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Organic no-till and strip-till systems for broccoli and pepper production

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ABSTRACT

Organic farmers rely extensively on tillage to incorporate plant residues, prepare seedbeds, and control weeds. However, tillage may have adverse effects on soil health, and conventional no-till production methods, which rely on herbicide for weed control, are not compatible with organic farming, so research was conducted on organic no-tillage (NT) and strip-tillage (ST), which rely on terminating a cover crop with a roller-crimper. Field research was carried out over two years (2013–14 and 2014–15) to compare two organic, cover crop-based reduced tillage systems (NT and ST) with conventional tillage (CT) in the production of organic bell pepper and broccoli. As nitrogen has been previously suggested as a limiting factor in organic NT systems, split fertilizer application was also included as a treatment to evaluate the impact of timing of nutrient addition on plant N status and yield. A cover crop mixture of cereal rye (*Secale cereal*e L.) and hairy vetch (*Vicia villosa* Roth) was seeded in all plots in the fall and either tilled in (CT) or terminated with a roller-crimper (NT and ST) in the spring before planting. Data were collected on vegetable crop growth, yield, crop quality, cover crop biomass, weed suppression, soil temperature and moisture, leachate nitrate concentration, and soil health as indicated by soil microbial biomass and microbial diversity.

For both crops, the effect of NT and ST on yield varied from year to year. Broccoli yield was reduced under NT and ST in 2014, but was not different from CT in 2015. Pepper yield, on the other hand, was similar among treatments in 2014, but reduced by NT and ST in 2015. While soils under ST had higher soil temperatures compared to NT, there were no differences between ST and NT in yield or crop N status for either crop in either year. Preplant and split fertility treatments produced similar marketable yields of broccoli in both years and for pepper in 2015, but preplant fertility increased marketable pepper yield in 2014. Costs of production varied minimally across treatments, so the highest yielding treatments had best economic performance. Nitrate concentration in leachate was lower under NT and ST compared to CT at three sampling dates in July 2014, but few differences were observed in subsequent samples. While there was a trend toward greater soil microbial biomass and diversity in NT and ST compared to CT plots in 2015, few significant soil health benefits were observed for NT and ST. Soil microbial biomass and diversity were both consistently higher in surface soil (0–7.5 cm) than the deeper soil (7.5–15 cm), but this occurred independently of treatments. While NT and ST did not consistently perform as well as CT, we found sufficient evidence of the potential for high yield and ecological benefits to warrant further study and fine-tuning of reduced tillage organic systems.

CHAPTER 1. GENERAL INTRODUCTION AND THESIS ORGANIZATION

Tillage is an important tool used by vegetable growers for soil preparation and weed control. Primary tillage loosens the soil, incorporates crop residues, and enhances soil warming in the spring (Johnson and Lowery, 1985), while secondary tillage is used to form a seedbed to provide good contact between the soil and the seed or transplant roots. After crop establishment, many organic farmers rely heavily on mechanical cultivation—or shallow tillage of the soil after the crop has been planted—to control weeds since synthetic herbicides are not available for use under organic standards. While tillage clearly has many functions in vegetable production, it has also been shown to have adverse effects on soil and environmental health. It can break down soil aggregates, decrease soil organic matter in surface soil, facilitate soil erosion (Magdoff and van Es, 2009; Moebius-Clune et al., 2008); and reduce water-holding capacity (Zibilske and Bradford, 2007). Thus, systems that reduce the intensity and frequency of tillage use in organic systems would be desirable.

Reduced tillage systems, such as strip tillage (ST) and no tillage (NT), have only recently been tried in organic production. However, an "organic no-till" system was developed in the 1990s by researchers at the Rodale Institute and other institutions. They found that cereal rye (*Secale cereal* L.) at the anthesis growth stage could be killed without tillage or herbicide by crushing the rye using a heavy roller. This allowed the possibility of growing a weed-suppressive mulch *in situ* using a high-biomass cover crop such as cereal rye, which spurred the development of a specialized implement called a roller-crimper (Fig. 1.1). While other nonchemical methods of terminating cover crops without tillage exist (mowing, roll-chopping, and undercutting [for raised beds]), there are benefits of using a roller-crimper instead of a flail mower: faster operation, reduced energy usage, improved summer weed suppression, and uni-directional stem orientation, which facilitates unobstructed operation of no-till planting equipment running parallel to the stems (Creamer and Dabney, 2002; Smith et al., 2011; Wayman et al., 2014).

A rolled cereal rye or cereal rye/hairy vetch (*Vicia villosa* Roth) cover crop mixture of sufficient biomass can effectively suppress emergence of most annual grass and broadleaf weeds (Silva, 2014; Smith et al., 2011). However, surface mulches generally fail to control perennial weeds (Mirsky et al., 2011), so tillage is typically used before seeding the cover crop to control perennial weeds. Because this system has distinct tillage management periods—conventional tillage (CT) before cover crop establishment, but NT from planting through harvest—it has been termed "organic *rotational* no-till" (Mirsky et al., 2012; Mirsky et al., 2013). This term can also be used to describe several years of organic NT followed by a year of CT production. While periodic use of tillage is assumed for long-term implementation of organic reduced tillage systems, the terms "no tillage" and "strip tillage" will be used to describe the system employed during the growing season.

Prior studies have found variability in the effects of organic NT systems on vegetable crop yields. Some researchers reported yields similar to or exceeding those of CT (Creamer et al., 1996; Delate et al., 2008; Delate et al., 2012; Lounsbury and Weil, 2014; Vollmer et al., 2010), but others observed yield reduction when using NT (Delate et al., 2003; Díaz-Pérez et al., 2008; Leavitt et al., 2011). Risk due to this inconsistency—combined with the need for specialized equipment and different management strategies—has slowed grower adoption of these systems. Reduced nitrogen (N) availability and soil temperature under NT are two factors thought to adversely affect crop productivity compared with CT (Delate et al., 2003; Griffith et al., 1988; Leavitt et al., 2011). However, in ameliorating these constraints, there is an unavoidable tradeoff with soil health: increasing soil temperature and aeration using tillage hastens mineralization of N from soil organic matter (MacDonald et al., 1995), thus supplying plants with available N at the potential cost of soil organic matter loss.

We hypothesized that ST, which integrates a tilled in-row (IR) region with an untilled, mulched between-row (BR) region, would be effective in improving crop growth and yield without sacrificing the soil health benefits of NT. Use of ST has been shown to create a similar degree of IR soil warming (Licht and Al-Kaisi, 2005) and comparable tomato yields (Thomas et al., 2001), compared to CT. Central questions in this research were whether ST would be effective in raising soil temperature and improving plant N status compared with NT, and whether these changes would translate to higher crop yields. To our knowledge, no previous studies have compared cover crop-based NT, ST, and CT in an organic vegetable system.

In addition to testing ST as a method of increasing N availability, split application of organic fertilizer was evaluated as a means of providing N to the crop during the period of N immobilization that can last for 6–8 weeks after rolling a cereal rye cover crop (Wells et al., 2013). Composted or dehydrated poultry manure is commonly used as a fertilizer in organic agriculture for both preplant and sidedress application. However, the rolled cover crop residue in NT and ST systems physically obstructs the incorporation of sidedress fertilizer with tillage, creating a challenge in supplementing the crop with fertilizer during the growing season. An alternative is liquid fish fertilizer, which, although more expensive per unit of N, can be applied through drip irrigation (fertigation), allowing for application of water-soluble N directly to the crop roots at times of peak N demand and low soil N availability. Fertility treatments in this study included *only preplant* fertilization (poultry manure) and *split* fertilizer application (poultry manure + liquid fish), both of which contained the same amount of total N. Data were also collected on an unfertilized subplot to measure for an overall fertilizer effect in the event that no differences were found between the two fertilized treatments.

Field studies were carried out in 2013–14 and 2014–15 to evaluate effects of NT, ST, and CT, along with split fertilizer application, on growth and yield of bell pepper (*Capsicum annuum* L.) and broccoli (*Brassica oleracea* L. var. *italica*). These crops were chosen because one is a warm-season (pepper) and the other a cool-season (broccoli) vegetable; they represent important vegetable crop families (Solanaceae and Brassicaceae); and they are among the top 12 most consumed vegetables in the U.S. (PBH Foundation, 2015). Soil and environmental health data (microbial biomass and diversity, leachate nitrate concentration) were collected only in the pepper study because its longer growing season allowed for a longer duration of sampling. We assumed that these environmental data would not be substantially affected by the cash crop being grown in the plot, and thus results could be applied to the tillage system more broadly, rather than to a specific crop. Chapters 2 and 3 cover the results of the broccoli and bell pepper studies, respectively. Finally, Chapter 4 provides overall conclusions drawn from the results of both studies, along with suggestions for future research.

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Fig. 1.1. A roller-crimper mounted on a front-end loader rolling a cereal rye cover crop.

CHAPTER 2. ORGANIC NO TILLAGE AND STRIP TILLAGE EFFECTS ON PLANT PERFORMANCE, WEED SUPPRESSION, AND ECONOMICS IN BROCCOLI PRODUCTION

Modified from a paper submitted to *HortScience*

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Abstract

Organic no-till and strip-till systems have gained attention because of their capacity to enhance soil health and suppress annual weeds. This study, conducted at the Horticulture Research Station, Ames, IA, over two years (2013–14 and 2014–15) compared no tillage (NT), strip tillage (ST), and conventional tillage (CT) in organic broccoli (*Brassica oleracea* L. *var. italica*) production, with data collected on broccoli yield and quality, plant health, weed suppression, soil temperature, and costs of production. A cover crop mixture of cereal rye (*Secale cereal*e L.) and hairy vetch (*Vicia villosa* Roth.) was seeded in all plots in September, and was either rolled-crimped (NT and ST) or tilled in (CT) in late spring the following year. Each whole plot tillage treatment was split into two subplot fertility treatments—one based entirely on preplant granular fertilizer, and the other split between preplant granular fertilizer and

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post-planting fertigation—to test the effect of fertigation on yield and plant growth under the typically N-limited reduced tillage conditions. In 2014, yield of broccoli was highest in CT treatments, averaging 5.4 $t \cdot ha^{-1}$, with no difference between ST and NT treatments. In 2015, yields were equal among tillage treatments, averaging 20.0 $t \cdot ha^{-1}$. Changing the timing of fertilizer application through use of fertigation did not affect yield. Weed density and biomass were lowest in the between-row regions of NT and ST plots in 2014, indicating effective early-season weed suppression. In 2015, NT and ST plots generally had lower weed biomass and density compared to CT plots, but weed growth in between-row and in-row regions of NT and ST plots was similar. Soil temperature was highest in CT plots throughout the year, and higher in ST than in NT plots only during some time periods. While production costs did vary slightly across treatments, profit per acre was most strongly affected by yield. Our findings suggest that organic NT and ST systems may be viable options for organic broccoli growers.

Introduction

Researchers have increasingly been investigating cover crop-based reduced tillage systems, such as no-till (NT) and strip-till (ST), as methods for mitigating some of the adverse effects of conventional tillage (CT). In these systems, cover crops are grown prior to cash crop establishment, and are terminated without incorporating residue into the soil, thus leaving a surface mulch into which the subsequent cash crop can be planted. While much of this research has been conducted on agronomic crops, such as corn and soybeans, researchers have also studied the application of reduced tillage in vegetable production systems. Many of those studies utilized herbicide for cover crop termination and supplemental weed control (Abdul-Baki et al., 1996; Brainard and Noyes, 2012; Haramoto and Brainard, 2012; Peachey et al., 2004). Organic producers, however, typically terminate cover crops mechanically—using a tool such as a roller-crimper or flail mower—and have few options for chemical control of weeds that come up through the cover crop mulch. There has been considerable variability in vegetable crop yield under reduced tillage in prior organic research. Some studies found that NT treatments yielded equal to or higher than CT in production of tomatoes (Creamer et al., 1996; Delate et al., 2012), bell pepper (Delate et al., 2008), spinach (Lounsbury and Weil, 2014), and onion (Vollmer et al., 2010), while others found that NT treatments yielded poorly (Díaz-Pérez et al., 2008; Leavitt et al., 2011). Schellenberg et al. (2009) found that a NT system using flail mowed warm-season legume cover crops [lablab (*Dolichos lablab* L.), soybean (*Glycine max* L.), sunn hemp (*Crotalaria juncea* L.), and a mixture of sunn hemp and cowpea (*Vigna sinensis* Endl.] had similar yields for spring broccoli, but reduced yields for fall broccoli, compared with CT. To make NT and ST systems viable options for growers, it is crucial to identify yield-limiting factors and develop strategies to mitigate them.

Two main factors that could limit yield in organic NT production of vegetables in northern regions include reduced nitrogen availability and low soil temperature. Nitrogen (N) is often a limiting factor in rolled cover crop systems (Wells et al., 2013) and in organic systems (Berry et al., 2002), where plant-available N is typically derived from mineralization of particulate organic matter, legume-fixed N, and supplemental purchased fertilizers (Gaskell and Smith, 2007). In a study using agronomic crop residue, Aulakh et al. (1991) showed that non-incorporated residue is mineralized more slowly than incorporated residue, and residue with a high carbon-to-nitrogen (C:N) ratio causes a greater rate of N immobilization. Cereal rye (*Secale* *cereale* L.), a cover crop commonly used in conjunction with no tillage, has a high C:N ratio at the time of termination and is left on the surface, suggesting likelihood for reducing nitrogen availability in these systems. An additional challenge in organic NT systems is the difficulty of side dressing granular fertilizers with typical equipment, because fertilizer cannot be effectively incorporated into the soil without disturbing the cover crop mulch. Use of fertigation may be one strategy to provide inorganic N to the crop in otherwise N-limited conditions.

Lower soil temperature, caused by the insulative effects and high albedo of surface residue (Baker et al., 2007), may also contribute to reduced yields in cover crop-based NT systems. Soil temperature has been shown to be lower in NT than in CT (Johnson and Lowery, 1985; Nyborg and Malhi, 1989), and in mulched as compared with bare ground systems (Creamer et al., 1996; Mochizuki et al., 2008). The heavy residue left on the soil surface in cover crop-based NT systems is thus likely to reduce soil temperature.

Strip tillage, in which tillage is confined to the planting row and untilled cover crop residue protects soil between rows, may minimize the negative effects of tillage while promoting N mineralization and soil warming. As compared with NT, ST may produce higher in-row soil temperature (Licht and Al-Kaisi, 2005) and may increase in-row N availability because the cover crop in that region is incorporated rather than left on the soil surface. As compared with CT, ST conserves soil moisture (Licht and Al-Kaisi, 2005) and retains many of the soil health benefits of NT in the between-row region. We hypothesized that ST may be more effective than NT for use in the Upper Midwest. To our knowledge, no studies have compared NT, ST, and CT side-by-side in an organic vegetable production system.

This study compared field production of organic broccoli under NT, ST, and CT management using either preplant application or split application of fertilizer using fertigation. Our objectives were to determine the effects of tillage system and split fertilizer application on crop yield, plant health, and weed biomass, and in particular, to evaluate ST as a tool for increasing soil temperature and improving N availability to the crop compared to NT.

Materials and methods

Site description

The experiment was conducted at the Iowa State University Horticulture Research Station in Ames, IA, in 2013–14 and 2014–15. The soils at the 2013–14 site were moderately well drained Clarion and somewhat poorly drained Nicollet loams (fine-loamy, mixed, superactive, mesic Typic Hapludolls). This land was first-year transitional organic and previous crops were oilseed radish (*Raphanus sativus* L.), yellow mustard (*Sinapis alba* L.), and cereal rye, followed by three months' bare fallow before seeding cover crops in Fall 2013. The soil at the 2014–15 site was a well-drained Lester loam (fine-loamy, mixed, superactive, mesic Mollic Hapludalf), and the previous crop was organically managed alfalfa (*Medicago sativa* L.).

Experimental design

The experimental design was a split-plot randomized complete block design with four replications. The whole-plot treatments were conventional tillage (CT), strip tillage (ST), or no tillage (NT). The subplot fertility treatments were preplant fertilizer only, split fertilizer application, or a no-fertilizer control. Whole plot dimensions were 4.6 m × 10.7 m, and each subplot consisted of a single 10.7 m row. Each whole plot contained five rows, with outer rows treated as guard rows. Rows were spaced 0.8 m apart and plants were spaced 0.3 m apart within rows.

Field management and vegetable culture

Dates of field operations and major data collection events can be found in Table 1. Before cover crop establishment, soil was tilled with a Terra Force GM102 rotary tiller (Terra Force, Inc., Carrollton, TX) and compressed by using a modified Brillion cultimulcher (Landoll Corporation, Marysville, KS) to provide a firm seedbed for cover crop establishment. All treatments were planted to a mixture of cereal rye 'Wheeler' and hairy vetch (*Vicia villosa* Roth, VNS in 2013–14 and 'Purple Bounty' in 2014–15). The cover crop was established on 10 Sept. 2013 and 8 Sept. 2014 at 3.8 cm depth using a no-till grain drill (Tye Pasture Pleaser, AGCO, Duluth, GA) with 0.3 m row spacing. The cereal rye was seeded at a rate of 112.1 $kg \cdot ha^{-1}$ and hairy vetch was seeded at a rate of 28 $kg \cdot ha^{-1}$. Seeds of hairy vetch were inoculated with *Rhizobium leguminosarum biovar viceae* (INTX Microbials LLC, Kentland, IN).

Strips that were 0.3 m wide were tilled in ST plots on 14 Nov. 2013 and 12 Oct. 2014 using a Hiniker 6000 strip tiller (Hiniker Co., Mankato, MN). The fall strip tillage operation was carried out at an earlier date in 2014 than in 2015 due to cover crop growth in 2013 impeding proper functioning of the strip tiller. The lower amount of cover crop biomass in 2014 was more completely incorporated by the strip tiller. Components of the strip tiller included a coulter, a subsurface shank, two concave discs, and a rolling basket. To increase down pressure of the discs for effective incorporation of the cover crop, the arms that allow the discs to float were fixed to the frame with U-bolts.

Cover crop termination date depended on the tillage treatment. In CT plots, the cover crop was mowed on 7 May 2014 and 13 May 2015, about 4 weeks prior to broccoli planting, using a Rhino flail mower (Alamo Group Inc., Seguin, TX) and incorporated with a rotary tiller. This early termination date allowed for decomposition of cover crop residue and was based on common practice on organic vegetable farms. The entire plot was tilled to create a seedbed just before planting, on 11 June 2014 and 5 June 2015.

The cover crop was terminated in NT and ST plots on 3 June 2014 and 1 June 2015 using a 3.2 m roller-crimper (I & J Manufacturing, Gap, PA) when cereal rye was at anthesis and the hairy vetch was in full bloom with a few young seedpods. Seedbeds were made in NT and ST plots on 11 June 2014 and 4 June 2015 after terminating the cover crop with the roller crimper. In 2014, NT plots were prepared by loosening a band of soil using the Hiniker strip tiller with the discs and rolling basket disengaged. The shank was more aggressive than we had anticipated, leaving a tilled band of 10-15 cm in most areas. In 2015, the NT plots were prepared using a custom implement consisting of a fluted coulter followed by a minimum-disturbance fertilizer knife and disc sealers to close the furrow created by the knife. This implement resulted in a tilled band of a more desirable 5.1–7.6 cm in width. In ST plots in both years, the previously tilled strips were tilled again with the strip tiller just before planting.

The fertilizer applied for each fertilized treatment contained 168 kg total N/acre. For the preplant fertility treatment, the entire amount of N was surface applied on 11 June 2014 and 4 June 2015 using dehydrated poultry manure crumbles [Chick Magic® (4.0N–1.3P–1.7K); S&R Egg Farm, Palmyra, WI] and incorporated during seedbed preparation. In 2014, poultry manure fertilizer was applied with a fertilizer hopper (MaterMacc, San Vito al Tagliamento, Italy) mounted on the Hiniker strip tiller and delivered via a tube on the backside of the shank at a depth of 10.1 cm. In 2015, fertilizer was hand-applied and incorporated with a hoe due to malfunction of the fertilizer hopper during a narrow window of dry weather in which the fertilizer had to be applied. In the split fertility treatment, two-thirds of the N was applied using the poultry manure fertilizer as in the preplant fertility plots, and the remaining one-third was from liquid fish fertilizer applied via fertigation. The fish fertilizer used in 2015 [Organic Liquid Grow (5.0N–0.4P–1.7K); Peaceful Valley Farm & Garden Supply, Grass Valley, CA] was different than the product used in 2014 [Phytamin Fish Gold® (5.0N–0.4P–1.7K); California Organic Fertilizers Inc., Hanford, CA] because Phytamin® was unavailable in 2015. The split fertility subplots were fertigated four times, beginning 4 July 2014 and 2 July 2015 and repeated at 7–14 d intervals, with frequency depending on rainfall. The liquid fertilizer was injected into the drip irrigation system using a Dosmatic SuperDos 20 fertilizer injector (Hydro Systems Co., Cincinnati, OH). Fertigated subplots were connected to a drip header separate from preplant only and no-fertilizer subplots in order to prevent contamination of non-fertigated treatments. The guard rows were not fertilized.

Untreated broccoli seeds (*Brassica oleracea* L. var. *italica* ‘Gypsy’; Johnny’s Selected Seeds, Winslow, ME) were sown on 5 May 2014 and 28 Apr. 2015 into an organic potting medium (Mix #11; Beautiful Land Products, West Branch, IA) in 128-cell plug trays and grown for four weeks in a greenhouse before being moved outdoors to harden off. Transplants were established on 13 June 2014 with a Holland 1500 transplanter (Holland Transplanter Co., Holland, MI) and on 9 June 2015 by hand. Hand transplanting was used in 2015 because the transplanter caused excessive disturbance to cover crop mulch in 2014 and was deemed unsuitable for use in high residue, reduced tillage conditions. The crop was irrigated as needed to achieve 1 inch of water per week. When split fertility subplots were fertigated, preplant only and no-fertilizer subplots were also irrigated to maintain parity of water supply among treatments.

Crops were scouted weekly for signs of insect pests and disease. Major insect pests were cabbage looper (*Trichoplusia ni* Hübner), imported cabbageworm (*Pieris rapae* L.), and large white caterpillars (*Pieris brassicae* L.) in both 2014 and 2015, and cabbage aphid (*Brevicoryne brassicae* L.) in 2015 only. *Bacillus thuringiensis* subsp. *kurstaki*, strain ABTS-351 (DiPel PRO DF, Valent U.S.A. Corp., Walnut Creek, CA) was applied on 3 and 29 July 2014 at a rate of 0.74 $L \cdot ha^{-1}$ as a control for lepidopteran pests. Insecticidal soap (Safer Brand, Woodstream Corp., Lititz, PA) was applied on 8 Aug. 2014 at a rate of 9.4 $L \cdot ha^{-1}$ for control of aphids. Disease symptomatic plants were submitted to the Plant and Insect Diagnostic Clinic at Iowa State University in 2014 and were found to be infected with fusarium yellows, a disease caused by the fungal pathogen *Fusarium oxysporum* f. sp. *conglutinans*.

Data collection

Aboveground cover crop biomass was determined by sampling two 50 × 50 cm-quadrats from each whole plot immediately before termination and oven-drying at 67 °C until constant weight. Weeds were sampled on 2 July 2014 and 8 July 2015, before the first weeding event, from two 25 × 25 cm quadrats from both the in-row and between-row regions of each whole plot. Weeds from each sample were counted and dried at 67 °C until constant weight before weighing. All rows were weeded on 16 and 24 July 2014 and 14 July 2015 using a combination of hoeing and hand weeding.

Mature broccoli heads were harvested twice weekly from 11 Aug. to 12 Sept. 2014 (total of 9 harvests) and 28 July to 3 Sept. 2015 (total of 10 harvests). Mature heads were harvested by cutting stems to achieve a total length of 17 cm. Broccoli heads were then graded according to marketability (USDA, 2006) and weight and number of heads were recorded. Average diameter of broccoli heads was determined by measuring five marketable heads per subplot at each harvest. Dry weight was measured by harvesting two whole representative plants from each subplot and drying them at 67 °C in a forced air oven until the plants reached a constant weight. Plants were sampled in the middle of the harvest period, and the head was included for the dry-weight measurement.

After the final fertigation application, on 8 Aug 2014 and 26 July 2015, five plants from the middle of each subplot row were selected for measurement of leaf chlorophyll, plant height, stem diameter, and N concentration of leaf tissue. Leaf chlorophyll, which has been shown to correlate with N content of leaves (Wood et al., 1992), was measured using a SPAD-502 Plus chlorophyll meter (Konica Minolta Sensing America Inc., Ramsey, NJ). For each of five plants, four readings were taken on the most recently developed, fully expanded leaf and averaged. Plant height was determined by measuring the distance from the soil at the base of the plant to the tip of the highest leaf. Stem diameter was measured 2 cm above soil using digital calipers. Leaf-petiole samples were taken for N concentration determination according to method described by Jones and Case (1990).

Hobo temperature sensors (Onset Computer Corp., Bourne, MA) were installed at a depth of 15.2 cm below the soil surface between plants within one of the data rows in each whole plot. Temperature was logged at 1-hour intervals from the week of transplant until after the final harvest. In addition, rainfall and air temperature were measured at a nearby weather station associated with the Iowa State University Soil Moisture Network.

Economic analysis

Enterprise budgets were created for each tillage × fertility combination to determine the profitability of each production system based on the method of Chase (2011). The economic analysis accounted for fixed and variable production costs, marketable crop yield, and selling price of $0.36 per 100 g, the average price for broccoli in the USDA National Fruit and Vegetable Organic Summary (USDA-AMS, 2015). Labor hours for weeding and harvest were recorded during field plot maintenance, and machinery costs were estimated using calculations described by Edwards (2015). Gross revenue was calculated by multiplying the marketable yield by the selling price of organic broccoli. Profit was calculated by subtracting fixed and variable costs of production from the gross revenue.

Data analysis

Analysis of variance (ANOVA) was conducted using the GLIMMIX procedure in SAS (version 9.3; SAS Institute, Cary, NC) to determine the effect of tillage and fertility treatments on yield, head diameter, leaf N concentration, leaf chlorophyll, plant height, stem diameter, cover crop and vegetable plant dry weight, soil temperature, and weed density and biomass. Block was treated as a random factor in all analyses. Data were log-transformed and square root-transformed as necessary to satisfy the homogeneity of variance and normality assumptions of ANOVA. Means on the log scale were considered medians on the original scale. With the exception of weed biomass and density analysis, means and medians were separated according to Fisher's protected least significant difference (LSD) test ($P \leq 0.05$) using the "lsmeans" statement with Satterthwaite option. Because our hypothesis was that the degree of weed suppression by tillage treatments would depend on region (in-row vs. between-row), an unprotected LSD test was used for weed density and biomass to allow for analysis of the tillage × region interaction despite a nonsignificant F test p-value.

Results

Weather

Figure 1 shows monthly rainfall and average monthly air temperature in 2014 and 2015 compared with 30-year averages. Monthly rainfall in 2014 was 2.3 and 2.1 inches below average in May and July, but 18.8 cm and 5.3 cm above average in June and August, respectively. The June rainfall was concentrated in the second half of the month, causing a three-week period of consistently saturated soil conditions starting soon after transplanting. Monthly rainfall in 2015 was 9.9 and 9.4 cm above average in June and August, respectively. Air temperature in 2014 was similar to the 30-year average through most of the season, but was 4 °C higher than average during July. Air temperature in 2015 was 1-2 °C below average from May to August, but was 5 °C above average in September.

Cover crop performance

As expected, cover crop biomass in NT and ST plots was greater than in CT plots due to the delayed termination date in those treatments (Table 2). In 2014, cover crop biomass in NT and ST plots was similar, with over twice the biomass compared with CT plots. Across all treatments, cover crop biomass in 2015 was lower than in 2014, and differences between NT, ST and CT treatments were also reduced. Carbon-to-nitrogen ratio of cover crop residue was highest for NT and ST treatments in both years.

Yield

Marketable broccoli yield was reduced under NT and ST management in 2014, but was unaffected by tillage treatment in 2015 (Table 3). In 2014, marketable yield in CT was 31% and 46% greater than in ST and NT plots, respectively. Fertilizer had a strong effect on yield, with unfertilized treatments producing an average of 85% less than the two fertilized treatments. This reduction in yield was a result of heads maturing at a small, unmarketable size, with many plants failing to produce a head. Total yield followed the same trend as marketable yield. Average head diameter was equal among tillage treatments, and an average of 1.8 cm greater for preplant and split fertility treatments than for the no-fertilizer treatment. Marketable and total yields of all treatments were substantially higher in 2015, with no difference among tillage treatments. Preplant and split fertility treatments produced equal yields, which were 40% higher than yields from no-fertilizer plots. As in 2014, head diameter was equal among tillage treatments, but greater by 1.8 cm for fertilized treatments than the no-fertilizer treatment. There were no significant interactions for yield or head diameter in either year.

Plant growth

Leaf N and SPAD. Leaf nitrogen (N) status was determined the week after the final fertigation application, eight weeks after transplanting, by analyzing dried and ground leaf-petiole samples and through estimation of leaf chlorophyll using a SPAD meter. There was no difference in leaf N or SPAD among tillage treatments in either year (Table 4). In 2014, leaf N was similar among fertility treatments, but SPAD reading of plants in fertilized plots was an average of 7.1 points higher than of plants in unfertilized plots. In 2015, both leaf N and SPAD readings were higher for fertilized than unfertilized treatments. There was a strong correlation (Pearson’s r = 0.971, *P*

< 0.0001) between leaf N and SPAD in 2014, and a weak correlation (Pearson's r = 0.374, P = 0.0247) in 2015.

Plant height. In 2014, height of broccoli plants was 6.9 and 11 cm greater in CT than in ST and NT plots, respectively (Table 4). Plant height in preplant and split fertility plots was equal, but an average of 14.7 cm greater than in no-fertilizer plots. A tillage × fertility interaction (P = 0.0003) occurred for plant height, whereby there was no difference between CT and NT when using preplant fertilization. In 2015, plant height was equal across tillage treatments, but an average of 8.1 cm less for no-fertilizer than for preplant or split fertility treatments.

Stem diameter. In 2014, stem diameter of broccoli plants was greater in CT than in NT plots, but neither was different from that in ST plots. There was no difference in stem diameter among tillage treatments in 2015 (Table 4). In both years, stem diameter was equal for preplant and split fertility treatments, but stem diameter averaged 5.3 and 3.7 mm greater than the no-fertilizer treatment in 2014 and 2015, respectively.

Plant biomass. There was no effect of tillage on broccoli plant dry weight in either year, but fertilization had a strong effect in both years (Table 4). In 2014, plants in preplant fertility plots weighed 18% and 42% more than those in split and no-fertilizer plots, respectively. In 2015, plant dry weight for preplant and split fertility treatments was equal, but was reduced by 24% in the no-fertilizer treatment. A tillage × fertility interaction (P = 0.016) occurred for plant dry weight, whereby the no-fertilizer treatment had greater dry weight than split fertility treatment in CT plots, but lower dry weight in NT and ST plots.

Soil temperature

Conventional tillage generally increased soil temperature throughout the season, which was divided into three seasons—denoted “early,” “mid,” and “late”—for analysis (Table 5). During the early season in both years, CT increased average daily minimum, mean, and maximum soil temperatures by 1.3 to 6.9 °C, as compared with ST and NT. There was no difference in early season temperature between ST and NT except in 2015 when ST had 1.1 and 2.0 °C higher mean and maximum temperatures, respectively. During midseason, CT increased average daily minimum, mean, and maximum soil temperatures by 1.0 °C to 4.2 °C, as compared to ST or NT, except minimum temperature in 2015, when there was no difference among treatments. Compared with NT, ST increased midseason minimum temperature by 1.0 °C in 2014, but was not different from NT in midseason mean or maximum temperature in either year. During the late season in both years, there was no effect of tillage treatment on average daily minimum temperature, but CT increased mean and maximum temperatures by 0.4 °C to 4.2 °C, as compared to ST or NT.

Weed suppression

Weed populations were sampled 3-4 weeks after broccoli was transplanted and before the first weed control event. The primary weed species present in the 2014 field site were common purslane (*Portulaca oleracea* L.), redroot pigweed (*Amaranthus retroflexus* L.), and yellow foxtail (*Setaria pumila* Poir.). The dominant weed species in the 2015 site were witchgrass (*Panicum capillare* L.), red clover (*Trifolium pratense* L.), and white clover (*Trifolium repens* L.). In 2014, the cover crop mulch provided effective weed suppression in NT and ST plots. Weed biomass and density were highest in IR and BR regions of CT plots and the IR region of

ST plots. The BR region of NT and ST plots had negligible weed growth. In 2015, weed biomass and density were highest in the BR region of CT plots and lowest in BR region of ST plots. However, weed biomass and density were similar in IR regions of ST and CT plots and both regions of NT plots.

Economics

Treatments with the highest profits were CT using preplant fertilization in 2014 and CT using split fertilization in 2015 (Table 7), although profit from the ST-Preplant treatment was only 2.3% lower than the CT-Split treatment in 2015. In both years, there were some differences in costs of production among treatments. In both years, pre-harvest labor costs were lowest for the NT treatment due to reduced weeding labor, and input costs were higher for split than preplant fertility treatments because the fish fertilizer cost per unit of N was greater than the dehydrated poultry manure. Total costs varied among treatments by a maximum of $730 in 2014 and $922 in 2015. Given that costs were similar among tillage treatments, differences in profit can be largely attributed to differences in yield.

Discussion and conclusions

Use of cover crops is already standard practice on most organic vegetable farms, but few organic growers in the Upper Midwest have experimented with reducing tillage. Our results suggest that NT or ST might be a viable option for production of broccoli. Tillage treatment affected measures of plant N status, but these differences did not always correspond with yield. Other factors, such as fertilizer and weed management, may also affect crop productivity in reduced tillage systems. Our data show that use of fertilizers that are low in inorganic N, such as dehydrated poultry manure, may be most effective if applied at the full rate before planting, and also that adequate control of annual weeds can be achieved with heavy cover crop residue. However, weed growth within the crop row may be substantial and difficult to control in a rolled cover crop system.

There was a large disparity in yield between years, with higher yields for all treatments in 2015. Two factors may explain why this occurred. First, whereas the preceding crop in 2014 was non-leguminous cover crops followed by three-month fallow, the preceding crop in the 2015 site was alfalfa, which likely increased nitrogen availability to the broccoli plants. Second, the occurrence of fusarium yellows disease in 2014 stunted plant growth and likely reduced yield. Since the broccoli was planted relatively late to accommodate the maturation date of the cover crops for roller-crimper termination, the plants experienced high temperatures known increase the severity of disease caused by *Fusarium oxysporum* f. sp. *Conglutinansi* (Bosland et al., 1988). While there was no difference among tillage treatments in 2015, yield of broccoli was lower in NT and ST than in CT plots during the 2014 growing season. We suspect that the effect of tillage on broccoli yield in 2014 may have been confounded by the occurrence of fusarium yellows. At the time of onset of disease symptoms in early July, plants in CT plots were larger and darker in color than plants in NT and ST plots. This early vigor of plants in CT plots may have caused differences among treatments in susceptibility to plant disease.

Nitrogen availability has previously been suggested as a limiting factor in cover crop-based reduced tillage systems (Leavitt et al., 2011; Wells et al., 2013). Leaf chlorophyll, as measured by the SPAD meter, was not correlated with marketable yield in 2014, but was in 2015 (Pearson's r = 0.501, P = 0.0019). Yield, SPAD reading, and leaf N concentration were all lower in unfertilized plots than in preplant and split fertility plots each year, reflecting a strong correlation between N and crop yield. In contrast, despite a yield reduction in NT and ST treatments in 2014, N status was similar among tillage treatments in both years. The lack of a positive relationship between yield and N status may be explained by leaf N concentrations from all tillage and fertility treatments being in the optimal ranges for broccoli of 3.0–4.5 $g \cdot kg^{-1}$ N (Hartz and Hochmuth, 1996). This would indicate that N may not have been limiting for NT and ST treatments in this study. However, because leaf N measurements were taken at only one point in time (7–8 weeks after planting), it is possible that plants in NT and ST treatments experienced N deficiency early in the 2014 season (Schellenberg et al., 2009).

Despite measures of plant N status indicating that plants in all treatments received sufficient N, crop yield was affected by the fertility treatment (Table 4). We hypothesized that splitting the fertilizer application between a preplant application of dehydrated poultry manure and successive applications of fish emulsion through drip irrigation would be most effective in supplying plant-available N during the period of rapid vegetative growth following transplanting. Both fish fertilizers used in this study contained 5% total nitrogen with 4.1–4.25% water soluble N, so we expected that use of fertigation in the split fertility treatment would increase yields. However, there was no difference in yield between preplant and split fertility treatments in either year.

In order to achieve equal total N in each fertilized treatment, split treatments had to be fertilized with a lower preplant rate of dehydrated poultry manure, the difference being made up through fertigation beginning three weeks after planting. Hadas et al. (1983) found that pelleted poultry manure incorporated into soil and incubated at 25 °C released 42% of organic N through mineralization after one week. Mineralization of N from poultry manure increased to only 50% after 60–90 d. Because the preplant fertility treatment received 168.1 $kg \cdot ha^{-1}$ of poultry manure, compared with 112.1 kg·ha^{-1} for the split fertility treatment, those plots may have received the equivalent of 23.5 kg·ha^{-1} more N than the split fertility plots during the first month of growth. The subsequent application of water-soluble N to split fertility plots via fertigation during weeks 3–7 after planting did not lead to higher yields than in preplant fertility plots. Applying granular fertilizer a single time before planting is simpler than making repeated applications of fish fertilizer using a fertilizer injector, making the preplant only system more desirable from a management standpoint. Furthermore, it is less expensive than fish fertilizer per unit of N, as reflected in our economic analysis, so we recommend use of poultry manure as the sole N source for broccoli production using rolled cover crop mulch.

Cover crop biomass in NT and ST plots exceeded that in observed in CT plots due to the later cover crop termination date in NT and ST systems. Weed suppression by the cover crop mulch was effective due to the large amount of biomass produced. Cover crop biomass exceeded the 8,000 kg·ha^{-1} level identified by Teasdale and Mohler (2000) as the minimum biomass necessary to inhibit emergence of annual weeds. Two factors that may have favored high biomass production in our study are the soil type and seeding date. The relatively high-organic-matter soil at the experimental sites (2.3% to 3.5% in 2014 and 2.7% to 4.1% in 2015, data not shown) likely provided sufficient nutrients to the cover crop despite lack of supplemental fertilization. In fact, cover crop biomass was not increased in the second season when the preceding crop was alfalfa. In a field experiment in Pennsylvania, Mirsky et al. (2013) found that cereal rye biomass ranged from 1,615 to 12,600 kg·ha^{-1} when seeded in 10-d intervals from late Aug. to mid-Oct. The early September seeding date used in the present experiment likely played a role in increasing biomass. Ryan et al. (2011) determined that increasing cereal rye seeding rate did not increase biomass, but did improve weed control by the subsequently rolled cover crop.

They suggested that the improvement in weed control achieved by increasing the rye seeding rate up to 209.6 kg·ha^{-1} was likely a result of increased early spring ground cover. The seeding rate used in the present study (112.1 kg·ha^{-1}) was higher than is typically recommended for cereal rye in a green manure system, but lower than the rates that were found to maximize ground cover in early spring. Given a fertile soil and an early seeding date, a moderate seeding rate of 112.1 kg·ha^{-1} appears to be sufficient to achieve good annual weed suppression in a rolled cover crop system.

Unlike annual weeds, perennial weeds, which were present in the 2015 site, were not suppressed effectively by the cover crop mulch, as indicated by the lack of a difference in weed biomass between IR and BR regions of NT and ST plots in 2015. The combination of larger, perennial weeds and a delayed sampling date (six days later in 2015) also explains the greater weed biomass across all treatments in 2015. However, with sufficient cover crop biomass and a field with minimal perennial weed populations, the principal weed management challenge in organically managed, cover crop-based reduced tillage systems is the control of in-row weeds. In NT systems, in-row weed pressure may be low if the crop can be planted with minimal disturbance to the cover crop mulch. However, few commercially available no-till transplanters exist in the U.S., so most growers may need to use a two-pass system—like the one used in the present study—to transplant through a rolled cover crop mulch. This narrow tillage pass with a shank to loosen soil ahead of transplanting may inevitably disturb a wider band of soil than is desired for minimization of weed seed germination, yet this disturbance may be necessary for proper functioning of a conventional transplanter. Use of a mechanical transplanter equipped with a coulter and shank mounted ahead of the planting unit, or a roller-crimper with with a shank mounted behind it, as described by Ciaccia et al., 2015, may allow for establishment of vegetable transplants with minimal disturbance to the mulch, thus maximizing the suppressive effect of the rolled cover crop.

The findings of this study contribute to the growing body of research that shows the potential for reduced tillage systems to produce yields equivalent to CT. However, the yield reduction observed in 2014 prevents us from drawing strong conclusions about the consistency of high yields under NT and ST. We have shown that despite increasing soil temperature, ST may not increase yield over that of NT. Furthermore, the additional field operations required to till the strips and the potential for increased weed pressure as a result of exposed IR soil are significant drawbacks to use of ST in organic systems.

Cover crop-based reduced tillage is an area worthy of further exploration by researchers. There is mounting evidence that NT and ST using winter annual cover crops can be successful in production of certain crops, but trials should be expanded to evaluate potential application to a broader diversity of vegetable crops. Such data would be of great value to the rapidly growing population of diversified vegetable farmers. Furthermore, organic NT research has focused heavily on cereal rye, which must be terminated at anthesis (Ashford and Reeves, 2003), thus restricting application to cash crops that should be planted early in the summer season. Cereal rye anthesis typically occurs in late-May to early-June in the Upper Midwest, may be outside of the normal planting dates for early spring- or late summer-planted successions of many cool-season vegetable crops. In order to increase adoption, future research should evaluate spring- and summer-planted cover crops that mature and can be terminated mechanically at different times of the year.

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Table 2.1. Schedule of major field operations and data collection events for the organic broccoli experiment, Ames, IA, 2014 and 2015.

	Date	
Event	2013–14	2014–15
Seeded cover crop	10 Sept. 2013	8 Sept.2014
Broccoli seeded in greenhouse	5 May	28 Apr.
Tilled strips[z]	14 Nov., 11 June	12 Oct., 4 June
Cover crop biomass samples taken	7 May[y], 3 June[x]	13 May[y], 1 June[x]
Cover crop flail mowed and tilled in[y]	7 May	13 May
Cover crop roller-crimped[x]	3 June	1 June
Preplant fertilizer applied	11 June	5 June
Seedbed made using rotary tiller[y]	11 June	5 June
Broccoli plugs transplanted	13 June	9 June
Weed biomass samples taken	2 July	8 July
Fertigation applications[w]	4, 17, & 26 July, 8 Aug.	2, 9, 14, & 21 July
All plots hand weeded	16 & 24 July	14 July
Plant height, stem diameter, SPAD measurements taken; leaf-petiole samples collected	8 Aug.	26 July
Harvest period	11 Aug.–12 Sept.	28 July–3 Sept.

[z]Applies to strip tillage treatment only.
[y]Applies to conventional tillage treatment only.
[x]Applies to strip tillage and no tillage treatments only.
[w]Applies to Split fertility treatment only.

Table 2.2. Aboveground biomass ($Mg \cdot ha^{-1}$) and carbon-to-nitrogen (C:N) ratio of cereal rye-hairy vetch cover crop at termination[z], Ames, IA, 2014 and 2015.

	2014		2015	
Treatment[y]	Biomass	C:N ratio	Biomass	C:N ratio
CT	6.2 b[w]	23:1 b	6.2 b	25:1 b
ST	13.0 a	42:1 a	9.3 a	31:1 a
NT	11.6 a	43:1 a	7.0 b	34:1 a
Significance	***	***	**	*

[z]Dates of termination: conventional tillage = 7 May 2014 and 13 May 2015; no tillage and strip tillage = 3 June 2014 and 1 June 2015.
[y]CT = Conventional tillage; ST = Strip tillage; NT = No tillage.
[x]Biomass data were log-transformed for homogeneity of variance and normality before analysis and back transformed for presentation.
[w]Means and medians within the same column followed by the same letter are not significantly different according to Fisher’s protected LSD ($P \leq 0.05$).
*, **, ***Significant at $P \leq 0.05$, 0.01, or 0.001, respectively, based on F test.

Table 2.3. Marketable and total broccoli yield and average marketable broccoli head diameter as affected by tillage and fertility treatments, Ames, IA, 2014 and 2015.

	2014			2015		
Treatment[z]	Marketable yield ($Mg \cdot ha^{-1}$)	Total yield ($Mg \cdot ha^{-1}$)	Head diam (cm)	Marketable yield ($Mg \cdot ha^{-1}$)	Total yield ($Mg \cdot ha^{-1}$)	Head diam (cm)
Tillage (T)						
CT	5.9 a[y]	7.1 a	8.6	20.6	21.3	11.3
ST	3.2 b	4.1 b	7.7	19.0	21.5	10.7
NT	4.1 b	3.9 b	8.5	20.4	19.8	11.1
Significance	***	**	NS	NS	NS	NS
Fertility (F)						
Preplant	6.4 a	7.2 a	9.1 a	22.6 a	23.5 a	11.7 a
Split	5.8 a	6.8 a	8.6 a	22.5 a	23.2 a	11.5 a
No fert	0.9 b	2.3 b	7.1 b	14.9 b	15.9 b	9.8 b
Significance	***	***	*	***	***	***
T × F	NS	NS	NS	NS	NS	NS

[z]CT= Conventional tillage; ST=Strip tillage; NT=No tillage; Preplant = only preplant fertilizer; Split = 2/3 of N from preplant fertilizer and 1/3 from fertigation; No fert = unfertilized control.

[y]Means in a column within the same column and treatment followed by the same letter are not significantly different according to Fisher's protected LSD ($P \leq 0.05$).

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, based on F test.

Table 2.4. Leaf nitrogen, SPAD readings, plant height, stem diameter, and dry weight of broccoli plants as affected by tillage and fertility treatments, Ames, IA, 2014 and 2015[z].

Treatment[y]	2014 Leaf N[x] (%)	2014 SPAD	2014 Plant height (cm)	2014 Stem diam[w] (mm)	2014 Plant dry weight[v] (g)	2015 Leaf N (%)	2015 SPAD	2015 Plant height (cm)	2015 Stem diam (mm)	2015 Plant dry weight (g)
Tillage										
CT	4.3[u]	70.9	48.1 a	16.9 a	195.3	3.9	75.0	63.7	20.5	226.5
ST	4.2	70.8	41.2 b	15.2 b	175.1	3.8	74.3	59.5	18.2	258.4
NT	4.1	67.5	37.1 b	14.2 b	156.2	3.7	74.0	57.7	19.9	255.1
Significance	NS	NS	*	**	NS	NS	NS	NS	NS	NS
Fertility										
Preplant	4.4	73.4 a	47.2 a	17.6 a	219.3 a	4.1 a	75.4 a	63.4 a	21.3 a	288.3 a
Split	4.2	70.8 a	46.8 a	16.8 a	180.4 b	3.9 a	75.1 a	62.6 a	20.2 a	247.7 a
No fert	4.0	65.0 b	32.3 b	11.9 b	126.9 c	3.4 b	72.7 b	54.9 b	17.1 b	203.9 b
Significance	NS	***	***	***	***	**	**	***	*	**
T × F	NS	NS	***	NS	*	NS	NS	NS	NS	NS

[z]Measurements were taken on 8 Aug. 2014 and 26 July 2015, after the final fertigation event.
[y]CT= Conventional tillage; ST=Strip tillage; NT=No tillage; Preplant = only preplant fertilizer; Split = 2/3 of N from preplant fertilizer and 1/3 from fertigation; No fert = unfertilized control.
[x]Percent nitrogen of dried and ground leaf-petioles. Samples were comprised of 20 broccoli leaves.
[w]Diameter of stem measured 2 cm above soil level.
[v]Dry weight of two whole plants.
[u]Means in a column within the same column and treatment followed by the same letter are not statistically different according to Fisher's protected LSD ($P \leq 0.05$).
NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, based on F test.

Table 2.5. Effects of no tillage, strip tillage, and conventional tillage on average minimum, mean, and maximum soil temperature (°C) at 6-inch depth during early[z], mid[y], and late[x] seasons of broccoli production, Ames, IA, 2014 and 2015.

	Minimum			Mean			Maximum		
Treatment[w]	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
				2014					
CT	20.2 a[v]	20.4 a	19.6	22.3 a	22.6 a	21.7 a	24.8 a	24.9 a	24.3 a
ST	19.4 b	19.8 b	19.6	20.9 b	21.2 b	20.9 b	22.7 b	22.7 b	22.4 b
NT	19.1 b	19.3 c	19.2	20.7 b	20.8 b	20.6 b	22.5 b	22.6 b	22.3 b
Significance	***	***	NS	***	**	*	***	*	***
				2015					
CT	20.6 a	22.3	19.9	23.0 a	23.8 a	22.0 a	25.9 a	25.6 a	24.7 a
ST	19.5 b	21.8	19.7	21.2 b	22.9 b	21.2 b	23.2 b	24.1 b	22.9 b
NT	19.3 b	21.8	19.6	20.6 c	22.8 b	20.9 b	22.1 c	23.9 b	22.3 b
Significance	**	NS	NS	***	**	***	***	**	**

[z]Early season: 14 June–14 July 2014; 17 June–12 July 2015.

[y]Midseason: 15 July–13 Aug. 2014; 13 July–6 Aug. 2015.

[x]Late season: 14 Aug.–15 Sept. 2014; 7 Aug.–2 Sept. 2015.

[w]CT= Conventional tillage; ST=Strip tillage; NT=No tillage.

[v]Means within column and year followed by the same letter are not significantly different according to Fisher's protected LSD ($P \leq 0.05$).

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, based on F test.

Table 2.6. In-row and between-row weed biomass (g·m^2) and density (weeds·m^2) as affected by three tillage treatments, Ames, IA, 2014[z] and 2015.

Tillage[y]	Region[x]	2014 Biomass	2014 Density	2015 Biomass	2015 Density
CT	BR	1.1 ab[w]	129.9 a	24.4 a	113.6 a
	IR	1.8 a	171.5 a	4.3 b	57.4 ab
ST	BR	0.3 c	1.3 b	0.6 c	4.5 c
	IR	1.0 ab	124.2 a	1.2 bc	29.8 bc
NT	BR	0.0 c	0.0 b	2.0 bc	29.8 bc
	IR	0.5 bc	53.9 ab	2.4 bc	36.9 bc

[z]Weeds were sampled on 2 July 2014 and 8 July 2015.
[y]CT= Conventional tillage; ST=Strip tillage; NT=No tillage;
[x]IR=In-row; BR=Between- row.
[w]Means within a column and treatment followed by the same letter are not significantly different according to the unprotected LSD ($P \leq 0.05$).
NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, based on F test.

Table 2.7. Enterprise budgets for organically produced broccoli in 2014 and 2015 as affected by tillage and fertility treatment (US$$\cdot$$ha^{-1})

	2014						2015					
	Preplant[z]			Split			Preplant			Split		
	CT[y]	ST	NT	CT	ST	NT	CT	ST	NT	CT	ST	NT
Broccoli yield (t$\cdot$ha^{-1})	7.3	4.4	6.8	7.3	4.6	4.6	19.6	22.5	21.3	23.3	21.4	19.1
Gross revenue	26,807	16,088	24,948	26,812	16,822	16,809	72,135	82,859	78,344	85,794	78,571	70,441
Interest expense	531	492	521	591	556	541	781	830	781	907	867	803
Seed and inputs[x]	3,156	3,156	3,156	4,141	4,141	4,141	3,207	3,207	3,207	4,196	4,196	4,196
Preharvest labor[w]	2,140	2,338	2,115	2,140	2,338	2,115	2,619	2,560	2,115	2,619	2,560	2,115
Harvest[v]	3,573	2,713	3,425	3,573	2,773	2,773	7,196	8,051	7,690	8,288	7,707	7,060
Ownership costs[u]	1,883	1,826	1,821	1,883	1,826	1,821	1,883	1,826	1,821	1,883	1,826	1,821
Total costs	11,280	10,524	11,036	12,328	11,634	11,392	15,686	16,475	15,612	17,890	17,154	15,993
Profit	15,527	5,564	13,912	14,483	5,188	5,418	56,449	66,384	62,732	67,904	61,417	54,448

[z]Preplant = only preplant fertilizer; Split = 2/3 of N from preplant fertilizer and 1/3 from fertigation.
[y]CT = Conventional tillage; ST = Strip tillage; NT = No tillage.
[x]Broccoli and cover crop seed, potting mix, fertilizer, drip tape, and insecticide.
[w]Labor for seeding flats, setting up irrigation, spraying insecticide, and handweeding. Based on a $12/hour wage ($10/hour wage plus payroll taxes).
[v]Cost of waxed boxes and labor for harvest, washing, and packing. Labor based on a wage of $12/hour.
[u]Fixed costs of machinery, greenhouse, and irrigation equipment, and land rent at 618\cdot$ha^{-1}/acre [based on the average 2015 rental rate in Iowa of 608\cdot$ha^{-1}/acre (Plastina et al., 2015)].

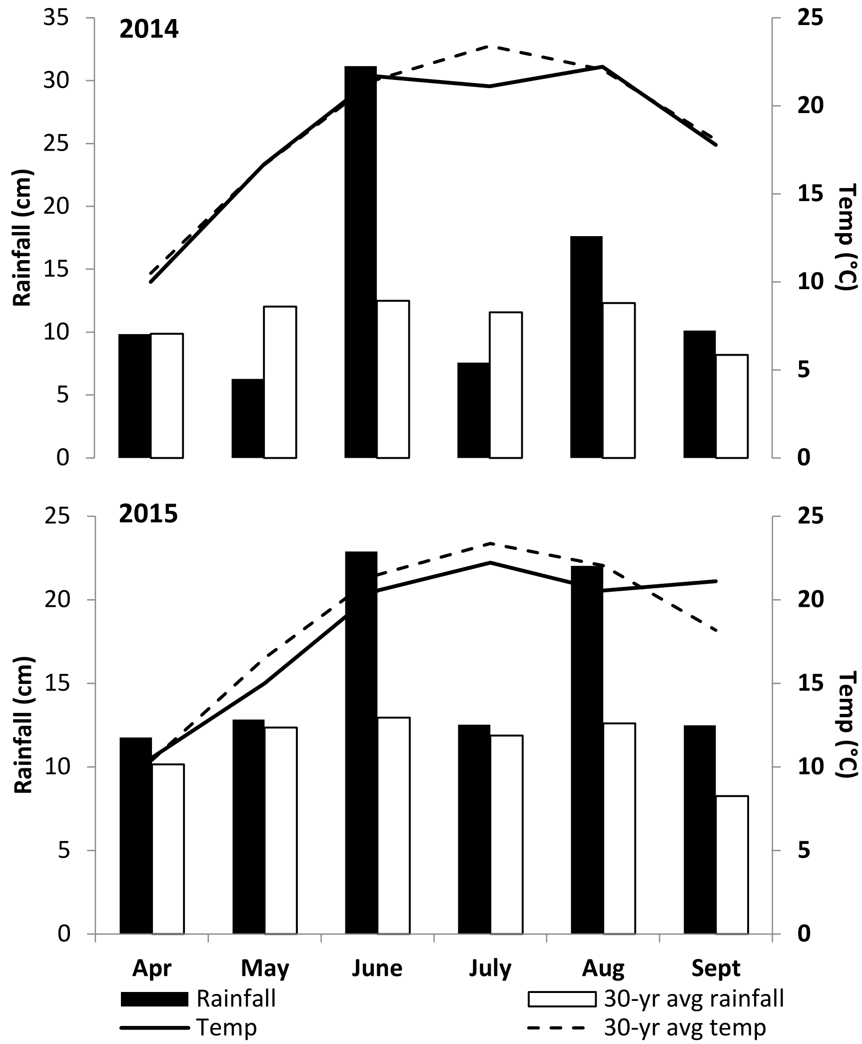

Fig. 2.1. Monthly rainfall and mean air temperature in 2014 and 2015 in Ames, IA compared with the 30-year average. Weather data were obtained from the Iowa State University Soil Moisture Network.

CHAPTER 3. EFFECTS OF REDUCED TILLAGE ON PLANT GROWTH, YIELD, AND SOIL HEALTH IN ORGANIC BELL PEPPER PRODUCTION

Modified from a paper submitted to *Soil and Tillage Research*

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Abstract

Concerns over soil erosion and nitrate leaching have generated interest in cover crop-based reduced tillage systems. A 2-year field study was conducted in Ames, IA in 2013–14 and 2014–15 to compare cover crop-based no tillage (NT) and strip tillage (ST) with conventional tillage (CT) in production of organic bell pepper (*Capsicum annuum* L.*)*. Two fertility treatments—preplant fertilizer only, or application split between preplant and post-planting fertigation—which applied the same amount of total N (90 kg ha^{-1}), were also evaluated. The experimental design was a split plot randomized complete block design with tillage as the whole plot (NT, ST, or CT) and fertility as the subplot treatment (preplant or split). A mixture of cereal rye and hairy vetch was seeded in September in all plots. The cover crop was terminated in mid-May using tillage in CT plots and in early June using a roller-crimper in NT and ST plots. Data were collected on plant growth, yield, soil temperature and moisture, weed suppression, nitrate leaching, and microbial biomass and diversity. Marketable yields were equal among tillage treatments in 2014, but higher for CT in 2015,

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with no difference between NT and ST in either year. Preplant fertility increased yield in 2014, but yields were lower in the preplant fertility treatment in 2015. Leaf N concentration was higher in CT than NT and ST, but plant height, stem diameter, and dry weight were similar across all treatments. Soil temperature was generally highest for CT and higher in ST than NT in one out of three instances. Soil moisture was unaffected by tillage in 2014, but was higher under NT and ST from June to late-August in 2015. The rolled cover crop mulch in NT and ST plots effectively suppressed annual weeds during period between planting and the first weeding event, reducing weed biomass and density compared to CT. Nitrate-N concentration in leachate was reduced under NT and ST only during early sampling dates in 2014. Soil microbial biomass and diversity were similar among tillage treatments on most sampling dates, but consistently higher in the 0–7.5-cm than the 7.5–15-cm soil profile. Results indicate the potential for high yields using NT and ST, but temperature and nitrogen may limit yield under some circumstances. Though observed only periodically in this study, benefits of cover crops and reduced tillage to soil health and water quality make organic NT and ST systems promising in addressing current environmental concerns in agriculture.

Introduction

Cover crops are widely used by organic farmers. According to the 2014 Organic Survey in the 2012 Census of Agriculture, 8,400 out of the 12,595 certified organic farms used green or animal manures (U.S. Dept. of Agriculture, 2015). Cover crops have been shown to provide many benefits to soil health and water quality. Soil benefits include reduced soil erosion (Kaspar et al., 2001), increased soil organic matter (Reicosky and Forcella, 1998), and symbiotically fixed nitrogen (N) from legume cover crops. Winter annual cover crops planted after a cash crop can scavenge nutrients and reduce nitrate leaching by up to 80% (Dabney et al., 2001, Staver and Brinsfield, 1998).

However, cover crops are typically incorporated into the soil using tillage before planting the following cash crop, thereby leaving soil vulnerable to erosion during the growing season (Magdoff and van Es, 2009). A non-tillage method for terminating cover crops in organic systems is rolling them flat with a roller-crimper during a particular stage of growth. Cover crops commonly used in this system are cereal rye *(Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth), which can be effectively killed when rolled at anthesis for cereal rye (Ashford and Reeves, 2003) and early pod stage for hairy vetch (Mischler et al., 2010). If sufficient biomass is produced, the rolled cover crop mulch can provide season-long annual weed suppression (Silva, 2014, Smith et al., 2011) for a cash crop planted through the mulch using no-till (NT) methods. This system enables NT production of organic crops by replacing the need for herbicide with weed-suppressive cover crop residue.

While several studies of organic NT vegetable production have shown NT can produce equal or superior yields compared to conventional tillage (CT) (Creamer et al., 1996, Delate et al., 2008, Delate et al., 2012, Lounsbury and Weil, 2014, Vollmer et al., 2010), others found that NT reduced yield (Delate et al., 2003, Díaz-Pérez et al., 2008, Leavitt et al., 2011). Yield reductions in these systems may be explained by reduced soil temperature and nitrogen availability (Delate et al., 2003, Griffith et al., 1988, Leavitt et al., 2011). Strip tillage (ST) is a hybrid of NT and CT, where tillage is restricted to a narrow band centered on the crop row. In a cover crop-based system, the rolled mulch is retained between strips, thus providing many of the benefits of NT within that region. Strip tillage can provide soil temperatures equal to those of CT (Licht and Al-Kaisi, 2005), but not necessarily if CT treatment includes plastic mulch (Tillman et al., 2015). Thomas et al. (2001) reported that yields of ripe processing tomato fruit were equal in CT and ST, but reduced under NT. Based on these findings, we hypothesize that ST may produce a higher yield than NT, in part due to increased soil temperature.

While warmer soil in strips may play a role in increasing N availability through more rapid mineralization of soil organic matter (MacDonald et al., 1995), the rolled cover crop mulch in both NT and ST systems poses challenges for N management. First, the high carbon-to-nitrogen (C:N) ratio of mature rolled cereal cover crops may significantly increase immobilization of N through at least the first six weeks after planting, compared to a CT system (Wells et al., 2013). A biculture of a cereal and a legume cover crop may lower the C:N ratio, and thus the immobilization potential (Ranells and Wagger, 1996), without reducing the weed suppressive capacity of the residue (Burgos and Talbert, 1996). Second, the physical obstruction of the cover crop mulch prevents mechanical sidedressing of granular fertilizers. Schellenberg et al. (2009) found that hand-applying a sidedress application of organic fertilizer increased yield of NT broccoli in a rolled cover crop system, but this practice would be impractical on large commercial scale. We hypothesize that fertigation could be a better method of delivering nitrogen to the crop in presence of surface mulch in NT systems.

While yield is of primary interest to growers, maintenance of soil health is essential to agricultural sustainability. Long-term NT crop production has been shown to improve soil health (Karlen et al., 2013), although improvements in soil health can be difficult to quantify during the relatively short duration of most field experiments. Indicators of soil health, such as microbial biomass and diversity, are considered more sensitive to management and thus useful tools in shorter timeframes (Bending, 2004, Schloter et al., 2003). Numerous studies have found that NT can increase microbial biomass in surface soil (Alvarez et al., 1995, Carter and Rennie, 1982, Doran, 1987), while not affecting or reducing microbial biomass of deeper regions in soil. This may have to do with the concentration of carbon (C) substrates (plant residues) on the soil surface, and more consistent soil moisture due to surface residue in NT systems (Doran, 1980). There may also be differential microbial responses in the tilled in-row (IR) region and untilled between-row (BR) region in ST. Overstreet and Hoyt (2008) found greater microbial biomass in the BR region than the IR region in an ST system after 10 years of management.

While total microbial biomass is a useful metric to assess microbial health of the soil, it does not account for diversity or activity of those organisms. Community-level physiological profiling (CLPP) uses sole-source-C substrate utilization as a measure to assess relative functional diversity of culturable soil microorganisms in soils from different treatments (Zak et al., 1994). Two such measures are substrate richness (S), which indicates the number of unique substrates oxidized by soil microbes, and average well color development (AWCD), which reflects both substrate richness and the respiratory activity of those communities. Govaerts et al. (2007) found that an NT system with retained plant residues increased AWCD compared to CT or NT with residues removed. Increased microbial diversity is also associated with suppression of plant pathogens and increased terrestrial resilience during periods of abiotic stress (Brussaard et al., 2007), which will be an increasingly important feature of agroecosystems as weather patterns become more volatile due to climate change.

In addition to agriculture's effect on soil health, impact on water quality is also coming under increasingly public scrutiny. A hypoxic zone in the Gulf of Mexico has been increasing in size since the 1960s (Diaz and Rosenberg, 2008), and nitrate and phosphorus lost from agricultural fields are major contributors (Burkart and James, 1999). Many states, including Iowa (Iowa State University, 2015), have enacted strategies aimed at reducing nutrient loading of the Mississippi River watershed from agricultural land, with a primary focus on nitrate. Cover crops (Constantin et al., 2010, Feyereisen et al., 2006), reduced tillage (Dinnes et al., 2002), and orgnic management (Cambardells et al., 2015) can be effective tools to reduce nutrient pollution coming from farm fields via leaching and erosion. However, the effect of NT has varied, with Constantin et al. (2010) finding only a small difference between NT and CT, and Oorts et al. (2007) finding no difference at all. Few studies have quantified the effects of organic NT and ST systems, which integrate cover crops with reduced tillage, on nitrate leaching.

In this study, we sought to obtain a holistic understanding of how different degrees of reduced tillage affect yield and growth of bell pepper plants, soil health as indicated by microbial biomass and diversity, and the nitrate concentration in leachate. We were particularly interested in whether ST would 1) increase soil temperature and nitrogen availability, 2) increase yield, and 3) not adversely affect soil health, as compared to NT. To this end, we conducted a two-year field study to compare organically managed CT, NT, and ST systems and two fertilization regimes in production of bell pepper.

Materials and methods

Site description

The study was carried at the Iowa State University Horticulture Research Station in Ames, IA, in 2013–14 and 2014–15. The soil types for the first year of the study were Clarion and Nicollet loams (fine-loamy, mixed, superactive, mesic Typic Hapludolls). The site was previously planted to demonstration plots of oilseed radish (*Raphanus sativus* L.), yellow mustard (*Sinapis alba* L.*)*, and cereal rye (*S. cereal* L.), after which it was fallow for 3 months before cover crops were established for this study in Sept. 2013. Due to the need to establish the cover crop for the second growing season before completion of pepper harvest in the first year, the plot location was changed in 2015. The soil type at the 2014–15 site was a Lester loam (fine-loamy, mixed, superactive, mesic Mollic Hapludalf), and the prior organically managed alfalfa crop was terminated four weeks prior to cover crop establishment.

Experimental design

The experimental design was a split-plot randomized complete block design with four replications, three whole-plot treatments (CT, ST, or ST), and two subplot treatments (preplant fertilizer only or split fertilizer application). Whole plot dimensions were 4.6 m × 10.7 m, with a subplot consisting of a single 10.7-m row. Each whole plot contained five rows, with the unfertilized outer rows and the center row serving as guard rows between the fertility subplot rows. Rows were spaced 76 cm apart and plants were placed 46 cm apart within each row for a total of 24 plants per row.

Field management and vegetable culture

Major field operations and data collection events are summarized in Table 1. The entire plot was rototilled before establishing the cover crop with a grain drill (Tye Pasture Pleaser, AGCO, Duluth, GA) at 25-cm row spacing. The cover crop mixture consisted of cereal rye ‘Wheeler’ (Albert Lea Seed, Albert Lea, MN) seeded at 112 kg ha^{-1} and hairy vetch (VNS; Albert Lea Seed in 2013–14 and ‘Purple Bounty’; Lancaster Agriculture Products, Ronks, PA in 2014–15) seeded at 28 kg ha^{-1}. ‘Purple Bounty’ hairy vetch, which is known to mature 1–2 weeks earlier than VNS, was used during the second season in an attempt to achieve a date of maturity similar to that of cereal rye. Hairy vetch seeds were inoculated prior to planting using N-DURE rhizobium inoculant (*Rhizobium leguminosarum* biovar *viceae*, INTX Microbials LLC, Kentland, IN).

A Hiniker 6000 strip tiller (Hiniker Co., Mankato, MN) was used to form 30 cm-wide strips in ST plots on 14 Nov. 2013 and 12 Oct 2014. Strips were tilled earlier in the 2014 than 2013 to allow the strip tiller—which was not designed to terminate an actively growing cover crop—to more effectively incorporate the cover crop. Components of the strip tiller included a coulter, a subsurface shank, a set of concave discs, and a rolling basket. To achieve more aggressive tillage action, the concave discs of the strip tiller were fixed to the frame using U-bolts.

Cover crop termination method depended on the tillage treatment. Cover crops in CT plots were flail mowed four weeks before planting and immediately incorporated with a rotary tiller. Cover crops in NT and ST plots were terminated one week prior to planting using a 3.2-m roller-crimper (I & J Manufacturing, Gap, PA) when cereal rye was at anthesis and hairy vetch was in full bloom with some seedpods.

Cover crop biomass was determined by taking whole plant samples from two 50 × 50-cm quadrats per whole plot on the day of termination. Soil was removed from roots and samples were dried at 67 °C until they reached a constant weight before weighing. Dried whole plant material was ground and analyzed for total C and N (ISU Soil and Plant Analysis Lab, Ames, IA). Weed populations were estimated on 2 July 2014 and 8 July 2015, before the first weeding event, within two 25 × 25-cm quadrats in the IR and the BR regions of each whole plot. Weeds were counted, dried at 67 °C to a constant weight, and weighed. Weeds were controlled in IR and BR regions of all tillage treatments on 16 July 2014 and 14 July 2015 through hoeing and hand weeding.

Seedbed preparation and preplant fertilizer application method also varied according to tillage treatment. In CT plots, fertilizer was surface applied by hand in the row 2 to 4 d before pepper planting and the entire plot was tilled using a rotary tiller. Seedbed preparation in ST and NT plots occurred on the same day as in CT plots, and was achieved by loosening a band of soil while leaving the rolled cover crop residue between rows. In ST plots, the Hiniker strip tiller was used to re-till existing strips while banding fertilizer via a dry fertilizer tube mounted onto the backside of a subsurface shank. In NT plots in 2014, the strip tiller was used to prepare the seedbed, but with the discs and rolling basket disengaged so that only the coulter and shank were in use. The aggressive shank disturbed a wider band of soil (10–15 cm) than was desired, so a custom implement was used in 2015. This implement, which consisted of a fluted coulter followed by a minimum-disturbance fertilizer knife and set of disc sealers to close the furrow created by the knife, left 5–10 cm tilled bands in NT rows. Preplant fertilizer was applied via a tube on the backside of the shank as with the strip tiller.

Fertilizer applied in both fertility treatments contained the same amount of total N (90 $kg \cdot ha^{-1}$), so treatments were designed to test the effect of timing and method of fertilizer application rather than rate. In plots receiving the preplant fertility treatment, the entire amount of N was applied in the form of dehydrated poultry manure crumbles [Chick Magic® (4.0N–1.3P–1.7K); S & R Egg Farm, Palmyra, WI]. In split fertility plots, two-thirds of the total N was applied using poultry manure fertilizer, and the remaining one-third was provided by liquid fish fertilizer via fertigation. Phytamin Fish Gold® (5.0N–0.4P–1.7K; California Organic Fertilizers Inc., Hanford, CA) was used in 2014, but due to unavailability of the product in 2015, Organic Liquid Grow (5.0N–1.0P–2.0K; Peaceful Valley Farm & Garden Supply, Grass Valley, CA) was used. The fish fertilizer was applied over four fertigation events, beginning four weeks after transplanting and repeated on 7–14 d intervals, with frequency depending on rainfall. This fertigation schedule allowed for application of 90 $kg\ ha^{-1}$ total N by early stages of fruit development. Rows receiving fertigation were connected to a header separate from that of preplant fertility plots to prevent contamination of non-fertigated treatments. Guard rows received no fertilizer. Yield, plant health, and soil nutrient data were collected from the center row, which served as a fertilizer control. This was done to verify whether there was a fertilizer effect in the event that no differences were found between preplant and split fertility treatments, which would leave open the possibility that residual N was sufficient for plant growth, thus masking any potential effect of the fertility treatment.

Because fertilizer consistently improved plant growth and yield, data from the control treatment are not presented in this paper.

Untreated ‘X3R Red Knight’ pepper seeds (Johnny’s Selected Seeds, Winslow, ME) were planted into a compost-based organic potting medium (Beautiful Land Products, West Branch, IA) in 288-cell trays and grown in a greenhouse (Table 1). After four weeks, seedlings were moved into 72-cell trays and grown in the greenhouse until about 1 week prior to field planting, at which point flats were moved outdoors to harden off. Transplants were planted in the field using a Holland 1500 mechanical transplanter (Holland Transplanter Co., Holland, MI) in 2014, and by hand in 2015. The transplanter was not used in 2015 because it had caused excessive disturbance to cover crop mulch in 2014 and was deemed unsuitable for use in high residue, reduced tillage conditions. Drip irrigation was applied as needed to supply 2.5 cm of water per week. When split fertility rows were fertigated, preplant fertility rows were also irrigated to maintain parity of water supply among treatments. Pepper plants were sprayed with insecticidal soap (Safer Brand, Woodstream Corp., Lititz, PA) at a rate of 9.4 L ha^{-1} on 18 Aug. 2014 to control green peach aphid (*Myzus persicae* Sulzer). No insecticide applications were necessary in 2015.

Plant measurements

Green bell peppers were harvested four times in 2014 and five times in 2015 (Table 1) from 24 plants per subplot. Peppers were harvested if they were greater than 6.6 cm in length and width and firm when squeezed, or if they had any noticeable defects, such as blossom end rot or sunscald. All peppers were graded according to marketability (USDA, 2005), with Fancy, Grade 1, and Grade 2 considered marketable, and fresh weight and number of fruits were recorded. Pepper plant dry weight was determined by harvesting two whole representative plants and drying at 67 °C until the plants reached a constant weight. Plants were sampled after the final harvest, and any remaining fruits were removed prior to drying.

The week after the final fertigation application, five plants from the middle of each subplot row were selected for measurement of plant height, stem diameter, and leaf chlorophyll. Plant height was measured from the soil at the base of the plant to the tip of the highest leaf. Stem diameter was measured 2 cm above the soil line using digital calipers. Leaf chlorophyll was measured using a SPAD-502 Plus chlorophyll meter (Konica Minolta Sensing America Inc., Ramsey, NJ), which is correlated with N concentration (Hartz and Hochmuth, 1996). For each of the five plants, SPAD readings were taken on the upper-right, upper-left, lower-right, and lower-left quadrants of the most recently developed fully expanded leaf and averaged. Leaf-petiole samples were collected using the method described by Jones and Case (1990), and then dried, ground, and analyzed for N concentration.

Environmental monitoring

Hobo® temperature sensors (Onset Computer Corp., Bourne, MA) were installed at a depth of 15 cm between plants in the row. One sensor was placed in each whole plot within all four blocks. Decagon 10HS soil moisture sensors (Decagon Devices, Pullman, WA) were installed horizontally into the soil at 15 cm depth in the row and connected to data loggers (Em5b; Decagon Devices). One soil moisture sensor was placed in each whole plot in three blocks. Both temperature and soil moisture sensors recorded measurements at 60 min intervals throughout the season.

Microbial biomass and community-level physiological profile (CLPP)

Composite soil samples were taken three times per year (early July, mid-August, and late September) and analyzed for microbial biomass C (MBC) and microbial biomass N (MBN) using chloroform-fumigation-extraction [modified from Vance et al. (1987)]. Composite soil samples, consisting of four subsamples taken with a 2.9 cm soil probe, were taken from two regions [in-row (IR) and between-row (BR)] and two depths (0–7.5 cm and 7.5–15 cm) from both subplot rows in three blocks. Field-moist soil was sieved (<4.75 mm) and two 15 g samples were picked free of roots and other organic material and then either immediately extracted using potassium sulfate (K_2SO_4) or fumigated for 48 h before extracting with K_2SO_4. Each 20 mL sample bottle received three drops of concentrated phosphoric acid and was stored at -20 °C until analysis. The 48-h fumigation was chosen instead of 24 hour fumigation because we wanted to ensure thorough chloroform penetration of the large soil aggregates in July 2014 samples, which were quite moist and did not readily crumble when passed through the sieve. Dry weight of soil samples was determined by weighing a 5 g field-moist soil sample before and after drying at 105 °C to a constant weight. Extracts were analyzed for non-purgeable organic C (NPOC) and total N (TN) using a Shimadzu TOC-L analyzer (Shimadzu Corporation, Columbia, MD). Conversion factors of 0.45 and 0.54 were used to convert NPOC and TN to MBC and MBN, respectively (Brookes et al., 1985, Vance et al., 1987).

Biolog-Ecoplates© (Biolog, Inc., Hayward, CA) were used to assess sole-carbon-source substrate utilization by culturable heterotrophic soil bacteria. In each year, 10 g field-moist subsamples were taken from the mid-August soil samples used for microbial biomass determination. Each of a total of 24 samples (two blocks × three tillage treatments × one fertility treatment (preplant) × two regions × two depths) was individually shaken in sterile saline solution, incubated, diluted, and pipetted into a Biolog-Ecoplate© using the method of Nair and Ngouajio (2012). Each 96-well Biolog-Ecoplate© contained three replicates of 31 sole carbon source substrates plus a blank. The utilization of these substrates was indicated by purple color development due to reduction of tetrazolium dye contained in each well. Plates were incubated at 23 °C and color development was measured as optical density at 590 nm using a microplate reader (Bio-Rad iMark; Bio-Rad Laboratories, Hercules, CA). Optical density (OD) readings were taken shortly after plating (day 0) and on 24 h intervals for seven days thereafter. Day 0 OD readings were subtracted from all samples to account for background color in the wells, and OD readings from the blank well in each replicate were subtracted from the readings of each of the 31 substrate wells. Substrate richness (S), the number of substrates utilized by bacteria in each sample, was determined by counting the number of positive OD measurements. Average well color development (AWCD) of each replication of each sample was calculated using the following equation:

$$AWCD = \frac{\sum OD_i}{31}$$

Leachate nitrate-N concentration

Suction lysimeters (Model 1900; Soil Moisture Equipment Corp., Santa Barbara, CA) were installed in both subplots in four blocks to sample soil water at a depth of 61 cm, which is considered below the rooting depth of pepper plants (Weaver and Bruner, 1927). In each subplot, a 5 cm diameter hole was made with a soil auger between two plants near the center of the plot. Lysimeters were installed using the method described by Linden (1977). Slurry of silica flour was used to ensure good contact between the soil and the ceramic cup at the base of the lysimeter, and a combination of bentonite clay pellets and tamped soil backfill were used to eliminate any voids that might have channeled water from the soil surface down to the ceramic cup. Sampling occurred on 7–10 d intervals from 1 July of each year until 3 Oct. and 18 Sept. in 2014 and 2015, respectively. After a rain or irrigation event, 40 kPa of vacuum was applied to the lysimeter to draw in soil water through the ceramic cup, and 24 h later, vacuum was applied to a Buchner flask connected to a plastic tube extending to the bottom of the lysimeter to extract soil water. Samples were frozen and stored at -20 °C until being analyzed for NO_3-N.

Soil chemical characteristics

Baseline soil samples were taken in April of each year to measure pH and organic matter content of soils. Since no fertility treatments had been applied to subplots at this point, samples were taken at the whole plot level. Soil pH was analyzed using a 1:1 ratio of soil to deionized water and organic matter was determined by combustion. Samples for extractable nutrients were taken after the final harvest. Nitrate and ammonium were extracted using a 2N potassium chloride solution, and P and K were extracted using a Mehlich III solution (Mehlich, 1984).

Data analysis

All data were analyzed in SAS (version 9.3; SAS Institute, Cary, NC). Analysis of variance (ANOVA) for all response variables was carried out using the GLIMMIX procedure with block considered random and all other factors fixed. Cover crop biomass, MBC, MBN, AWCD, and substrate richness data were log-transformed, and weed biomass was square root-transformed, before analysis to satisfy the normality and homogeneity of variance assumptions of ANOVA. Back-transformed means on the log scale were considered medians on the original scale. Statistical separation of means and medians was accomplished using contrasts (MBC, MBN, AWCD, and substrate richness) and Fisher's protected least significant difference (LSD) test (all remaining variables) with the Satterthwaite adjustment for degrees of freedom. Significance level was set at $P \leq 0.05$ for all variables besides microbial biomass, for which a $P \leq 0.1$ significance level was used.

Results and discussion

Weather

Rainfall was above average in June, August, and September of both years, and below average in May and July of 2014 (Fig. 1). Although total June rainfall was the same in both 2014 and 2015, it was highly concentrated during the second half of June in 2014, creating prolonged saturated soil conditions in the plot. Air temperature in both years was similar to the 30-year average, with temperatures in 2015 being slightly below average in May through August, but above average in September.

Soil temperature and moisture

Soil temperature and moisture data were divided into subsets of the season for analysis, with the first third, second third, and final third of the season denoted as early, mid, and late season, respectively. Soil temperature was generally highest in CT plots and lowest in NT plots (Table 2). Conventional tillage increased minimum soil temperature by an average of 1.3 °C during early and mid-seasons of both years, but there were no differences in minimum temperature among treatments during the late season. Mean soil temperatures were different for all treatments during early and mid-seasons of both years, with CT being the highest and NT the lowest. Maximum soil temperature was highest for the CT treatment during early and mid-seasons in both years, with ST increasing maximum temperature over NT in 2014 but not in 2015.

The increased temperature under CT compared with NT is well supported in the literature (Johnson and Lowery, 1985, Tollner et al., 1984). Our hypothesis was that ST would increase temperature over that of NT, as was observed by Licht and Al-Kaisi (2005). Average temperature was found to be higher in ST than NT from planting through late August, a critical period of establishment and vegetative growth. Minimum temperature was not different between ST and NT, which suggests that heat gained in tilled soil during the day was lost during the night, likely due to absence of a surface mulch in the IR region under ST.

Soil moisture was similar among treatments throughout the season in 2014, but in 2015, NT and ST increased soil moisture by 0.046 and 0.037 m^3 m^{-3} soil during early and mid-seasons, respectively, compared with CT (Table 3). The same trend was seen in late season, but differences were not significant. This confirmed our hypothesis that the surface mulch in NT and ST plots would help retain moisture, compared to the bare ground under CT. Moisture conservation in NT systems is due to reduced evaporation as a result of surface residue (Mundy et al., 1999). Surface residue in a cover crop-based reduced tillage systems is generally thicker than the crop residue under conventional NT, likely resulting in an even stronger moisture conservation effect. The lack of treatment effects on soil moisture in 2014 may have been due to the somewhat finer soil texture in the 2014 site. The greater water-holding capacity of the soil in 2014 (not directly measured), combined with the fact that irrigation was applied during dry periods, may have allowed CT plots to maintain high levels of soil moisture despite the lack of a surface mulch.

Yield

Marketable and total fresh weight and number of peppers were equal among tillage treatments in 2014, averaging 16.8 Mg ha^{-1} (Table 4). Preplant fertility plots produced a greater marketable and total number of fruits, and higher marketable yield, as compared with the split fertility treatment. In contrast to 2014, CT significantly increased fresh weight and fruit number in 2015. Marketable yield of CT plots was an average of 67% higher than NT and ST plots, with no difference in yield between NT and ST. Marketable yield was similar for preplant and split fertility treatments, but total yield and marketable and total number of fruits were both higher in split than in preplant fertility plots.

Our 2014 results were similar to those of Delate et al. (2008), who found that an organic ST pepper system produced yields equal to those of organically and conventionally managed CT systems. Production was higher in 2015 across all treatments, increasing by 101%, 36%, and 41% for CT, NT, and ST, respectively, compared with 2014. It is possible that NT and ST treatments produced less than the CT treatment in 2015 because CT plots had warm and drier soil. Plants in CT plots may have had faster root development due to higher soil temperatures in CT plots (Kaspar and Bland, 1992), enabling them to more rapidly utilize soil N released through breakdown of the prior alfalfa crop in the 2015 site. These conditions may have thus preferentially benefited CT plants during the early season. However, despite the higher CT yield in 2015, yields of all treatments compared favorably to the national average organic yield of 22.3 Mg ha^{-1} (USDA-NASS, 2015).

We hypothesized that ST would improve yield compared to NT due to potentially warmer soils and increased N mineralization as a result of increased tillage. However, ST failed to produce higher yields in either year, despite increasing mean soil temperature. The effect of increased soil temperature in an ST vs. NT system may depend on latitude, with greater yield benefits from ST in northern regions with shorter growing seasons. These results were different than those found by Thomas et al. (2001), who showed that ST improved yield of conventionally grown tomato over that of NT at locations in southwest Ontario at latitudes similar to central Iowa. While growers may prefer ST over NT for management reasons—such as the desire to use conventional planting equipment or be able to sidedress granular fertilizer—our results suggest that ST may not increase yield of bell pepper in locations with climates similar to that of central Iowa.

Plant growth

Nitrogen concentration in pepper leaves was 0.4% to 0.6% higher in both years for plants in CT plots, compared with those in NT and ST plots (Table 5). Despite the reduced N concentration of leaves in NT and ST plots, plants from all treatments tested in the optimum recommended range for pepper of 3.0% to 5.0% (Hochmuth et al., 2010), indicating that nitrogen may not have been limiting in NT and ST plots at the time of sampling (6–8 weeks after planting). Sampling date was chosen to be after the completion of the final fertigation event in split fertility plots. While this point in the season was a time of peak N demand, it is possible that leaf N concentration varied throughout the year. Leaf N concentration may have been higher in CT plants than in ST or NT plants during the early season, thus enabling more rapid growth and development that could have resulted in ultimately higher yields. Future studies should more frequently measure N status of plants in order to better understand N dynamics throughout the season. There was no difference between preplant and split fertility treatments in either year.

Chlorophyll content of leaves followed a trend similar to that of N concentration. The SPAD number was similar among tillage treatments in 2014, but was higher for plants in CT than in NT or ST plots in 2015. The SPAD numbers of NT and ST treatments were equal in both years. In 2014, plants that received the preplant fertility treatment had higher SPAD numbers than those which received split fertility, but that effect was not observed in 2015.

Plant height was similar among tillage treatments in both years, but was 16.4 cm greater in 2015 than in 2014 when averaged across treatments. Delate et al. (2008) also found that plant height of ST pepper plants was similar to that of CT, but Delate et al. (2003) reported reduced plant height for ST compared to CT. Plant height in preplant fertility plots was 2.9 cm greater than in split fertility plots in 2014, but not different in 2015. Following a pattern similar to that of plant height, stem diameter did not vary among tillage treatments in either year, but was 31% greater in 2015 than in 2014, averaged across treatments. There were no significant main effects of fertility treatment on stem diameter in either year. However, a significant interaction ($P \leq 0.05$) occurred in 2015, where stem diameter for preplant was greater than for the split fertility treatment in CT plots, but not in NT or ST plots. There was no difference in end-of-season plant dry weight among tillage or fertility treatments, though it was nearly twice as great in 2015 compared to 2014. A lack of difference in plant dry weight in 2015, when yield of NT and ST were reduced, conflicts with the findings of Díaz-Pérez et al. (2008), who reported lower yield and shoot and root dry weight for NT bell peppers. However, Díaz-Pérez et al. (2008) sampled plants for dry weight before their first harvest, whereas we sampled plants after the final harvest. Since faster early growth and higher early yields were expected under CT, it is not surprising that plant dry weight before the first harvest was greater for CT than for NT.

Cover crop performance

The time of cover crop termination depended on the tillage treatment, with termination occurring earlier in CT plots to allow time for residue breakdown before planting. As a result, dry weight of aboveground biomass was lowest for the CT treatment in both years (Table 6). In 2014, biomass in CT plots was about half that in NT and ST plots. In 2015, all treatments were different, with dry weights of 4.0, 6.5, and 9.5 Mg ha^{-1} for CT, NT, and ST, respectively. Soil heterogeneity is the likely explanation for the difference in cover crop biomass between NT and ST plots, given that there was no major difference in management. The only difference was the tractor pass in ST plots in the fall, but this additional compaction would likely only decrease biomass, not increase it. The minimum biomass of mulch required to inhibit germination of annual weeds (8,000 kg ha^{-1} dry weight) recommended by Mirsky et al., (2013), was greatly exceed in both NT and ST plots in 2014, but only narrowly achieved in ST plots, and not achieved in NT plots, in 2015. Biomass was similar to or greater than the levels reported in previous studies (Ashford and Reeves, 2003, Mirsky et al., 2011)

The C:N ratio of the cover crop residue also differed among tillage treatments and was lowest in CT and highest in NT plots in both years. The C:N ratio of CT cover crop residue was 19:1 and 24:1 in 2014 and 2015, respectively, and therefore unlikely to have caused any N immobilization, whereas surface residue in NT and ST plots (C:N greater than 32:1 in both years) likely caused immobilization of N (Quemada and Cabrera, 1995). The C:N ratios of NT and ST cover crop biomass were much higher, which was as expected due to the increased maturity due to a later termination date. The C:N ratio for NT was slightly but statistically higher than for ST.

Weed populations

Weed biomass in between-row (BR) and in-row (IR) regions was higher for CT than for NT and ST treatments in both years (Fig. 2). This was expected due to the lack of a weed-suppressing surface mulch in CT plots. Biomass was generally similar for NT and ST treatments, though NT reduced IR weed biomass in 2014, as would be expected due to the smaller amount of soil exposed in that system. The increased BR weed biomass in NT and ST plots in 2015 was likely caused by the lower cover crop biomass produced that year (Mirsky et al., 2013) and the higher proportion of perennial weeds, which are not effectively suppressed by cover crop mulches (Mirsky et al., 2011), at the 2015 site.

It is important to note that these data were taken about one month after cover crop termination, which is relatively early in the growing season. While late-season weed growth was not quantified in this study, we did observe heightened weed pressure in NT and ST plots, especially in the IR region, during the second half of the season. Weeds are difficult to control in a rolled cover crop system, as the mulch obstructs mechanical cultivation and decreases efficiency of hand weeding activities. Season-long weed suppression, while attainable between rows with a heavy cover crop mulch (Silva, 2014), remains difficult in the row where soil is typically disturbed in the spring to allow for planting. For this reason, crops grown at wider row spacing may have fewer weed management challenges than those grown at narrower row spacing.

Microbial biomass and activity

There was no effect of tillage or fertility treatment on microbial biomass carbon (MBC) in either year, although NT and ST did trend higher than CT in 2015 (Tables 7 and 8). No tillage increased microbial biomass nitrogen (MBN) by 15–24 $\mu g\ g^{-1}$ soil over CT at the early sampling date in 2014 and mid and late dates in 2015, and by 18 $\mu g\ g^{-1}$ soil over ST at the early date in 2014. Strip tillage did not increase MBN, except for mid-season in 2015, where it exceeded that of CT. The reason some differences in MBN were observed despite a lack of differences in MBC may be related to microbial community composition. The MBC:MBN ratio may indicate predominance of fungi vs. bacteria in the soil microbial community (Moore, 2000). Treatments with increased MBN but not increased MBC may have a higher proportion of bacteria than fungi, due to the higher nitrogen concentration in bacterial biomass. There were no differences in MBC or MBN between BR and IR regions, except for midseason sampling date in 2014, where both were higher in IR than BR. The most consistent differences in MBC and MBN were between sampling depths. Shallow soil had higher MBC and MBN in mid and late seasons in both years.

While microbial biomass was generally higher in shallow than in deeper soil, there was no significant tillage × depth interaction that would show that microbial biomass increased in surface soil under NT and ST but not CT, as has been found by others (Alvarez et al., 1995, Carter and Rennie, 1982, Doran, 1987). As a result, we presented only the main effects, which did not show reduced tillage to consistently increase soil microbial biomass.

Average well color development (AWCD) reflects the overall activity of soil bacteria, combining the effects of diversity and abundance into a single parameter. No significant differences in AWCD were observed in the main effect of tillage treatments in either year (Table 9). However, like with MBC, AWCD for NT and ST treatments trended higher than CT in at both sampling depths in both BR and IR regions in 2015. A significant depth × region × tillage interaction occurred in 2015 ($P = 0.0185$) (Fig. 3), where AWCD of ST and NT were higher than CT in shallow soil of the BR region and deeper soil of the IR region. Meanwhile, AWCD was similar among treatments in shallow depth of the IR region. Microbial activity in CT plots should be higher in the IR than the BR region, as unlike NT and ST, CT does not maintain organic residue on the soil surface of BR region. Furthermore, plant root exudates influence the rhizosphere microbial community (Baudoin et al., 2003). Lupwayi et al. (1998) found that NT soil had more bacterial diversity than CT in bulk soil but not in the rhizosphere. Substrate richness was represented by the number of substrates utilized by soil microbes (number of positive OD readings). No differences among treatments were observed, indicating that differences found in AWCD were a result of increased activity (higher OD readings) rather than increased diversity.

Research has shown that reduced tillage management improves soil health, and soil microbes—part of the labile fraction of soil organic matter—is considered a short-term indicator of soil health (Schloter et al., 2003). However, the duration of reduced tillage management in this study may have been too short to detect differences. Because pepper harvest continued until nearly a month after the cover crop would have needed be seeded for the second year of the study, it was necessary to move to a different plot for the 2015 growing season. As a result, this study had only one year of reduced tillage management. Prior studies have similarly found that changes in the soil microbial community require prolonged management changes. Moore et al. (2000) found increased MBC and MBN under NT management in 4-year and 12-year experiments, but not at a site where the experiment had only been carried out for 2 years. Lupwayi et al. (1998) found no differences in microbial diversity indices in the first year of a study investigating the effects of NT and preceding green manure crops in wheat production. It is likely that a longer duration of management would have been necessary to reveal tillage and cover crop effects on microbial biomass and diversity.

An additional factor that distinguishes this study from prior studies, and potentially helps explain the lack of consistent soil health benefits under reduced tillage, is the inclusion of a cover crop in the CT system. The cover crop in CT plots was flail mowed and incorporated throughout the 15-cm soil profile, whereas the cover crop in NT and ST plots was left intact on the soil surface and thus may not have been available as a food source for microbes well below the soil surface. While microbial biomass tends to be reduced by long-term tillage, it may increase rapidly after incorporation of a cover crop in a CT system (Hu et al., 1997, Wyland et al., 1996). However, Hu et al. (1997) reported a decrease in MBC three weeks after cover crop incorporation. Long-term effects of tillage on soil health in cover crop-intensive systems have not been well studied.

Organic management of NT and ST systems presents additional challenges, particularly with regards to weed management. The challenge of in-row weed control, in addition to the failure of a cover crop mulch to suppress perennial weeds (Mirsky et al., 2011), means that full-width tillage is generally periodically necessary. Such a system has been previously termed “organic rotational no-till” (Halde et al., 2014, Mirsky et al., 2012, Mirsky et al., 2013). In the present study, cover crop establishment in each year was preceded by full-width tillage to control existing crop plants or weeds. As a final point, use of irrigation to maintain adequate soil moisture in all treatments may have decreased the potential microbial biomass differential between CT and NT, given that preferable soil moisture status has been shown to increase microbial biomass in NT systems (Doran, 1987).

Soil chemical characteristics

Table 10 shows results of soil chemical analysis after the final harvest in each year. No differences among tillage and fertility treatments were observed for inorganic N (NO_3^- + NH_4^+), P, K, pH, organic matter, or cation exchange capacity.

Nitrate-N concentration in leachate

Averaged over fertility treatments, NO_3-N concentration in leachate was reduced in NT and ST plots by 7.8–21.2 ppm during the first three collection dates of 2014, but all treatments were equal on August and September sampling dates (Fig. 4). In 2015, NO_3-N concentration in leachate was equal among tillage treatments in most of the sampling dates, and overall NO_3-N concentrations were much higher than in 2014. The pattern was similar to that of 2014, with increasing NO_3-N concentrations through July, followed by a decline through August and September. This may reflect the mineralization of N from poultry manure fertilizer, which occurs rapidly during the first month after application and wanes after that (Hadas et al., 1983).

A possible contributing factor to the high concentrations of NO_3-N in CT plot leachate in 2014 is the high volume of rain received during the final two weeks of July, which created standing water in much of the plot. Such conditions are conducive to leaching of NO_3^-, and it is possible that the presumed immobilization (not directly measured) of soil N in NT and ST plots due to the presence of high-C:N-ratio cover crop residue (Table 6) reduced nitrate leaching in those plots. This effect was absent in 2015, however. A likely cause for this, and the higher overall levels of nitrate leaching in 2015, is higher residual soil N from the previous alfalfa crop. Indeed, Table 10 shows that season-end soil inorganic N levels were nearly five-fold higher in 2015 than 2014, a disparity similar to that of NO_3-N concentrations in leachate. The lack of N-immobilizing conditions under NT and ST in 2015 might have negated any benefit for those treatments. There was no significant difference between preplant and split fertility treatments in either year, suggesting that soluble N additions from fish fertilizer were either utilized by the plant or matched the NO_3^- leaching caused by the increased poultry manure rate applied in the preplant treatment.

Conclusion

While the NT and ST yields were similar to that of CT in the first year, they were lower than CT in the second year, despite yields for all treatments increasing in 2015. Contrary to our hypothesis, use of ST did not improve yield or plant growth compared to NT, despite increasing mean soil temperature. It is likely that the benefit of ST would vary with geographic location, with growers in cooler climates in northern regions gaining more from the enhanced soil warming provided by ST. Nitrogen status of plants was generally higher for CT, but N was likely not limiting under NT or ST at the time of measurement during early flowering stage. The timing of fertilizer application had differing effects on yield and plant growth from one year to the next, so a definitive conclusion cannot be drawn. Weed control is another management factor that will influence the success of reduced tillage production systems. While BR weed control can be achieved with sufficient cover crop biomass, IR weed control can be a challenge, particularly when using ST.

Soil health benefits of reduced tillage, as indicated by microbial biomass and diversity, were not consistently observed during the short duration of treatments in this study. There were some trends of increased microbial biomass and activity, but a longer-term study would likely be necessary to find significant differences. We also found consistently higher microbial biomass in surface soil. While nitrate leaching was reduced under NT and ST during the first part of the 2014 season, differences were not observed for the remainder of the study. Overall, soil and water quality benefits associated reduced tillage management were not consistently seen in this study, but sufficient trends were observed to warrant further study.

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Table 3.1. Schedule of major field operations and data collection events for the organic pepper experiment, Ames, IA, 2014 and 2015.

	Date	
Event	2013–2014	2014–2015
Seeded cover crop	10 Sept. 2013	8 Sept. 2014
Soil samples taken	8 Apr., 22 Oct.	6 Apr., 23 Sept.
Peppers seeded in greenhouse	11 Apr.	8 Apr.
Tilled strips[v]	14 Nov., 11 June	12 Oct., 4 June
Cover crop biomass samples taken	7 May[w], 3 June[x]	13 May[w], 1 June[x]
Cover crop flail mowed and tilled in[w]	7 May	13 May
Cover crop roller-crimped[x]	3 June	1 June
Preplant fertilizer applied	11 June	5 June
Seedbed made using rotary tiller[w]	11 June	5 June
Pepper plugs transplanted	13 June	9 June
Lysimeter sample collection period	1 July–3 Oct.	1 July–18 Sept.
Weed biomass samples taken	2 July	8 July
Fertigation applications[y]	4, 17, & 26 July, 8 Aug.	2, 9, 14, & 21 July
Microbial biomass soil samples taken	8 July, 13 Aug.[z], 29 Sept.	2 July, 13 Aug.[z], 23 Sept.
Crop rows hand weeded	16 July	14 July
Plant height, stem diameter, SPAD measurements taken; leaf-petiole samples collected	8 Aug.	26 July
Harvest period	21 Aug.–3 Oct.	31 July–22 Sept.

[v]Applies to strip tillage treatment only.
[w]Applies to conventional tillage treatment only.
[x]Applies to strip tillage and no tillage treatments only.
[y]Applies to Split fertility treatment only.
[z]Samples also analyzed for community-level physiological profile (CLPP)

Table 3.2. Effects of no tillage, strip tillage, and conventional tillage on minimum, mean, and maximum soil temperature (°C) at 15 cm depth during early, mid, and late seasons of pepper production, Ames, IA, 2014 and 2015.

Treatment[y]	Minimum			Mean			Maximum		
	Early[x]	Mid	Late	Early	Mid	Late	Early	Mid	Late
2014									
CT	20.3 a[z]	22.0 a	16.9	22.7 a	25.2 a	18.8	25.2 a	27.0 a	20.8 a
NT	18.9 b	20.5 b	16.7	20.7 c	23.1 c	18.1	22.6 c	23.6 c	19.7 b
ST	18.9 b	20.7 b	16.4	21.4 b	23.7 b	18.6	24.2 b	25.6 b	21.5 a
Significance	***	***	NS	***	***	NS	***	***	*
2015									
CT	22.1 a	22.9 a	19.3	24.7 a	24.4 a	21.4 a	27.7 a	27.8 a	23.9 a
NT	20.6 b	21.7 b	19.3	22.3 c	22.0 c	20.5 b	24.1 b	24.7 b	22.0 b
ST	20.8 b	22.0 b	19.3	22.8 b	22.9 b	20.9 ab	25.1 b	25.6 b	22.7 b
Significance	***	***	NS	***	***	*	***	***	*

[x]Early: 14 June – 21 July 2014; 14 June – 17 July 2015. Mid: 22 July – 28 Aug. 2014; 18 July – 19 Aug. 2015. Late: 29 Aug. – 2 Oct. 2014; 20 Aug. – 22 Sept. 2015.

[y]CT= Conventional tillage; ST=Strip tillage; NT=No tillage.

[z]Means within a column and year followed by the same letter are not significantly different according to Fisher's protected lsd ($P \leq 0.05$).

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, based on F test

Table 3.3. Effects of tillage treatments on volumetric soil moisture content (m^3 m^{-3} soil) measured at 15 cm depth during early, mid, and late seasons[x] of pepper production, Ames, IA, 2014 and 2015.

	2014			2015		
Treatment[y]	Early	Mid	Late	Early	Mid	Late
CT	40.1[z]	38.7	39.2	29.8 b	29.4 b	30.8
ST	40.3	38.8	39.7	34.4 a	33.3 a	33.5
NT	39.4	37.9	39.0	34.4 a	32.9 a	33.0
Significance	NS	NS	NS	***	**	NS

[x]Early: 26 June – 31 July 2014; 20 June – 22 July 2015. Mid: 1 Aug. – 31 Aug. 2014; 23 July – 23 Aug. 2015. Late: 1 Sept. – 2 Oct. 2014; 24 Aug. – 24 Sept. 2015.

[y]CT= Conventional tillage; ST=Strip tillage; NT=No tillage.

[z]Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD ($P \leq 0.05$).

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, based on F test

Table 3.4. Marketable and total pepper yield as affected by tillage and fertility treatments, Ames, IA, 2014 and 2015.

Treatment[y]	2014				2015			
	Marketable		Total		Marketable		Total	
	Yield (Mg ha^{-1})	No. of fruits (1000s ha^{-1})	Yield (Mg ha^{-1})	No. of fruits (1000s ha^{-1})	Yield (Mg ha^{-1})	No. of fruits (1000s ha^{-1})	Yield (Mg ha^{-1})	No. of fruits (1000s ha^{-1})
Tillage (T)								
CT	17.9	107	21.5	140	37.7 a	202 a	43.8 a	257 a
NT	16.0	96	19.9	134	21.8 b	143 b	27.7 b	208 b
ST	16.6	102	26.4	152	23.4 b	139 b	29.3 b	193 b
Significance	NS	NS	NS	NS	**	**	**	*
Fertility (F)								
Preplant	18.9 a[z]	114 a	25.6	156 a	26.1	153 b	31.4 b	203 b
Split	14.7 b	90 b	19.6	127 b	29.2	169 a	35.8 a	236 a
Significance	**	**	NS	**	NS	*	*	**
T × F	NS	NS	NS	NS	NS	NS	NS	*

[y]CT= Conventional tillage; ST=Strip tillage; NT=No tillage; Preplant = only preplant fertilizer; Split = 2/3 of N from preplant fertilizer and 1/3 from fertigation.

[z]Means within a column and treatment followed by the same letter are not significantly different according to Fisher's protected LSD ($P \leq 0.05$).

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, based on F test

Table 3.5. Plant growth (leaf nitrogen concentration, SPAD readings, plant height, stem diameter, and dry weight) as affected by tillage and fertility treatments, Ames, IA, 2014 and 2015[u].

Treatment[v]	2014					2015				
	Leaf N[w] %	SPAD	Plant height (cm)	Stem dia[x] (mm)	Plant dry weight[y] (g)	Leaf N %	SPAD	Plant height (cm)	Stem dia (mm)	Plant dry weight (g)
Tillage (T)										
CT	5.1 a[z]	60.0	35.3	9.0	109.3	4.6 a	67.3 a	52.1	12.6	211.2
NT	4.5 b	58.0	38.4	9.3	91.5	4.2 b	60.1 b	54.7	12.4	211.1
ST	4.5 b	57.5	39.8	10.2	105.5	3.9 b	60.9 b	56.0	12.3	205.9
Significance	*	NS	NS	NS	NS	*	***	NS	NS	NS
Fertility (F)										
Preplant	4.8	59.9 a	39.3 a	9.6	109.6	4.2	63.3	54.1	12.4	213.3
Split	4.6	57.1 b	36.4 b	9.4	94.6	4.2	62.2	54.4	12.5	205.5
Significance	NS	**	**	NS	NS	NS	NS	NS	NS	NS
T × F	NS	NS	NS	NS	NS	NS	NS	NS	*	NS

[u]Leaf N, SPAD, height, and diameter measurements were taken on 8 Aug. 2014 and 26 July 2015, after the final fertigation event. Plant dry weight samples were collected on 3 Oct. 2014 and 22 Sept. 2015.
[v]CT= Conventional tillage; ST=strip tillage; no tillage (NT). Preplant = only preplant fertilizer; Split = 2/3 of N from preplant fertilizer and 1/3 from fertigation.
[w]Percent nitrogen of dried and ground leaf-petioles. Samples were comprised of 40 pepper leaves.
[x]Stem diameter measured 2 cm above soil level.
[y]Dry weight of two whole plants with fruits removed.
[z]Means within the same column and treatment followed by the same letter are not statistically different according to Fisher's protected LSD ($P \leq 0.05$).
NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, based on F test.

Table 3.6. Aboveground biomass and carbon-to-nitrogen (C:N) ratio of cereal rye/hairy vetch cover crop at time of termination with roller crimper, Ames, IA, 2014 and 2015.

	2014		2015	
Treatment[y]	Dry weight (Mg ha^{-1})	C:N Ratio	Dry weight (Mg ha^{-1})	C:N Ratio
CT	6.7 b[z]	19 c[z]	4.0 c	24 c
NT	13.9 a	40 a	6.5 b	37 a
ST	13.7 a	35 b	9.5 a	32 b
Significance	***	***	***	***

[y]CT= Conventional tillage; ST=Strip tillage; NT=No tillage.
[z]Medians within dry weight columns and means within C:N ratio columns followed by the same letter are not significantly different according to Fisher's protected LSD ($P \leq 0.05$). Dry weight data were log-transformed for homogeneity of variance and converted to original units for presentation.
NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, based on F test.

Table 3.7. Main effects of tillage, fertility, sampling region, and sampling depth on microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) on early mid, and late sampling dates[x], Ames, IA, 2014.

	MBC ($\mu g\ g^{-1}$ oven-dry soil)			MBN ($\mu g\ g^{-1}$ oven-dry soil)		
	Early	Mid	Late	Early	Mid	Late
Tillage						
Conventional (CT)	452[z]	334	568	87	51	78
No tillage (NT)	498	320	528	108	48	73
Strip tillage (ST)	440	335	580	90	48	83
Fertility[y]						
Preplant	464	341	538	101	51	75
Split	462	319	580	89	48	81
Region						
Between-row	466	305	544	90	44	76
In-row	459	357	573	100	56	80
Depth						
0–7.5 cm	495	367	596	101	56	85
7.5–15 cm	432	297	522	89	43	72
Contrasts						
CT vs. NT	0.1977	0.5599	0.3423	**0.0512**	0.6153	0.5498
CT vs. ST	0.7268	0.9794	0.7784	0.7508	0.6171	0.5976
NT vs. ST	0.1061	0.5428	0.2229	**0.1020**	0.9980	0.2641
Fertility	0.9405	0.2143	0.1552	0.1643	0.5149	0.4470
Region	0.7471	**0.0010**	0.2865	0.2399	**0.0082**	0.5962
Depth	**0.0046***	**<.0001**	**0.0065**	0.1416	**0.0037**	**0.0710**

[x]Early = 8 July 2014; Mid = 14 Aug. 2014; Late = 30 Sept. 2014.

[y]Preplant = only preplant fertilizer; Split = 2/3 of N from preplant fertilizer and 1/3 from fertigation.

[z]Data were log-transformed for homogeneity of variance and converted to original units for presentation.

*P-values highlighted in bold font are significant ($P \leq 0.10$) based on 1-df contrasts.

Table 3.8. Main effects of tillage, fertility, sampling region, and sampling depth on microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) on early, mid, and late sampling dates, Ames, IA, 2015.

	MBC ($\mu g\ g^{-1}$ oven-dry soil)			MBN ($\mu g\ g^{-1}$ oven-dry soil)		
Treatment:	Early[x]	Mid	Late	Early	Mid	Late
Tillage						
Conventional (CT)	832[z]	729	698	118	87	100
No tillage (NT)	891	788	789	116	102	124
Strip tillage (ST)	914	819	744	123	104	116
Fertility[y]						
Preplant	870	776	754	119	98	115
Split	887	779	732	120	97	111
Region						
Between-row	896	787	744	128	98	112
In-row	861	768	742	111	97	114
Depth						
0–7.5 cm	902	843	831	118	104	124
7.5–15 cm	856	718	664	120	91	103
Contrasts						
CT vs. NT	0.3817	0.2906	0.1821	0.8783	**0.0872**	**0.1026**
CT vs. ST	0.2328	0.1245	0.4824	0.7852	**0.0618**	0.2750
NT vs. ST	0.7393	0.5992	0.5174	0.6704	0.8736	0.5867
Fertility	0.7094	0.9318	0.6503	0.9374	0.9219	0.7474
Region	0.4027	0.5524	0.9692	0.1776	0.9478	0.9069
Depth	0.2744	**0.0001***	**0.0002**	0.8339	**0.0965**	**0.0846**

[x]Early 1 = 2 July 2015; Mid = 14 Aug. 2015; Late = 23 Sept. 2015.

[y]Preplant = only preplant fertilizer; Split = 2/3 of N from preplant fertilizer and 1/3 from fertigation.

[z]Data were log-transformed for homogeneity of variance and converted to original units for presentation.

*P-values highlighted in bold font are significant ($P \leq 0.10$) based on 1-df contrasts.

Table 3.9. Interaction effects of sampling depth, region, and tillage treatment on average well color development (AWCD) and substrate richness based on community-level physiological profiling, Ames, IA, 2014 and 2015.

Treatment			AWCD		Richness	
Depth	Region	Tillage	2014	2015	2014	2015
0 – 7.5 cm	Between-row	Conventional	0.385[z]	0.629	21.3	24.9
		No tillage	0.415	1.088	18.2	26.7
		Strip tillage	0.274	1.247	19.0	28.3
	In-row	Conventional	0.351	1.010	21.0	25.8
		No tillage	0.507	1.033	17.2	25.8
		Strip tillage	0.429	1.189	21.7	27.5
7.5 – 15 cm	Between-row	Conventional	0.308	0.665	20.7	22.7
		No tillage	0.346	0.747	19.7	23.3
		Strip tillage	0.223	1.065	16.5	26.5
	In-row	Conventional	0.357	0.661	20.7	22.0
		No tillage	0.260	0.989	19.0	19.2
		Strip tillage	0.465	1.166	22.3	27.2
	Significance					
		Depth (D)	0.1198	**0.0026***	0.9545	0.0867
		Region (R)	0.1087	0.4056	0.5451	0.7095
		Tillage (T)	0.7546	0.0588	0.6646	0.7107
		D × R	0.9756	0.8062	0.6646	0.7107
		D × T	0.3220	0.7055	0.5383	0.3264
		R × T	0.1097	0.8397	0.7337	0.5553
		D × R × T	0.3582	**0.0185**	0.4594	0.8493

[z]Data were log-transformed for analysis and converted to original units for presentation.
*P-values highlighted in bold font are significant ($P \leq 0.05$) based on 1-df contrasts.

Table 3.10. Post-harvest soil chemical characteristics as affected by tillage and fertility treatments, Ames, IA, 2014 and 2015.

Treatment[y]	2014					2015				
	Inorg. N	P	K	pH[z]	OM[z]	Inorg. N	P	K	pH	OM
	(mg kg^{-1})				(%)	(mg kg^{-1})				(%)
Tillage										
CT	0.22	25	146	6.7	3.3	1.11	33	116	6.6	4.0
NT	0.32	34	132	6.8	3.2	1.55	45	112	6.8	4.0
ST	0.29	34	144	6.7	3.2	1.25	36	98	6.7	4.0
Significance	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Fertilty										
Preplant	0.25	38	138	---	---	1.48	52	113	---	---
Split	0.29	39	144	---	---	1.11	42	112	---	---
Significance	NS	NS	NS			NS	NS	NS		

[y]CT= Conventional tillage; ST=Strip tillage; NT=No tillage; Preplant = only preplant fertilizer; Split = 2/3 of N from preplant fertilizer and 1/3 from fertigation.

[z]pH and organic matter (OM) were sampled only to the whole plot level before fertilizer treatments were applied.

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, based on F test.

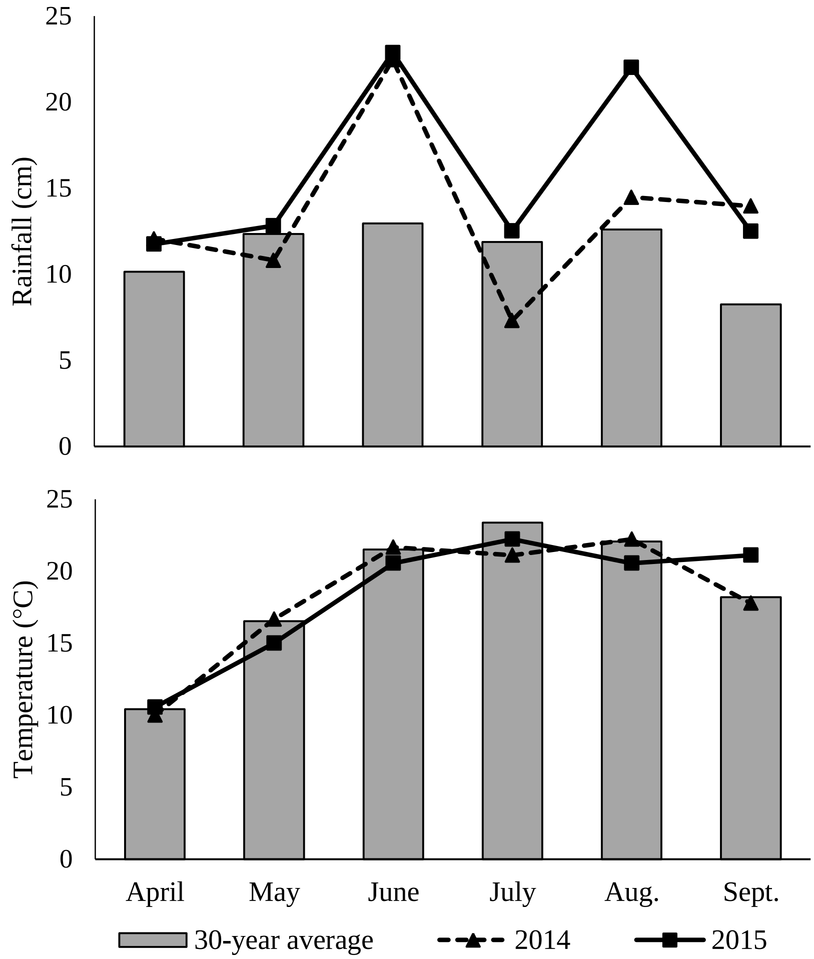

Fig. 3.1. Average monthly rainfall (above) and air temperature (below) in 2014 and 2015 compared with 30-year averages in Ames, IA. Data were obtained from the Iowa Environmental Mesonet Network, Iowa State University.

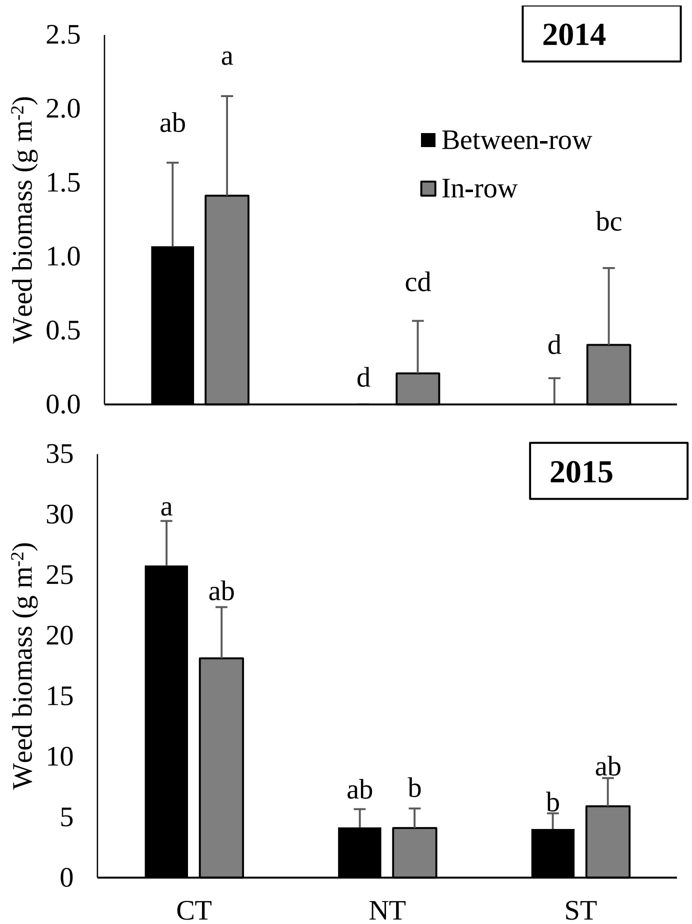

Fig. 3.2. Weed biomass in between-row and in-row regions of conventional tillage (CT), no tillage (NT), and strip tillage (ST) plots in 2014 (top) and 2015 (bottom). Samples were taken on 2 July 2014 and 8 July 2015. Bars with labels not containing the same letter are significantly different according to Fisher's protected LSD ($P \leq 0.05$). Error bars represent standard errors of means.

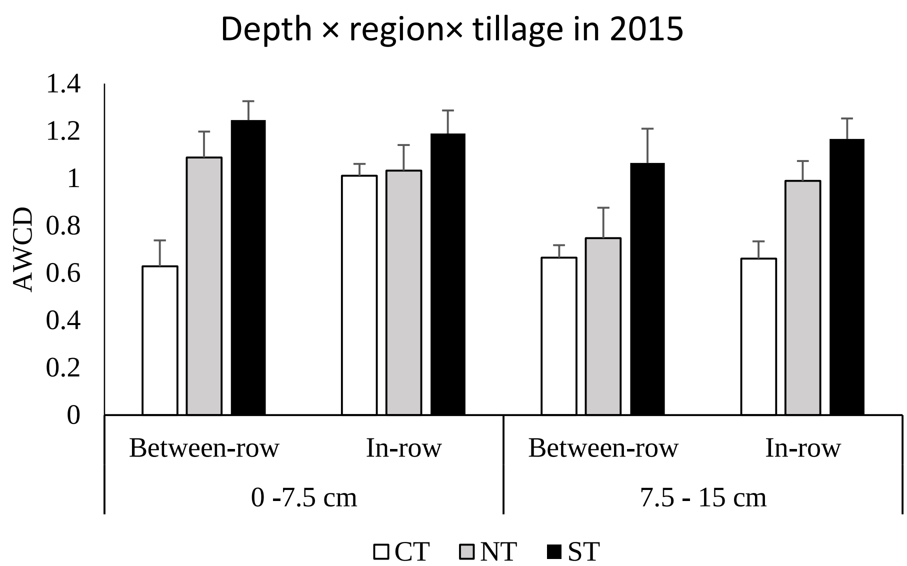

Fig. 3.3. Interaction effects of sampling depth, region, and tillage treatment on average well color development (AWCD) in Biolog-Ecoplates© in 2015. Error bars represent standard errors of means.

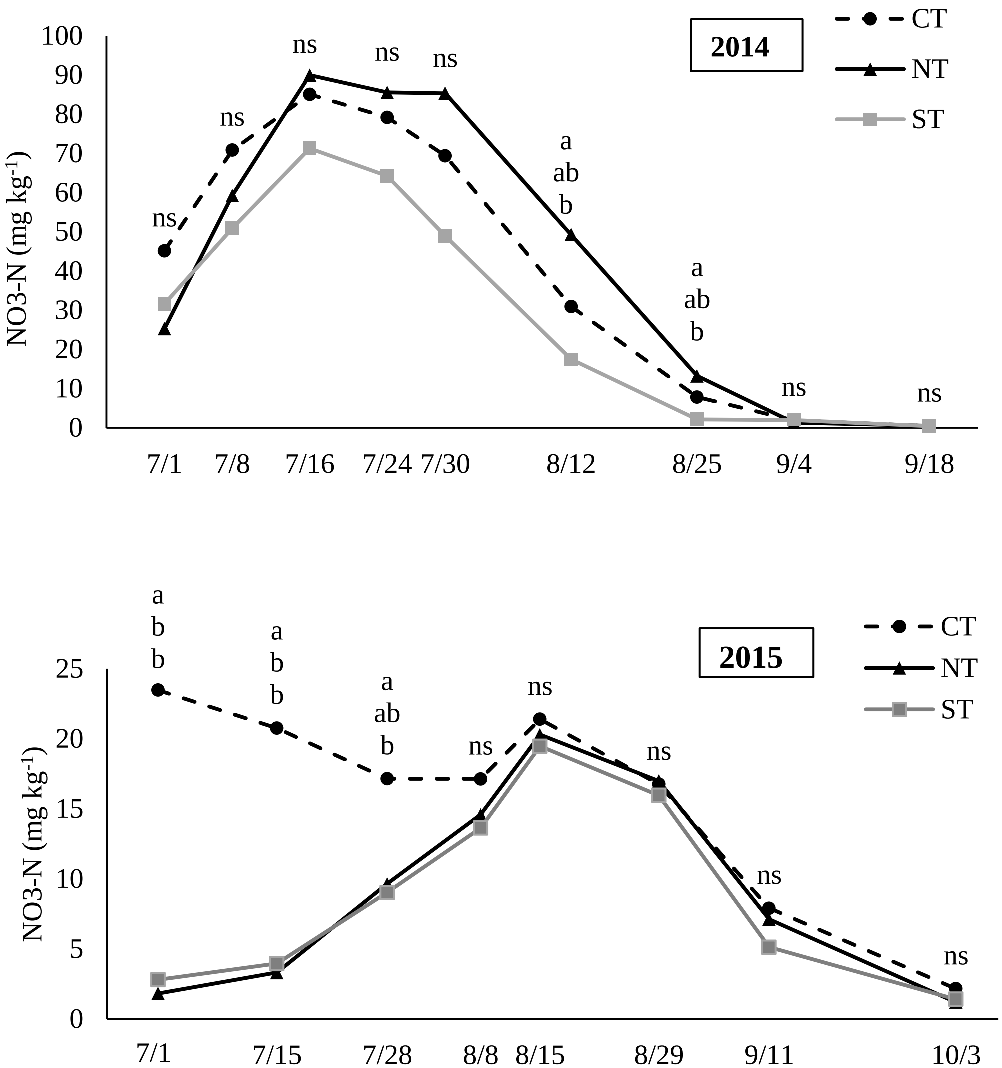

Fig. 3.4. Nitrate-N concentration in leachate under conventional tillage (CT), no tillage (NT), and strip tillage (ST). Samples were collected on different dates in 2014 (above) and 2015 (below) from lysimeters installed to 24-inch depth. Points within a date containing the same letter are not significantly different according to Fisher's protected LSD ($P \leq 0.05$). NS = nonsignificant.

CHAPTER 4. CONCLUSIONS

Organic no tillage (NT) and strip tillage (ST) provided yields equivalent to conventional tillage (CT) for both bell pepper and broccoli in one out of two years, but year-to-year variability prevents us from drawing conclusions about the suitability of these systems in organic vegetable production. The poor performance of NT and ST broccoli in 2014 may have been related to the high volume of rain in late-June, which caused prolonged saturated soil conditions. Because broccoli yield in all treatments was low in 2014 compared to 2015 yields and the national average, it seems prudent not to make strong conclusions based on the results of the 2014 season. Pepper yields were higher for all treatments in 2015. Even though CT yield was the highest yielding treatment in 2015, NT and ST yields were 35% to 40% higher in 2015 than in 2014. It is likely that the change in field plot location between years, which resulted in alfalfa preceding the 2015 experiment, played a role in the overall increase in yield of both crops. Attempts should be made in future studies to apply treatments to the same plots in each year, or if cover crop establishment timing prevents use of the same site, as it did in this study, to choose sites with soils of the same classification to reduce the potentially confounding influence of environment on treatment effects.

A major question in this research was whether ST could combine the yield-enhancing characteristics of CT with the soil-conserving properties of cover crop-based NT. Strip tillage did generally increase soil temperature compared with NT, but it did not raise soil temperature to the level measured under CT, as was observed by Licht and Al-Kaisi (2005). A possible explanation for this is the presence of the rolled cover crop mulch in this study, which may have provided greater insulation than the corn or soybean residue present in prior conventional NT studies. Despite increasing soil temperature, ST yield was not significantly different from NT for broccoli or pepper in either year. Plant growth was also similar between NT and ST, indicating that IR tillage did not lead to increased N uptake or plant growth. It is possible that the increased mean temperature under ST, although statistically higher (0.4–0.9 °C in the pepper study), was not of a magnitude to affect yield. While strips were tilled for the first time in the fall, the cereal rye/hairy vetch cover crop growth quickly shaded the strip in the spring, likely minimizing solar gain in tilled soil during the time leading up to planting. Had the cover crop been rolled and strips re-tilled for a longer duration preceding crop planting, the benefit of ST over NT may have been more pronounced. The lack of a yield increase for broccoli or pepper, combined with a greater potential for IR weed competition, leads us to conclude that ST is not better suited than NT for use in organic vegetable production in the Upper Midwest.

As described in Chapter 3, NT and ST did not consistently increase soil microbial biomass or diversity—two indicators of overall soil health—compared with CT. This may have been due to re-location of the field plot from year to year, resulting in only a single season of reduced tillage management at the time of soil health measurement. However, the need for periodic tillage to control perennial weeds in organic NT and ST systems (Mirsky et al., 2012) leaves questions about the positive effects these systems may have on soil physical and biological properties. For example, Grandy et al. (2006) found that tilling soils which had previously been under long-term conventional NT management significantly decreased soil aggregation as soon as 31 d after the tillage event. In contrast, VandenBygaart and Kay (2004) measured changes in soil organic carbon (SOC) after plowing a long-term NT field and found homogenization of SOC throughout the soil profile, but no changes in total SOC in sandy clay loam, silty clay loam, and high-initial-SOC sandy loam soils, 18 months. after the tillage event. That study measured effects of only a single tillage event, after 22 years of NT management, so it is unclear how more frequent tillage events would affect soil health in rotational NT systems. Despite questions about the effects of rotational NT on soil biology and structure, use of a fall cover crop and the retention of the rolled mulch throughout the season should provide consistent protection from soil erosion, a clear benefit of this system.

While adding fall-sown cover crops into a rotation has consistently been shown to decrease nitrate leaching (Dabney et al., 2001; Staver and Brinsfield, 1998), reducing tillage, by itself, has not. Compared with CT, the generally cooler and less aerated soils under NT slow microbially mediated mineralization of soil organic matter. This reduces concentrations of NH_4^+ ions, and in turn, the concentration of leachable NO_3^- ions as a result of nitrification. However, despite lower soil NO_3^- concentrations, NT does not consistently reduce total NO_3-N lost via leaching, in part because of the development of more continuous pores in NT soils increases the drainage rate of soil water (Di and Cameron, 2002). We did not observe consistent reductions in NO_3-N concentrations in leachate under NT or ST. This may be explained by the fact that the CT treatment included a cover crop—as is standard in tilled organic systems—which is known to be one of the most effective tools for reducing NO_3^- leaching. Unfortunately, we did not monitor the total volume of leachate in this study, so it is difficult to conclude how the tillage systems evaluated would affect landscape-scale NO_3^- leaching.

Overall, the effects of organic rotational NT and ST systems remain mixed. This and previous studies have shown that NT and ST can achieve vegetable yields equal to those of CT, but variability in yield remains an impediment to drawing broad conclusions. Furthermore, soil health benefits could not be consistently shown in this study, and research to date has not demonstrated the capacity of organic *rotational* NT systems to improve soil biological and physical properties. Areas of future research and development should include the following:

1. Quantify the soil health benefits of organic NT over longer periods of implementation, both with and without periodic tillage.
2. Monitor plant N status and soil inorganic-N concentrations frequently throughout the season to identify whether periods of N deficiency may be inhibiting crop growth and yield under organic NT.
3. Test effects of different rates of N fertilization in NT systems to determine whether vegetable crops respond differently to N under NT compared to CT. Most N recommendations for vegetable crops were established based on use of CT. A long-term experiment established on previously tilled soil would be best, as it would tell us whether improvements in soil health under NT would lead to decreased supplemental fertilizer requirements.
4. Monitor both NO_3-N concentration in leachate, as well as total volume leached, to identify the quantity of NO_3-N lost per unit area.
5. Breed for earlier-maturing hairy vetch varieties to synchronize maturity with cereal rye.

6. Evaluate spring- and summer-sown cover crops for use in organic NT systems in order to broaden the planting window for vegetable crops in such systems. This would build on the work already done by Schellenberg et al. (2009).
7. Develop improved NT transplanting equipment that establishes transplants with minimal disturbance to rolled cover crop mulch.

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