Exploring Overwintered Cover Crops as a Soil Management Tool in Upper-midwest High Tunnels

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Abstract. High tunnels are an important season extension tool for horticultural production in cold climates, however maintaining soil health in these intensively managed spaces is challenging. Cover crops are an attractive management tool to address issues such as decreased organic matter, degraded soil structure, increased salinity, and high nitrogen needs. We explored the effect of winter cover crops on soil nutrients, soil health and bell pepper (*Capsicum annuum*) crop yield in high tunnels for 2 years in three locations across Minnesota. Cover crop treatments included red clover (*Trifolium pratense*) monoculture, Austrian winter pea/winter rye biculture (*Pisum sativum*/*Secale cereale*), hairy vetch/winter rye/tillage radish (*Vicia villosa*/*S. cereale*/*Raphanus sativus*) polyculture, and a bare-ground, weeded control. Cover crop treatments were seeded in two planting date treatments: early planted treatments were seeded into a standing bell pepper crop in late Aug/early September and late planted treatments were seeded after bell peppers were removed in mid-September. At termination time in early May, all cover crops had successfully overwintered and produced biomass in three Minnesota locations except for Austrian winter pea at the coldest location, zone 3b. Data collected include cover crop and weed biomass, biomass carbon and nitrogen, extractable soil nitrogen, potentially mineralizable nitrogen, microbial biomass carbon, permanganate oxidizable carbon, soil pH, soluble salts (EC), and pepper yield. Despite poor legume performance, increases in extractable soil nitrogen and potentially mineralizable nitrogen in the weeks following cover crop residue incorporation were observed. Biomass nitrogen contributions averaged 100 kg·ha⁻¹ N with an observed high of 365 kg·ha⁻¹ N. Cover crops also reduced extractable soil N in a spring sampling relative to the bare ground control, suggesting provision of nitrogen retention ecosystem services.

High tunnels, also called hoop houses or poly tunnels, are semipermanent covered structures used to extend the growing season and intensify crop production in cold regions (NRCS, 2015). Heat capture by the polyethylene cover extends the growing season through creation of a warmer microclimate (O'Connell et al., 2012; Ward and Bomford, 2013; Zhao and Carey, 2009), a benefit that has driven dramatic increases in the use of this technology in temperate climates throughout the world (Carey et al., 2009; Lamont, 2009). Common high tunnel rotations are often longer than in the open field, and include tomatoes (*Solanum lycopersicum*), peppers (*Capsicum* spp.), and cucumbers (*Cucumis sativus*) in the summer, and lettuce

(*Lactuca sativa*) and spinach (*Spinacia oleracea*) in the spring and fall (Carey et al., 2009; Huff, 2015; Knewton et al., 2010). The resulting intensified production system offers benefits such as increased marketable yield, extended harvests, and reduced post-harvest disease (Blomgren et al., 2007; Kadir et al., 2006; Reeve and Drost, 2012; Yao and Rosen, 2011), but may also jeopardize long term system sustainability due to natural resource decline.

There are increasing concerns that high tunnel production may place substantial demands on soil resources. The greater number of available growing degree days in high tunnels intensifies soil use through longer

planting cycles, along with increased tillage operations and nutrient demands (Wildung and Johnson, 2012). When these practices are coupled with high temperatures and irrigation under protected conditions, high tunnel soils are left vulnerable to degradation through loss of organic matter and increased soil salinity (Hajime et al., 2009). Soil health degradation is a major concern for growers, especially those who are certified organic and directed by the National Organic Standards to maintain or improve the physical, chemical, and biological condition of soil (USDA, 2017). In addition to the above concerns, high tunnel producers commonly use compost derived from animal manure for nitrogen (N) fertility (Ghesm and Brown, 2018; Knewton et al., 2010), which can lead to excess soil phosphorus and high salinity (Montri and Biernbaum, 2009).

A potential management tool to mitigate soil health issues and provide N without importing excess phosphorus is the use of cover crops, defined here as nonharvested plants grown between cash crop cycles to achieve a variety of benefits, including soil improvement. N-fixing legume cover crops in particular have been shown to provide sufficient N for subsequent crops (Drinkwater et al., 1998; Finney et al., 2016; Parr et al., 2011; Tonitto et al., 2006; White et al., 2017), and fields with a history of legumes in rotation have reduced phosphorus excesses than fields without legumes in rotation (Schipanski and Drinkwater, 2011). The limited studies that exist demonstrate that legume cover crops in high tunnels can increase soil organic matter, supply sufficient N for a summer crop, and increase microbial activity (Montri and Biernbaum, 2009; O'Connell et al., 2012; Rudisill et al., 2015).

In cold climates, the winter months between November and March may present an ideal window for cover crop production, with the least disruption to commonly used income-generating rotations (Knewton et al., 2010). However, shorter overall growing seasons and extreme cold in more northern climates may limit overwintered cover crop productivity, even in the extended periods of growth possible in high tunnel environments. Although performance of specific cover crop species in protected high tunnel environments is not well understood, red clover (*Trifolium pratense*), rye (*Secale cereale*), and hairy vetch (*Vicia villosa*) overwinter in open fields in Minnesota, yet unreliably and sometimes with limited biomass production (Perrone et al., 2020). The objectives of our study were to 1) identify productive winter annual cover crop legume mixtures in cold-climate high tunnel environments, 2) quantify effects of high tunnel overwintered cover crops on soil health indicators, and 3) assess impacts of overwintered cover crops on cash crop productivity.

Materials and Methods

Site description. This experiment was conducted over 2 years from Aug. 2015 to Sept.

Table 1. Site characteristics.

	Site		
	Grand Rapids	Morris	Rosemount
High tunnel dimensions and area	15.2 m × 6.4 m 97.3 m ²	14.6 m × 9.1 m 132.9 m ²	14.6 m × 9.1 m 132.9 m ²
High tunnel orientation (long side)	N/S	NE/SW	E/W
High tunnel covering	Single layer polyethylene	Single layer polyethylene	Double layer polyethylene
Previous management	Winter annual cover crop with summer bell pepper crop (preliminary study)	Winter annual cover crop with summer bell pepper crop (preliminary study)	Soil covered with landscape fabric; various crops planted in pots aboveground
U.S. Dept. Agr. hardiness zone	3b	4a	4b
Soil type	Shooker very fine sandy loam	Byrne silt loam	Waukegan silt loam
% OM	2.9	5.9	5.3
Nitrate-N (ppm)	25	20	120
Bray-P (ppm)	341	282	63
K (ppm)	253	424	423
Mg (ppm)	236	709	651
Ca (ppm)	1563	3471	3131
Na (ppm)	65	68	45
S (ppm)	38	135	121
Zn (ppm)	5.7	8.5	5.9
Mn (ppm)	13	35	46
Fe (ppm)	58	24	54
Cu (ppm)	1.8	3.2	1.1
B (ppm)	1.0	2.2	0.7

2017 at three sites in Minnesota: North Central Research and Outreach Center in Grand Rapids (lat. 47.242539, long. -93.492791), West Central Research and Outreach Center in Morris (lat. 45.593615, long. -95.878379), and Rosemount Research and Outreach Center in Rosemount (lat. 44.717434, long. -93.099067). Existing high tunnels used in this experiment varied in environmental, soil, and construction characteristics (Table 1). Baseline soil samples were collected at all three sites in Sept. 2015 and sent to Midwest Laboratories (Omaha, NE) for analysis.

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Experimental design. Plots were arranged in a randomized complete block design within one tunnel at each of three sites, including a split plot and three replicate blocks in each tunnel. Only three replications were used due to high tunnel space limitations and the need to include buffer zones between experimental plots. Cover crop treatment was the main plot factor and cover crop planting date the split plot factor. Cover crop planting date was applied as a split plot rather than a factorial design to evenly distribute the effect of observed low temperature and high moisture observed along the edges of the high tunnels. Cover crop treatments consisted of 1) red clover monoculture [(13.5 kg·ha⁻¹), *Trifolium pratense*]; 2) winter pea/rye 1:1 biculture [(84.1 kg·ha⁻¹), *Pisum sativum* and *Secale cereale*]; 3) hairy vetch/tillage radish/rye 4:1:15 mix [(84.1 kg·ha⁻¹), *Vicia villosa*, *Raphanus sativus*, and *S. cereale*]; and 4) a bare-ground, weeded control. Two planting date treatments consisted of an early planting with cover crops interseeded between pepper rows in late August, or a late planting with cover crops broadcast after pepper removal in mid-September. Subplots were 2.3 m × 1.4 m at Grand Rapids and 2.3 m × 2.1 m at Morris and Rosemount, and cover crop by planting date treatment combinations remained in the same plot location for both years. Digital data loggers were installed and collected data every 15 min at each site with one air temperature sensor per site (Fig. 1). All site management practices followed U.S. Department of Agriculture (USDA) organic standards.

Site management. Legume seed was inoculated by moistening seeds with a 1:4 sucrose solution, mixed with the recommended rate of inoculant, and allowing seeds to air dry overnight. Cover crops were either interseeded between pepper rows in late August or broadcast after pepper removal in mid-September (Table 2). After broadcasting, seed-soil contact was improved by raking seeds until they were

no longer visible on the surface, then seeds watered in. Cover crops were watered overhead as needed. After 7–10 weeks of growth, cover crops were covered with 42.4 g·m⁻² spun-bonded polypropylene row cover, propped up with low tunnel wire hoops, and side curtains closed. Each site was watered for 1 h before shutting off irrigation for the winter. Morris and Rosemount did not receive additional water until spring. Grand Rapids received two applications of 8 mm of water in 2016 and 2017. In spring, once night temperatures were consistently above -5°C, row cover was removed and automatic side curtains used to control internal temperatures. High tunnel curtains were set to open when internal temperature exceeded a threshold of 23.9°C, and curtains closed when internal air temperatures fell below this threshold. In May, cover crops were terminated with a riding mower at Grand Rapids and Rosemount in 2016 and with a flail mower mounted on a walk-behind tractor at Morris in 2016. In 2017, a flail mower mounted on a walk-behind tractor was used to terminate cover crops at all sites. Cover crops were left to dry on soil surface for 2–5 d, then tilled into soil with a rototiller to 20 cm (Table 2).

‘Sweet Sunrise’ bell peppers (Johnny’s Selected Seeds, Fairfield, ME) were started in the greenhouse 8–10 weeks before planting. Peppers were transplanted 5–10 d after cover crop termination in staggered double rows with 45 cm spacing between plants and 90 cm spacing between rows. Peppers were irrigated with drip irrigation and weeded weekly by hand. No fertilizer was added to any plots for the duration of the experiment, however shortly before project initiation and cover crop planting in Rosemount 2015, the tunnel received 22.7 kg of 9–10–25 synthetic fertilizer. Peppers were trellised using a Florida weave system with stakes every four plants. Pepper harvest began when individual fruits were 90% yellow (Table 2). Peppers were harvested

Fig. 1. Monthly average high and low air temperatures for all sites in (A) Y1 and (B) Y2, shown with approximate dates for (*) cover crop planting, (**) cover crop termination and tillage and pepper planting, and (***) pepper plant termination and cover crop planting.

every 7–14 d and sorted, counted, and weighed according to USDA standards for marketable (combined categories Fancy, No. 1, and No. 2) and unmarketable (USDA, 2005). Due to small plot size, pepper rows on plot edges were excluded from the data, leaving two rows for data collection in Morris and Rosemount plots and one row for data collection in Grand Rapids plots. Harvest continued until pepper plants were removed by pulling out entire plants in mid-September (Table 2).

Cover crop sampling and analysis. Cover crops were sampled at time of termination in 2016 and 2017 (Table 2). Two 0.1 m² quadrats per plot were sampled by clipping cover crops to ground level and pooling samples. Samples were then sorted according to plant type, dried at 60 °C for 72 h, ground to 1 mm, and run on a combustion analyzer for percent carbon (%C) and percent nitrogen (%N). Cover crops were seeded at the same rate for both early and late planted cover crop treatments, but due to the area occupied by standing pepper

plants in the early planted treatment, the effective seeding rate for the early planted treatment was higher than the late planted treatment. An effort was made to adjust biomass in the early-seeded cover crop treatments to account for this increased seeding rate and the presence of “gaps” where no cover crops were planted, allowing us to compare biomass contributions of similar seeding rates across early and late treatments. Using the area represented by the 30.5 cm wide strip not planted to cover crops, we multiplied the actual harvested plot biomass value by the percentage of the total plot area that was seeded, 77.8% at Grand Rapids and 71.4% at Rosemount and Morris, to arrive at an estimate of adjusted biomass for early and late planted treatments.

Soil sampling and analysis. To quantify changes in soil properties resulting from cover crops, soil was sampled four times over the growing season, capturing key points when impact from cover crop cultivation was expected: 1) at cover crop termination (0 weeks), 2) two weeks after cover crop incorporation, 3) five weeks after cover crop incorporation, and 4) final pepper harvest (Table 2). Eight random soil cores within pepper rows were taken in each plot to 20 cm deep and pooled. A fraction of each sample was sieved to 2 mm, stored at 4 °C, and analyzed within 2 weeks of collection for fresh soil analyses. Remaining soil was dried at 35 °C for 72 h and ground to 2 mm for dry soil analysis.

Extractable nitrogen (ExN), potentially mineralizable nitrogen (PMN), and microbial biomass (MB) analyses were conducted on fresh soils. Briefly, ExN (Perrone et al., 2020) was determined by shaking 10 g fresh soil and 40 mL 1 M KCl for 1 h at 240 rpm, then filtering with Whatman No 1 filter paper. PMN was determined with a 28-d aerobic incubation per Drinkwater et al. (1998), where 10 g fresh soil was held at field capacity moisture in the dark at 37 °C. After 28 d, samples were shaken with 40 mL 1 M KCl for 1 h at 240 rpm, then filtered with Whatman No 1 filter paper. The PMN is reported as the net NH₄-N after anaerobic incubation. Microbial biomass carbon (MBC) analysis used the direct chloroform extraction method (Gregorich et al., 1990; Setia et al., 2012), with the modification that biomass C and N values were not corrected for extraction efficiency, representing a flush of C and N biomass rather than absolute field values (Fierer et al., 2003). Two 10 g fresh soil subsamples were extracted

Table 2. Dates of field operations.

	Y1			Y2		
	Grand Rapids	Morris	Rosemount	Grand Rapids	Morris	Rosemount
Early planted cover crop	28 Aug. 2015	24 Aug. 2015	2 Sept. 2015 ²	25 Aug. 2016	30 Aug. 2016	2 Sept. 2016
Late planted cover crop	16 Sept. 2015	18 Sept. 2015	22 Sept. 2015	16 Sept. 2016	14 Sept. 2016	20 Sept. 2016
Cover crop termination/soil sample 1	17 May 2016	6 May 2016	4 May 2016	18 May 2017	4 May 2017	2 May 2017
Soil sample 2	6 June 2016	25 May 2017	23 May 2016	5 June 2017	23 May 2017	19 May 2017
Soil sample 3	27 June 2016	14 June 2016	16 June 2016	26 June 2017	12 June 2017	9 June 2017
First pepper harvest	25 Aug. 2016	11 Aug. 2016	5 Aug. 2016	3 Aug. 2017	7 Aug. 2017	28 July 2017
Final pepper harvest/soil sample 4	16 Sept. 2016	13 Sept. 2016	12 Sept. 2016	15 Sept. 2017	13 Sept. 2017	18 Sept. 2017

²No existing peppers, seeds broadcasted.

with 0.5 M K₂SO₄ after one subsample received 0.5 mL chloroform. Both chloroformed and nonchloroformed samples were shaken for 4 h at 150 rpm, and then filtered with Whatman No 1 filter paper. Chloroformed extracts were bubbled with a forced air vacuum apparatus for 25 min to remove any traces of chloroform. ExN, PMN, and MB extracts were analyzed for total organic carbon and total nitrogen on a TOC-CPH analyzer with a TNM-1 module and ASI-V autosampler (Shimadzu Scientific Instruments, Columbia, MD) resulting in a measurement of total inorganic N and C in the sample, including possible trace amounts of dissolved organic C and N.

Permanganate oxidizable carbon (POXC), pH, and electrical conductivity (EC) measurements were taken on dry soil. POXC analysis reacted 2.5 g dry soil with 2 mL 0.2 M KMnO₄ in 18 mL distilled water. After shaking for 2 min at 120 rpm, samples were incubated for 10 min in the dark at room temperature, and then 0.5 mL of supernatant was transferred to 49.5 mL water. This diluted sample was analyzed for absorbance at 550 nm. EC and pH measurements were made on a 1:1 solution with distilled water using a pH/EC meter.

Statistical analysis. Data were analyzed by site-year as a split plot design with cover crop mix as a whole plot factor and cover crop planting date as a subplot factor. Blocks were treated as replications. For measurements taken more than once over the course of a season, time was treated as a split-split plot factor. Analysis of variance was conducted using the split plot and split-split plot function in the R package “agricolae,” to determine main effects and interactions (de Mendiburu, 2017; R Core Team, 2017). Square root transformations were used when data failed to meet assumptions of normality. *P* values are reported if less than 0.10, but only *P* values below 0.05 were considered significant and investigated further. *P* values between 0.05 and 0.10 are discussed as “trends.” Means were reported by the main factor only (cover crop treatment), unless the split plot factor (plant date) or the interaction was significant (*P* > 0.05). Mean separation was performed using Fisher’s least significant difference (*P* = 0.05).

Results

Cover crop biomass and nitrogen contribution. We found that total biomass (combined cover crop and weed biomass) differed by cover crop treatment and was affected by cover crop planting date (early planting vs. late planting) at the cooler site of Grand Rapids in both study years, and in the warmer site of Morris only in Y2. There was a cover crop treatment by planting date interaction at Morris and Rosemount in Y1 and Grand Rapids in Y2 (Table 3). Early planting of cover crops did not increase overall cover crop biomass accumulation. In fact, at all but the warmest, southernmost site (Rosemount), sowing cover crops later in the fall after pepper plants were removed generally increased total biomass from 30% to 70% that of the early planted plots (Table 3). This effect was

Table 3. Total biomass (cover crop and weed), legume biomass, and weed biomass results, analyzed by site year. Data are reported by cover crop treatment only (main factor), unless plant date or plant date × cover crop interaction was significant (*P* < 0.05). Cover crop treatments are red clover (RC), pea mix (PM), vetch mix (VM); plant date treatments are early planted (Early) and late planted (Late).

		Y1			Y2		
		Grand Rapids	Morris	Rosemount	Grand Rapids	Morris	Rosemount
Total biomass (kg·ha ⁻¹)							
RC	Early	705 d ^z	812 d	1,286 b	3,698 bc	988 bc	1,707 b
	Late	1,131 c	768 d	1,151 b	3,565 c		
PM	Early	1,959 b	1,644 bc	1,254 ab	3,873 c	14,602 a	6,095 a
	Late	2,619 a	2,412 a	1,209 b	11,830 a		
VM	Early	1,606 b	1,310 c	726 c	2,075 bc	4,641 b	5,234 a
	Late	1,834 b	2,217 ab	1,761 a	7,018 b		
Legume biomass (kg·ha ⁻¹)							
RC	Early	412 a	668 a	1,116 a	2,185 a	140 ab	931 ab
	Late	88 b					
PM	Early	9 c	109 c	539 b	32 c	558 a	3,442 a
	Late	2 c					
VM	Early	102 b	346 b	80 c	588 b	551 a	2,895 a
	Late	147 b					
Weed biomass (kg·ha ⁻¹)							
RC	Early	293 b	14 b	24 bc	745 b	848 b	776 ab
	Late	1,044 a	231 a	181 a	2,148 a		
PM	Early	96 bc	14 b	25 bc	231 bcd	6,934 a	2,636 a
	Late	141 bcd	29 b	0 c	103 cd		
VM	Early	34 cd	0 b	77 bc	444 bc	591 b	1,002 ab
	Late	45 cd	2 b	107 bc	34 cd		

^zLetters represent significant differences ($\alpha = 0.05$) between values for a single biomass type within a single site-year column. Mean separation performed using a least significant difference test using square root transformed data. No cover crop control plots (NCC) were assumed to have zero biomass due to weekly weed management.

particularly notable in Grand Rapids Y2, where later planting of pea and vetch cover crop mixes increased total biomass by 3-fold compared with earlier-planted treatments. Overall, total plant biomass was higher in Y2 than Y1 for all sites, reaching a maximum of 14,602 kg·ha⁻¹ for the pea mix at Morris in Y2 (Table 3). Treatments that included rye (both the pea mix and vetch mix) had the highest total biomass for each site-year, except for the early planted vetch mix treatment at Rosemount in Y1 (Table 3). When analyzing legume biomass alone, quantity was variable across site years, but red clover consistently produced among the highest biomass when compared with other species (Table 3). We found that species mix composition drove trends in legume biomass production for all site-years except Morris in Y2 (*P* = 0.086, Table 3). At Grand Rapids, vetch produced more biomass than pea in both years.

Weeds and nonlegume species (rye) comprised a majority of total plant biomass at all sites. We observed that cover crop species treatments differed in weed biomass (weediness) in all site-years except Rosemount Y2 (*P* = 0.055, Table 3). Planting date affected weed biomass at Morris in Y1, with later cover crop planting dates having higher weed biomass in the slow-growing red clover plots than earlier planting dates (Table 3). The cover crop treatment × plant date interaction was significant at Grand Rapids in Y1 (*P* = 0.046) and Y2 (*P* = 0.032) and at Rosemount in Y1 (*P* = 0.009, Table 3). Cover crop treatments that included rye reduced weeds to a level statistically indistinguishable from the

weed-free bare control 80% of the time at Rosemount and Morris (Table 3). Two notable exceptions are the rye-pea mix treatments in Morris and Rosemount in Y2, which had the highest weed biomass for their respective site-years (Table 3). The most commonly observed weeds at each site were common chickweed (*Stellaria media*) at Grand Rapids, groundsel (*Senecio vulgaris*) at Morris, and lamb’s quarters (*Chenopodium album*) and shepherd’s purse (*Capsella bursa-pastoris*) at Rosemount. The no cover crop control was free of all measurable biomass due to weekly hand weeding.

Cover crops species varied in their %N from 3.72 to 5.30 (Table 4), but species differences were only identified at the Grand Rapids (*P* = 0.042) site, where clover had lower %N compared with pea and vetch in both years. The C:N of total biomass at termination varied by cover crop species in Y1 and Y2 in Morris (*P* = 0.005, *P* = 0.014). In Y2 Grand Rapids, a trend toward pea mix having the highest C:N of all species at that site was observed, with tissue C:N ranging from 10.60 to 30.91 (Table 4, *P* = 0.063). The total amount of biomass N contributed by cover crops is a factor of biomass accumulation and %N at termination. Across all treatment combinations, total N contributed from cover crops was higher in Y2 than in Y1 (Table 4). The highest biomass N contribution was in the pea mix treatment in Morris in Y2 with 365 kg·ha⁻¹ N (Table 4); this treatment also produced the highest total biomass of any treatment for any site-year (Table 3). Three additional treatments also produced more than 200 kg·ha⁻¹ N, including the pea mix and

Table 4. Legume percent nitrogen (%N), total treatment C:N (including legume cover crops, nonlegume cover crops, and weeds), and total biomass nitrogen (N) (including legume cover crops, nonlegume cover crops, and weeds) results. Data are reported by cover crop treatment only (main factor) unless plant date or plant date $\times$ cover crop interaction was significant ($P < 0.05$). Cover crop treatments are red clover (RC), pea mix (PM), vetch mix (VM), and no cover crop control (NCC); plant date treatments are early planted (Early) and late planted (Late).

		Y1			Y2		
		Grand Rapids	Morris	Rosemount	Grand Rapids	Morris	Rosemount
Legume %N							
	RC	3.98 b ^z	4.17	4.17	3.80 b	4.13	3.72
	PM	4.59 a	3.84	4.03	5.30 a	4.27	4.39
	VM	4.72 a	4.50	4.91	4.55 a	4.93	4.77
Total weighted C:N							
	RC	17.02 b	11.57 b	11.09	13.82 b	12.17 b	11.90
	PM	30.91 a	21.47 a	16.73	26.15 a	18.93 a	10.60
	VM	20.38 b	21.23 a	12.70	21.97 ab	16.26 a	11.50
Treatment biomass N (kg·ha ⁻¹)							
RC	Early	21.8 d	32.1 b	50.5 a	129.0 ab	33.8 bc	64.5 b
	Late	24.1 cd		52.3 a	109.3 bc		
PM	Early	38.1 b	53.0 a	56.1 a	65.0 c	365.0 a	268.1 a
	Late	43.7 ab		34.5 ab	204.3 a		
VM	Early	34.2 bc	43.5 ab	19.7 b	119.7 bc	124.8 b	201.3 a
	Late	58.1 a		58.2 a	139.0 ab		

^zLetters represent significant differences ($\alpha = 0.05$) between values of a single data type within a single site-year column. Mean separation performed using a least significant difference test on untransformed data for legume %N and total weighted C:N and square root transformed data for total biomass N. If no letters are reported, there were no differences between treatments. No cover crop control plots (NCC) were assumed to have zero biomass due to weekly weed management.

vetch mix in Rosemount Y2 and pea mix in Grand Rapids Y2 (Table 4). The vetch mix's high N content and biomass in the late planted treatment, when cover crops were planted after pepper plant removal, resulted in a 70% improvement in biomass N relative to the early planted vetch mix.

Soil analyses. We investigated three soil health indicators including 1) ExN, 2) MBC, and 3) POXC, over multiple sampling time points throughout the cash crop season; PMN was measured once at 2 weeks after cover

crops were incorporated via tillage to capture short-term impacts of cover crop residue incorporation, and pH and EC once at final pepper harvest. Measures of soil N (ExN and PMN) were influenced by cover crop species and time at which soil samples were taken (Table 5). Since the proportion of legumes comprising the treatment mixtures was low to negligible at time of termination for all treatments, soil nutrient cycling was likely driven by noncover crop components. ExN was affected by cover crop treatment $\times$ sampling

time interaction at all site-years except Rosemount in Y1. At two of the three sites, ExN was highest in the bare control treatment at time of cover crop tillage (0 weeks, Fig. 2A), suggesting removal of residual soil N by actively growing cover crops. At more than half of the sites (Grand Rapids in both years, and Morris in Y2), soil ExN increased during the period from 2 to 5 weeks after cover crop tillage, a time in pepper growth which requires substantial nitrogen (Fig. 2A). ExtN also generally increased at the Grand Rapids and Morris

Table 5. PMN sampled at 2 weeks after cover crop termination, pH sampled at final pepper harvest, and electrical conductivity (EC) sampled at final pepper harvest. Data reported by cover crop treatment (main factor), unless plant date or plant date $\times$ cover crop interaction was significant ($P < 0.05$). Cover crop treatments are red clover (RC), pea mix (PM), vetch mix (VM), and no cover crop control (NCC), and plant date treatments are early planted (Early) and late planted (Late).

		Y1			Y2		
		Grand Rapids	Morris	Rosemount	Grand Rapids	Morris	Rosemount
PMN (mg·kg ⁻¹ N dry soil)							
RC	Early	11.5	67.0 ab ^z	47.1 a	66.1 ab	68.5 b	40.8 bc
	Late		48.9 b	25.0 b			53.5 abc
PM	Early	17.1	74.0 ab	42.5 a	67.6 a	87.0 a	57.6 ab
	Late		45.2 b	24.1 b			44.1 bc
VM	Early	39.1	93.1 a	50.9 a	82.0 a	72.9 ab	45.6 bc
	Late		47.5 b	22.9 b			70.9 a
NCC	Early	10.3	49.1 b	44.5 a	48.1 b	62.1 b	41.6 bc
	Late		43.6 b	15.9 b			38.6 c
pH							
RC	Early	6.77 ab	7.33	6.78	6.77 ab	7.17	6.62
	Late				6.87 ab		
PM	Early	6.80 a	7.32	6.88	6.80 ab	7.20	6.80
	Late				6.90 a		
VM	Early	6.78 a	7.38	6.92	6.73 b	7.17	6.73
	Late				6.80 ab		
NCC	Early	6.73 b	7.23	6.93	6.80 ab	7.13	6.83
	Late				6.83 ab		
EC (dS·cm ⁻¹)							
	RC	0.32	1.53	0.42	0.22	0.89	0.37
	PM	0.30	1.18	0.38	0.23	0.89	0.28
	VM	0.40	1.04	0.42	0.27	0.83	0.31
	NCC	0.38	1.53	0.52	0.23	0.76	0.32

^zLetters represent significant differences ($\alpha = 0.05$) between values within a single site-year column; mean separation performed using a least significant difference test. If no letters are reported, there were no differences between treatments.

Fig. 2. Extractable nitrogen (ExN) values over sampling time plotted by (A) cover crop treatment (main plot factor) and (B) plant date (split plot factor). Error bars represent ± 1 SE.

sites from 0 to 2 weeks in Y1 of the study. While ExtN in the bare control also increased over these time periods, the magnitude of the increase was less than that observed in the cover cropped plots. The range of ExN observed, ≈ 10 – 50 $\text{mg} \cdot \text{kg}^{-1}$ N soil, was similar across site-years except for at Rosemount in Y1 at tillage (0 weeks) where 225 – 275 $\text{mg} \cdot \text{kg}^{-1}$ N soil was observed following the fertilization event that occurred before experiment initiation (Fig. 2A). This fertilization event may have masked any increases in ExtN from 0 to 2 weeks that may have resulted from cover crop incorporation at the Rosemount site. For all sites in Y1, soil in the early-planted cover crop treatments had higher ExN values two weeks post tillage compared with their late-planted counterparts (Fig. 2B). We also found that the early planted treatment had higher soil PMN than the late planted treatments, with PMN increasing 18% to 121% (Table 5). All sites showed a steep decrease in MBC from tillage to 2 weeks post tillage in Y1, but not in Y2 (Fig. 3). Mean MBC values at tillage (0 weeks) decreased from Y1 to Y2 by 77% at Grand Rapids, 68% in Morris, and 83% in Rosemount. EC varied across sites, however, was unaffected by cover crop treatment or plant date.

Pepper yield. Marketable yellow pepper yield was unaffected by cover crop treatment, plant date, or the cover crop treatment $\times$ plant

date interaction except at Rosemount in Y1 where the red clover treatment produced higher pepper yield than the no cover crop control, with 0.83 kg/plant and 0.53 kg/plant , respectively (Table 6). The amount of unmarketable fruit was unaffected by cover crop treatment, plant date, or the cover crop treatment $\times$ plant date interaction, except at Rosemount in Y2 where the early planted red clover and vetch mix treatment showed reduced weight of unmarketable fruit relative to the late planted treatments.

Discussion

We explored the potential for cover crops to establish and produce appreciable biomass under organically managed high tunnels during winter, when many Upper Midwest tunnels are not in production. We found that legume cover crop species that are challenged in open field winter conditions in our region survived in most cases in the slightly warmer and protected high tunnel environment. Early cover crop planting between productive pepper plants did not meaningfully improve biomass contributions of cover crops, perhaps due to competition with existing mature pepper plants or less ideal seeding conditions when compared with late planted cover crop. When cover crops supply more than 110 $\text{kg} \cdot \text{ha}^{-1}$ N, organic cash crop yields can perform as well as conventional systems (Tonitto et al., 2006), a

threshold which was exceeded by two thirds of cover crop treatments that included legumes in our study's second year.

Legumes did not compete well with some nonlegume, including weeds and rye in treatment mixes. In particular, Austrian winter pea underperformed at Grand Rapids, located in Northeast Minnesota in plant hardiness zone 3b, but proved to be winter hardy in tunnels in zones 4a and 4b (Morris and Rosemount, MN). This is an extended range compared with open field studies in central New York (zone 5a) and Pennsylvania (zones 6a and 6b), which both found that Austrian winter pea winter-killed (Hively and Cox, 2001; White et al., 2017), and suggests that pea is a viable option for high tunnel producers even in the coldest regions. At Rosemount in Y1, legume biomass was possibly reduced by rapid growth of tillage radish that outcompeted vetch in the mixture following Rosemount high tunnel fertilization, which occurred before starting the experiment in Y1. Since nitrogen supplied by cover crops, especially legumes, can provide well-timed N to subsequent cash crops (Domagała-Świątkiewicz et al., 2019; Parr et al., 2011), efforts to increase the proportion of surviving legumes in high tunnel cover crop mixes is warranted and could serve to increase the overall impact of N contribution to high tunnel soils.

Fig. 3. Microbial biomass carbon (MBC) values over sampling time plotted by (A) cover crop treatment (main plot factor) and (B) plant date (split plot factor). Error bars represent ± 1 SE.

Weed control was challenging and likely contributed to low legume biomass production when slow-establishing legumes could not outcompete weeds. Specific cover crop treatments and cover crop treatment $\times$ planting date combinations provided greater weed control than others. It has been suggested that the primary mechanism by which cover crops control weeds is via their capacity for biomass production (Finney et al., 2016). For some species, cover crop sowing date appeared to dictate weed control capacity. For example, in red clover at all sites in Y1, and in Grand Rapids in Y2, spring weed biomass was consistently higher in the late planted treatment than the early planted treatment, suggesting that in high tunnel environments red clover is more effective at weed suppression when planted earlier in the fall and has an opportunity to establish. Cover crop treatment mixes with more than one species, including pea mix and vetch mix, also resulted in a lower proportion of weed biomass. This is likely due to increased biomass coverage provided by the nonlegumes such as rye in the mix, or increased species number, both of which are known to improve weed suppression (Finney et al., 2016; Lawson et al., 2015).

Positive effects on soil N indicators were observed in cover cropped plots both during growth and following termination and

incorporation of biomass. Cover crop production initially reduced ExN during growth relative to the bare ground control, suggesting that cover crops in our region may carry out critical N retention ecosystem services that result in removal of soil N at risk of loss during periods with no cash crop growth (Wauters et al., 2021). This cover crop N retention role may be important in Minnesota high tunnels during periods when farmers remove plastic in winter months, about every 3–4 years before plastic replacement, and precipitation events could impact soil N movement. Following tillage, soil N indicators tended to increase across all cover cropped treatments, and we identified differences particularly between plots where cover crops were seeded before pepper plant removal and those with later-planted and higher-biomass cover crops. In plots where cover crops were planted earlier, higher soil N and MBC were observed two weeks following spring cover crop termination and incorporation via tillage compared with later planted plots, a phenomenon typically related to quantity of cover crop biomass inputs and residue quality (Parr et al., 2014). Early planted cover crop treatments at two sites (Morris and Rosemount) also had higher PMN values two weeks following termination compared with their later-planted counterparts. These observations appeared not to be driven by quantity

of contributed aboveground cover crop biomass contributed to soils, since biomass from cover crops (total biomass, legume biomass, and weed biomass) either was lower in early-planted treatments or was indistinguishable between early and late planted treatments. Combined, these results point toward meaningful impacts on soil N driven by cover crop planting time, growth duration, and possibly biomass quality (C:N and species composition). Additionally, since cover crop growth was shown to remove available soil N, it is possible that treatments with higher biomass may have removed a greater proportion of existing available soil N during growth than the lower-biomass crops, reflected in soil N measurements. The earlier fall planting date may also have stimulated shifts in root composition, quality, and morphology, driving changes in soil N metrics, yet roots were unaccounted for in our analyses. Roots are an N source typically underestimated in cover cropping systems. They have been found to represent 35% to 50% of total plant N (Li et al., 2015), with differences in root morphology impacting soil N dynamics (Jani et al., 2015). Nonliving roots from both legume and nonlegume cover crops can increase net immobilization of soil N, unless aboveground biomass of low C:N ratio material is also incorporated (Li et al., 2020). As below-ground root

Table 6. Marketable yellow fruit per plant, unmarketable fruit per plant, and average weight of marketable yellow fruit results. Data reported by main factor, cover crop treatment, unless planting date or planting date $\times$ cover crop interaction was significant ($P < 0.050$). Cover crop treatments are red clover (RC), pea mix (PM), vetch mix (VM), and no cover crop control (NCC) and planting date treatments are early planted (Early) and late planted (Late).

		Y1			Y2		
		Grand Rapids	Morris	Rosemount	Grand Rapids	Morris	Rosemount
Marketable fruit (kg/plant)							
RC		0.25	0.90	0.83 a ^z	0.20	0.57	0.51
PM		0.12	0.88	0.70 ab	0.17	0.60	0.37
VM		0.27	0.93	0.70 ab	0.25	0.67	0.45
NCC		0.20	0.95	0.53 b	0.20	0.60	0.38
Unmarketable fruit (kg/plant)							
RC	Early	0.03	0.13	0.08	0.03	0.10	0.00 b
	Late						0.07 a
PM	Early	0.02	0.12	0.07	0.07	0.08	0.07 a
	Late						0.07 a
VM	Early	0.03	0.13	0.08	0.10	0.08	0.00 b
	Late						0.07 a
NCC	Early	0.05	0.17	0.03	0.07	0.05	0.03 ab
	Late						0.03 ab
Average marketable pepper weight (kg)							
RC		0.16	0.24	0.17 a	0.13 b	0.18	0.16
PM		0.17	0.23	0.16 ab	0.13 b	0.18	0.15
VM		0.19	0.24	0.16 ab	0.15 a	0.19	0.15
NCC		0.16	0.24	0.15 b	0.13 b	0.19	0.15

^zLetters represent significant differences ($\alpha = 0.05$) between values within a single site-year, mean separation performed using a least significant difference test on square root transformed data. If no letters are reported, there were no differences between treatments.

biomass was not quantified in this study, it is possible that earlier-planted treatments contributed greater root biomass than later-planted treatments, and subsequently modified ExN and MBC, either via root exudation or by direct contributions of root biomass upon termination. Since field plots with incorporated cover crop residues have been shown to reach peak N as late as six weeks following termination (Parr et al., 2014), measurement of N indicators taken even five weeks after incorporation may not be sufficient to capture a complete picture of soil nutrient pool impacts. In our study, two of our three sites in both years, available soil N pools were higher five weeks after cover crop incorporation relative to baseline when cover crops were terminated, with the third site showing no increase likely due to a fertilization event that substantially increased soil N at baseline. Clearly, cover crop high tunnel production requires further exploration to tease apart interactions between biomass quantity and quality, and the downstream effects on soil N.

We found the soil health indicators POXC and EC to be unaffected by the short-term production of cover crops, which was unexpected based on previously published data (Domagała-Swiątkiewicz et al., 2019). Cover crop treatment affected POXC for only one out of 6 site years, at Grand Rapids in Y2 (Fig. 4). It is possible that high soil organic matter at Morris (5.9%) and Rosemount (5.3%) may have buffered any differences from residue additions (Table 1). We found that cover crops did not increase EC relative to the bare control following the 2 years of production. The EC threshold at which salt sensitive plants are affected in silty loam soils using the 1:1 method is 1.4–2.5 dS·cm⁻¹ (Whitney, 1988). Only Morris Y1 soils were slightly saline, all other site-years were nonsaline. Tomatoes and peppers, both of which are high value crops commonly grown in high tunnels, experience salt stress at

2.5 dS·cm⁻¹ and 1.5 dS·cm⁻¹, respectively (Blomgren et al., 2007) and it is recommended that EC be monitored following high tunnel management changes. In this study, cover crops were used as a source of N for 2 years without increasing EC, contrasting other studies that found EC to increase (0.03 dS·m⁻¹) in cover cropped treatments relative to a bare control after 3 years of high tunnel production, though the relatively small observed differences in EC did not impact production (Rudisill et al., 2015).

Although cover crops have occasionally been shown to reduce vegetable yield (Leavitt et al., 2011), we found that the cover crop mixtures and management strategies demonstrated in this experiment did not reduce pepper yield relative to bare fallow. In one instance, red clover treatments in Rosemount Y1 increased marketable yield relative to the bare control, consistent with previous studies of solanaceous crops (Abdul-Baki et al., 1996; Muchanga et al., 2019). Increased weight of marketable fruits is desirable because larger fruits are more likely to meet the highest USDA grade, ‘Fancy’, and can be sold for a higher price (USDA, 2005). High tunnel growers rely on high-quality and quantity yields from high tunnels to mitigate the economic risk of farming (Belasco et al., 2013). In this study, baseline soil tests indicated adequate fertility for pepper production. Compared with a yield goal of 0.7–1.0 kg/plant ($\approx 22,000$ to $25,000$ kg·ha⁻¹) for open field pepper production in Missouri (Trinklein, 2006), some site-years in this study reached this production standard while others did not. Similar pepper production data are not available for Minnesota, a colder climate that is expected to have lower overall productivity than Missouri. One cause for production lower than the Missouri baseline was

removal of actively-producing pepper plants from all sites in mid-September to sow cover crops, an estimated 1–3 weeks before high tunnel production was likely complete. All plants across the study had mature green fruits, immature green fruits, and flowers at plant termination. Mature green fruits can be sold at a lower market value or left to ripen on plants as long as temperatures remain warm in the high tunnel.

Conclusions

This study demonstrated overwintered cover crop production in northern climate high tunnels to be a possible soil management strategy for cool climate producers, although not all soil health indicators were impacted by cover crop treatments after 2 years of study. High tunnels are an increasingly popular and profitable tool for growers (Belasco et al., 2013; Huff, 2015), but are vulnerable to soil health problems due to their unique microclimate and intensive production (Hajime et al., 2009). In this study, red clover, hairy vetch, Austrian winter pea, winter rye, and tillage radish were grown successfully in high tunnel environments in zones 3b–4b, though legume establishment due to competition with nonlegumes (driven by weeds, and rye in the mixes) was a formidable challenge. A notable finding was the extended production range for Austrian winter pea when planted in a protected high tunnel environment, although this species did not fare well in our coldest study zone (3b). An important practical consideration is that pepper production in cover cropped plots was not reduced compared with plots without cover crops.

Despite poor legume performance, we also found evidence of enhanced N cycling in high tunnel soils following incorporation of cover crop biomass. Winter annual cover crop

Fig. 4. Permanganate oxidizable carbon (POXC) values over sampling time plotted by (A) cover crop treatment (main plot factor) and (B) plant date (split plot factor). Error bars represent ± 1 SE

mixtures of legume and nonlegumes in high tunnels delivered up to $200 \text{ kg} \cdot \text{ha}^{-1}$ N in cover crop biomass in addition to increases in both ExN and PMN in the weeks following cover crop termination across all sites and study years. Cover crops reduced ExN during their growth relative to the bare ground control, suggesting N retention ecosystem service provision. The dominant high tunnel fertility management strategy of compost addition (Knewton et al., 2010) presents the potential problem of soil and water body contamination via excess P (Möller et al., 2018) if plastic is removed during high precipitation winter months and spring snow melt. Including cover crops could provide an alternative high tunnel nutrient source, especially if legume productivity can be improved. Employed selectively in multiyear rotations, overwintered cover crops may be a feasible organic alternative to compost and manure to meet N fertility needs and replenish soil organic matter.

Additional challenges related to cash crop and cover crop trade-offs also exist. For example, a relatively long cover crop production period is required for establishment and maturation of overwintered cover crops in northern climates. Season extension benefits may be reduced if crop plants need to be removed before the end of their productive season to establish a winter annual cover crop. Further research is required to quantify these potential trade-offs between cash and

cover crop productivity that may be associated with cover crop production. Interseeding cover crops into standing crop rows remains an option to maximize both pepper production and establish fall cover crops. This study suggests that overwintered cover crops in high tunnels in Minnesota are a promising management tool for growers, but long-term soil health benefits require further study. We suggest that cover crop N contributions could possibly reduce fertilizer N requirements in high tunnel horticultural systems, especially if legume contributions can be increased and N mineralization is timely.

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