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Strip Tillage and Oat Cover Crops Increase Soil Moisture and Influence N Mineralization Patterns in Cabbage

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***Abstract*. Strip tillage (ST) is a form of conservation tillage in which disturbance is limited to the crop rows while the rest of the soil remains undisturbed. Compared with conventional, full-width tillage (CT), ST may reduce tillage costs, protect soil from erosion, and benefit cool-season crops including cabbage (*Brassica oleracea* L. var. 'capitata') by improving water retention, reducing soil temperatures, and improving the synchrony of inorganic nitrogen (IN) supply with crop demand. Field experiments were conducted in 2010 and 2011 in central Michigan to assess the effects of tillage (CT vs. ST) and a preceding cover crop (none vs. oats, *Avena sativa* L. var. 'Ida') on soil temperature, moisture, N dynamics, and yields in transplanted cabbage. Oats were sown in April and terminated 2 to 3 weeks before cabbage transplanting in early July. In-row (IR) soil moisture, temperature, and IN content were assessed from transplanting until cabbage harvest in October. In 2010, IR soil moisture was higher season-long in ST compared with CT and in oat compared with non-oat treatments, but these effects were not detected in 2011. Tillage and oat residue had little or no effect on IR soil temperature. Shortly after tillage in both years, soil IN availability was greater in CT treatments without oats compared with both ST treatments and CT with oats. However, these differences dissipated after 3 to 4 weeks, and hypothesized improvements in N release patterns under ST were not observed. No differences in cabbage marketable yield were detected in either year, although the proportion of plants that produced a marketable head was lower in cover-cropped plots in 2010. These findings suggest that soil conservation and input savings potentially associated with ST production systems may be attained without a yield penalty. More research is needed to understand and optimize cover crop management in ST systems to realize potential benefits in N use efficiency, moisture retention, and soil temperature moderation.**

Although more common in certain agronomic crops, ST is an emerging practice in vegetable production (Hoyt, 1999). A narrow strip (15 to 30 cm depending on equipment and crop) is tilled into otherwise undisturbed soil and a crop is seeded or planted into this strip. Soil between rows (BR) is left undisturbed, which may reduce the potential for erosion and maintain soil quality—advantages that ST provides compared with CT. Strip tillage also offers advantages compared with no-till—it offers a better seedbed for the crop IR and helps to warm and dry soil in the spring, which is important in geographic locations with cool, wet springs like Michigan (Mochizuki et al., 2007). Because of more flexible planting and harvest dates, vegetable fields offer more opportunities to integrate cover crops into rotations. Cover crop residues may help ameliorate some of the negative effects of disturbance IR by adding organic matter; BR, the residue remains as surface mulch, which may help retain soil moisture (Mochizuki et al., 2007; Wilhoit et al., 1990), prevent germination and emergence of weed seeds (Teasdale and Mohler, 1993), and further protect against erosion.

Tillage occurs IR in both ST and CT fields, although interactions with untilled BR areas may influence IR soil temperature, moisture, and IN dynamics in ST. These different growing conditions may result in improved crop growth and yield. For example, strip width influenced in-row soil temperature—with 15-cm wide strips, IR soil temperature was 1 °C cooler at night compared with IR soil temperature with full-width tillage or ST with 30-cm strips (Mochizuki et al., 2007). For warm-season vegetable crops in northern areas, lower soil temperatures associated with reduced tillage systems with cover crop residue can decrease yields or delay maturity. However, for cabbage—a cool-season crop—reductions in soil temperature during the hottest part of the growing season may be beneficial. BR soil temperature is generally lower in ST compared with CT (Licht and Al-Kaisi, 2005; Overstreet and Hoyt, 2008), whereas soil moisture is typically higher in this location (Hoyt and Konsler, 1988).

Differences between IR and BR in ST may be heightened when cover crops are used. Surface mulches tend to hold more soil moisture and further decrease soil temperature (Wagner-Riddle et al., 1997); incorporated residues also help retain more soil moisture. If the BR area can act as a soil moisture reservoir, more moisture may be available to crops grown with ST—indeed, higher yields of transplanted cabbage with ST were attributed to higher moisture availability in a dry year (Wilhoit et al., 1990). Characterization of soil temperature and moisture changes is important for understanding the direct impact of ST on crops as well as the effects of ST on soil biological and chemical processes, which affect crop growth.

Strip tillage and cover crops may also influence crop yields through changes in soil N dynamics. Tillage typically increases N mineralization, resulting in a flush of plant-available N (Calderon et al., 2000). Incorporating a non-legume cover crop like oats tends to decrease mineralization and increase immobilization, making less inorganic N available to the following crop, at least temporarily (Cheshire et al., 1999). Burying oat straw residue through tillage led to faster decomposition than leaving it on the surface, although surface oat straw residue immobilized less N than incorporated residue (Mulvaney et al., 2010). To our knowledge, no studies have examined soil N dynamics in ST vegetable systems, particularly those with cover crops. Tillage studies in agronomic crops have often included ST treatments but have not examined soil N dynamics in IR and BR areas separately (see Sainju and Singh, 2008). For example, combined over IR and BR areas, ST soils from 0 to 15 cm with an overwintering rye cover crop had a net gain in N over three years in a cotton/sorghum rotation, whereas soils with only weed cover and no cover crops over the winter lost N over this period (Sainju and Singh, 2008).

Strip till systems are characterized by distinct zones with different expected rates of N mineralization (Luna et al., 2012). Compared with CT, ST is likely to result in reduced initial N availability in the untilled BR zone as a result of both lower temperatures and lack of aeration from tillage. However, with non-legume cover crops, lack of incorporation in the BR zone of ST may reduce initial N immobilization relative to CT (Cheshire et al., 1999). The net effect of these two mechanisms is difficult to predict. The IR zone is tilled in both ST and CT, so smaller differences in N availability might be expected compared with the BR zone. To add to the complexity, N dynamics of ST may be influenced by movement between BR and IR zones of both biotic factors influencing mineralization rates and of soluble N along soil moisture gradients. Overstreet and Hoyt

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(2008) hypothesized a "radius of influence" in ST systems from IR into BR; they found, for example, that microbial biomass N and carbon were intermediate at the strip edge—higher than BR but lower than IR.

Delayed mineralization of cover crop residues in ST BR areas, combined with movement of soluble N from the BR zone to the IR zone, may result in better synchrony of N supply and crop demand under ST compared with CT when cover crops are used. This effect would be most pronounced where soil moisture content was low in the IR zone relative to the BR zone and where N was largely in the nitrate form. Strip tillage in combination with surface residues may also reduce N losses through leaching and runoff, resulting in greater N availability to the crop (Al-Kaisi and Licht, 2004).

Because of the aforementioned differences in IR growing conditions, yield differences may be expected when crops are produced with ST and cover crops compared with those grown in CT without cover crops. Yields of potato (*Solanum tuberosum* L.) and sweetpotato [*Ipomoea batatas* (L.) Lam] (Hoyt and Monks, 1996), pumpkin in one year (*Cucurbita pepo* L.) (Rapp et al., 2004), and sweet corn (*Zea mays* L.) (Luna and Staben, 2002) produced with ST were similar to, or greater than, yields produced with CT. Yields of transplanted cabbage after a winter rye (*Secale cereale* L.), barley (*Hordeum vulgare* L.), or wheat (*Triticum aesthivum* L.) cover crop were similar between ST and CT (Hoyt et al., 1996; Wilhoit et al., 1990). Cabbage yield and quality, measured as head width and length, core width and length, and overall head appearance, were similar between tillage treatments that included rototilling and different widths of zone tillage, a form of ST (Mochizuki et al., 2007). With CT, cabbage yield was increased after an oat cover crop (Franczuk et al., 2010) but lower after a sorghum–sudangrass (*Sorghum bicolor* × *S. bicolor* var. sudanense) cover crop (Finney et al., 2009).

The primary objectives of this experiment were to evaluate the impacts of ST and oat cover crop residue on soil temperature and moisture, IN content, and cabbage yield. A secondary objective, not reported here, was to evaluate the effects of ST and oat residue on weed suppression before cabbage planting and weed/cabbage competition. We anticipated that, compared with CT, the IR areas in ST plots would have: 1) lower soil temperature and higher soil moisture, particularly where oat cover crop residue was present; 2) improved synchrony of N availability and crop N demand; and hence 3) equivalent or higher cabbage yields.

Materials and Methods

Plot establishment. Field trials were conducted in 2010 and 2011 at the Kellogg Biological Station in Hickory Corners, MI (lat. 42.4058°, long. –85.3845°). Weather conditions during the two years are summarized in Table 1. The fields used in these experiments were in no-till soybeans for at least three years before the onset of these trials. The treatments were: ST with an oat cover crop, ST without a cover crop, CT with an oat cover crop, and CT without a cover crop. These treatments were part of a larger experiment investigating weed population dynamics and competition with cabbage; soil characteristics and yields from weed free subplots within this experiment are presented. Subplots were 3.1 m wide × 4.7 m long in 2010 and 4.3 m long in 2011; each treatment was replicated four times within a randomized complete block design.

Field operations are summarized in Table 2. In 2010, a survey of the field found few emerged weed seedlings, so weeds were not controlled before planting the oats. However, glyphosate was applied before oat planting in 2011 to kill emerged weeds in all plots. The oat cover crop, sown at 93.1 $kg\cdot ha^{-1}$, was planted on 20 Apr. 2010 and 13 Apr. 2011 using a no-till drill (John Deere 750). Fertilizer was applied to all plots as 19–19–19 [42.6 kg each of N, phosphorus (P), and potassium (K)/ha; urea as the N source] on 18 May 2010 and as urea (46.8 kg N/ha) on 19 May 2011. Weeds were controlled in all bare soil plots by either glyphosate application or hand removal; two small areas were left untreated to allow for density and biomass measurements. Weeds were not controlled in cover-cropped plots during oat growth. Density of weeds growing in all plots was measured and identified to species in May and June of both years; cover crop and/or weed biomass was sampled before termination with a glyphosate application on 17 June of both years. Cover crop residue was flail-mowed on 29 June and 24 June in 2010 and 2011, respectively.

Just before tillage, on 1 July 2010 and 30 June 2011, additional fertilizer was applied by hand across the entire experimental area according to soil test recommendations for cabbage (Warncke et al., 2004). A combination of monoammonium phosphate, triple superphosphate, potash, and urea was used in 2010 (81.3 kg N/ha, 100 kg P/ha, and 69.4 kg K/ha) and 19–19–19 (with urea as the N source), potash, and urea was used in 2011 (78.26 kg N/ha, 28.35 kg P/ha, and 112.45 kg K/ha). Tillage was performed immediately after fertilization. In ST treatments, a Hiniker® Model 6000 two-row strip-tiller (equipped with notched trash-cleaning discs, cutting-coulter, shank-point assembly, berming disks, and rolling basket) was used to create 25 cm wide × 25-cm deep strips at 76.2 cm between-strip spacing (center to center). Conventional tillage was accomplished with a 3.1-m wide chisel plow followed by two passes with a field cultivator.

Cabbage (variety Blue Dynasty) transplants were grown to the four- to five-leaf stage in the greenhouse and hardened off before transplanting. On 8 July 2010 and 13 July 2011, transplants were hand-planted into the field with 76.2 cm center-to-center row

Table 1. Weather summary for Apr. to Oct. 2010 and 2011 at the Kellogg Biological Station in Hickory Corners, MI.[z]

	Avg temp (°C)			Total precipitation and irrigation (in parentheses) (mm)			Estimated evapotranspiration (mm)[y]	
	2010	2011	10-yr avg[x]	2010	2011	10-yr avg[x]	2010	2011
April	11.9	7.6	9.4	71	246	73	—	—
May	16.1	15.1	14.4	135	142	112	—	—
June	20.2	20.2	20.1	184	47	85	—	—
July	23.5	24.1	22.1	149	187[w] (18)	94	31	24
August	22.5	20.7	21.0	34 (20)	96	101	87	79
September	16.5	15.6	17.1	67	83	94	74	66
October	11.6	10.5	10.3	48	90	82	25	27
During cabbage growth[v]	19.0	19.1	18.1	295	306	321		

[z] Irrigation provided an additional 20 and 18 mm of water in 2010 and 2011, respectively.

[y] Estimated as potential evapotranspiration multiplied by crop coefficient for cabbage.

[x] 2002–11.

[w] Rainfall in July 2011 was scattered, with 59 mm falling before cabbage planting and 117 mm falling within 3 d (27 to 29 July). Supplemental irrigation added on 15 and 19 July.

[v] While cabbage was in the ground, from 8 July to 29 Oct. 2010, and 13 July to 18 Oct. 2011.

Table 2. Timeline for field operations.

Operation	2010	2011
Soil sampled for nutrient recommendations	20 Apr.	13 Apr.
Glyphosate application	—	13 Apr.
Oat cover crop established—variety Ida	20 Apr.	13 Apr.
Oat and weed biomass measured	17 June	16 June
Cover crop ended with glyphosate	17 June	17 June
Residue flail mowed	29 June	24 June
Fertilizer applied and plots tilled	1 July	30 June
Cabbage transplanted—variety Blue Dynasty	8 July	13 July
Nitrogen sidedress application	12 Aug.	15 Aug.
Midseason growth measured on cabbage	18 Aug.	23 Aug.
Bt application	10 Aug., 17 Sept.	22 Aug.
Cabbage harvested	29 Oct.	18 Oct.

spacing and 38.1 cm in-row spacing between plants. Weed management was accomplished with a combination of flame-weeding and hand-weeding after transplanting, both IR and BR. Sidedressing (45 kg·ha^{-1} N applied as urea) occurred on 15 Aug. 2010 and 12 Aug. 2011. Bt (as Dipel®) was applied as needed for insect management (on 10 Aug. and 17 Sept. 2010 and 22 Aug. 2011) as a 0.25% v:v solution with a sticker/spreader adjuvant.

Data collection. Before oat termination, oat and weed density and biomass were assessed in two 0.25-m^2 quadrats per plot; these were measured in areas that received no weed management in bare soil plots so weeds remained. Aboveground biomass was clipped at the soil surface and dried at 60 °C until a constant biomass was obtained.

After cabbage transplanting, soil samples were collected biweekly to 20-cm depth for gravimetric soil moisture determination and extraction for inorganic N. Samples were drawn from a composite of eight to 10 soil cores from an area within each plot that contained both cabbage and a fixed density of the weed Powell amaranth (*Amaranthus powellii* L.) as part of a larger experiment with multiple objectives. For moisture determination, ≈10 g of wet soil was weighed, dried at 100 °C, and weighed again. Gravimetric water content (GWC) was calculated as follows:

$$\text{GWC} = [(\text{wet soil weight}) - (\text{dry soil weight}) \\ / \text{ dry soil weight}] * 100$$

For inorganic N determination, 10 g of dry soil was extracted in 50 mL of 1M KCl following Gelderman and Beegle (1998); extracts were analyzed for NO_3^- and NH_4^+ at the Michigan State University Soil and Plant Nutrient Laboratory.

Soil temperature was monitored using waterproof HOBO® Temperature/Light Pendant® Data Logger sensors (Onset Computer Corporation, Bourne, MA) placed at a depth of 2.5 cm IR, approximately equidistant from adjacent cabbage plants. One sensor was located in each plot. Sensors logged temperature on an hourly basis. Logging began on 14 July 2010 [Julian day (JD) 195] and immediately after tillage (2 July; JD 183) in 2011. Sensors were removed and replaced on 16 July 2011; data are not shown for 5 d while sensors equilibrated. Mean daily maximum and minimum temperature was determined for each treatment.

Cabbage was hand-harvested in October of each year. After discarding the individuals closest to the plot edges, all heads in the center two rows of the plots were cut and separated into marketable or non-marketable categories based on head diameter (greater than 10 cm was considered marketable). Total fresh weight of all marketable and non-marketable heads was obtained. Plant biomass remaining after head harvest was also collected and weighed. Total yield was expressed on a per-hectare basis.

Data analysis. All data were subjected to normality tests and checked for equality of variances during analysis. Transformations of data were not necessary to meet these assumptions, so all analyses were performed on untransformed data. Because year-by-treatment effects were significant for all dependent variables, data were analyzed separately by year. Early-season weed biomass was analyzed with a one-way analysis of variance (ANOVA) using PROC MIXED in SAS® software (Version 9.2; SAS 9.2, 2002–10) with cover crop as the factor and block as a random effect. Soil moisture, soil temperature, soil N, and yield information were analyzed with a two-way factorial ANOVA using PROC MIXED with tillage and cover crop as fixed effects and block and interactions with block as random effects. When significant interactions were observed ($P < 0.05$) between tillage and cover crop factors, means were separated with a Tukey adjustment. Soil moisture, N, and temperature data were analyzed separately for each date collected.

Results and Discussion

Weather. The two study years had similar average temperatures during cabbage growth (early July through mid–late October), although July was warmer in 2011 and August was warmer in 2010 (Table 1). Although there was 50% more precipitation in 2011 than in 2010, precipitation during cabbage growth was similar in both years. In addition, irrigation applied similar amounts of additional water in both years. Rainfall in July 2011 was episodic with 176 mm (out of 187 mm) falling over the course of 4 d—1 d before cabbage was planted and 3 consecutive days at the end of the month. Monthly irrigation plus rainfall exceeded estimated evapotranspiration in most months with the notable exception of Aug. 2010 and, to a lesser degree, Sept. 2010. During that period, cabbage likely experienced drought stress.

Cover crop and weed density and biomass. Oat biomass was similar in both years of the study with dry biomass averaging 68.2 g/0.25 m^2 (2728 kg·ha^{-1}) in 2010 and 70.3 g/0.25 m^2 (2812 kg·ha^{-1}) in 2011 (Table 3). Weed biomass and density at the time of oat termination was higher in 2010 compared with 2011 regardless of whether oats were present (Table 3). This difference may have been attributable in part to the fact that glyphosate was applied before oat planting in 2011 but not in 2010. In 2010, weed biomass was similar between bare soil and oat plots, although weed density was reduced in the oat plots by 17%. In 2011, weed biomass and density in oat treatments were 13% and 60% of that in bare soil treatments, respectively. Such suppression may be beneficial for minimizing the risk of weeds persisting and reducing yields in subsequent cash crops. Differences in weed density before crop planting are important because weed management tactics are often density independent; they effectively control a certain portion of individuals regardless of the density of those individuals (Gallandt, 2006); a higher initial density would then result in more survivors. Larger weeds may also be better able to survive control tactics like herbicide applications or tillage. If control measures are successful, however, then higher density might be desirable as more seeds are removed from the soil seed bank.

Soil moisture. In 2010, both cover crop and tillage main effects on soil moisture were significant for all but one of the dates examined (Fig. 1A–B). However, in 2011, neither cover crop nor tillage effects were significant (Fig. 1C–D), although the trends and magnitudes were similar to 2010. We had anticipated that surface oat residue present under ST would have a greater effect on soil moisture than incorporated oat residue in CT, but no significant tillage × cover crop interaction was observed for any date in either year. Lack of significant effects in 2011 may have been attributable in part to high variability in soil moisture (Figs. 1C–D), resulting in low statistical power to detect differences. Higher variability in 2011 may have been attributable, in part, to site variability (sloped ground) in this year that was not adequately removed by blocking.

In 2010, IR soil moisture was higher in plots with oat residue compared with those without oats (Fig. 1A). This result is consistent with previous studies. For example, incorporated cut or ground residues of winter rye and winter oilseed rape increased soil moisture compared with soil without cover crops (Kruidhof et al., 2011). Others have reported that surface cover crop residues also increase soil moisture relative to bare soil (Krueger et al., 2011; Teasdale and Mohler, 1993).

In 2010, IR soil moisture was higher in ST plots compared with CT plots (Fig. 1B). The 2010 data suggest that BR areas may be acting as a soil moisture reservoir, contributing to higher IR soil moisture. This is consistent with previous results that have shown higher soil moisture both IR and BR in ST fields (Hoyt and Konsler, 1988). Another possibility is that cabbage in CT plots had greater rates of transpiration than cabbage in

Table 3. Weed and cover crop biomass before termination.^{z}

	Cover crop dry biomass [g/0.25 m^2, avg (SE)]		Weed dry biomass [g/0.25 m^2, avg (SE)]		Weed final density [number/0.25 m^2, avg (SE)]	
	2010	2011	2010	2011	2010	2011
Bare soil	—	—	40.8 (8.9) a	20.6 (3.2) a	400.9 (122.3) a	181.4 (12.5) a
Cover crop	68.2 (9.5)	70.3 (5.2)	27.1 (7.8) a	2.7 (0.7) b	333.9 (104.1) b	108.5 (13.8) b

^{z}Weeds were chemically or physically controlled in bare soil plots, but quadrats were left untreated to allow biomass collection. Biomass was collected from two 0.25-m^2 quadrats per plot. Averages and SEs (in parentheses) are presented. Within each year, means followed by the same letter were not significantly different at α = 0.05.

ST plots as a result of greater biomass accumulation. However, this is unlikely because total aboveground cabbage weight did not vary between ST and CT treatments in 2010 (Table 4).

Soil temperature. IR soil temperature showed different patterns in 2010 and 2011 (Fig. 2), attributable in part to daily differences in ambient temperature (Table 1). Unlike Mochizuki et al. (2007), we did not observe any differences in minimum temperature resulting from tillage or cover crops. Mean daily maximum temperature was unaffected by tillage but was affected by cover crop residue early in the season in both years (Fig. 2). Consistent with expectations, in 2010, lower temperature maxima were observed from JD 195 to 199 (13 to 17 d after tillage) with cover crop residue compared with no cover crop residue. However, in 2011, the opposite was observed—mean maximum soil temperatures were higher after the oat cover crop from JD 185 to 188 (4 to 7 d after tillage). Air temperature was also warmer during this initial period in 2011 (data not shown).

The reasons for differences in oat residue effects on soil temperature in the two years of this study are unclear. Cover crops or crop residues may influence soil temperatures by reflecting or absorbing solar radiation differently than bare soil, by insulating the soil, or by changing the heat capacity of the soil through changes in soil moisture content (Power et al., 1986). In most cases these mechanisms result in cooler soil temperatures where crop residues are present (e.g., Carter and Rennie, 1984; Power et al., 1986). In our study, reductions in soil temperature in oat compared with non-oat treatments in 2010 may be explained in part by greater soil moisture content in those treatments (Fig. 1) because moist soil has higher heat capacity than dry soil. Higher soil temperatures in oat treatments in 2011 are more difficult to explain because no differences in soil moisture were detected between oats and bare soil treatments in 2011.

Soil nitrogen. Because cabbage can use both ammonium and nitrate as an N source (Turan and Sevimli, 2005), total soil IN content is presented as the sum of nitrate, nitrite, and ammonium. Ammonium represented ≈10% to 40% of total IN depending on the date (data not shown). After sidedressing and

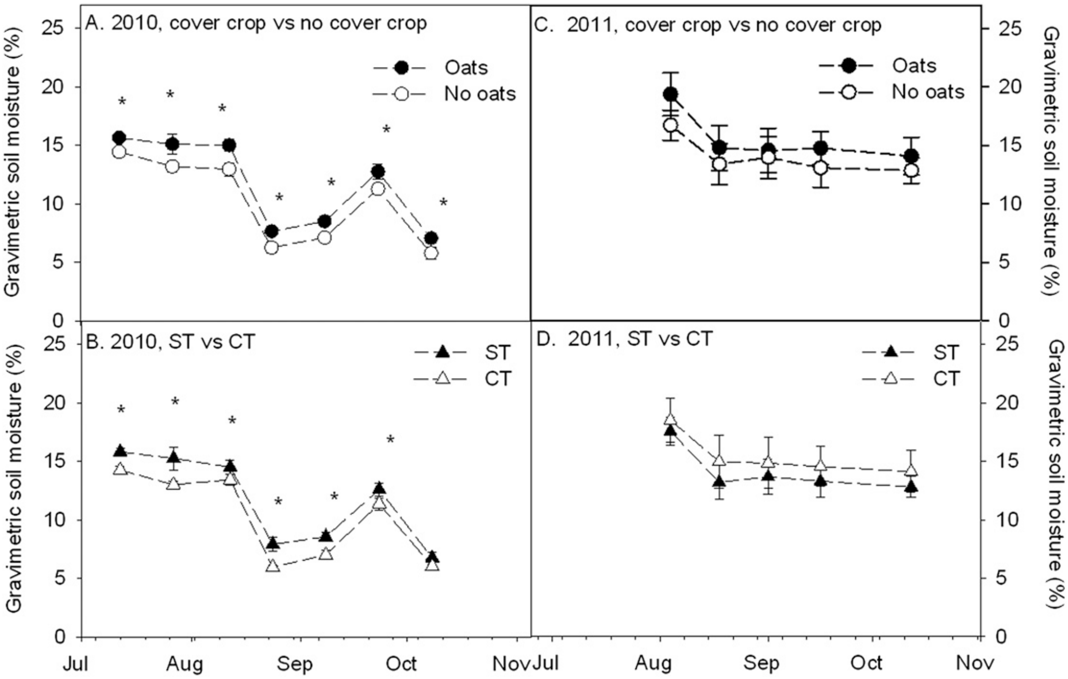

Fig. 1. In-row gravimetric soil moisture in 2010 and 2011. Error bars represent SE. Soil moisture was measured to 20 cm using soil cores. Each date was analyzed separately using a two-way analysis of variance with cover crop and tillage as the main factors. No significant interactions between cover crop and tillage were detected for any date in either year, so main effects of tillage and cover crop are shown. For dates in 2010, significant main effects of cover crop and tillage at $\alpha = 0.05$ are shown with an asterisk (*). In 2011, there were no significant differences at any date.

Table 4. Mean and SE of marketable yield, proportion of plants yielding marketable head, and average fresh plant biomass of cabbage harvested in 2010 and 2011.[z]

	Avg marketable head biomass (kg/head)[y]				Marketable yield (t·ha^{-1})[x]				Proportion of plants yielding marketable head[w]				Avg plant fresh biomass (kg/plant)[v]			
	2010		2011		2010		2011		2010		2011		2010		2011	
Treatment	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
ST oat	1.33	0.04	1.43	0.19	28.27	3.37	44.95	7.53	0.91	0.03	0.94	0.02	1.79	0.06	2.31	0.24
ST none	1.49	0.08	1.36	0.04	36.06	2.82	43.24	2.43	1.00	0.00	0.90	0.07	2.24	0.08	2.19	0.09
CT oat	1.16	0.12	1.32	0.12	25.74	2.27	41.05	7.01	0.95	0.02	0.91	0.09	1.72	0.15	2.12	0.20
CT none	1.09	0.23	1.60	0.04	27.16	5.77	53.20	1.69	1.00	0.00	0.98	0.03	1.79	0.22	2.50	0.06
ANOVA results																
Tillage	NS		NS		NS		NS		NS		NS		NS		NS	
CC	NS		NS		NS		NS		*		NS		NS		NS	
Tillage*CC	NS		NS		NS		NS		NS		NS		NS		NS	

[z] ANOVA results based on $\alpha = 0.05$.

[y] Total fresh weight of marketable heads divided by the number of marketable heads.

[x] Fresh weight of marketable heads per plot area, extrapolated to t·ha^{-1}.

[w] Number of plants producing a marketable head/total number of plants per plot.

[v] Average fresh per plant biomass (head plus vegetative material).

ST = strip tillage; CT = conventional, full-width tillage; ANOVA = analysis of variance; CC = cover crop; NS = non-significant.

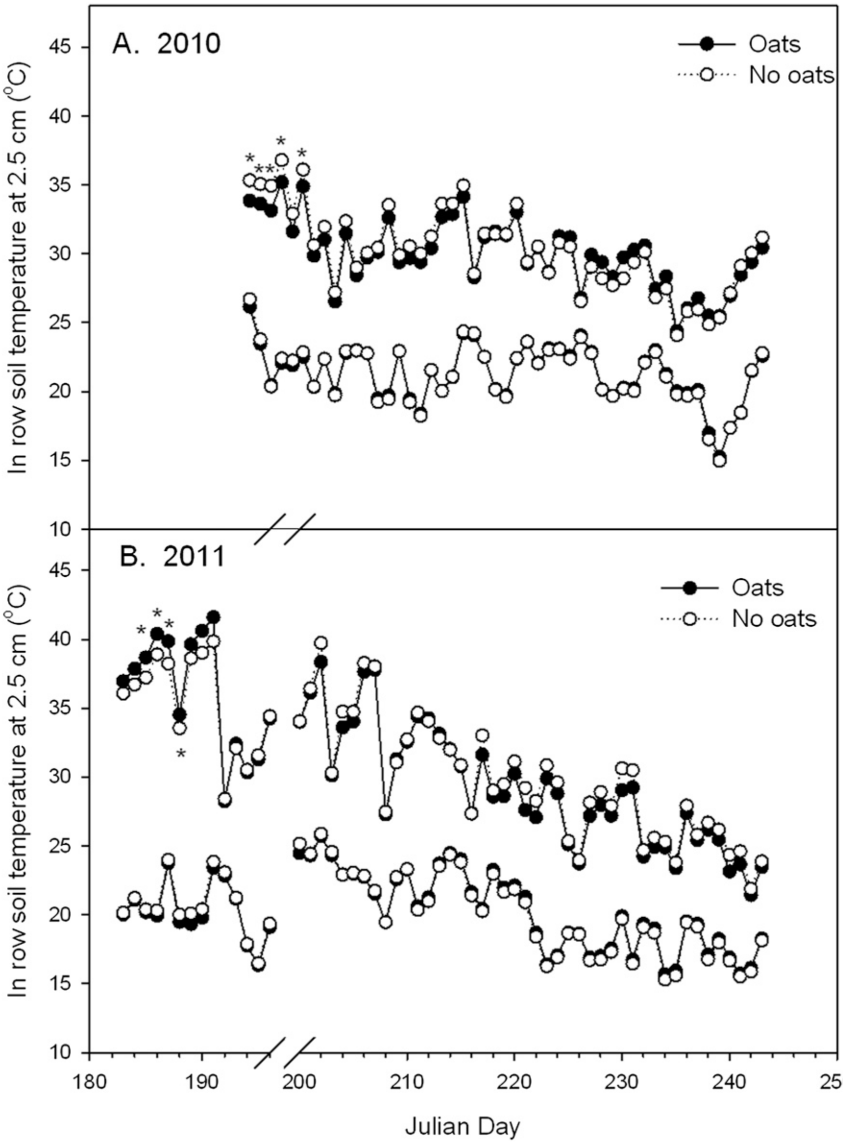

Fig. 2. Average daily maximum and minimum soil temperature at 2.5 cm in °C in 2010 (**A**) and 2011 (**B**). Data collection started on Julian day (JD) 195 (14 July) in 2010. A break is shown in 2011 after data loggers were moved. At dates noted with an asterisk (*), there was a significant cover crop effect at $\alpha = 0.05$ with oat treatments having lower temperature in 2010 and higher temperature in 2011. There were no main effects of tillage and no significant cover crop by tillage interactions in either year so data are shown averaged over tillage levels.

during cooler periods, ammonium represented a higher fraction of total IN.

Shortly after tillage, total IN was either similar in all treatments (2010; Fig. 3A) or higher in the CT treatment without oats than in the remaining treatments (2011; Fig. 3B). At the second sampling date in 2010 (11 Aug.), total IN was higher in CT without oats compared with the remaining treatments (Fig. 3A). Soil IN was similar in all treatments for the remaining dates in 2010 (Fig. 3A). In 2011, however, soil IN at the second sampling date (4 Aug.) was higher in plots without cover crops compared with plots with cover crops and also higher in CT than in ST plots (Fig. 3B). At the third and fourth sampling dates in 2011 (18 Aug. and 2 Sept.), soil N was again highest in the CT treatment without oats, intermediate in both treatments with oats, and lowest in the ST treatment without oats; the ST treatment without oats had significantly less IN than the CT treatment without oats (Fig. 3B). At the fifth sampling date in 2011 (16 Sept.), soil IN was highest in the ST treatment without oats, intermediate in the two CT treatments, and lowest in the ST treatment with oats; this treatment had significantly less N than the ST treatment without oats (Fig. 3B).

It is important to note that in this experiment, N fertilizer was broadcast on the soil surface in all treatments before tillage. Therefore, in ST treatments, this broadcast N was not incorporated BR and may have been more susceptible to losses resulting from volatilization or runoff compared with the incorporated N fertilizer in the BR zone of CT. Currently, many adopters of ST apply N fertilizer at a depth behind the shank during tillage operations. This approach would likely result in more efficient N use in ST than occurred in our trial.

Cover crop residue effects on soil IN differed under CT and ST systems. In CT, oats residue reduced available IN early in the growing season in both years but did not result in significant differences in IN later in the season in 2011 (Fig. 3). This result is consistent with the well-established fact that cover crop residue can tie up N for several weeks after incorporation. In contrast, under ST, the impact of oats residue on IN did not conform to a simple pattern of initial N tie-up followed by release. Under ST, oats had little effect on N availability in 2010 and variable and complex effects on N availability in 2011. Surprisingly, in ST treatments in 2011, oat residue resulted in higher IN on 18 Aug. but lower IN on 16 Sept.; the opposite was anticipated if oat residue initially immobilized N that was subsequently released as it decomposed. This more complex pattern of N availability under ST may be attributable to different rates of mineralization in the distinct IR and BR zones combined with movement of nitrate between zones. It is also possible that differences in IN between the tilled areas of ST and CT were influenced by differing tillage intensity. The CT treatments were worked with a chisel plow and a field cultivator, which resulted in more intensive tillage than the cutting disks, shank, and rolling baskets used to till the IR portion of ST. In addition, the strip tiller was equipped with trash cleaners, which may have moved variable amounts of residue out of the row area.

Cabbage yield. Because of a significant year-by-treatment effect, cabbage yield was analyzed separately by year. Within each year, neither tillage, nor cover crops, nor their interactions were significant (Table 4). However, it should be noted that large variability in yield—particularly in oat treatments in 2011—limited the statistical power to detect yield differences. Variability in cabbage growth in oat treatments may have been the result of greater heterogeneity of soil characteristics resulting from non-uniform distribution of oat residue or greater incidence of pests of cabbage where oats were present. Although these effects were not quantified, damage from imported cabbage worm did occur despite Bt applications (Table 2) and may have been greater in oat treatments.

Yields in 2011 were greater than those in 2010 (Table 4) and may have been attributable in part to lower rainfall in late summer of 2010 compared with 2011 (Table 1). Irrigation during that period was not sufficient to overcome periods of low soil moisture in Aug. 2010 that were not present in 2011 (Fig. 1). However, higher soil moisture observed in the cover-cropped plots and in the ST plots (Fig. 1) during late August and early Sept. 2010 did not result in higher yields. Lower yields in 2010 may also have been attributable in part to lower N availability throughout the growing season in 2010 compared with 2011 (Fig. 3). In 2010, soil IN levels for the entire growing season were under 24 mg

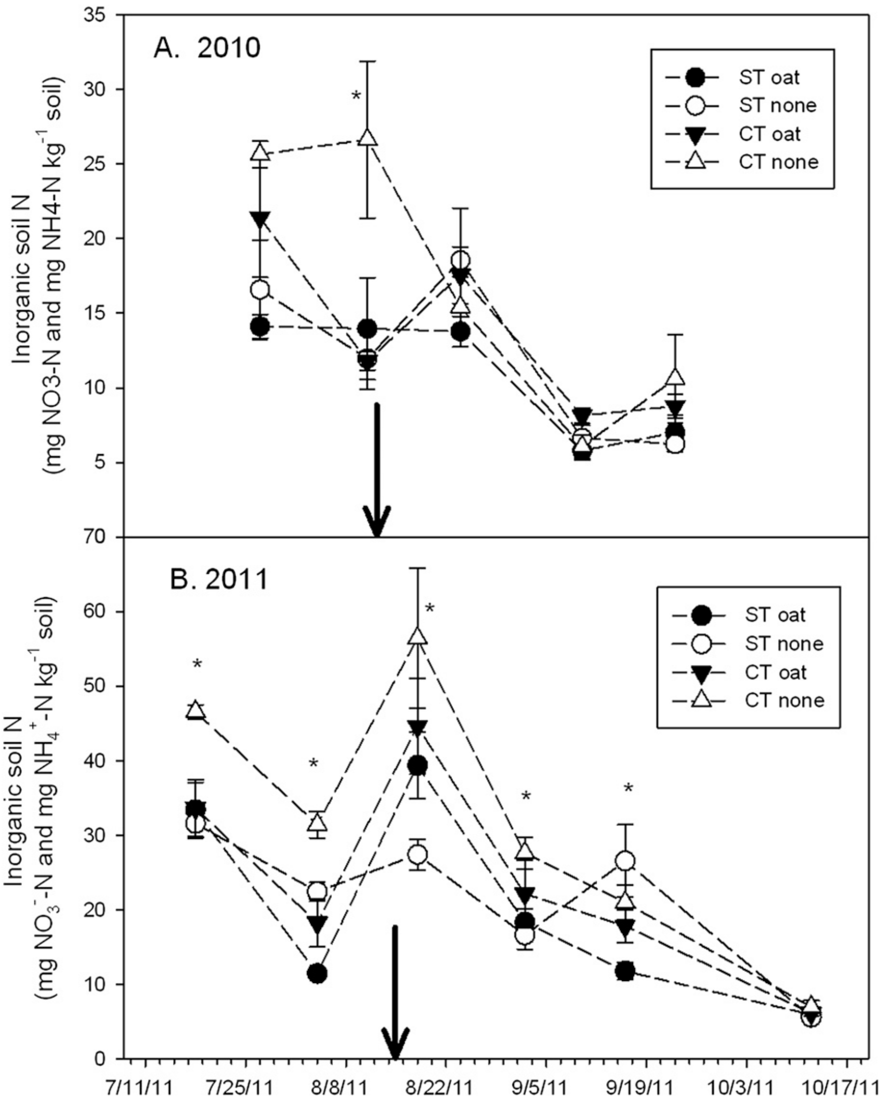

Fig. 3. In-row inorganic soil nitrogen (sum of mg NO_3^--N and mg NH_4^+-N/kg soil) in 2010 (**A**) and 2011 (**B**). Error bars represent SE. Soils were sampled to 20-cm depth and NO_3^- and NH_4^+ were measured using a 1 M KCl extract. Analysis of variance was performed separately for each date. At dates signified with an asterisk (*), there were significant differences in soil inorganic nitrogen (IN) between the treatments at $\alpha = 0.05$; specific differences are discussed in the text. Arrows note when sidedressing occurred.

NO_3^--N and NH_4^+-N/kg soil, the level at which N is considered to be limiting for cabbage growth (Heckman et al., 2002). Again, however, higher yields were not observed in the CT treatment without oats despite initially higher soil IN in this treatment. In 2010, the proportion of plants that produced a marketable head was lower in plots with cover crops compared with plots without cover crops; this effect was not observed in 2011. Average plant fresh biomass also did not differ between treatments in either year.

Conclusion

In 2010, our results corroborated our hypothesis that ST plots would have higher IR soil moisture levels than CT plots and that cover crops would contribute to soil moisture retention. Results in 2011, which were more variable, did not support this hypothesis. Our results also did not support the hypothesis and observation in a previous study (Mochizuki et al., 2007) that ST and cover crops reduce soil temperatures IR. Soil temperature effects were short-lived and contradictory in the two years of the study. Under CT, the effects of cover crops on soil IN conformed to a simple pattern of initial N tie-up. However, under ST, IN patterns were more complex, reflecting the complexity of two distinct zones of mineralization and possible movement of soluble N between these zones. Despite a reduction in the proportion of plants that produced a marketable head in one year, and more variability in yield after a cover crop in the second year, our findings are similar to others (Hoyt et al., 1996; Mochizuki et al., 2007; Wilhoit et al., 1990) that have reported similar yields of cabbage in ST compared with CT. Observed differences in soil moisture, temperature, and N dynamics did not result in changes in crop yield.

Our results suggest that ST is a viable option for cabbage growers in northern climates. Strip till systems have the potential to reduce tillage costs and protect soils from damaging wind and rain events, especially where cover crop residues are present. However, more research is needed to understand and optimize cover crop and N management in these systems to improve crop N use efficiency and minimize losses of N to the environment. Future studies aimed at understanding interactions between adjacent zones, which influence soil temperature, moisture, and N availability, will be useful for designing optimal ST systems for horticultural crops.

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