations in both study years. Compared to Lamberton, tissue N content at St. Paul was considerably higher in 2008 and 2009 largely due to higher initial soil nutrient levels prior to cover crop planting. All treatments had a significant change in biomass N content throughout the course of the season at St. Paul in 2008 and 2009 (Fig. 3). Biomass N content of winter rye, hairy vetch and the mixture were highest at 3-6 WAR in 2008 at 147.7, 151.8, 143.2 kg N/ha and 68.7, 123.9, 87.2 at 2-4 WAR in 2009. In both years, residue N content of winter rye and the mixture decreased after rolling, while hairy vetch increased until 2-6 WAR then declined. The increase in hairy vetch residue N content can be explained by high reside N concentrations and continued biomass re-growth following the rolling event. Residue N concentration of winter rye and the mixture ranged from 16.1 to 23.4 g N/kg in 2008 and 9.0 to 15.8 g N/kg in 2009; while hairy vetch N concentration ranged from 33.4 to 22.0 and 40.8 to 16.5 mg N/kg in 2008 and 2009 respectively (data not shown).

Trends in cover crop biomass N content at Lamberton were less apparent in both study years. The winter rye and hairy vetch treatments had a significant change in residue N content over time in 2008, while in 2009; the hairy vetch content remained relatively constant despite biomass re-growth (Fig. 4). Biomass N content of winter rye, hairy vetch and the mixture were highest at 11-14 WAR at 93.2, 91.0, 115.37 kg N/ha in 2008 and 38.2, 96.6, and 80.5 kg N/ha at 2-4 WAR in 2009. There were no differences detected between cover crop treatments from 7-14 WAR in 2008, but winter rye and hairy vetch increased in residue N content until 14 WAR then declined thereafter. Winter rye in 2009 had noticeably lower N content than all treatments until 18 WAR, which is likely due to low biomass yields and low overall residue N concentration. High proportions of hairy vetch re-growth in the mixture treatment in 2009 can account for aberrant fluctuations in biomass N content. Residue N concentrations of the winter rye and the mixture treatments varied from 8.7 to 16.2 g N /kg in 2008 and 8.5 to 19.0 mg N/kg in 2009. Hairy vetch biomass N concentration was predictably higher in both years, ranging from 18.2 to 24.0 g N/kg in 2008 and 19.3 to 30.6 mg N/kg in 2009.

Soil Moisture, Temperature, and Extractable Nitrogen.

Gravimetric soil moisture between the vegetable rows, without supplemental irrigation, was largely adequate at St. Paul in 2008 and 2009 (data not shown). On July 30, 2008, a time of moisture deficit, percent soil moisture in the cover crop treatments measured 22.5%, 14.7%, 20.5%, and 18.7% in the winter rye, hairy vetch, mixture, and no-cover control, respectively. Similar differences were observed on July 17, 2009 where moisture levels in the winter rye, hairy vetch, mixture, and no-cover control treatments measured 20.3%, 13.8%, 20.1%, and 15.6%. When soil moisture levels were lowest at St. Paul, the winter rye and mixture mulch were superior at retaining soil moisture than the no-cover control and hairy vetch in both study years. At Lamberton in early July 2008, winter rye (18%) and the no-cover control (19%) had higher soil moisture levels than the mixture (16%) and hairy vetch (14%) mulch residues but no treatment differences were detected at future time periods. No significant treatment effects on soil moisture were detected at Lamberton in 2009. Low levels of gravimetric soil moisture in the hairy vetch were due to poor kill by the roller-crimper (Table 9) and continued re-growth of the cover crop.

Treatment differences in soil growing degree days (GDD) were detected for early season (date of planting – August 1) and total season (date of planting – October 30) in both study years and both environments. In a combined analysis over years and locations, year x cover and year x location interactions were highly significant ($P \leq 0.05$); this suggests that cover crops had varying effects upon soil temperature in different study years and locations. Generally, the no-cover control had the highest early season soil GDD of all the treatments but was similar to cover crops in some years. At St. Paul in 2008, the hairy vetch had higher early season soil GDD than the winter rye and mixture treatments, but all were lower than the no-cover control (Table 12). In 2009, the no-cover control treatment had more soil GDD than winter rye or the mixture but was not statistically different from hairy vetch. At Lamberton, the no-cover control had greater early season soil GDD than all the cover crops in 2008 and the mixture and hairy vetch in 2009.

Treatment differences in total soil GDD were not detected at either location in 2009 (Table 11). In 2008, the no-cover control was similar to the hairy vetch and both had greater total season soil GDD than the winter rye and mixture at St. Paul. Total season soil GDD in the hairy vetch was not different from the winter rye and mixture at Lamberton in 2008. In addition, the no-cover control had greater total soil GDD than the winter rye and mixture.

Cover crop treatments significantly affected soil N concentration throughout the season at St. Paul in both years and early in the year at Lamberton in 2009. Pre-plant soil test N levels at St. Paul in October of 2007, were sufficient for vegetables at 24.8 mg N/kg from 0 to 15 cm depth. Mineral N levels prior to vegetable planting in April of 2009 were lower in all environments totaling 16.2 and 10.3 mg N/kg at St. Paul and Lamberton, respectively. Both the mixture and the winter rye treatments had low soil mineral N in all years and all locations, whereas the no-cover control generally had the highest levels of soil N at St. Paul in both years.

At the first sampling date in St. Paul, the no-cover control and hairy vetch had the most N at the 0 to 15 cm depth in 2008 and 2009, whereas the mixture and winter rye had the least N. Soil N in the winter rye and mixture treatments increased until mid-August in 2008 then declined, where hairy vetch soil N increased from August until the end of the growing season. Fish emulsion application appeared to have no effect on soil N levels in 2008 (Fig. 5). In 2009, the no-cover control had more N than all cover crop treatments until the end of July (Fig. 6). Soil N concentration in the hairy vetch treatment was greater than the winter rye and mixture in late June and early July. The large spike in inorganic N in mid-July in the no-cover control was likely due to fertilizer contamination in the no-cover control samples, however, no other treatments appeared to respond to fertilizer application. At Lamberton in 2009, no differences in soil N were detected beyond mid June where hairy vetch and the no-cover control treatments had greater soil N concentrations than the winter rye and mixture (Fig. 7). Soil N levels of all treatments were very low, but no response to fertilizer application was observed.

Discussion

Winter annual cover crops such as winter rye and hairy vetch can provide numerous benefits to a no-tillage, organic system (Sustainable Agriculture Network, 1998). In this study we evaluated a previously described (Ashford and Reeves, 2003; NRCS, 2002) tractor-mounted roller-crimper for suppression of winter cover crops in organic systems in the upper-Midwest. We found the anthesis growth stage to be an effective time to manage a winter rye cover crop using a roller-crimper, which confirms other research (Mirsky et al., 2009; Ashford and Reeves, 2003). The roller was not an effective tool for terminating hairy vetch at a vegetative growth stage (5-10% bloom) alone or in the mixture, but no additional growing season time could be spared to allow the vetch to mature to early pod set which occurred mid to late June in Pennsylvania, and would likely occur even later in Minnesota (Mischler et al., 2010). All vegetables in this study were planted 2-6 weeks after recommended vegetable planting dates to allow for minimum acceptable cover crop maturity.

The winter rye and mixture, and to a lesser extent hairy vetch, were effective at reducing annual weed density throughout the growing season and retaining soil moisture during times of low rainfall compared to bare soil; however, marketable and total yield of tomato and zucchini were consistently lowered in all environments and study years compared to the no-cover control. Marketable vegetable yield losses from utilizing winter annual cover crops were similar to other research investigating summer squash (Walters and Young, 2008), bell pepper (Díaz-Pérez et al., 2008), and tomatoes (Roberts and Cartwright, 1991; Price and Baughan, 1985; Jelonkiewicz and Borowy, 2000; Wahle and Masiunas, 2002; Yaffa et al., 2000) planted into rye and/or hairy vetch. Cauliflower and bell pepper yield responses to winter cover crop mulch were variable by location and study year. Cauliflower’s inconsistent growth and yield in all years and environments could be explained by aberrant fluctuations in soil or air temperature or moisture levels during curd formation (Fujime and Okuda, 1996). Adapting this system to cool climate regions presents its own unique challenges and marketable yield losses may be due to several factors such as reduced soil temperature, nutrient immobilization, plant mortality and replacement, weed competition, allelopathy, and/or soil moisture.

Walters and Young (2008) found that no-tillage plots with killed winter rye lowered soil temperatures 5 to 6° C compared to a no-cover control which resulted in delayed maturity of zucchini and reduced yields (Walters et al., 2005; NeSmith et al., 1994). Soil temperatures in the cover crop treatments were lowered at St. Paul and Lamberton by comparable levels early in the growing season; temperatures under the winter rye and mixture treatments at both locations, at 1-2 WAR, were at or below 13°C. Soil root-zone temperatures of 10-15° C, and even up to 18° C, can negatively impact root and shoot growth (Gosselin and Trudel, 1984; Tacibana, 1982), nutrient uptake (Smart and Bloom, 1991; Tachibana, 1982), and water translocation (Ahn et al., 1999; Allen and Ort, 2001). In addition, bell pepper, squash, and tomato are all sensitive to low soil temperatures (Saltveit and Morris, 1990). These data do not corroborate the results of Teasdale and Abdul-Baki (1995), who found no effect of soil temperature in comparing total tomato yields between black plastic, bare soil and hairy vetch mulch when this system was studied in Maryland. The authors observed minimum soil temperatures of 13-15°C up to 3 weeks after transplanting in one of two study years. These soil temperatures resulted in delayed maturity and reduced early yields, which were corroborated by our research and others (Teasdale and Daughtry, 1993; Teasdale and Mohler, 1993; Teasdale and Abdul-Baki, 1998; Yaffa et al., 2000), but tomatoes grown in hairy vetch mulch ultimately produced equivalent or greater total yields to black plastic and bare soil.

Vegetable plants grown in the cover crop mulches at St. Paul and Lamberton remained stunted and variably chlorotic throughout the season even when soil temperatures returned to within the optimum range (20 to 30°C) for summer vegetables at about 4-5 WAR in 2008 and 2009 (Fig. 5 and 6) (Marschner, 1986). Compared to the no-cover control, vegetables grown in the cover crops never regained growth or vigor as the season progressed.

Low soil N concentrations (< 10 mg/kg) likely contributed to reduced marketable yield of vegetables grown in winter cover crop mulches and the chlorotic appearance of vegetables in situ. Prior to cover crop rolling and vegetable planting, a significant amount of N was taken up by the cover crops or immobilized by microbial degradation as evidenced by large discrepancies between bi-weekly soil N sampling and pre-season soil testing. High biomass N content of the winter rye and mixture residues, notably at St. Paul in 2008 and 2009, suggests a large amount of available soil N was taken up by the cover crops and subsequently immobilized. Despite additional fertilization throughout the growing season, soil N concentrations were consistently below 20-25 mg NO_3-N/kg, an amount identified by Heckman et al. (2002) as a critical pre-sidedress level for cabbage, which has similar nutrient requirements to most vegetables investigated in this study (Rosen and Eliason, 2005; Hartz, 2003). Levels of soil N underneath cover crops, managed with no-tillage, were similar to those found by Hoyt and Mikkelsen (1991), who observed consistent low levels of soil N (< 10 mg/kg to <2 mg /kg) down to 102-127 cm. Soil N accumulation by growing cover crops, especially winter rye (Ranells and Wagger, 1997; Feyereisen et al., 2006), and microbial tie-up of N during decomposition of high C residues after rolling likely contributed to low N levels during the 2008 and 2009 growing seasons. Additionally, under heavier residues with higher moisture and lowered temperatures, such as winter rye and mixture, soils could potentially be less aerobic and have less available N than the no-cover control (Doran and Smith, 1991). No-cover control plots had equally low soil N comparative to optimum levels, especially at Lamberton in 2009, but produced superior marketable yields. The absence of cover crop residues, which accumulate residual soil N, and vigorous growth of vegetable crops might be an explanation for this observation. Additionally, shallow sampling depth and inter-row sampling sites where no fertilization occurred may have resulted in low soil N concentrations; though samples at shallower depths often correlate well with levels deeper in the soil profile (Hartz, 2000).

High rates of plant mortality, especially in the hairy vetch at Lamberton and the winter rye and mixture at St. Paul, were another likely contributor to lowered vegetable yields in 2008 and 2009. Vegetable plants replaced at 2 and 4 WAR would have delayed yield onset compared to the field survivors. Primary causes of plant mortality included poor transplant planting, cutworm (*Agrotis*, *Amathes*, *Peridroma*, *Prodenia* spp.) and rodent predation, and perennial weed and/or cover crop competition. Successful transplanting was complicated by high rates of cover crop mulch and dry soil conditions during planting, which could have limited adequate soil to root contact in all environments and years. Despite adequate fencing and pest control, rodent and cutworm predation was localized in some areas, especially on field perimeters, which have been found to be problematic in no-till agriculture (Witmer et al., 2007).

Annual weed density remained low in the winter rye and mixture treatments and was probably not a yield-limiting factor either year. While weed density was also reduced in the hairy vetch treatment compared to the no-cover control, less overall soil coverage and higher light transmittance through the mulch resulted in greater weed pressure which may have contributed to reduced yields (Teasdale and Daughtry, 1993). This would suggest that hairy vetch is good at controlling early season weeds during spring biomass accumulation but the weed suppressive ability of the mulch decreases as the season progresses and the mulch degrades (Mohler and Teasdale, 1993).

Perennial weed density at Lamberton in all cover crop treatments in both study years also contributed to lower marketable yields in 2008 and 2009. Winter seeded cover crops planted for one season are usually not effective at reducing perennial weed density (Teasdale et al., 2007; Fisk et al., 2001).

Allelopathic interference may have contributed to reduced marketable yields within winter annual cover crop plots, especially those with winter rye. Allelopathic compounds in winter rye (Barnes and Putnam, 1983), and to a lesser extent, hairy vetch (White et al., 1989), can negatively impact the growth and development of small-seeded crops and weedy species (Burgos and Talbert, 2000), although transplants with vigorous root systems are usually less susceptible to these chemicals (Morse, 1995). Transplants at St. Paul and Lamberton, in both years, were planted into rye residue only hours after it was rolled, although mature residues are usually less allelopathic than rye seedlings (Sustainable Agriculture Network, 1998). Smeda and Weller's (1996) results suggested no apparent affect of allelopathy on tomatoes transplanted into rye compared to plots with no rye. However, Walters and Young (2008) surmised that significant yield reductions of zucchini were likely due to allelopathy of rye residues.

Winter annual cover crops have the potential to extract soil moisture that could be used for crop growth especially in dry spring years (Unger and Vigil, 1998; Liebl et al., 1992). Although soil moisture levels were low (at or below permanent wilting point) on three sampling dates at St. Paul in 2008 and 2009 and four sampling dates at Lamberton in 2008, it is unlikely that soil moisture alone could account for yield differences between treatments due to in-row irrigation. Winter rye and mixture cover crop treatments had higher gravimetric soil moisture throughout the majority of the season and yet also had the lowest marketable yields of some crops in some years. Additionally, bare soil controls had the highest yields of most vegetable crops but had amongst the lowest soil moisture during times of limited precipitation at St. Paul. Hairy vetch mulch had equivalent or lower levels of soil moisture than the no-cover control but yielded greater marketable zucchini than winter rye or the mixture in 2009. We can surmise that more vigorous growth of vegetable plants in the no-cover control plots resulted in lower gravimetric soil moisture, compared to vegetables grown in cover crop treatments.

Conclusion

Our data suggest that winter cover crops, winter rye and hairy vetch, have potential to control weeds in organic production in the upper-Midwest. However, organic, no-tillage vegetable production, utilizing winter cover crops, presents unique implementation challenges in cool, northern states where growing seasons are short and soil temperatures remain low. Rolled winter rye and hairy vetch lowered soil temperatures well into June in all cover crop treatments. Combining some form of moderate tillage, such as strip tillage, with high residue cover crops in cool season states may adequately warm the soil for vegetable production, which has seen some success in field trials (Hoyt, 1999; Delate et al., 2008). In addition, winter seeded cover crops lowered extractable soil N far below optimum levels, and additional fertilization at the time of planting and throughout the season is needed to overcome these deficits.

For the roller crimper to be most effective at controlling cover crops, early flowering varieties of vetch may need to be investigated and integrated into this system to allow for adequate growing degree days for the cash crop and avoid re-growth from ineffective mechanical control. Moreover, to reduce the risk of allelopathic interference often exhibited by winter rye residues, additional cover crop species, mixtures or spring-planted niches may provide better yield results than a winter seeded system utilizing cold hardy species. There is considerable interest in adapting this system in the upper-Midwest and additional field studies are needed to reduce the risk of incorporating cover crops and reduced tillage into organic vegetable production systems.

Tables and Figures

Table 1. Monthly total precipitation[z] and 30 year average[y] in two study years at Saint Paul and Lamberton.

	Saint Paul			Lamberton		
Month	2008	2009	30 yr. avg.	2008	2009	30 yr. avg.
			mm			
March	46.0	40.9	48.8	23.4	29.5	44.7
April	104.1	38.1	64.5	74.9	38.4	69.3
May	71.4	12.4	94.7	82.3	41.4	82.8
June	70.6	68.1	126.5	91.2	102.4	98.8
July	51.6	40.6	112.0	85.1	42.2	91.2
August	58.9	155.2	111.0	15.0	87.6	86.1
September	48.5	11.2	81.3	53.6	70.9	65.0
October	63.0	157.7	63.8	106.9	138.4	49.3
November	31.2	8.9	53.1	25.1	9.1	35.8
Total Precipitation	545.3	533.1	755.7	557.5	559.8	623.1

[z] Monthly averages for 2008 and 2009, by location were gathered from the Minnesota Climatology Working Group (2010).

[y] 30 year average was accessed from the Midwest Regional Climate Center website (2010).

Table 2. Mean monthly air temperature[z] and 30 year average[y] from March-November in two study years at Saint Paul and Lamberton.

	Saint Paul			Lamberton		
Month	2008	2009	30 yr. avg.	2008	2009	30 yr. avg.
			C°			
March	-1.6	0.7	0.4	-2.3	-1.4	-0.7
April	7.3	8.9	8.4	5.4	6.7	7.2
May	13.7	16.0	15.5	13.3	14.6	14.9
June	19.9	19.7	20.2	19.4	19.0	20.4
July	23.7	19.7	22.8	22.6	19.4	22.3
August	22.1	19.8	21.6	20.8	19.8	20.7
September	17.7	18.4	16.6	16.6	17.8	15.7
October	10.7	5.6	9.9	9.1	5.2	8.8
November	1.8	4.9	0.7	0.7	4.8	-0.4

[z] Monthly averages for 2008 and 2009, by location were gathered from the Minnesota Climatology Working Group (2010).

[y] 30 year average was accessed from the Midwest Regional Climate Center website (2010).

Table 3. Total marketable yield of 'Celebrity' tomato produced in four, rolled cover crop treatments in 2008 and 2009.

	Lamberton			Saint Paul	
Treatment	2008	2009		2008	2009
			Mg/ha		
Winter Rye	0.8 b[z]	12.7 b		5.6 b	28.6 ab
Hairy Vetch	0.1 b	22.4 b		8.0 b	20.8 b
Winter Rye + Hairy Vetch	0.2 b	18.5 b		4.9 b	21.5 b
No Cover (Control)	14.3 a	86.6 a		32.5 a	48.3 a

[z] Any two means within a column not followed by the same letter are different using Fischer's protected LSD (0.05).

Table 4. Total marketable yield of 'Anton' or 'Raven' zucchini produced in four, rolled cover crop treatments in 2008 and 2009.

	Lamberton		Saint Paul	
Treatment	2008	2009	2008	2009
	Mg/ha			
Winter Rye	1.4 b[z]	17.6 c	5.6 b	31.5 bc
Hairy Vetch	1.3 b	32.2 b	8.6ab	36.3 b
Winter Rye + Hairy Vetch	1.7 b	32.8 b	5.6 b	27.9 c
No Cover (Control)	18.7 a	58.6 a	17.4 a	44.0 a

[z] Any two means within a column not followed by the same letter are different using Fischer's protected LSD (0.05).

Table 5. Total marketable yield of 'Snowball' cauliflower produced in four, rolled cover crop treatments in 2008 and 2009.

	Lamberton		Saint Paul	
Treatment	2008	2009	2008	2009
	Mg/ha			
Winter Rye	0.0 b[z]	0.2 b	0.8 a	1.2 b
Hairy Vetch	0.0 b	0.8 a	0.9 a	2.0 ab
Winter Rye + Hairy Vetch	0.0 b	0.1 b	0.3 a	0.9 b
No Cover (Control)	0.9 a	0.4 ab	0.3 a	5.0 a

[z] Any two means within a column not followed by the same letter are different using Fischer’s protected LSD (0.05).

Table 6. Total marketable yield of 'California Wonder' bell pepper produced in four, rolled cover crop treatments in 2008 and 2009.

Treatment	Lamberton		Saint Paul	
	2008	2009	2008	2009
	Mg/ha			
Winter Rye	0.0 b[z]	2.6 b	0.7 ab	3.2 ab
Hairy Vetch	0.0 b	3.2 b	0.0 c	0.8 b
Winter Rye + Hairy Vetch	0.0 b	2.5 b	0.4 bc	2.2 b
No Cover (Control)	11.6 a	18.1 a	2.6 a	7.4 a

[z] Any two means within a column not followed by the same letter are different using Fischer's protected LSD (0.05).

Table 7. The effects of four, rolled cover crop treatments on annual weed density at 2, 4, 8, and 16 weeks after rolling (WAR) at St. Paul and Lamberton in 2008 and 2009.

Treatment	Lamberton				Saint Paul			
	2 WAR	4 WAR	8 WAR	16 WAR	2 WAR	4 WAR	8 WAR	16 WAR
	no./m^2							
2008								
Winter Rye	1 a[z]	2 a	12 b	18 a	0 b	0 b	2 b	7 b
Hairy Vetch	107 a	34 a	49 a	44 a	1 b	27 b	54 a	80 a
Winter Rye + Hairy Vetch	10 a	5 a	20 ab	25 a	0 b	2 b	1 b	8 b
No Cover (Control)	6 a	-- [y]	4 b	62 a	58 a	642 a	290 a	159 a
2009								
Winter Rye	0 b	31 a	18 a	16 a	0 c	0 c	6 bc	8 a
Hairy Vetch	0 b	2 b	4 a	10 a	32 b	18 b	24 ab	38 a
Winter Rye + Hairy Vetch	0 b	1 b	2 a	8 a	0 c	0 c	4 c	10 a
No Cover (Control)	30 a	4 ab	11 a	12 a	178 a	98 a	225 a	26 a

[z] Any two means within a column for 2008 or 2009 not followed by the same letter are different using Fischer's protected LSD (0.1). Different study years were compared with a separate ANOVA.

[y] Data were not collected.

Table 8. The effects of four, rolled cover crop treatments on perennial[z] weed density at 2, 4, 8, and 16 weeks after rolling (WAR) at Lamberton in 2008 and 2009.

	2008[v]				2009[u]			
Treatment	2 WAR	4 WAR	8 WAR	16 WAR	2 WAR	4 WAR	8 WAR	16 WAR
				no./m^2				
Winter Rye	6 a[x]	16 a	14 a	42 a	12 a[w]	12 a	31 a	20 a
Hairy Vetch	2 a	12 a	16 a	42 a	0 b	2 b	7 bc	13 ab
Winter Rye + Hairy Vetch	10 a	10 a	26 a	34 a	2 b	8 a	11 b	10 b
No Cover (Control)	16 a	-- [w]	0 b	0 b	0 b	0 b	4 c	0 c

[z] Perennial weeds counted at this location were Canada thistle (*Cirsium arvense* L.) and alfalfa (*Medicago sativa* L.).

[x] Any two means within a column not followed by the same letter are different using Fischer's protected LSD (0.1).

[w] No data collected

[v] In 2008 all cover crop plots were mowed on July 13 and August 13 (4 and 8 WAR).

[u] In 2009 all cover crop plots were mowed on June 24, July 8, 15, and 22, August 6, 17, and 27, and September 14 (3, 5, 6, 8, 9, 10, 12, 14 WAR).

Table 9. Percent kill of four, rolled cover crop treatments at 2, 4, and 8 weeks after rolling (WAR) at St. Paul and Lamberton in 2008 and 2009.

	Lamberton			Saint Paul		
Treatment	2WAR	4WAR	8WAR	2WAR	4WAR	8WAR
			%			
2008						
Winter Rye	83 a[z]	97 a	97 a	97 a	96 a	99 a
Hairy Vetch	33 a	0 c	11 c	13 c	97 a	75 c
Winter Rye + Hairy Vetch	71 a	91 b	88 b	91 b	88 b	88 b
2009						
Winter Rye	88 a	88 a	99 a	93 a	92 a	98 a
Hairy Vetch	2 c	64 b	77 b	12 b	63 b	96 a
Winter Rye + Hairy Vetch	33 b	63 b	80 b	90 a	91 a	90 b

[z] Any two means within a column for 2008 or 2009 not followed by the same letter are different at $P \leq 0.1$. Letters are assigned based upon pair-wise t-tests in the ranked ANOVA procedure for non-parametric data.

Table 10. Total person labor hours for removing annual weeds from control plots, clipping perennial weeds in the treatments, and managing re-growth of rolled cover crops.

	Lamberton		Saint Paul	
Treatment	2008	2009	2008	2009
Winter Rye	2.0	11.1	0.0	3.0
Hairy Vetch	13.5	18.6	12.0	20.3
Winter Rye + Hairy Vetch	2.0	11.1	0.0	3.0
No Cover (Control)[z]	9.9	11.5	8.0	11.9

[z] Control plots were weeded by hand at two week intervals following weed counting throughout the duration of the season.

In 2008 all cover crop plots were controlled by hand on July 13 and August 13.

In 2009 all cover crop plots were weed-wacked on June 24, July 8,15, and 22, August 6, 17, and 27, and September 14.

A B

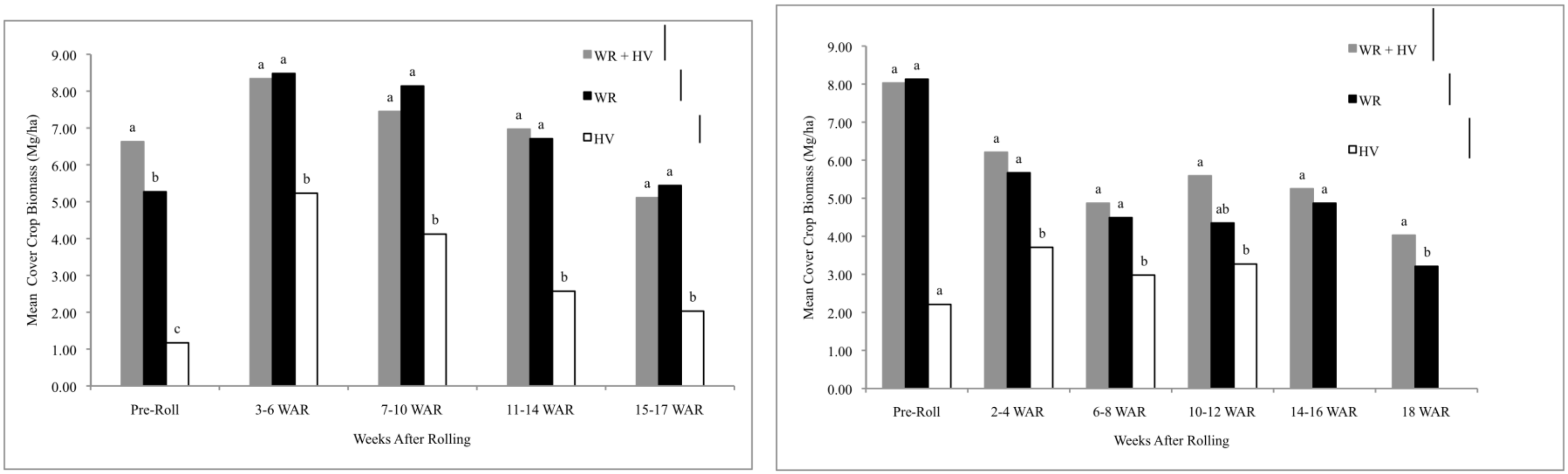


Figure 1. Biomass of three, rolled cover crop treatments: winter rye (WR), hairy vetch (HV) and a mixture (WR + HV) in (A) 2008 and (B) 2009 at St. Paul, Minnesota. No biomass was present in control plots. Treatment mean values with a common letter at weeks after rolling (WAR) are not different using Fischer's Protected LSD (0.05). There was no HV biomass available for sampling in 2009 (B) at 14-16 WAR and 18 WAR. Bars right of legend indicate LSD (0.05) within year for comparing cover crop treatment means over WAR.

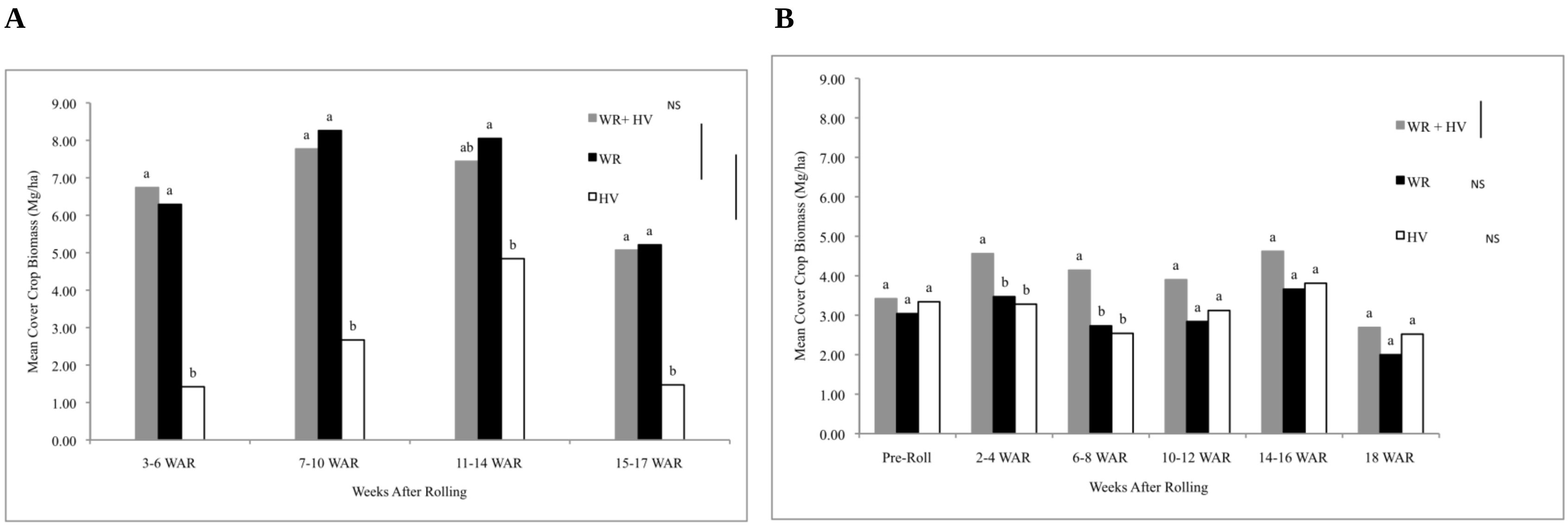
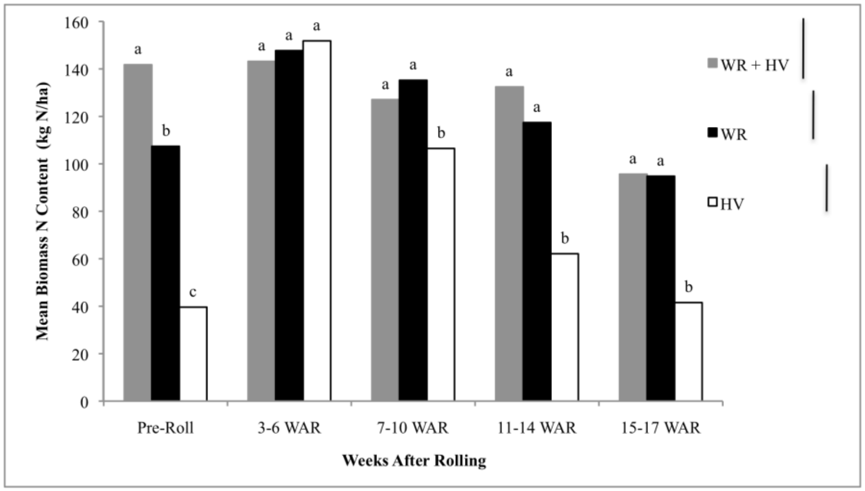


Figure 2. Biomass of three, rolled cover crop treatments: winter rye (WR), hairy vetch (HV) and a mixture (WR + HV) in (A) 2008 and (B) 2009 at Lamberton, Minnesota. No biomass was present in the control plots. Treatment mean values with a common letter at weeks after rolling (WAR) are not different using Fischer's Protected LSD (0.05). There was no pre-roll cover crop biomass harvested in 2008 (A). Bars right of legend indicate LSD (0.05) within year for comparing cover crop treatment means over WAR.

A



B

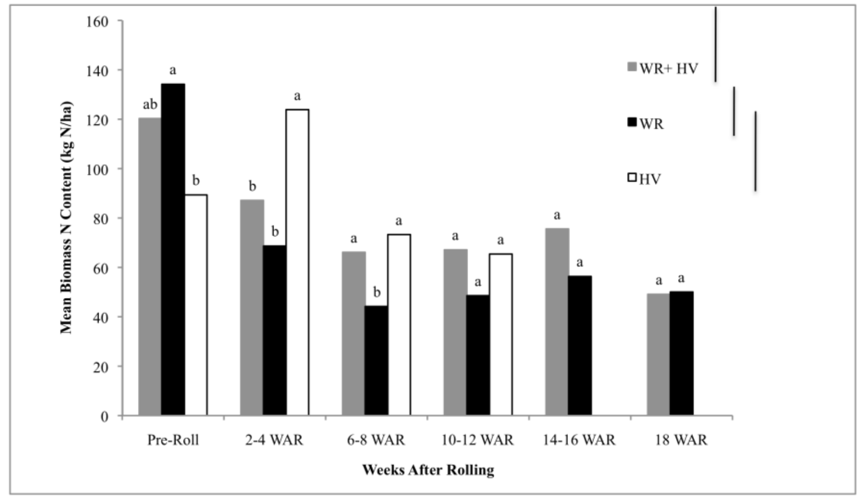


Figure 3. Biomass nitrogen content of three cover crops: winter rye (WR), hairy vetch (HV) and a mixture (WR + HV) in (A) 2008 and (B) 2009 at St. Paul, Minnesota. No biomass was present in the control plots. Treatment mean values with a common letter at weeks after rolling (WAR) are not different using Fischer's Protected LSD (0.1). There was no hairy vetch biomass available for sampling in 2009 (B) at 14-16 WAR and 18 WAR. Bars right of legend indicate LSD (0.1) within year for comparing cover crop treatment means over WAR.

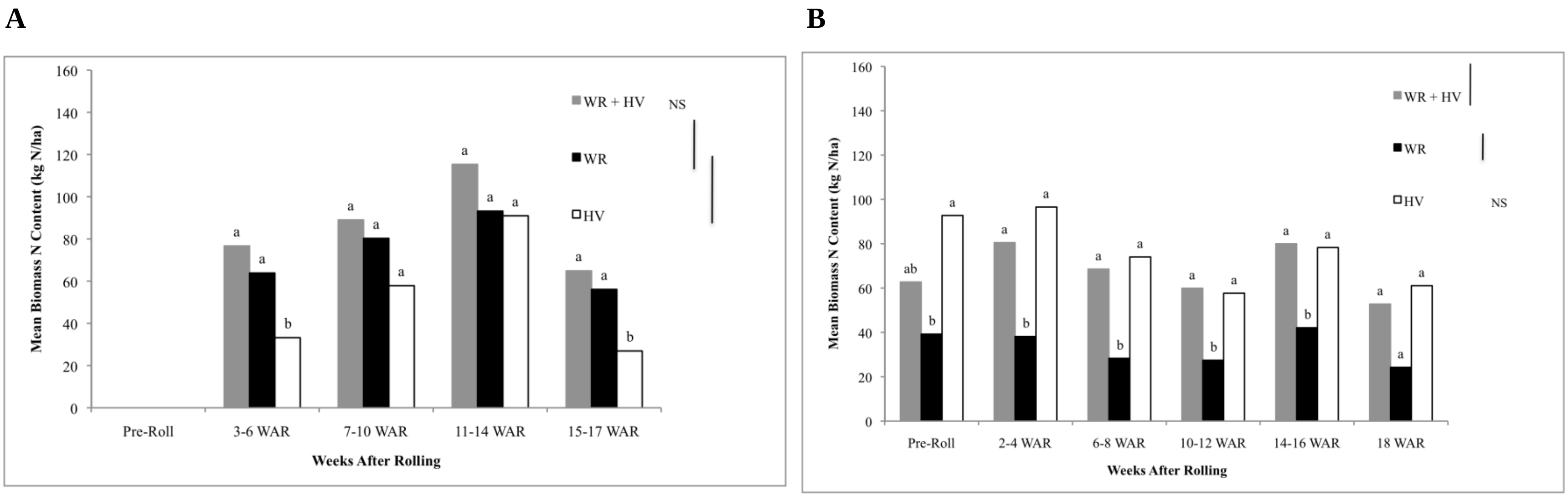


Figure 4. Biomass nitrogen content of three cover crops: winter rye (WR), hairy vetch (HV) and a mixture (WR + HV) in (A) 2008 and (B) 2009 at Lamberton, Minnesota. No biomass was present in the control plots. Treatment mean values with a common letter at weeks after rolling (WAR) are not different using Fischer's Protected LSD (0.1). There was no pre-roll cover crop biomass collected in (A) 2008. Bars right of legend indicate LSD (0.1) within year for comparing cover crop treatment means over WAR

Table 11. Effects of four. rolled cover crop treatments on total season soil GDD (base 10° C) at Lamberton and St. Paul in 2008 and 2009.[z]

	Saint Paul		Lamberton	
Treatment	2008	2009	2008	2009
		GDD		
Winter Rye	1781 b	1910 a	1935 b	2360 a
Hairy Vetch	2152 a	2122 a	2049 ab	2209 a
Winter Rye + Hairy Vetch	1916 b	1930 a	1849 b	2231 a
No Cover (Control)	2354 a	2089 a	2485 a	2427 a

[z] Season GDD calculated from date of planting to October 30 using hourly temperature readings. Date of planting was about June 16 in 2008 and about June 1 in 2009.

Table 12. Effects of four, rolled cover crop treatments on early season soil GDD (base 10° C) at Lamberton and St. Paul in 2008 and 2009.[z]

	Saint Paul		Lamberton	
Treatment	2008	2009	2008	2009
		GDD		
Winter Rye	833 c	1007 b	910 b	1271 a
Hairy Vetch	1023 b	1100 ab	965 b	1127 b
Winter Rye + Hairy Vetch	876 c	1010 b	858 b	1135 b
No Cover (Control)	1272 a	1209 a	1223 a	1334 a

[z] Early season GDD calculated from date of planting to August 1 using hourly temperature readings. Date of planting was about June 16 in 2008 and about June 1 in 2009.

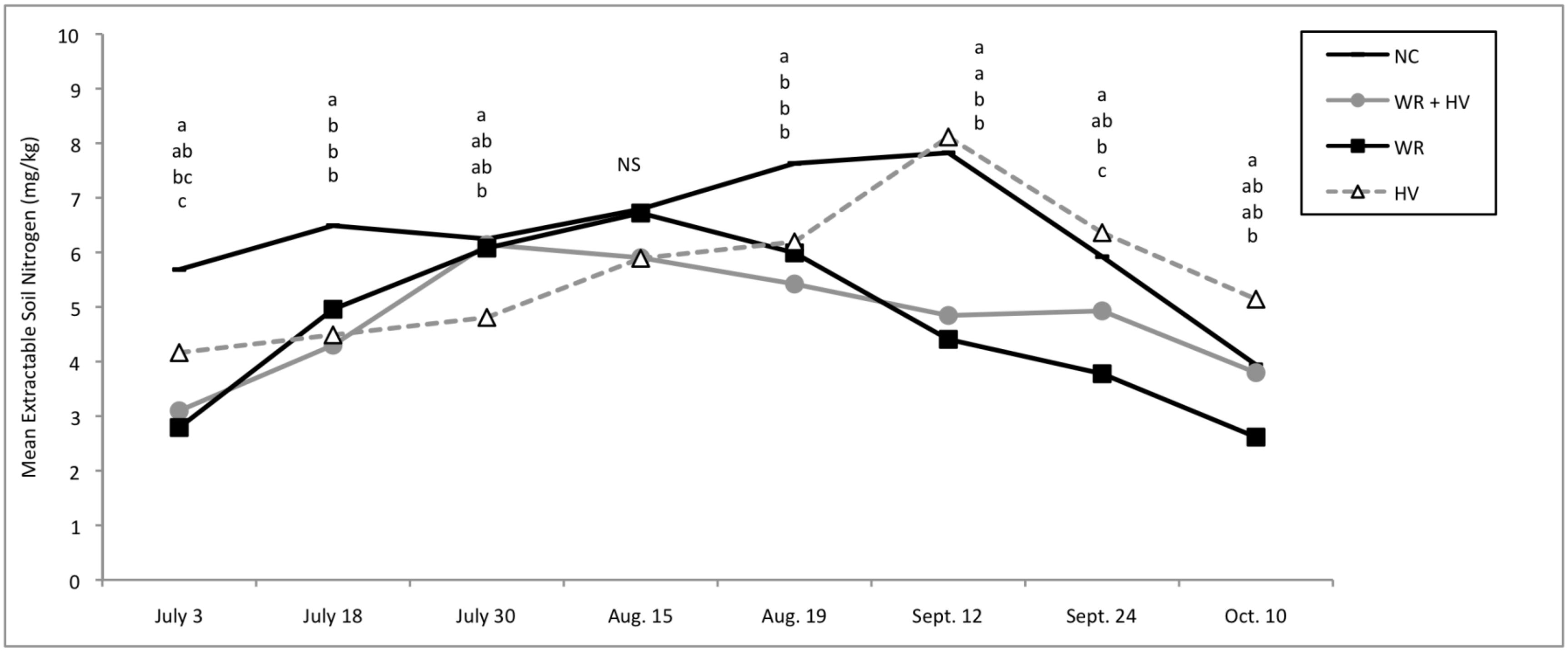


Figure 5. Total extractable soil N ($NH_4^+ + NO_3^-$) by NC (no cover), WR + HV (mixture), WR (winter rye) and HV (hairy vetch) treatments, in the top 15.2 cm of the soil profile at St. Paul, 2008. Plots were fertilized with fish fertilizer on July 3 and July 18. Mean seperation within date by Fischer's protected LSD (0.05).

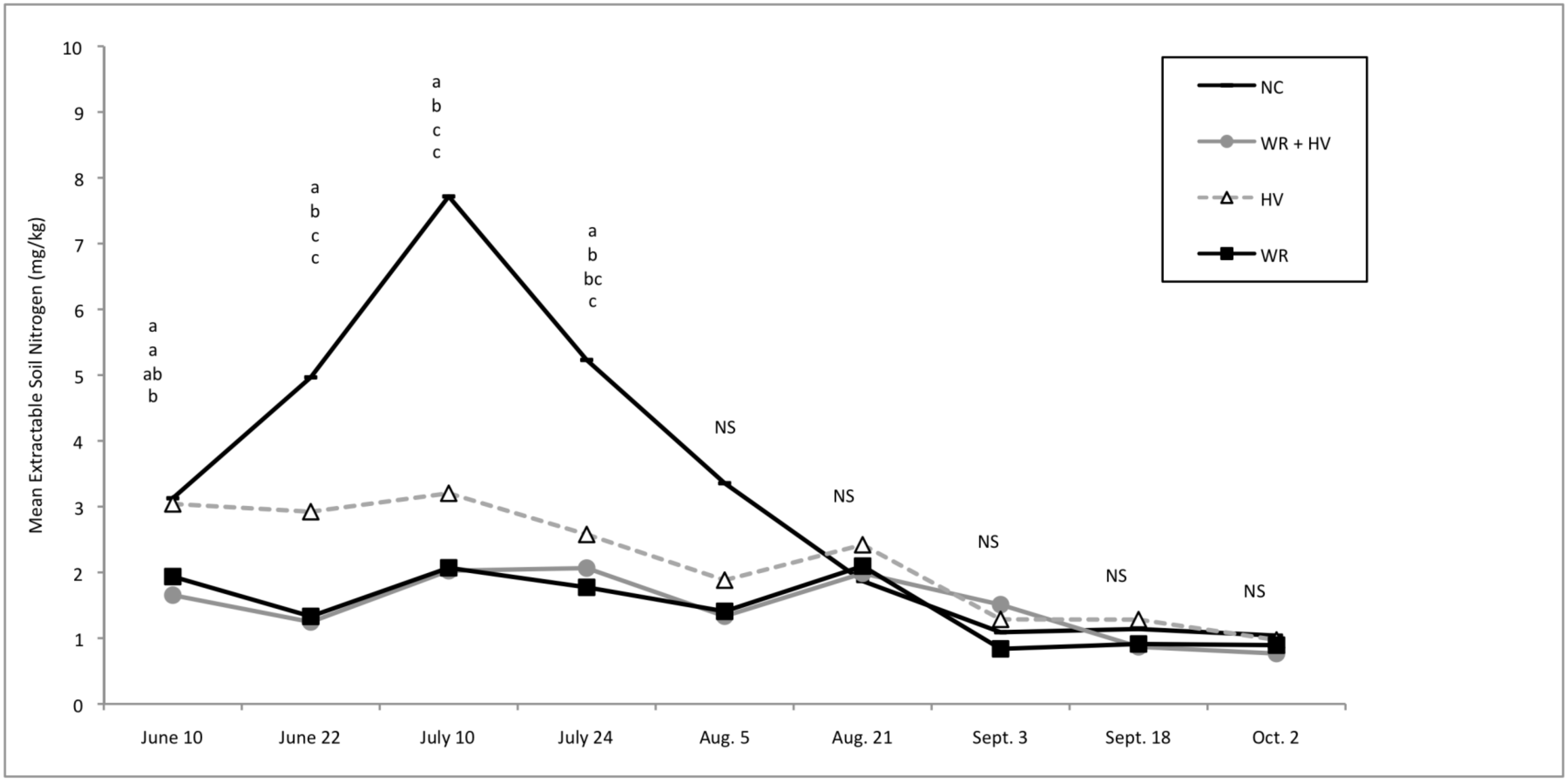


Figure 6. Total extractable soil N (NH_4^+ + NO_3^-) by NC (no cover), WR + HV (mixture), WR (winter rye) and HV (hairy vetch) treatments, in the top 15.2 cm of the soil profile at St. Paul, 2009. Fish fertilizer was applied on June 29 and July 7 and composted turkey manure was applied on July 13. Mean seperation within date by Fischer's protected LSD (0.05).

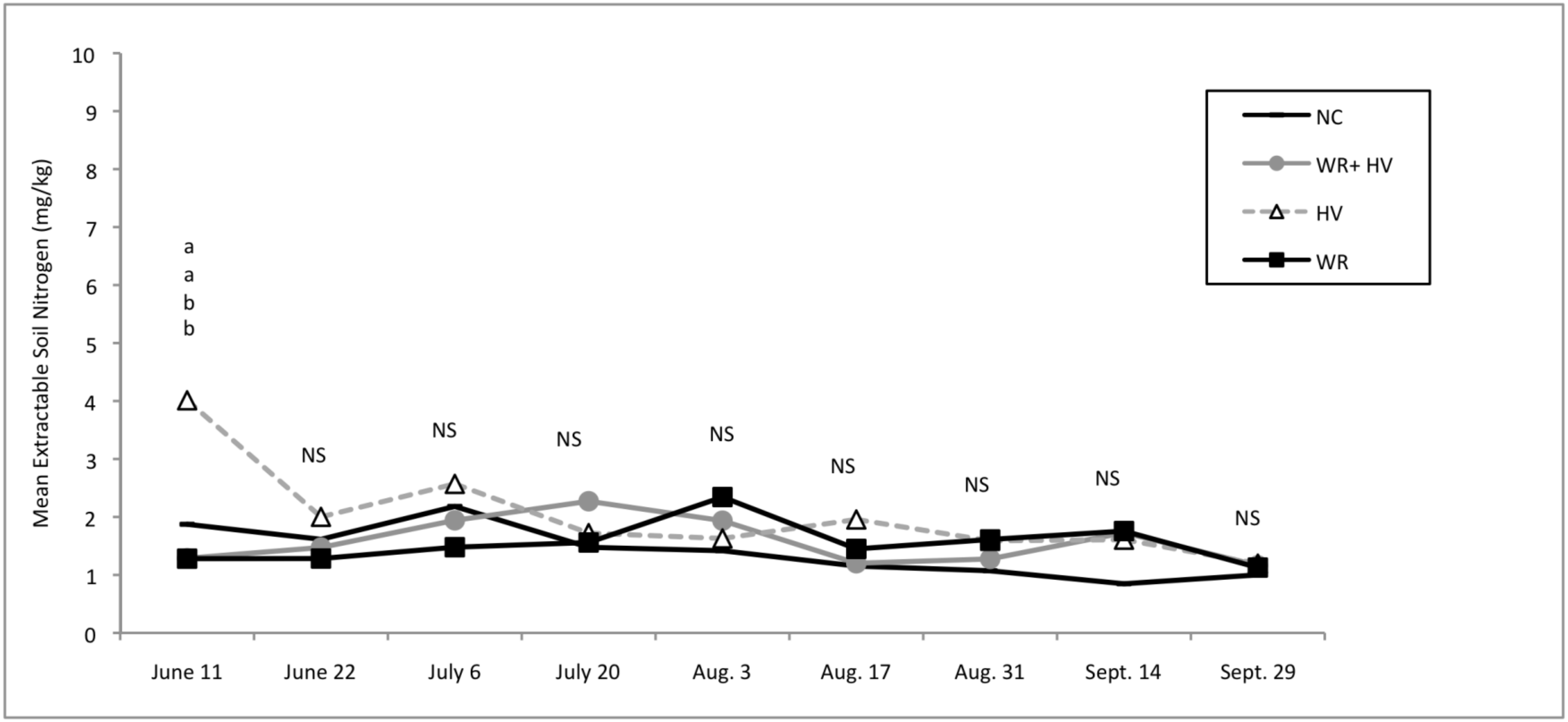


Figure 7. Total extractable soil N (NH_4^+ + NO_3^-) by NC (no cover), WR + HV (mixture), WR (winter rye) and HV (hairy vetch) treatments, in the top 15.2 cm of the soil profile at Lamberton, 2009. Fish fertilizer was applied on June 30 and July 8 and composted turkey manure was applied on July 15. Mean seperation within date by Fischer's protected LSD (0.05).

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Appendix A: Additional Data Tables and Figures

Table 1. Analyses of variance for yield as a function of year, location and cover crop.

		Probability			
Source	df	Cauliflower	Pepper	Zucchini	Tomato
Variable: Yield					
Year (Y)	1	0.0006	0.0001	0.0001	0.0001
Loc (L)	1	0.0012	0.0098	0.0042	0.0023
Y x L	1	0.2507	0.1259	0.0139	0.0009
Cover (C)	3	0.0623	0.0001	0.0001	0.0001
Y x C	3	0.3512	0.825	0.1311	0.7171
L x C	3	0.674	0.0001	0.0002	0.0873
Y x L x C	3	0.0217	0.2237	0.0795	0.0064

Table 2. Total yield of 'Celebrity' tomato produced in four, rolled cover crop treatments at St. Paul in Lamberton in 2008 and 2009.[z]

	Lamberton		Saint Paul	
Treatment	2008	2009	2008	2009
		Mg/ha		
Winter Rye	1.1 b[y]	14.4 c	11.6 b	48.2 b
Hairy Vetch	0.2 b	25.6 b	13.8 b	41.9 b
Winter Rye + Hairy Vetch	0.2 b	21.9 bc	10.8 b	37.1 b
No Cover (Control)	14.8 a	101.3 a	47.6 a	74.4 a

[z] Total Yield is marketable yield plus cull yield.

[y] Any two means within a column not followed by the same letter are different using Fischer's protected LSD (0.05).

Table 3. Total yield of 'Anton' and 'Raven' zucchini produced in four, rolled cover crop treatments at St. Paul and Lamberton in 2008 and 2009.[z]

	Lamberton			Saint Paul	
Treatment	2008	2009		2008	2009
			Mg/ha		
Winter Rye	2.4 b[y]	22.3 c		8.42 b	59.5 b
Hairy Vetch	1.9 b	40.8 b		13.5 ab	63.6 b
Winter Rye + Hairy Vetch	2.6 b	40.5 b		9.48 b	53.2 b
No Cover (Control)	29.7 a	85.6 a		30.6 a	93.8 a

[z] Total Yield is marketable yield plus cull yield.

[y] Any two means within a column not followed by the same letter are different using Fischer's protected LSD (0.05).

Table 4. Total yield of 'Snowball' cauliflower produced in four, rolled cover crop treatments at St. Paul and Lamberton in 2008 and 2009.[z]

	Lamberton			Saint Paul	
Treatment	2008	2009		2008	2009
			Mg/ha		
Winter Rye	--[x]	0.2 a[y]		--	2.9 bc
Hairy Vetch	--	1.1 a		--	4.6 ab
Winter Rye + Hairy Vetch	--	0.5 a		--	1.4 c
No Cover (Control)	--	4.6 a		--	8.6 a

[z] Total yield is marketable yield plus cull yield.

[y] Any two means within a column not followed by the same letter are different using Fischer's protected LSD (0.05).
[x] No data collected.

Figure 5. Total yield of 'California Wonder' bell pepper produced in four, rolled cover crop treatments at St. Paul and Lamberton in 2008 and 2009.[z]

	Lamberton		Saint Paul	
Treatment	2008	2009	2008	2009
		Mg/ha		
Winter Rye	--[x]	4.7 b[y]	--	8.1 ab
Hairy Vetch	--	6.1 b	--	2.5 c
Winter Rye + Hairy Vetch	--	5.4 b	--	5.6 bc
No Cover (Control)	--	21.8 a	--	13.4 a

[z] Total Yield is marketable yield plus cull yield.

[y] Any two means within a column not followed by the same letter are different using Fischer’s protected LSD (0.05).

[x] No data collected.

Table 6. Replacement rate at 2 and 4 WAR for all vegetables in four, rolled cover crop treatments at St. Paul and Lamberton in 2008.

Treatment	Cauliflower	Pepper	Zucchini	Tomato
		%		
Lamberton				
Winter Rye	2 a[z]	9 b	3 a	18 b
Hairy Vetch	15 a	64 a	21 a	61 a
Winter Rye + Hairy Vetch	4 a	9 b	5 a	37 a
No Cover (Control)	12 a	20 b	5 a	13 b
St. Paul				
Winter Rye	13 a	31 a	35 a	3 a
Hairy Vetch	5 a	12 a	14 a	15 a
Winter Rye + Hairy Vetch	24 a	7 a	35 a	0 a
No Cover (Control)	7 a	5 a	0 b	0 a

[z] Any two values within a column not followed by the same assigned letter are significantly different with $P \leq 0.1$ with pair wise t-tests between treatments . Data were non-normal and analyzed with non-parametric ranked ANOVA. Locations were analyzed separately.

Table 7. Replacement rate at 2 and 4 WAR for all vegetables in four, rolled cover crop treatments at St. Paul and Lamberton in 2009.

Treatment	Cauliflower	Pepper	Zucchini	Tomato
		%		
Lamberton				
Winter Rye	12 a[z]	5 a	0 a	10 a
Hairy Vetch	2 a	2 a	4 a	3 a
Winter Rye + Hairy Vetch	29 a	6 a	3 a	6 a
No Cover (Control)	25 a	9 a	3 a	0 a
St. Paul				
Winter Rye	6 a	10 a	3 a	0 a
Hairy Vetch	2 a	4 a	0 a	0 a
Winter Rye + Hairy Vetch	20 a	8 a	0 a	6 a
No Cover (Control)	6 a	4 a	3 a	0 a

[z] Any two values within a column not followed by the same letter are significantly different at $P \leq 0.1$. Data were non-normal and analyzed with non-parametric ranked ANOVA with pair wise t-tests between treatments. Locations were analyzed separately.

Cover crop density was determined by examining two, randomly distributed 0.25 m^2 quadrants on a 0-100 percentage scale at two-week intervals for the entire season from 0% (no soil covered with residue) to 100% (soil completely covered with residue). The two sub-measurements were averaged.

Table 8. Percent cover[z] of four, rolled cover crop treatments at 2, 4, 8, and 16 weeks after roll-crimping (WAR).[y]

	Lamberton				Saint Paul			
Treatment	2WAR	4WAR	8WAR	16WAR	2WAR	4WAR	8WAR	16WAR
				%				
2008								
Winter Rye	86	94	83	83	99	97	97	94
Hairy Vetch	87	96	88	79	94	96	78	70
Winter Rye + Hairy Vetch	86	89	86	90	99	97	96	97
2009								
Winter Rye	69	77	93	93	90	95	95	97
Hairy Vetch	98	95	87	91	66	64	78	23
Winter Rye + Hairy Vetch	94	91	94	94	89	96	98	95

Table 9. Percent gravimetric soil moisture at selected dates of low precipitation in four, rolled cover crop treatments at St. Paul.

Treatment	July 17	July 30	August 5	August 19
			%	
2008				
Winter Rye	--[z]	22 a[y]	23 a	23 a
Hairy Vetch	--	15 c	16 c	16 c
Winter Rye + Hairy Vetch	--	20 ab	21 b	22 a
No Cover (Control)	--	19 b	19 b	19 b
2009				
Winter Rye	20 a	23 a	22 a	--
Hairy Vetch	14 b	15 b	17 a	--
Winter Rye + Hairy Vetch	20 a	22 a	21 a	--
No Cover (Control)	16 b	17 b	17 a	--

[z] Soil moisture sufficient and no treatment effects observed.

[y] Any two means within a column by year not followed by the same letter are different using Fischer's Protected LSD (0.05).

Table 10. Percent gravimetric soil moisture at selected dates of low precipitation in four, rolled cover crop treatments at Lamberton.

Treatment	July 16	July 20	August 3	August 6	August 12
			%		
2008					
Winter Rye	18 a[y]	--[z]	--	20 a	20 a
Hairy Vetch	14 b	--	--	18 a	19 ab
Winter Rye + Hairy Vetch	16 b	--	--	19 a	17 b
No Cover (Control)	19 a	--	--	18 a	19 ab
2009					
Winter Rye	--	21 a	23 a	--	21 a
Hairy Vetch	--	19 a	20 a	--	20 a
Winter Rye + Hairy Vetch	--	21 a	22 a	--	21 a
No Cover (Control)	--	20 a	20 a	--	19 a

[z] Soil moisture sufficient and no treatment effects observed.

[y] Any two means within a column by year not followed by the same letter are different using Fischer's Protected LSD (0.05).

A B

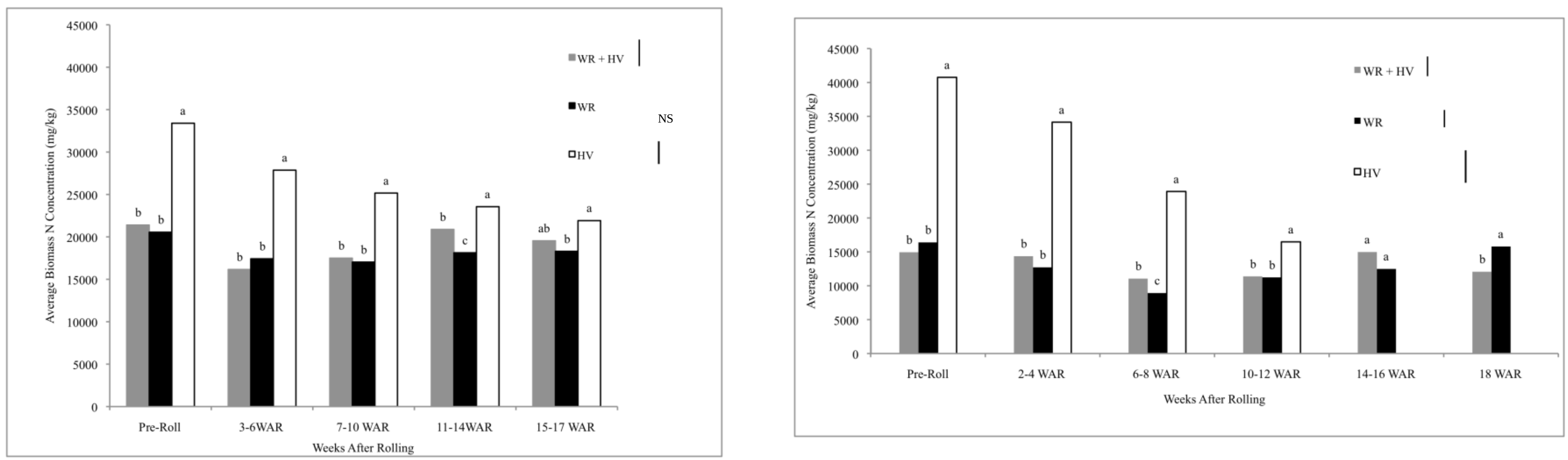


Figure 1. Biomass nitrogen concentration of three cover crops: winter rye (WR), hairy vetch (HV) and a mixture (WR + HV) in (A) 2008 and (B) 2009 at St. Paul, Minnesota. No biomass was present in the control plots. Treatment mean values with a common letter at weeks after rolling (WAR) are not different using Fischer's Protected LSD (0.05). There was no hairy vetch biomass available for sampling in 2009 (B) at 14-16 WAR and 18 WAR. Bars right of legend indicate LSD (0.1) within year for comparing cover crop treatment means over WAR.

A **B**

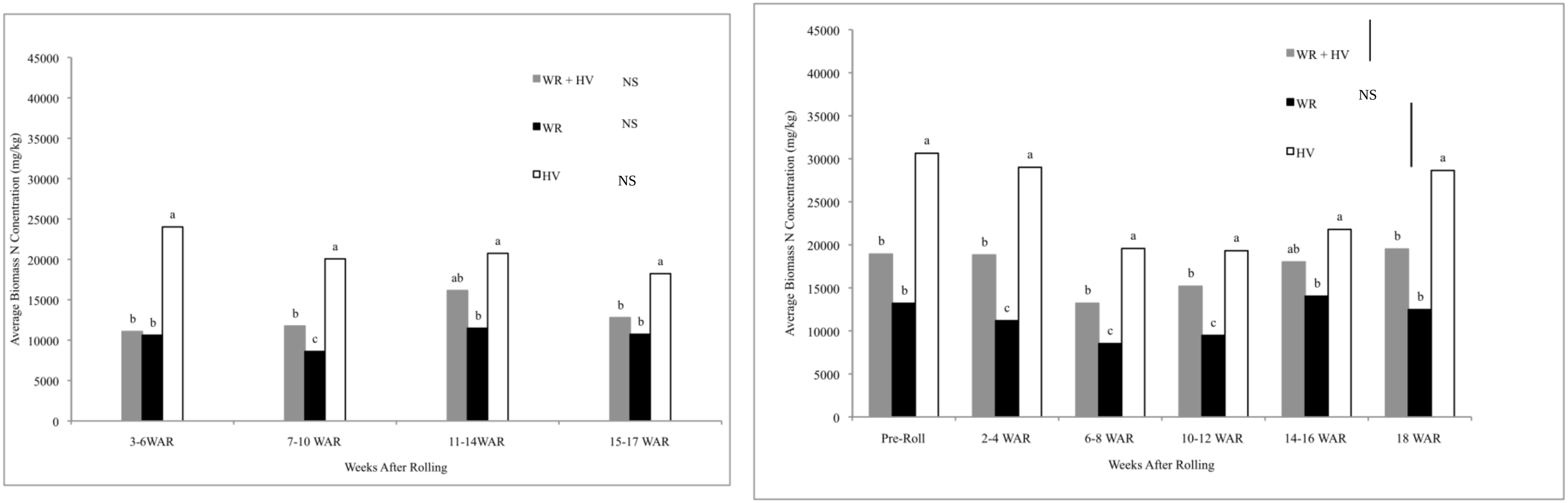
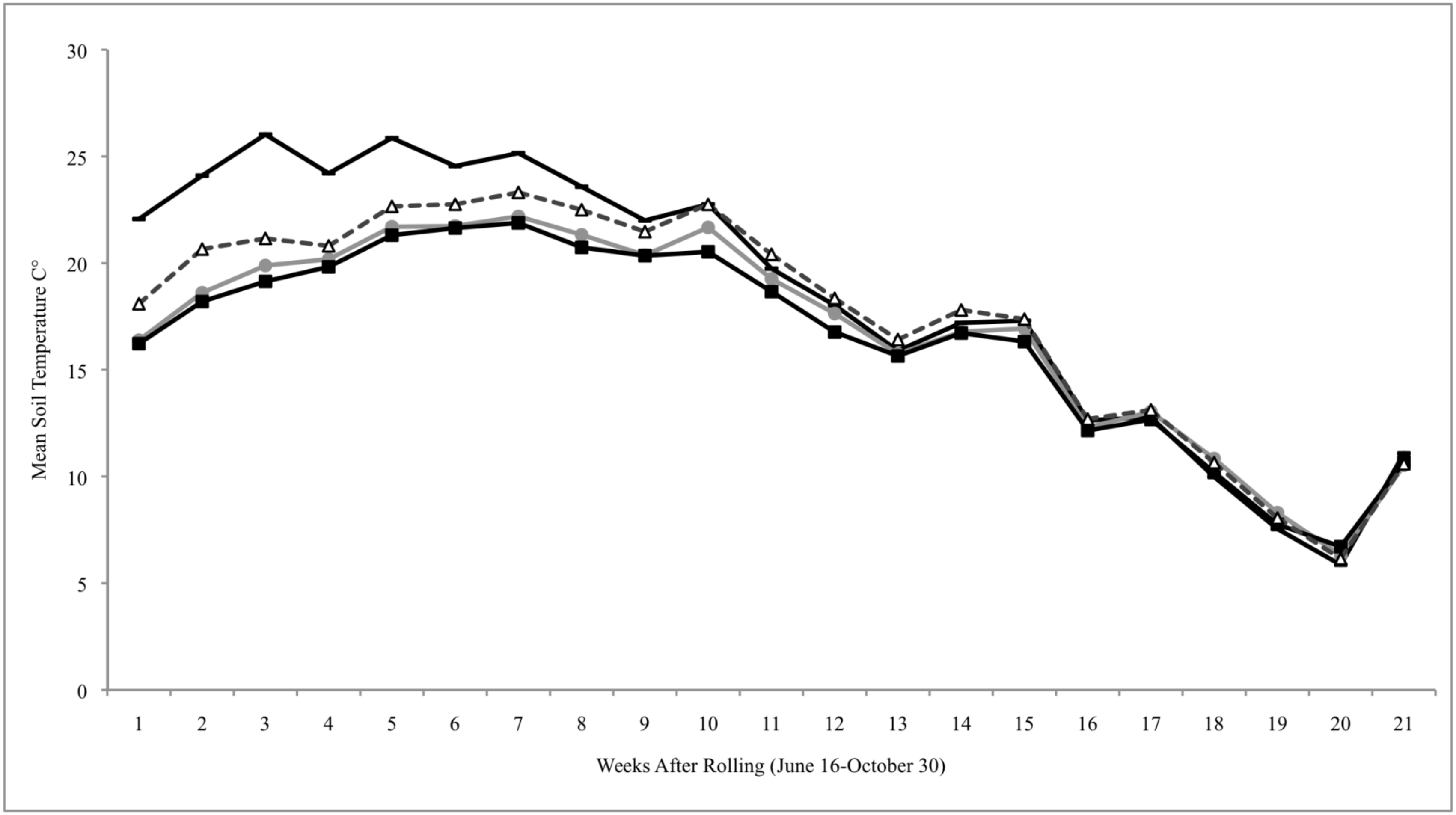


Figure 2. Biomass nitrogen concentration of three cover crops: winter rye (WR), hairy vetch (HV) and a mixture (WR + HV) in (A) 2008 and (B) 2009 at Lamberton, Minnesota. No biomass was present in the control plots. Treatment mean values with a common letter at weeks after rolling (WAR) are not different using Fischer's Protected LSD (0.05). There was no pre-roll cover crop biomass collected in (A) 2008. Bars right of legend indicate LSD (0.1) within year for comparing cover crop treatment means over WAR

Tissue N concentration in the biomass residues was consistently higher in the hairy vetch than the winter rye and the mixture in all study years and all locations (Fig. 3 and 4). Significant time x cover crop interactions for biomass concentration were observed at St. Paul in both years and at Lamberton in 2009. These interactions occurred because biomass N concentration of hairy vetch declined while the N concentrations in the mixture and winter rye changed little over time. At St. Paul in 2008, hairy vetch biomass N concentration declined throughout the season from pre-roll levels to 15-17 WAR when it had similar concentration to the mixture. Additionally, in 2009, hairy vetch residue N declined from pre-rolling to 10-12 WAR. Degradation of the hairy vetch mulch, due to continued control with hand labor and low residue C/N ratios, likely accounted for precipitous reductions in biomass N concentration. Residue N concentration of winter rye and the mixture were similar in both years until mid-season in 2009 and late season in 2008. At Lamberton in 2008, hairy vetch residue N concentration was larger than winter rye and mixture at all sampling dates but concentration in all covers was similar over time. In 2009, hairy vetch and mixture N concentrations declined over time at 6-8 WAR and increased until 18 WAR while winter rye remained constant. The higher proportion of hairy vetch in the mixture likely accounted for higher mixture N concentration.

A



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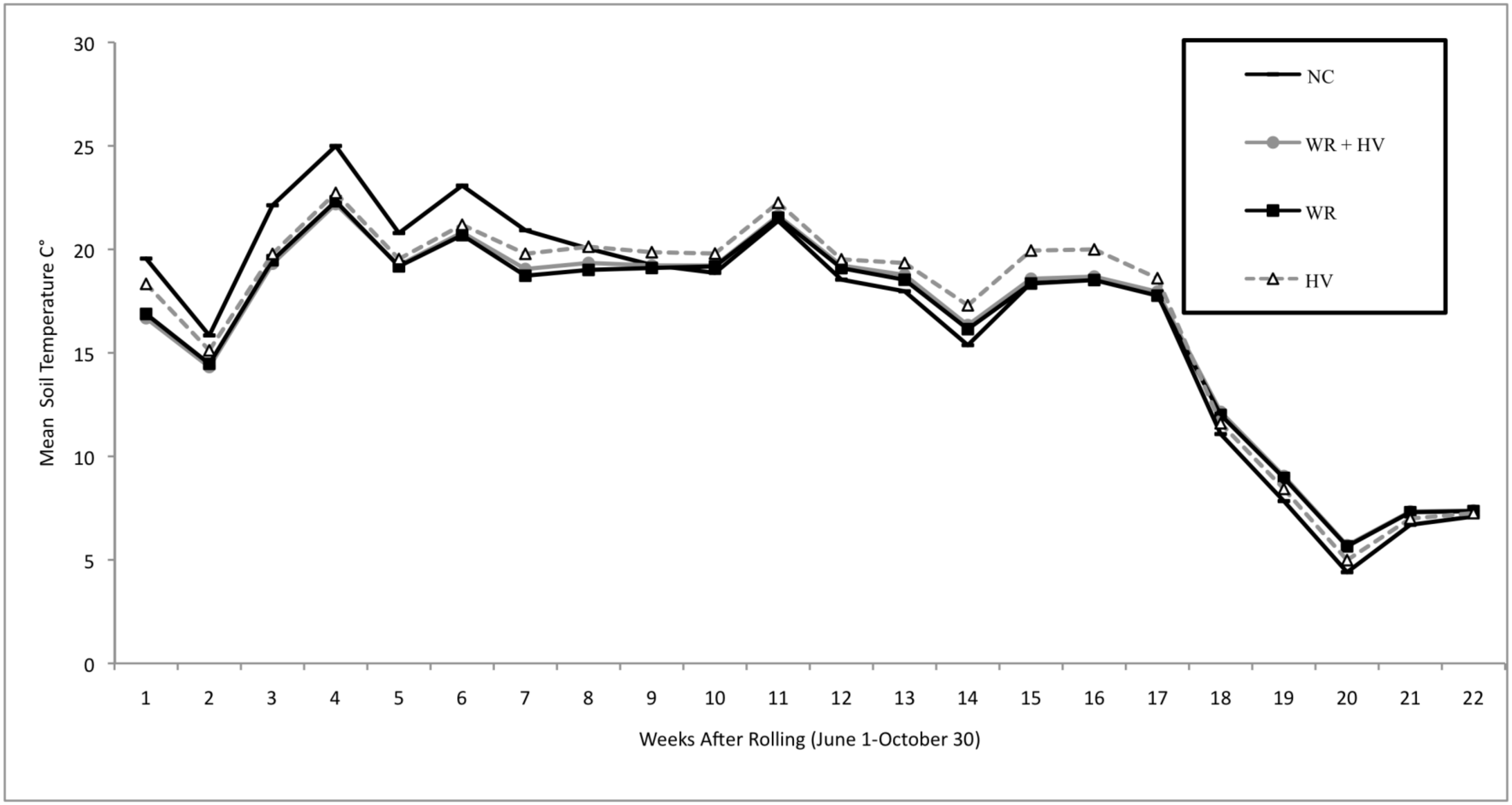
Weeks After Rolling (June 16-October 30)

B


NC
WR + HV
WR
HV
Mean Soil Temperature C°
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25
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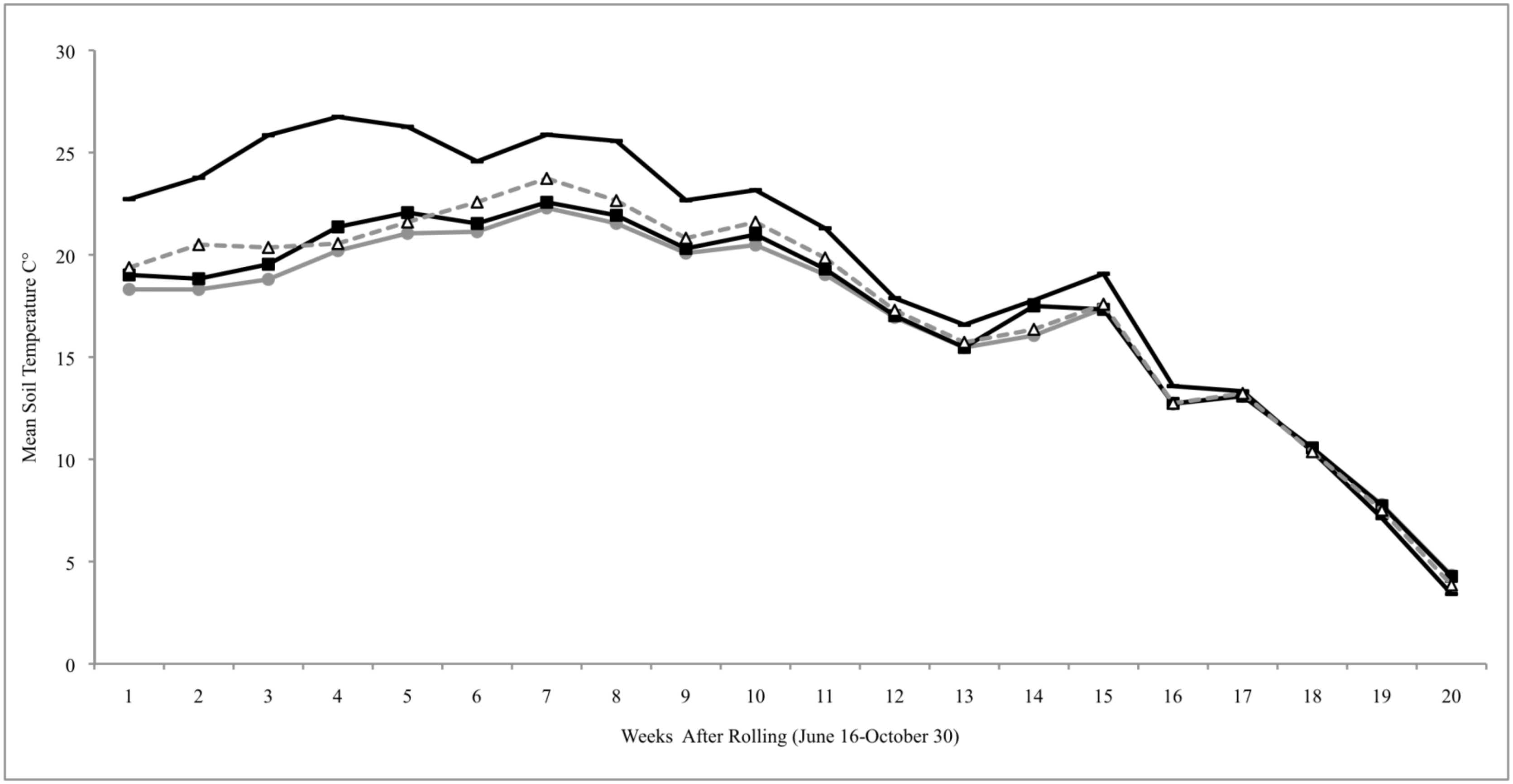
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
Weeks After Rolling (June 1-October 30)

Figure 3. Mean soil temperatures at 0-5 cm in four, rolled cover crop treatments of winter rye (WR), hairy vetch (HV), a mixture of both (WR + HV), and a bare soil control (NC) at St. Paul in (A) 2008 and (B) 2009. Hourly collected data is presented as soil temperature at weeks after rolling (WAR) starting on the date of planting at about June 15 (A) and June 1 (B).

A



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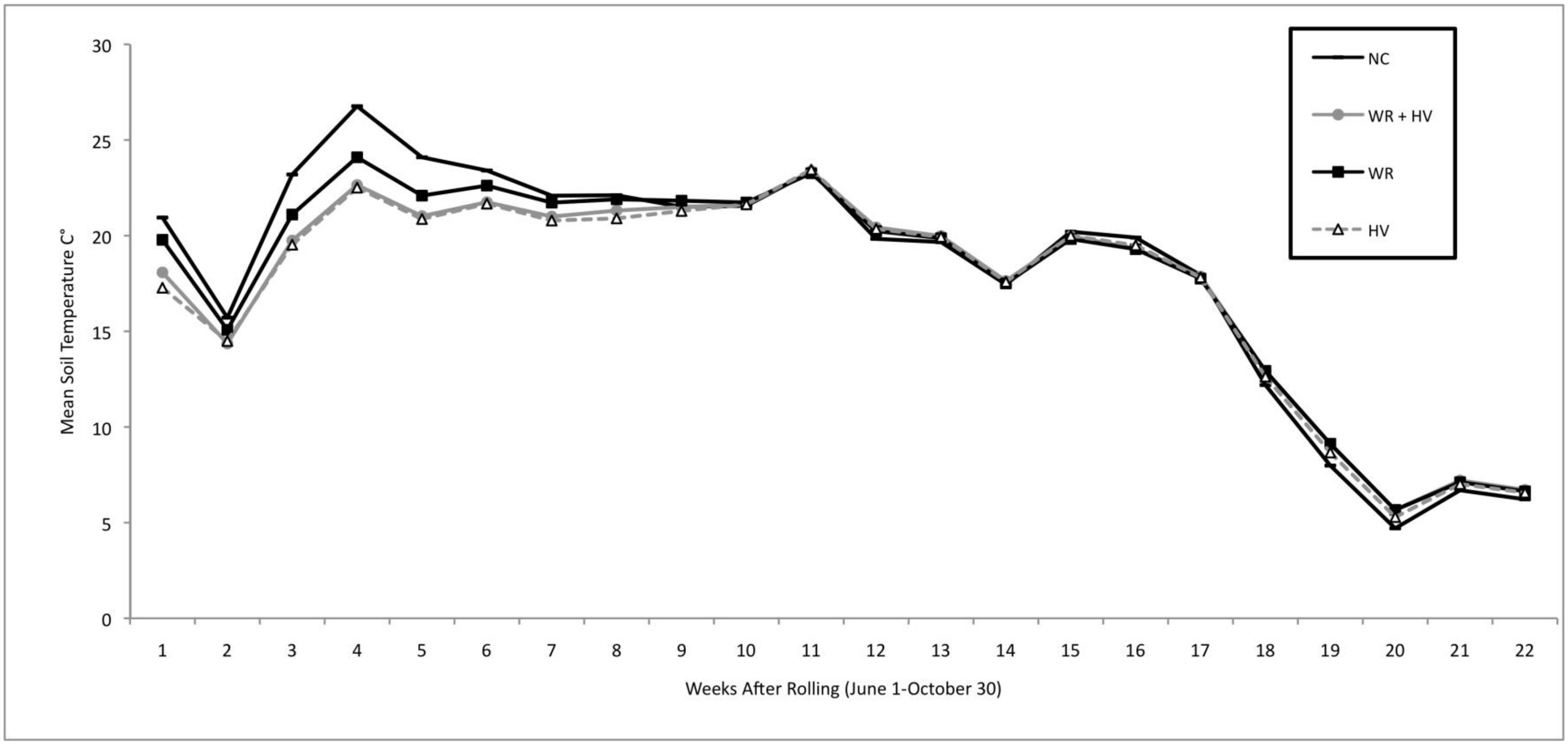
Weeks After Rolling (June 16-October 30)

B



Mean Soil Temperature C°
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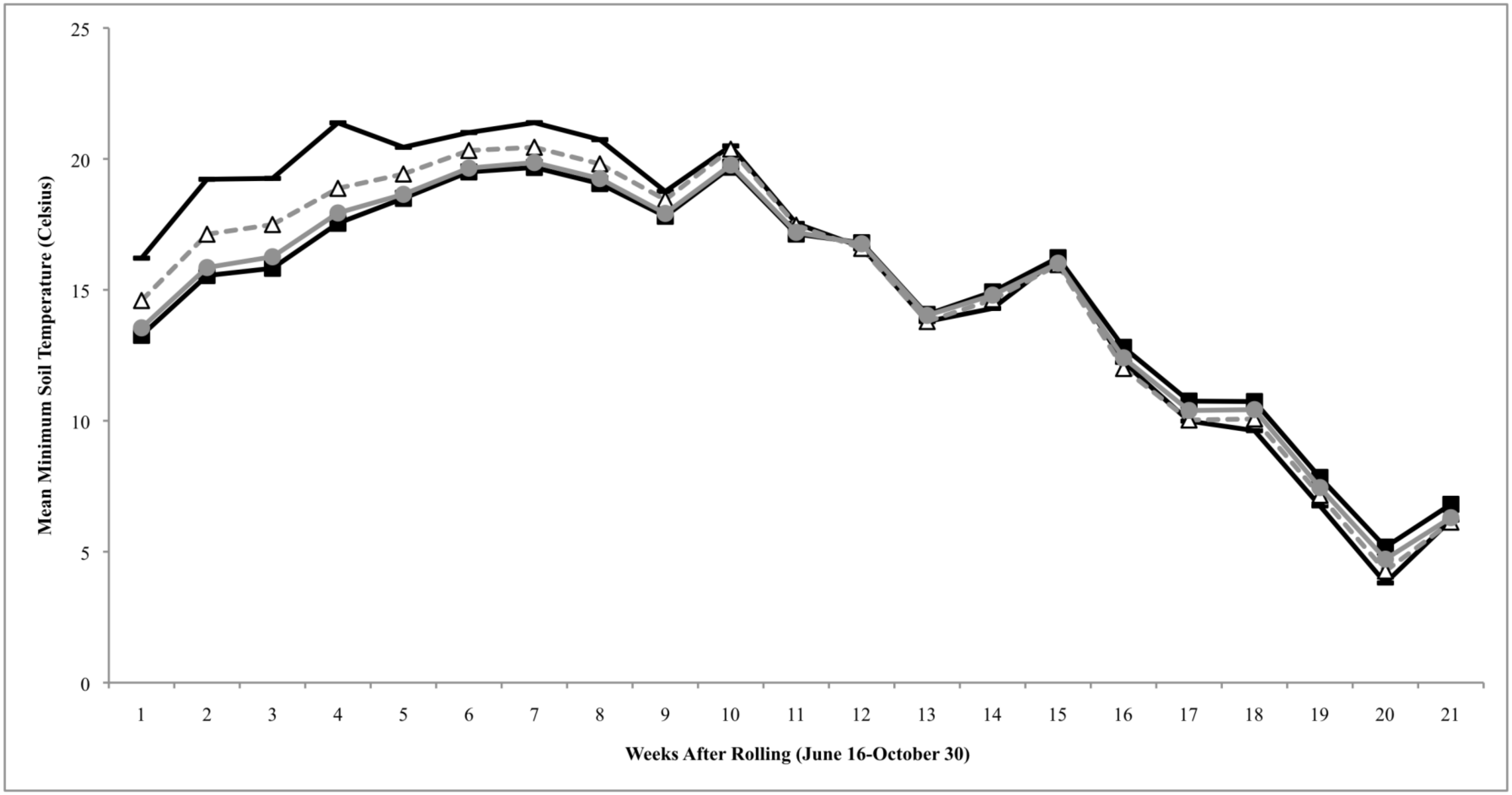
Weeks After Rolling (June 1-October 30)
NC
WR + HV
WR
HV

Figure 4. Mean soil temperatures at 0-5 cm in four, rolled cover crop treatments of winter rye (WR), hairy vetch (HV), a mixture of both (WR + HV), and a bare soil control (NC) at Lamberton in (A) 2008 and (B) 2009. Hourly collected data is presented as soil temperature at weeks after rolling (WAR) starting on the date of planting at about June 15 (A) and June 1 (B).

A


Mean Minimum Soil Temperature (Celsius)
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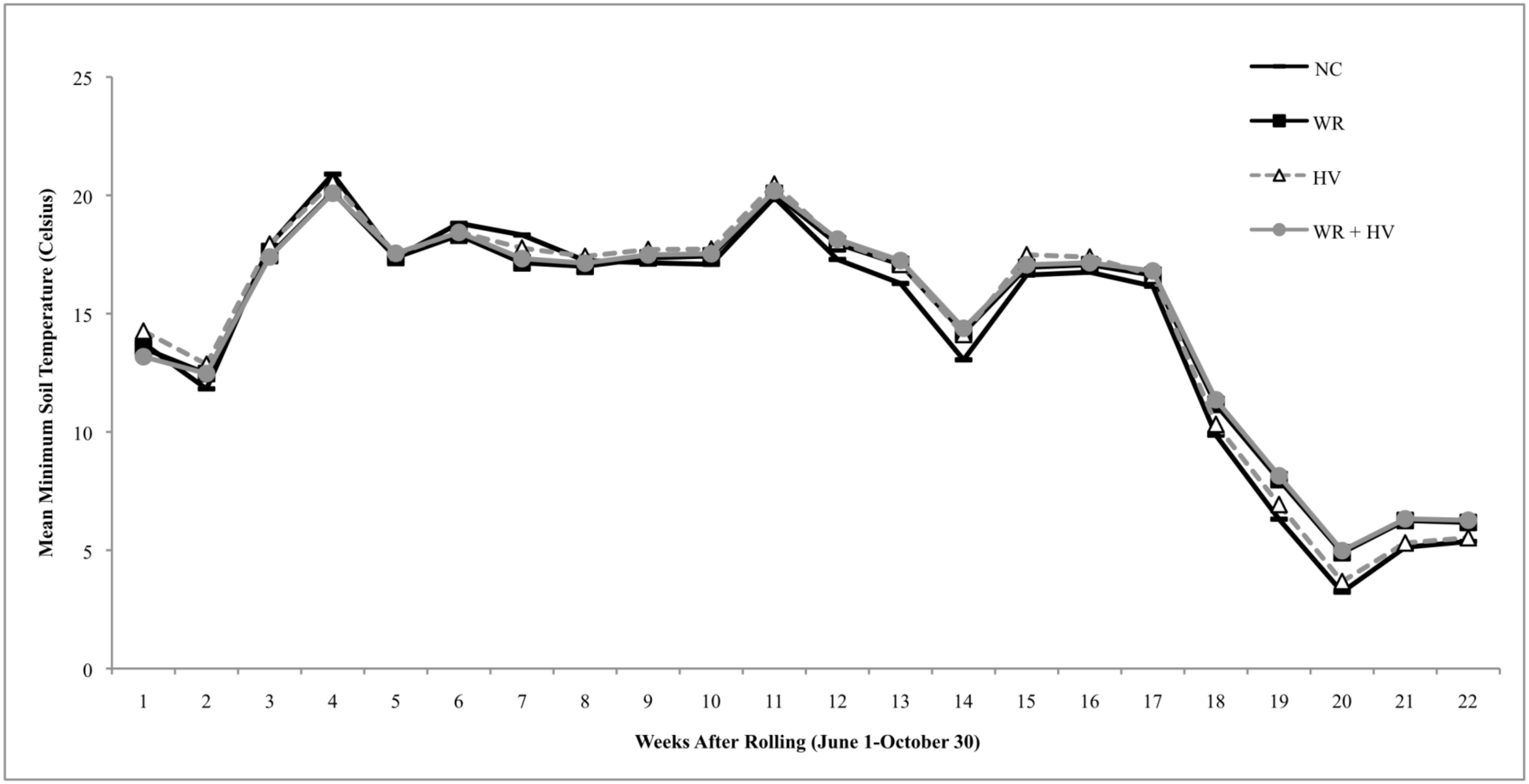
Weeks After Rolling (June 16-October 30)

B



NC
WR
HV
WR + HV
Mean Minimum Soil Temperature (Celsius)
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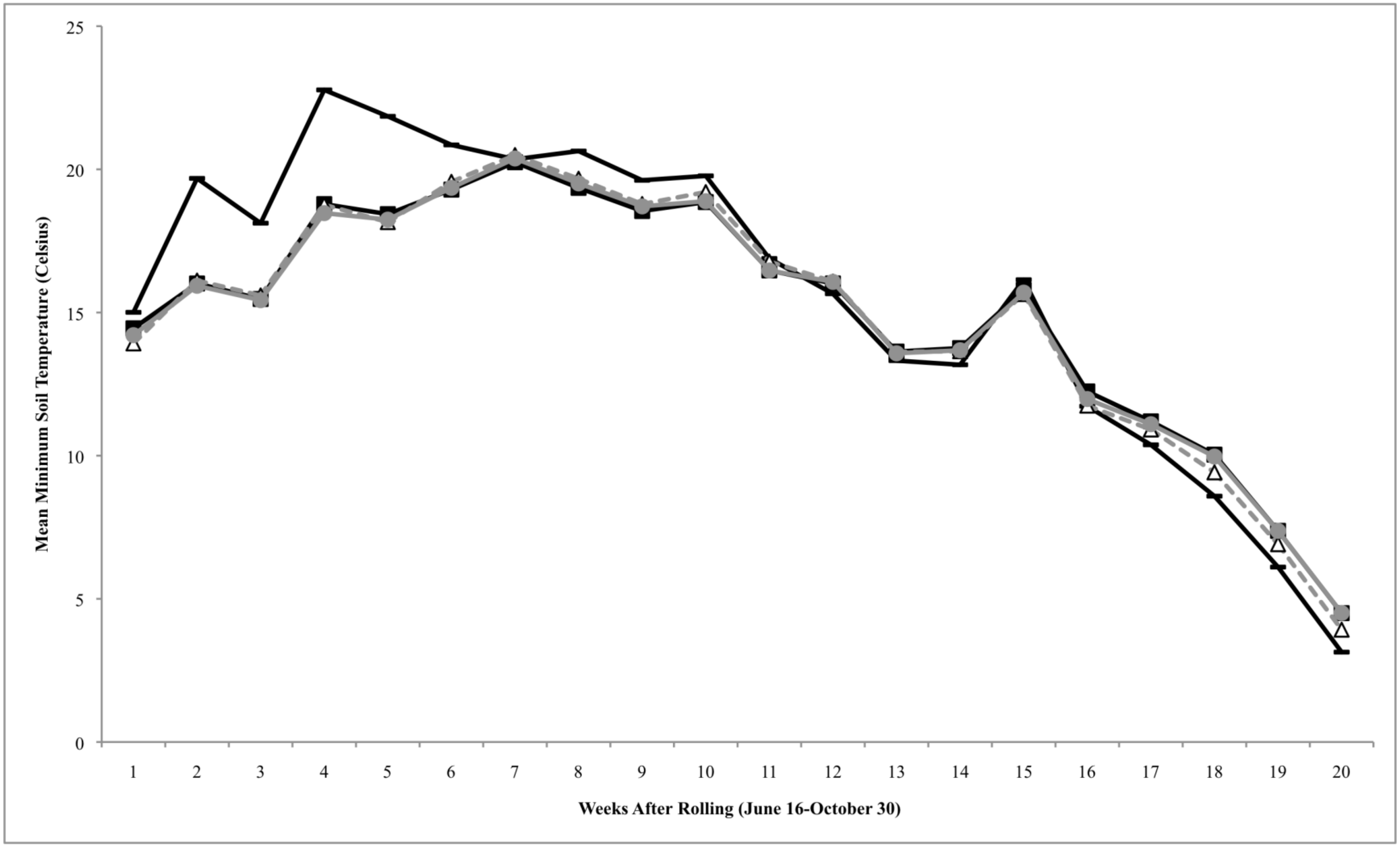
21
22
Weeks After Rolling (June 1-October 30)

Figure 5. Mean minimum soil temperatures at 0-5 cm in four, rolled cover crop treatments of winter rye (WR), hairy vetch (HV), a mixture of both (WR + HV), and a bare soil control (NC) at St. Paul in (A) 2008 and (B) 2009. Hourly collected data is presented as soil temperature at weeks after rolling (WAR) starting on the date of planting at about June 15 (A) and June 1 (B).

A



Mean Minimum Soil Temperature (Celsius)
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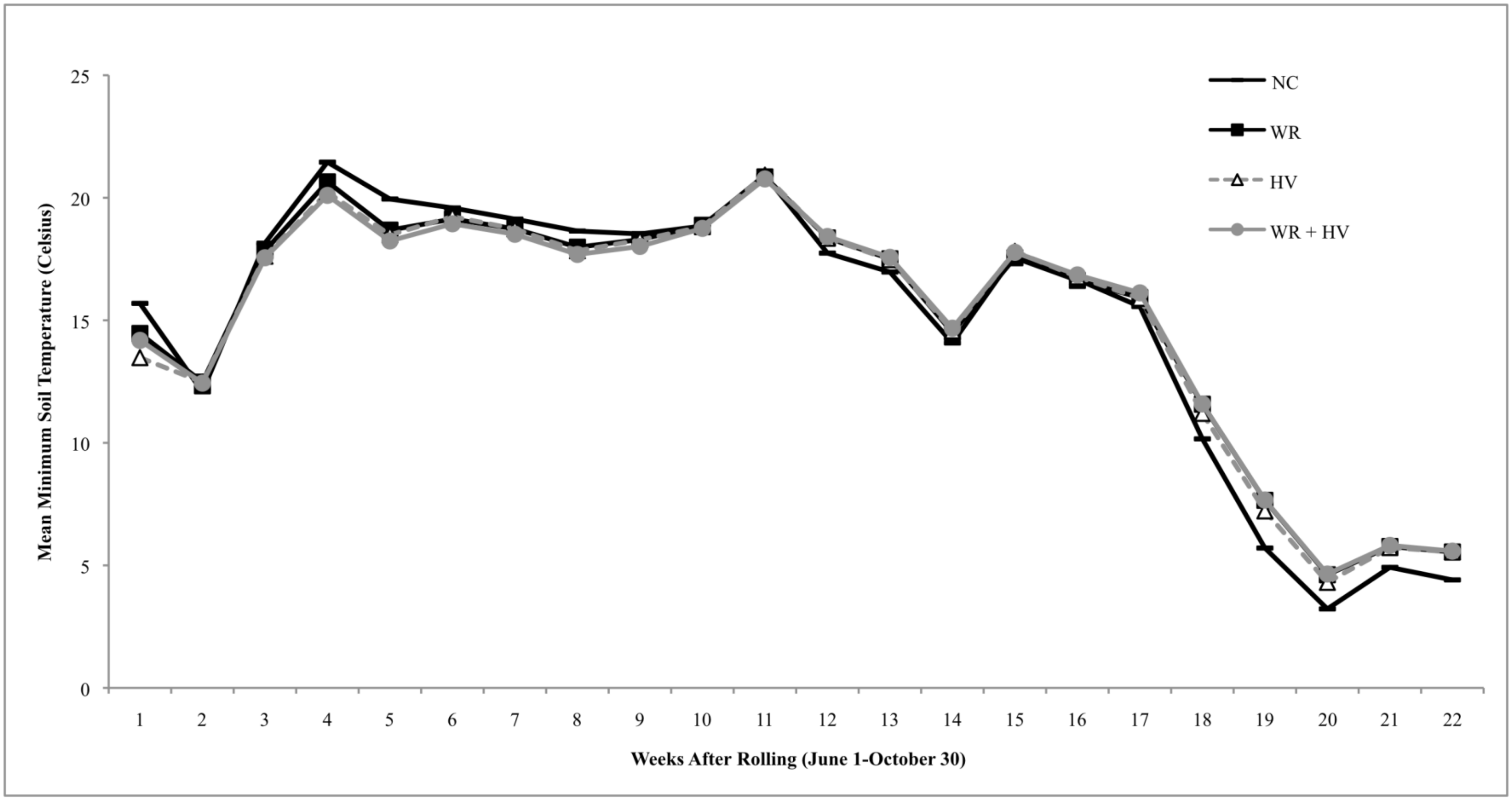
Weeks After Rolling (June 16-October 30)

B



Mean Minimum Soil Temperature (Celsius)
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18
19
20
21
22
Weeks After Rolling (June 1-October 30)
NC
WR
HV
WR + HV

Figure 6. Mean minimum soil temperatures at 0-5 cm in four, rolled cover crop treatments of winter rye (WR), hairy vetch (HV), a mixture of both (WR + HV), and a bare soil control (NC) at Lamberton in (A) 2008 and (B) 2009. Hourly collected data is presented as soil temperature at weeks after rolling (WAR) starting on the date of planting at about June 15 (A) and June 1 (B).