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# Strip-tillage decreases soil nitrogen availability and increases the potential for N losses in a cover cropped organic system

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A R T I C L E I N F O

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A B S T R A C T

Reduced-tillage systems that augment soil inorganic N availability while reducing N losses can improve the nitrogen-use efficiency of cover crop-based organic cropping systems. We conducted a three year full factorial field experiment in the upper Midwest, USA to examine the effects of strip-tillage and a cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) cover crop mixture on (1) soil inorganic nitrogen (N) concentrations throughout the growing season, (2) sweet corn (*Zea mays* L.) crop productivity and N uptake, and (3) potential N loss via denitrification and leaching. We compared full-width tillage (FWT) vs. strip-tillage (ST) with and without a rye-vetch cover crop. ST decreased soil inorganic N concentrations 16–40% compared to FWT, with soil inorganic N higher in the tilled in-row zone compared to the undisturbed between-row zone in 1 of 3 years. The rye-vetch cover crop did not provide a consistent increase in soil inorganic N. ST increased soil leachate N concentrations by ~50% and increased the potential for denitrification by 18% but depressed sweet corn biomass and N contents in only one of three years, when hairy vetch biomass and soil moisture was lowest. We conclude that utilizing ST in combination with a cover crop is not likely to improve N use efficiency or crop yields, and may increase N losses within an organic cover crop-based cropping system.

## 1. Introduction

Reducing or eliminating tillage can provide a number of ecological and agronomic benefits in annual cropping systems, including increased soil aggregation and organic matter accumulation (Bhardwaj et al., 2011; Franzluebbers, 2002; Wander and Bollero, 1999; West and Post, 2002), and reduced soil erosion (Karlen et al., 1994; Triplett and Dick, 2008) and fuel use (Gebhardt et al. 1985; Phillips et al., 1980). No-till, or the complete elimination of tillage, is promoted as an effective strategy of climate change adaptation (Palm et al. 2014; Paustian et al., 1997), due to its potential to increase soil water infiltration and water holding capacity (Franzluebbers, 2002; Mahli and O'Sullivan, 1990). However, tillage provides a number of important services in cropping systems, including weed control and the incorporation of plant residues, which are especially important in organic systems. No-till can result in poor crop performance due to reduced soil temperatures and residue interference at planting (Mahli and O'Sullivan, 1990; Mirsky et al., 2012), greater weed competition (Brainard et al., 2013; Mirsky et al. 2012), and reduced pools of inorganic N (Doane et al., 2009; Dou et al., 1994).

Reduced plant available N has been widely reported in no-till systems (Dou et al., 1995; Johnson and Hoyt, 1999), especially ones that rely on a preceding legume cover crop as the primary nitrogen input. Cover crop residues that remain on the soil surface exhibit reduced rates of decomposition and N mineralization (Drinkwater et al., 2000; Dou et al., 1994; Varco et al., 1993), especially in years or sites with cool or dry soil conditions (Dou et al., 1995; Cook et al., 2010; Rannells and Wagger, 1996; Ruffo and Bollero, 2003). However, lower pools of inorganic N in no-till may also decrease reactive N lost to the environment through leaching or denitrification (Dinnes et al., 2002; Constantin et al., 2010).

Strip-tillage (ST) utilizes a combination of narrowly placed disks and rolling baskets (often attached to a shank) to confine tillage to a narrow strip where the crop will be planted (Luna and Staben, 2002). This divides the cropping system into two distinct adjacent zones: tilled and untilled. Tillage within the crop row can create a finer seedbed (Licht and Al-kaisi, 2005) and the untilled zone between rows maintains the

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benefits of no till, such as improved water infiltration, soil organic matter retention, and decreased erosion (Franzluebbers, 2002; Johnson and Hoyt, 1999; Karlen et al., 1994; Syswerda et al., 2011). Strip-tillage enables a greater level of control over organic matter turnover. Incorporating crop residue within-row enables faster decomposition and mineralization of organic matter to increase nutrient availability within the immediate rooting zone of crops. The between-row (BR) zone is left undisturbed, and when combined with a preceding cover crop, residue is preserved on the soil surface for weed suppression, soil moisture conservation, and reduced soil erosion Mohler and Teasdale, 1993; Unger and Vigil, 1998).

Compared to no-till, ST effects on soil N dynamics have been much less studied. Haramoto and Brainard (2012) found that in the absence of a cover crop, ST decreased soil inorganic N within the crop row compared to conventional full-width tillage (FWT); however, when an oat cover crop was present, soil inorganic N was equivalent in the two tillage systems. Al-Kaisi and Licht (2004) found few significant differences in soil leachate N concentrations among no-till, ST, and FWT, but both ST and no-till resulted in lower N accumulation at deeper depths. Sainju et al. (2007) did not find any differences in N accumulated in the soil profile between ST and conventional FWT. Thus far, research on ST effects on inorganic N and N losses has mostly occurred in production systems reliant on fertilizers (Al-Kaisi and Licht, 2004; Jokela and Nair, 2016) rather than cover crops.

Here we examine the effects of ST with and without a cereal rye and hairy vetch cover crop on (1) soil inorganic N concentrations throughout the growing season, (2) crop productivity and N uptake, and (3) the potential for N losses through denitrification and leaching within a sweet corn crop. Regardless of cover crop presence, we hypothesize that ST will decrease system-wide soil inorganic N concentrations compared to FWT, thus resulting in lower denitrification and N leaching potentials. We also hypothesize that within ST, soil inorganic N concentrations will be higher in within-row compared to between-row zones, and will be equivalent to N concentrations in FWT, resulting in equivalent crop N uptake, biomass, and sweet corn yield.

## 2. Materials and methods

### 2.1. Site description and experimental design

The experiment was conducted for three years beginning in Fall 2012 on proximate fields organically managed for 5–7 years at the W.K. Kellogg Biological Station in Hickory Corners, MI (85°24′W, 42°24′ N). Mean annual precipitation (30-year mean) is 1005 mm and mean annual temperature is 10.1 °C. Soils are well-drained co-mingled Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, mesic Typic Hapludalfs) loams (Crum and Collins, 1995), developed on glacial outwash with intermixed loess (Luehmann et al., 2016).

Each fall we established four treatments in a full factorial combination of two tillage levels (ST vs. FWT) and two levels of cover crop (Rye-Vetch vs. No cover crop (NoCC)). The plots without the rye and vetch cover crop consisted of winter annual weeds. The experiment alternated each year between two fields in close proximity over the three-year study (year 1 in field 1, year 2 in field 2, and year 3 back to field 1). Prior to our study, the fields were either in winter wheat or cereal rye grown for seed. Within each cover crop and tillage combination we included a split plot crop factor with two levels (with a sweet corn crop (With Corn) or without a crop (Bare Soil); Fig. 1a and b). The Bare Soil subplots (in which sweet corn plants were immediately removed after emergence) allowed us to examine patterns in soil inorganic N without crop uptake, thereby providing a better characterization of N availability to the crop (Fig. 1c and d). Zones within the cropping systems were also treated as sub-plots: within-row (WR) is the 25.4 cm zone where the crop was planted and where tillage occurred. Between-row (BR) is the 50.8 cm zone between crop rows that was left untilled in the ST treatment (Fig. 1). The sweet corn sub-plots measured 27.3 $m^2$ (9.1 m × 3.0 m), 37.2 $m^2$ (6.1 m × 6.1 m), and 41.0 $m^2$ (9.1 m × 4.5 m) in 2012, 2013, and 2014 respectively. Bare Soil subplots were 9.0 $m^2$ (3.0 m × 3.0 m) in 2012 and 2013, and 20.3 $m^2$ (4.5 m × 4.5 m) in 2014.

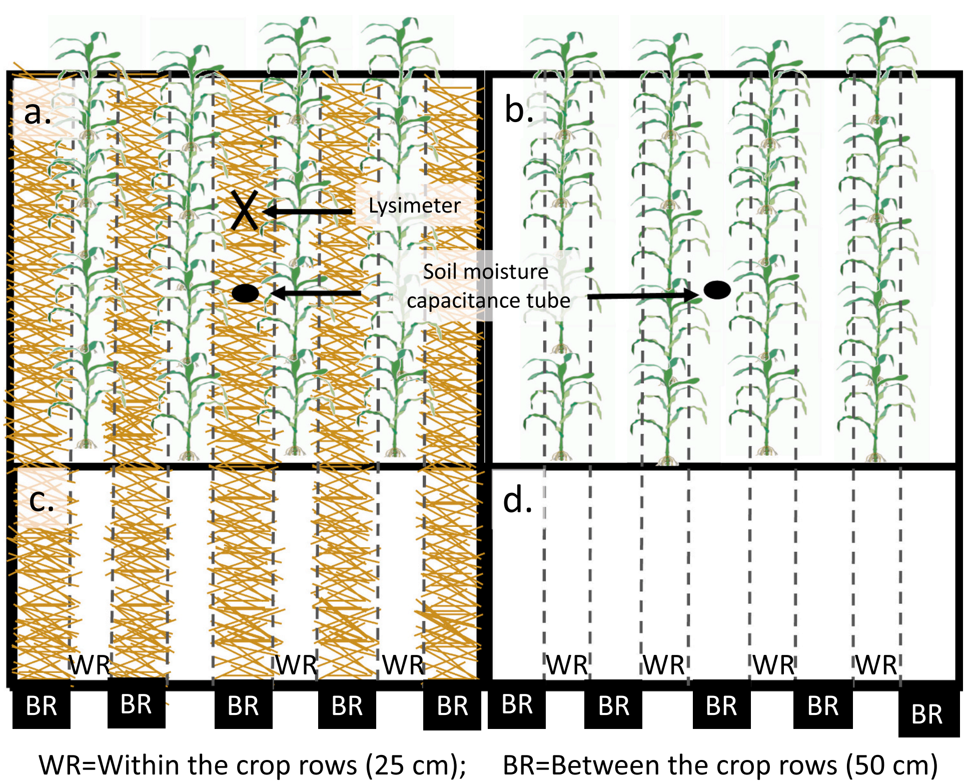


**Fig. 1.** Location of sampling for key response variables. Main plots consisted of a full factorial of tillage (Strip-tillage (a and c) and Full-width tillage (b and d)) and Cover Crop (Rye-Vetch and No Cover Crop). Main plots were split into subplots including: (a and b) with a sweet corn crop and (c and d) Bare Soil. Sweet corn, lysimeter and denitrification data were taken from the sweet corn subplots (Lysimeter data were only collected from Rye-Vetch plots). Soil inorganic N samples were collected throughout both the between-row (BR) and within-row (WR) zones but excluded from approximately 2.5 cm from the border of the BR/WR zones.

### 2.2. Agronomic Management

Field activities were performed as described in Table 1. Both cereal rye and hairy vetch seeds ("Variety Not Stated") were organically certified. Cereal rye was planted with a grain drill at 62.7 kg $ha^{-1}$. Hairy vetch was planted with a Jang push-seeder at 22.4 kg $ha^{-1}$. Between-row spacing for cereal rye and hairy vetch was 19 cm. No N fertilizers were added prior to planting either the cover crop or sweet corn crop. Additional organic forms of P and K were added according to soil tests: 34 kg K $ha^{-1}$ and 34 kg P $ha^{-1}$ as NOP certified potassium sulfate plus and Tennessee brown phosphate, respectively, in 2012 and 34 kg K $ha^{-1}$ of potassium sulfate plus in 2013.

Once hairy vetch reached approximately 50% flowering in mid- to late-May of each year, cover crops were flail mowed twice to reduce interference with ST equipment and reduce potential for cover crop regrowth (we saw negligible cover crop regrowth in any year). FWT treatments were chisel plowed to a 20–25 cm depth, and then rototilled to break up and incorporate cover crop residue. A Hiniker (Hiniker Model 6000, Mankato, MN) two-row strip tiller (with a 25 cm depth shank and equipped with cutting-coulter, berming discs, and rolling basket) was used for WR tillage in ST plots. To improve soil tilth in ST plots, a walk behind rototiller was used to simulate a multivator for secondary tillage within the ST WR, a common practice among vegetable growers that use strip-tillage. The resulting WR zone was approximately 25.4 cm wide and 20–25 cm deep.

Two weeks after cover crop termination, sweet corn (variety 'Luscious') was planted in all treatments using a high residue planter (Monosem vacuum seeder, Monosem, Edwardsville, KS) at a row spacing of 76 cm, and the in-row spacing of sweet corn seeds was 10 cm. Once sweet corn emerged, population density was thinned to an in-row spacing of 16.5–20 cm, and removed via hoeing in Bare Soil subplots (Fig. 1). Weeds were removed through a combination of hand weeding and hoeing. Sweet corn was irrigated during low-rainfall periods in 2012 and 2014, totaling 62.2 and 46.8 mm of irrigation water, respectively, applied throughout the sweet corn season.

### 2.3. Cover crop biomass and C:N ratio

Dry weights of cover crop and winter annual weed biomass were obtained before cover crop termination by clipping shoot tissue at ground level from two 0.25-$m^2$ quadrats in every plot. Fresh cover crop biomass was separated into hairy vetch, cereal rye, and weeds, dried at 60 °C, and weighed. Aboveground tissue samples of hairy vetch and cereal rye were analyzed for total C and N at the University of California-Davis Stable Isotope Facility (SIF) using an elemental analyzer (ANCA-GSL, PDZ Europa, Norwich, Cheshire, UK). To obtain the C:N ratio of the cereal rye and vetch mixture we summed the C:N ratio of each species multiplied by its proportion in the mixture.

**Table 1**
Table of activities and operations.

| Activity | Dates of operation 2012 | 2013 | 2014 |
|---|---|---|---|
| Installed lysimeters | 11 November 2011 | 9 September 2012 | 5 September 2013 |
| Planted cover crops | 31 August 2011 | 10 September 2012 | 6 September 2013 |
| Cover crops flail-mowed | 5 June 2012 | 4 June 2013 | 10 June 2014 |
| Primary tillage[a] | 13 June 2012 | 19 June 2013 | 16 June 2014 |
| Secondary tillage[a] | 15–18 June 2012 | 19 June 2013 | 17 June 2014 |
| Planted corn | 19 June 2012 | 21 June 2013 | 27 June 2014 |
| Diviner tube installed | NA | 24 June 2013 | 30 June 2014 |
| Harvested corn | 4 September 2012 | 4 September 2013 | 11 September 2014 |

[a] Primary tillage included chisel plowing in full-width tillage, and both strip-tillage and chisel plow were to a depth of 20–25 cm. Secondary tillage included roto-tilling in full-width tillage, and we used a walk-behind roto-tiller to improve soil tilth in strip-tillage.

### 2.4. Soil inorganic N

Soil samples were collected every 7–14 days (8 times in 2012 and 2013 and 9 times in 2014) throughout the growing season in all treatments and subplots. Samples were collected throughout both the between-row (BR) and within-row (WR) zones but excluded from approximately 2.5 cm from the border of the BR/WR zones.

At each sampling date, approximately 12 cores (2.5 cm diameter and 20 cm deep) were taken from each plot and zone. Soil samples were dried at 38 °C for 2–3 days, and ground to pass through a 1-mm screen with a Wiley mill. Fifty milliliters of 1 M KCl were used to extract soil inorganic N on 10 g of dry soil. Extracts were analyzed at the Michigan State University Soil and Plant Nutrient Laboratory via the ammonium salicylate and cadmium reduction methods, respectively on a Lachat QuikChem 8500 Flow Injection (Gelderman and Beegle, 1998).

To convert soil N concentrations (sum of ammonium $NH_4^+$ and $NO_3^-$) to an areal basis, we determined soil bulk density on three soil cores (5-cm internal diameter and 25-cm depth) from both the WR (tilled) and BR (untilled) zones per plot. We then multiplied soil N concentration (g $kg^{-1}$) by the product of bulk density (Mg $m^{-3}$) and depth of sampling (m) to calculate kilograms of N per hectare (kg N $ha^{-1}$).

To calculate soil inorganic N across whole plots (WP), after conversion to areal extents we used weighted means of the measured values from the WR and BR zones adjusted by their respective areas:

$$\text{WP Soil inorganic N} = \text{WR soil inorganic N}*1/3 + \text{BR soil inorganic N}*2/3 \quad (1)$$

### 2.5. Sweet corn yield and aboveground biomass and N content

To quantify sweet corn yield, we removed all primary ears from sweet corn plants in designated harvest areas of 9.3, 14, and 22.3 $m^2$ in 2012, 2013, and 2014, respectively. Sweet corn ears were classified as nonmarketable and marketable based on the circumference of the thickest portion of the ear; marketable ears had a circumference greater than 13 cm. Secondary corn ears were grouped with nonharvested biomass and consisted of no greater than 5% of total non-harvested biomass.

To obtain sweet corn dry weight and percent N, we collected the non-harvested aboveground portion of 5 randomly sampled plants, and 5 representative corn ears from the center rows of each sweet corn subplot (Fig. 1). We removed a 2.5 cm disk from corn ears (by cutting at 2.5 cm and 5 cm from the base of the ear), dried to determine a fresh to dry weight ratio, and multiplied this ratio by total fresh weight to estimate total ear dry weight. Both nonharvested corn biomass and corn ear sections were dried at 60°C and ground to pass through a 1 mm screen. A Kjehldahl digest (Kalra, 1998) was performed on 0.15 g samples of nonharvested corn biomass and corn ears (2 lab replicates per sample) and analyzed for total Kjehldahl N with a QuikChem 8500 Flow Injection Analyzer.

### 2.6. Leachate inorganic N

Suction lysimeters (Soil Moisture Corp., Santa Barbara, CA) were installed to a depth of 1.2 m in the center of selected sweet corn subplots (Fig. 1) to examine the effects of tillage on soil leachate inorganic N concentrations. Lysimeters were installed in plots that included cereal rye and hairy vetch (ST+Rye-Vetch and FWT+Rye-Vetch) and were first installed in November 2011, taking care to avoid cover crop damage. In subsequent years lysimeters were installed prior to cover crop planting (Table 1). We inserted lysimeters into a 5 cm diameter augered hole and used a silica-sand slurry to fill the gap between the cavity wall and the lysimeter. Once lysimeters were in place, the hole was filled with ~2.5 cm of bentonite clay to minimize preferential flow through the installation hole, followed by sieved soil. Trenches (30–35 cm depth) were created to run sample collection tubes outside of plots. Soil water samples were collected within 48 h of every significant (>2 cm) rainfall or irrigation event. A 500 kPa vacuum was applied to each lysimeter which was then allowed to drain for 12–48 h prior to collection; samples were frozen until analysis.

### 2.7. Denitrification potential

We used the denitrification enzyme assay (Groffman et al. 1999) to assess denitrifier biomass and thus the potential for denitrification (including both as $N_2O$ and $N_2$) in all cover crop and tillage combinations three times in 2013 and 2014: at planting (0 days after planting; DAP), midseason (25–29 DAP) and harvest (68–77 DAP). Soil samples to 20 cm depth were collected from each tillage, zone (WR and BR), and cover crop combination in subplots with sweet corn (Fig. 1) and stored at 4 °C until analysis. Soil was then passed through a 4 mm sieve, and 25 g of moist soil were weighed into 125 mL Erlenmeyer flasks. To each flask we added 25 mL of a 2X DEA media (1.44 g/L $KNO_3$, 0.02 g/L chloramphenicol, and 0.5 g/L dextrose), then flasks were sealed and flushed with $N_2$ gas. Thirteen mL of acetylene were added to bring headspace concentrations to ~10 kPa, and flasks were placed on an orbital shaker for 90 min. Headspace samples (3 mL) were collected at 30, 60, and 90 min and stored in evacuated glass vials (5.9 mL, Exetainer; Labco, HighWycombe, UK). Headspace samples were then analyzed using a gas chromatograph (7890 A Agilent Technologies Inc., Santa Clara, CA) equipped with a $^{63}Ni$ electron capture detector operating at 350 °C. The $N_2O$ dissolved in the slurry was calculated using the Bunsen coefficient of 0.632 for 20 °C (Groffman et al., 1999). Denitrifying enzyme activity was calculated as the linear slope of $N_2O$ accumulation during incubation. Denitrification potential was adjusted by bulk density to convert to kg N $ha^{-1}$ $d^{-1}$, and WP denitrification potentials were calculated using Eq. (1).

### 2.8. Statistical analysis

All data were analyzed using linear mixed effects models using the restricted maximum likelihood (REML) method with MIXED procedure in SAS (Version 9.3, SAS Institute, Cary, NC). The experiment was modeled as a randomized complete block factorial design, with presence of a crop and zone treated as subplots where appropriate. We evaluated assumptions of normality and homogenous variances, and used unequal variance models when needed. All inorganic N data were log-transformed. When significant treatment effects were detected, means were separated using Fisher's protected LSD $P < 0.05$.

To examine the effects of tillage and cover crop on concentrations of soil inorganic N concentrations, the Bare Soil and With Corn subplots were analyzed separately. Additionally, when examining treatment effects on soil inorganic N concentrations, years were analyzed separately and date within year was treated as a repeated factor using repeated measures mixed models. AIC (Akaike) values were compared to determine the best model fit. For the With Corn subplots, fixed effects included tillage (FWT vs ST), cover crop (Rye-vetch vs. No cover crop (NoCC)) and their interactions for effects on WP concentrations of soil inorganic N. For Bare Soil subplots, fixed effects included tillage, cover crop, zone and their interactions to examine zonal differences in soil inorganic N.

N leachate concentrations were analyzed using repeated measures mixed models with date included as a repeated factor, and AIC (Akaike) values were compared to determine best model fit. For N leachate data, years were analyzed together and only the fixed effects of tillage, year, date, and their interactions were analyzed, since leachate was collected only from With Corn subplots in treatments with cereal rye and hairy vetch.

To examine the effects of tillage and cover crop on sweet corn aboveground biomass and N content, as well as for denitrification potential, years were analyzed together, and year was treated as a fixed factor. If there were no interactions between year and other fixed effects, then year was pooled. Additionally, timepoint was also treated as a fixed factor when analyzing tillage and cover crop effects on denitrification potential, and timepoints were pooled if there were no interactions with other fixed effects.

## 3. Results

### 3.1. Cover crop and weed biomass and C:N ratios

Cereal rye biomass in Rye-Vetch mixtures varied less between years than hairy vetch biomass (Table 2, and Lowry and Brainard, 2016). Hairy vetch biomass in 2013 was less than 50% of 2012 and 2014 levels. The C:N ratio of the Rye-Vetch mixture ranged from 31 to 43 and was lowest in the year in which hairy vetch constituted the greatest portion of the mixture (in 2014). Winter annual weed biomass within the NoCC treatments was between 1.4 and 2.5 Mg $ha^{-1}$ over the three years of our study, while within the Rye-Vetch treatments weed biomass ranged between 0.4 and 1.5 Mg $ha^{-1}$. The mean C:N ratio of winter annual weeds (measured only in NoCC treatments) ranged between 23 and 37.

### 3.2. Soil inorganic N concentrations

Compared to FWT, ST reduced soil inorganic N in With Corn subplots in two out of three years (2013 and 2014: $p < 0.05$, Fig. 2, Supplemental Table 1). However, these effects varied with sampling date (Till*Date: 2013 $p = 0.013$; 2014 $p = 0.015$). With Corn, the effect of tillage tended to increase until mid-July to August when soil inorganic N peaked, and then decreased until the end of the season during corn exponential growth and peak N demand. Due to crop depletion of soil inorganic N, fewer tillage differences in soil inorganic N were observed at later sampling dates, and no differences in soil inorganic N were observed by the time of crop harvest.

In Bare-Soil plots, ST reduced soil inorganic N in all three years (Fig. 2, Supplemental Table 2), and the difference in soil inorganic N between FWT and ST tended to increase throughout the summer (Till*Date: $0.001 < p < 0.002$). ST reduced the seasonal average of soil inorganic N throughout the season by only 16% in 2012, while this difference was much greater in 2014, during which ST reduced soil inorganic N by 40%. In 2013, the effect of tillage on soil inorganic N varied by cover crop (Till*Cover*Date $p = 0.006$). In 2013, ST reduced soil inorganic N by approximately 65% when combined with the Rye-Vetch cover crop, but in the NoCC treatments, ST reduced soil inorganic N by only 20%. Contrary to our expectations, WR soil inorganic N

**Table 2**
Mean (standard error of the mean (SEM)) aboveground biomass of cereal rye, hairy vetch, and total biomass, as well as C:N ratio of the mixture, in Rye-Vetch cover crop treatments.

| | Cover crop | | | | | No cover crop | |
|---|---|---|---|---|---|---|---|
| | Cereal rye | Hairy vetch | Total biomass | Winter weeds | C:N ratio | Winter weeds | C:N ratio |
| | Mg $ha^{-1}$ | | | | | Mg $ha^{-1}$ | |
| 2012 | 5.5 (0.44) | 2.7 (0.25) | 8.2 (0.45) | 1.50 (0.32) | 42.6 (2.2) | 2.5 (0.43) | 37.1 (2.0) |
| 2013 | 4.7 (0.55) | 1.3 (0.28) | 5.9 (0.64) | 0.42 (0.07) | 40.0 (7.6) | 2.0 (0.25) | 27.7 (1.4) |
| 2014 | 4.7 (0.46) | 3.0 (0.39) | 7.7 (0.70) | 0.58 (0.07) | 30.9 (4.2) | 1.4 (0.10) | 23.2 (0.6) |

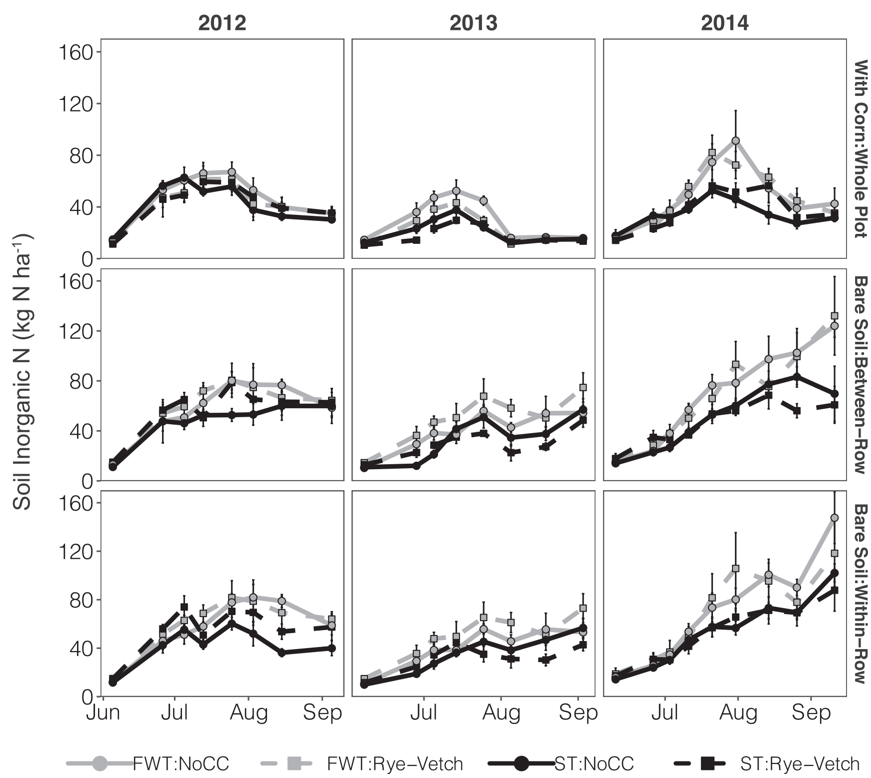


**Fig. 2.** Mean (±SEM) soil inorganic N to 20 cm depth across the whole subplot (top, weighted average of within-row (WR) and between-row (BR)) of With Corn subplots, and the BR (middle) and WR (bottom) zones of Bare Soil subplots in 2012, 2013, and 2014. Soil inorganic N comparisons include full-width tillage (FWT) and strip-tillage (ST) combined with either no cover crop (NoCC) or a cereal rye and hairy vetch mixture (Rye-Vetch).

within the tillage zone of ST was lower than soil inorganic N within FWT over all three years in Bare Soil subplots (Fig. 2). Tillage within the crop row of ST increased soil inorganic N compared to the undisturbed BR in only 1 out of 3 years (in 2013; Till*Zone, $P = 0.028$).

The Rye-Vetch cover crop had small and variable effects on soil inorganic N. With Corn, the Rye-Vetch cover crop had no effect on soil inorganic N in 2012, and increased soil inorganic N at one time-point in early August in 2014 (Fig. 2, Supplemental Table 1). In 2013, the Rye-Vetch cover crop increased soil inorganic N during the month of July, but only when combined with FWT, and had no effect on soil inorganic within ST. In Bare Soil, Rye-Vetch increased season long inorganic N by approximately 10% in 2012 across both tillage systems (Fig. 2, Supplemental Table 2). In 2013, Rye-Vetch increased soil inorganic N when combined with ST in the early part of July, but decreased soil inorganic N in ST during late August. In 2014, Rye-Vetch increased soil inorganic N at sweet corn planting, but had no effect throughout the rest of the season.

**Table 3**
Mean (±SEM) sweet corn marketable ear mass, along with results from mixed effects ANOVA comparing fixed effects of tillage (full-width tillage (FWT) and strip-tillage (ST)) and cover crop (No cover crop (NoCC) or cereal rye and hairy vetch mixture (Rye-Vetch)) in 2012, 2013, and 2014.

| | | 2012 | | 2013 | | 2014 | | Three years combined | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mg ha$^{-1}$ | | | | | | | |
| *Tillage Main Effect* | | | | | | | | | |
| FWT | | 10.94 | (0.79) | 9.96 | (1.54) | 5.96 | (0.50) | 8.95 | (0.73) |
| ST | | 10.44 | (1.02) | 7.07 | (1.34) | 7.10 | (0.55) | 8.20 | (0.65) |
| *Cover Crop Main Effect* | | | | | | | | | |
| | Rye-Vetch | 12.46 | (0.50) | 9.46 | (1.51) | 7.20 | (0.52) | 9.71 | (0.70) |
| | NoCC | 8.91 | (0.73) | 7.57 | (1.49) | 5.86 | (0.50) | 7.45 | (0.61) |
| *Interactive Effects* | | | | | | | | | |
| FWT | Rye-Vetch | 12.41 | (0.84) | 10.87 | (1.95) | 6.54 | (0.25) | 9.94 | (0.99) |
| FWT | NoCC | 9.47 | (0.88) | 9.05 | (2.58) | 5.37 | (0.94) | 7.97 | (1.03) |
| ST | Rye-Vetch | 12.52 | (0.68) | 8.05 | (2.34) | 7.86 | (0.95) | 9.48 | (1.02) |
| ST | NoCC | 8.36 | (1.22) | 6.09 | (1.49) | 6.35 | (0.38) | 6.93 | (0.67) |
| | | Significance of Fixed Effects | | | | | | | |
| | | *F* | *p* | *F* | *p* | *F* | *p* | *F* | *p* |
| Tillage (T) | | $0.37_{(1, 6)}$ | 0.584 | $3.86_{(1, 9)}$ | 0.081 | $2.67_{(1, 9)}$ | 0.137 | $1.52_{(1, 27)}$ | 0.228 |
| Cover Crop (CC) | | $18.63_{(1, 6)}$ | 0.005 | $1.65_{(1, 9)}$ | 0.231 | $3.65_{(1, 9)}$ | 0.088 | $13.81_{(1, 27)}$ | 0.001 |
| T*CC | | $0.56_{(1, 6)}$ | 0.484 | $0.0_{(1, 9)}$ | 0.959 | $0.06_{(1, 9)}$ | 0.814 | $0.22_{(1, 27)}$ | 0.641 |
| Year (Y) | | – | – | – | – | – | – | $3.81_{(2, 9)}$ | 0.063 |
| T*Y | | – | – | – | – | – | – | $3.71_{(2, 27)}$ | 0.038 |
| CC*Y | | – | – | – | – | – | – | $1.19_{(2, 27)}$ | 0.318 |
| T*CC*Y | | – | – | – | – | – | – | $0.07_{(2, 27)}$ | 0.929 |

### 3.3. Sweet corn yield, aboveground biomass and N content

Tillage effects on sweet corn yield (Till*Year: $p = 0.038$, Table 3) and aboveground biomass (Till*Year: $p = 0.018$, Fig. 3) varied by year, but not by cover crop treatment. ST decreased sweet corn aboveground biomass in 2013 by 15% relative to FWT (Till: $p = 0.038$), but had no effect in 2012 or 2014. Tillage effects on sweet corn yield mirrored those on aboveground biomass, however, the decrease in sweet corn yield in ST in 2013 was only marginally significant (Till: $p = 0.081$, Table 3). We found no statistical difference between the two tillage systems and their effects on total aboveground N contents across the three years of the study.

Across the three years of our study, the Rye-Vetch cover crop increased sweet corn yield ($p = 0.001$, Table 3), aboveground biomass ($p < 0.001$, Fig. 3-top) and total N content ($p = 0.002$, Fig. 3-bottom), and the effect of cover crop did not interact with year ($p > 0.05$). Rye-vetch biomass effects on sweet corn yield and aboveground biomass was greatest in 2012, the year with the greatest vetch biomass, when Rye-Vetch increased sweet corn yield and biomass by 40% and 44%, respectively. However, the increase in sweet corn yield was between 23% and 25%, while the increase in aboveground biomass was between 13% and 20%, in Rye-Vetch compared to the NoCC treatment in 2013 and 2014.

### 3.4. Soil leachate N

Strip tillage increased soil leachate N concentrations by approximately 50% compared to FWT across the three years of the study (Till: $p = 0.011$; Fig. 4, Supplemental Table 3), and this effect did not vary by year. In 2012 and 2014, soil leachate N concentrations in ST systems tended to increase throughout the season, while concentrations in FWT systems peaked in early-August. In 2013, both FWT and ST leachate N concentrations peaked in early August, and then N concentrations in the soil leachate sharply declined in both tillage systems following multiple heavy rain events (Fig. 4, top). Leachate N concentrations during cover crop growth periods in spring 2013 and 2014 were negligible (data not shown).

### 3.5. Denitrification potentials

ST increased WP denitrification potential by 18% compared to FWT, and this effect did not vary by cover crop, year, or time-point (Till: $p = 0.024$, Fig. 5A). We found no effect of cover crop on WP denitrification potential.

ST and FWT systems showed different patterns in denitrification potentials between their respective WR and BR zones (Fig. 5B), and the effect of tillage did not interact with cover crop. At planting, there was no difference between FWT tillage zones (since tillage was the same and crop was not yet present), so FWT BR and WR were pooled. ST plots had 90% greater denitrification potentials in BR compared to WR zones (Till*Zone: $p = 0.016$) at planting (approximately one week after tillage). Denitrification potentials were consistent between the Mid-season and Harvest time points, so these were pooled. We found 33% greater denitrification potential in the ST BR compared to the ST WR at later sampling dates. In contrast, within FWT, denitrification potential WR was 30% greater than BR at the later sampling points (Till*Zone, $p < 0.001$).

Cover crop effects on denitrification potentials varied within the WR and BR zones of sweet corn plots at the later (Mid-Season and Harvest combined) sampling points (Fig. 5C). Denitrification potentials were lower in the sweet corn WR zone of NoCC plots compared to the BR zone and compared to the WR and BR zones of Rye-Vetch plots (Cover*Zone, $p = 0.023$), but we detected no zonal differences between the WR and BR of Rye-Vetch treatments.

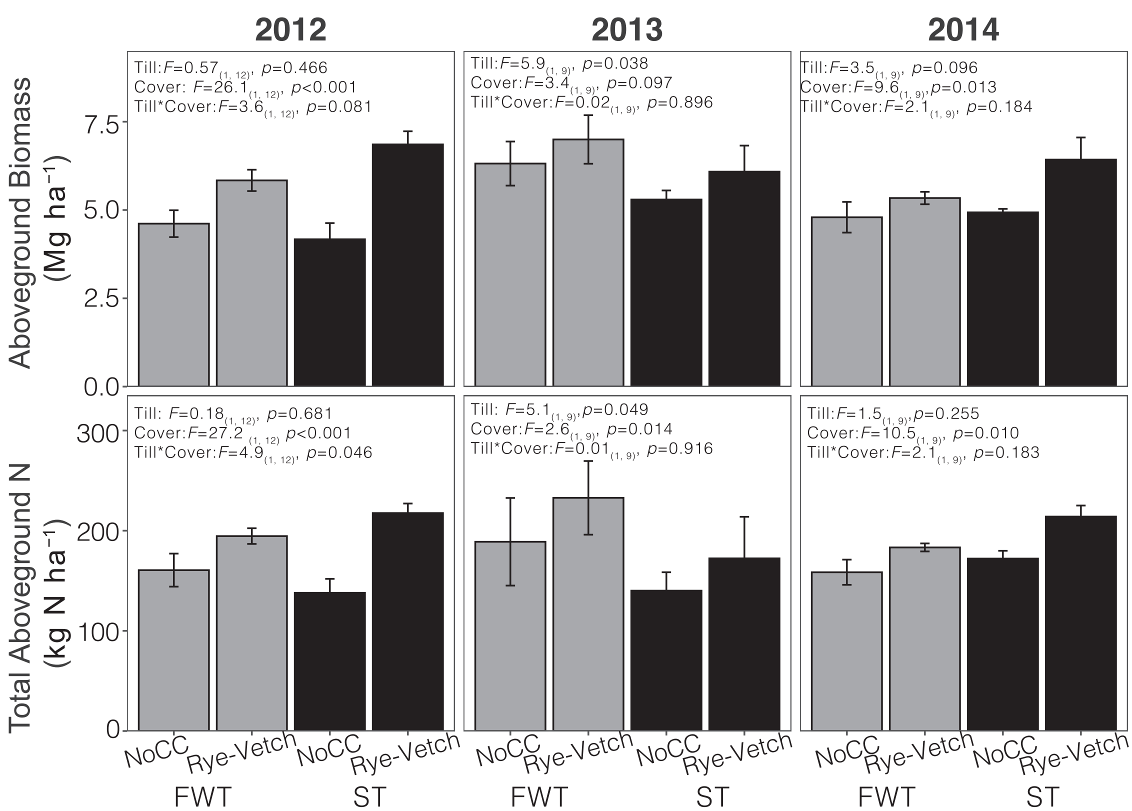


**Fig. 3.** Mean (±SEM) sweet corn aboveground biomass (top) and total aboveground N content (bottom) in 2012, 2013, and 2014, as well as results from mixed effects ANOVA comparing fixed effects of tillage (full-width tillage (light shading, FWT) and strip-tillage (dark shading, ST)) and cover crop (no cover crop (NoCC) or a cereal rye and hairy vetch mixture (Rye-Vetch)).

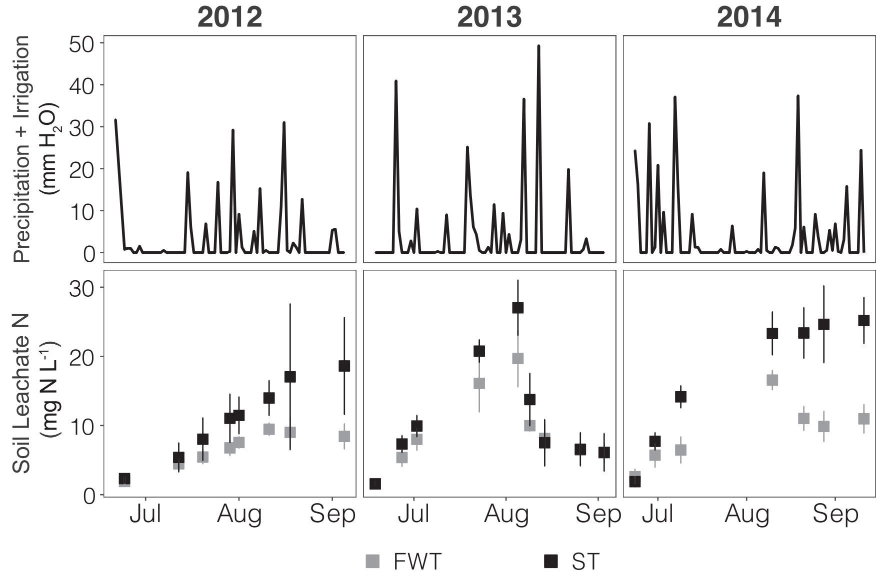


**Fig. 4.** Precipitation in Hickory Corners, MI (top) and mean (±SEM) inorganic N in soil leachate (bottom) sampled at a depth of 1.2 m during the sweet corn growing season in With Corn subplots in 2012, 2013, and 2014. Tillage comparisons include full-width tillage (FWT) and strip-tillage (ST).

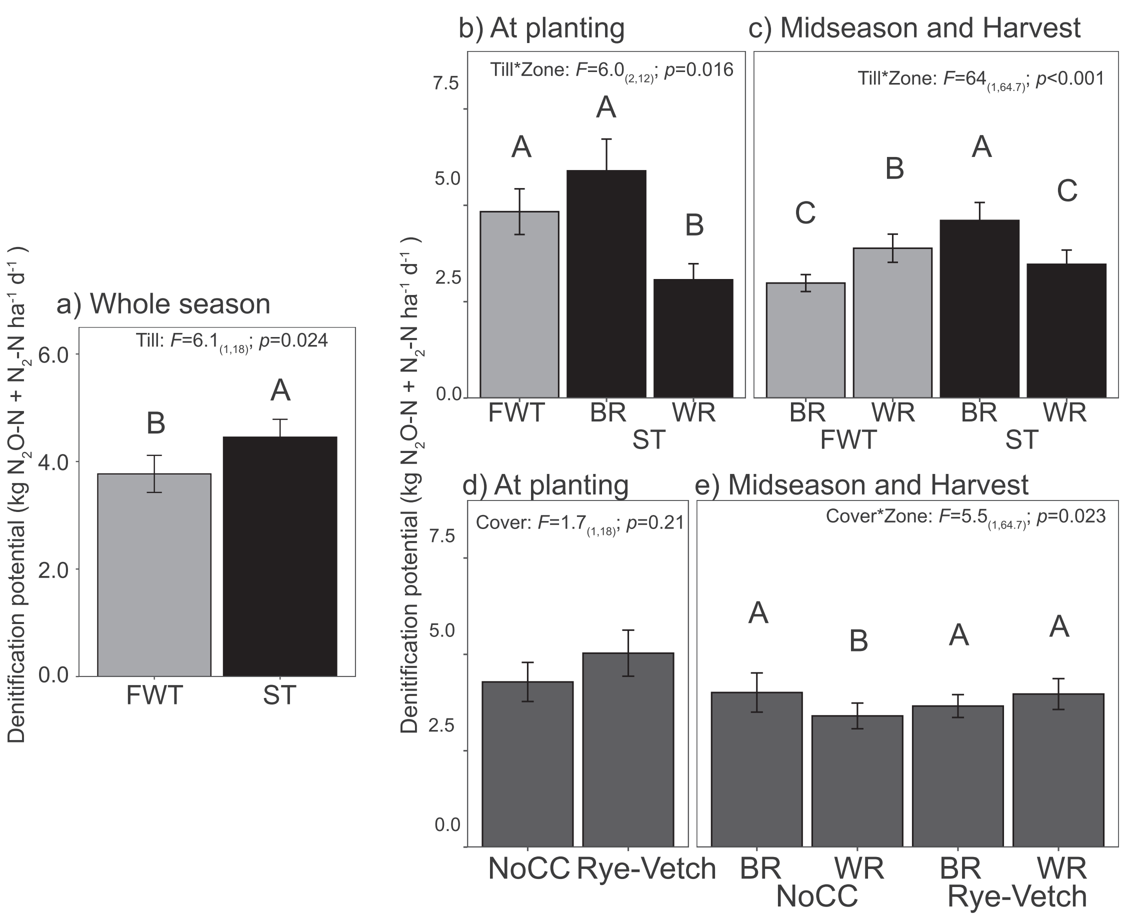


**Fig. 5.** Mean (±SEM) soil denitrification potentials sampled to 20 cm depth pooled over two years (2013 and 2014). Denitrification potential estimates include: (a) across the whole plot (weighted average of WR and BR zones) in both full-width (FWT) and strip-tillage (ST) pooled over the three sampling timepoints (0 DAP, 25–29 DAP; 68–77 DAP); (b) and (d) at planting (0 DAP); and (c) and (e) with midseason (25–29 DAP) and harvest (68–77 DAP) timepoints pooled. Fixed effects include: (b) and (c) tillage (FWT and ST) and (d) and (e) cover crop (no cover crop (NoCC) or a cereal rye and hairy vetch mixture (Rye-Vetch)) and its effects on denitrification potential within different zones (WR = within corn row, BR = between crop rows) in the cropping system.

## 4. Discussion

We examined strip-tillage effects on soil N dynamics, including soil inorganic N concentrations throughout the entire growing season and the potential for N losses when used with and without a cereal rye and hairy vetch cover crop. We found that ST decreased soil inorganic N concentrations in all three years of our study. Despite this, ST only negatively affected sweet corn biomass and perhaps yield in one out of three years, the year with the greatest reduction in soil inorganic N concentrations in ST compared to FWT. Both N leachate concentrations and denitrification potentials were greater within ST, indicating a potential for greater N losses with ST in a cover crop based system. Surprisingly, we found the cereal rye and hairy vetch cover crop resulted in a small and inconsistent increase in soil inorganic N concentrations. This was associated with inconsistent effects on sweet corn yields.

### *4.1. ST reduced soil inorganic N availability, with inconsistent impacts on crop productivity and N uptake*

Our results support our hypothesis that ST decreases soil inorganic N pools, which is consistent with numerous studies showing lower N availability from cover crop residues when tillage is reduced or eliminated (Cook et al., 2010; Drinkwater et al., 2000; Dou et al., 1994; Rannells and Wagger, 1996; Ruffo and Bollero, 2003; Varco et al., 1993). Lower soil N concentrations in reduced tillage systems are generally attributed to lower oxidation of soil organic matter and slower decomposition of preceding plant residues when left on the surface, both of which decrease N mineralization (Mulvaney et al., 2010). In ST, the preceding cereal rye and hairy vetch or winter weed residue was incorporated in the WR tillage zone. Therefore, we expected to see greater inorganic N availability in the tilled WR compared to the untilled BR zone, yet this was only the case in one of three years (2013). Perhaps WR tillage in ST did not result in a more consistent increase in soil inorganic N because soil disturbance within ST was less aggressive than FWT, and thus resulted in lower break up and incorporation of cover crop residues. ST implements can also push surface residue out of the way of the tillage implements, which also would have reduced cover crop residue incorporated into the WR tillage zone. Alternatively, greater N losses could have reduced soil inorganic N concentrations. Either way, our results are consistent with Haramoto and Brainard (2012), who also reported lower soil inorganic N within the tillage zone of ST compared to FWT.

Despite lower soil inorganic N concentration in ST compared to FWT across all three years, ST only reduced sweet corn N uptake, biomass, and perhaps yield in 2013. This effect is likely due to N deficiency because 2013 was also the year with the lowest hairy vetch biomass and lowest season-long levels of soil N availability. It is possible that increased soil moisture in ST compared to FWT compensated for lower inorganic N in 2012 and 2014 (Supplemental Fig. 1). Lower soil inorganic N in ST could not be explained by differences in crop N uptake, because crop N uptake in ST was either less or equal to FWT across the three years of our study.

Contrary to our expectations, we found no consistent benefit in soil inorganic N pools from the Rye-Vetch cover crop. Legume-cereal mixtures are often highly variable in the proportion of each species within the mixture, which determines the C:N ratio of the mixture and ultimately the release of N (Kuo and Sainju, 1998). Within our study, the C:N ratio of Rye-Vetch varied between 30 and 40, while a C:N ratio of 25 or below is believed to be required for net N mineralization (Allison, 1966). The NoCC treatment consisted of winter annual weeds which had a lower C:N ratio than the Rye-Vetch mixture across all three years, which may explain why we did not see more of an increase in inorganic N resulting from the Rye-Vetch cover crop.

### *4.2. ST increased soil leachate N and denitrification potential*

Contrary to our hypothesis, we found evidence for greater potential for N losses both through leaching and denitrification in ST compared to FWT. While this was surprising given the lower soil inorganic N levels in ST compared to FWT, it is possible that the greater N losses were a contributing factor to decreased soil inorganic N within ST. We are aware of no other studies that directly examine ST leaching in organic cover-cropped systems without added fertilizer. However, our results are in contrast to other studies with added fertilizer which found either no (Al-Kaisi and Licht, 2004; Pisani et al., 2017) or lower (Haramoto, 2014; Jokela and Nair, 2016) leachate or soil N concentrations at depth, including one that also included a cereal rye and hairy vetch cover crop mixture (Jokela and Nair, 2016).

Higher leachate N concentrations in ST were surprising and likely reflect greater leaching rates. Increased nitrogen leaching can result from either greater N concentration in soil leachate or greater water drainage, or both (Dinnes et al., 2002; Izaurralde et al. 1995; Syswerda et al., 2012). We did not measure soil drainage in our study, and therefore cannot definitively state that N leaching during the growing season was greater with ST. However, three lines of evidence suggest that greater leachate N concentrations in ST mean greater leaching losses. First, transpiration in ST was likely equal to or lower than FWT because crop aboveground biomass was either equal to or lower than FWT. Second, soil evaporation was likely lower in ST because of the cover crop residue covering two-thirds of the soil surface (Lascano et al., 1994; Unger and Vigil, 1998). Finally, a previous study that compared NT to FWT within the same soil series and site as our study found drainage was approximately 15% higher in NT compared to FWT (Syswerda et al., 2012). It thus seems reasonable to conclude that ST drainage either equaled or exceeded FTW drainage, allowing us to infer greater leaching in ST from greater lysimeter N concentrations.

Why might ST lead to greater N leaching than FWT? One explanation involves the differences in both soil porosity and cover crop distribution within the soil between tilled and untilled soils. Untilled soil contains a greater proportion of macropores compared to tilled soils (Thomas et al., 1973; Wu et al., 1992), resulting in greater infiltration rates and the channeling of water through the rooting zone (Ogden et al., 1999). When water travels through macropores, it bypasses much of the soil matrix and has less contact with micropores and lower replacement of initial soil water (Bandaranayake et al., 1998; Quisenberry and Phillips, 1976; Tyler and Thomas, 1977). In a cover crop-based low or no-till system in which organic residues remain upon the soil surface, N mineralization becomes stratified (Johnson and Hoyt, 1999; Logan et al., 1991). Mineralized N is initially concentrated in the top few centimeters of the soil, and must percolate down through the soil profile. Precipitation infiltrating the soil in untilled soils likely captures recently mineralized N at the soil surface, causing mineralized N to bypass the soil matrix as it travels through the rooting zone through preferential flow pathways. In the disturbed soils of FWT, incorporated cereal rye and hairy vetch residues are distributed throughout the top-soil layer. As water slowly percolates through the soil matrix within FWT, recently mineralized N has a greater chance of entering and being stored in soil micropores.

Despite lower soil inorganic N availability, ST also increased denitrification potential (including both $N_2O$ and $N_2$) compared to FWT. Greater bulk density and soil moisture in the untilled BR zone of ST (Supplemental Fig. 1) likely increased water-filled pore space and reduced aeration, all of which might be expected to increase denitrification and thus denitrifier biomass (Aulakh et al., 1991; Robertson, 2000; Rochette, 2008; Weier et al., 1993). In the field, $O_2$ is the dominant control on denitrification rates (Robertson and Groffman, 2015), which likely explains why we saw greater denitrification potential in ST even though inorganic N was lower. While we are aware of no other studies using the denitrification enzyme assay to compare denitrification potentials within ST to FWT, previous studies have compared $N_2O$

emissions directly in the field in both tillage systems and have found inconsistent results (Drury et al., 2006; Omonode and Vyn, 2019).

In FWT, greater denitrification potential was found in the WR zone compared to the BR across the midseason and harvest timepoints. The WR and BR zones of FWT were both tilled the same (unlike in ST), and in both zones the cover crop treatment (NoCC or Rye-Vetch) was equally incorporated into the soil. Therefore, any WR/BR differences within FWT must be due to the presence of the crop within WR. The sloughing off of corn root cells and root exudates likely provided a labile carbon source to enhance denitrification (Mahmood et al., 1997; Prade and Trolldenier, 1988), and in unsaturated soils labile carbon is a strong promoter of denitrification (Robertson and Groffman, 2015). Mahmood et al. (1997) found that maize plants stimulated denitrification at both high and low water-filled pore space and attributed the effects to increased C availability with maize roots present. Previous studies have found that denitrification is often limited by carbon in agricultural systems, and may be more limited by carbon than nitrogen (Kennedy et al., 2013; Luo et al., 1998). These results reinforce the importance of considering WR and BR differences when sampling soil within agricultural systems. Given that the same mechanisms by which the crop enhanced denitrification potential within the WR of FWT are also operating in the WR of ST, this suggests that the mechanisms enhancing denitrification potential in the BR of ST were greater.

Increased reactive N lost through leaching and denitrification is concerning because of the potential for negative environmental ramifications. Leached N is a major contributor to hypoxic zones within marine systems, and denitrified-N lost as $N_2O$ is a potent greenhouse gas with a global warming potential 300 times greater than $CO_2$ (Robertson and Vitousek, 2009). Additionally, increased N losses are especially problematic in cover crop-based organic systems, which already tend to be N deficient (Cavigelli et al., 2008; Clark et al., 1999; Poudel et al., 2002).

## 5. Conclusion

Understanding how reduced-tillage practices affect soil inorganic N availability and the potential for nitrogen losses is essential to developing strategies that improve both the profitability and sustainability of agricultural systems. We found lower soil inorganic N, as well as greater denitrification potential and leachate N concentrations in ST compared to FWT. The greater potential for N losses within ST are concerning, not only because N is a limiting resource in organic systems, but also because of the negative environmental impacts resulting from agricultural losses of reactive N. Our study supports previous work showing that adoption of reduced tillage practices within organic production systems can be problematic for a variety of reasons, including N management. Future research should examine the mechanisms responsible for increased N losses in ST, as well as examine strategies to increase nitrogen use efficiency and decrease N losses in legume-based reduced tillage systems.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2021.107524.

## References

Al-Kaisi, M., Licht, M.A., 2004. Effect of strip tillage on corn nitrogen uptake and residual soil nitrate accumulation compared with no-tillage and chisel plow. Agron. J. 96, 1164–1171.

Allison, F., 1966. The fate of nitrogen applied to soils. Adv. Agron. 18, 219–258.

Aulakh, M., Doran, J., Walters, D., Mosier, A., Francis, D., 1991. Crop residue and placement effects on denitrification and mineralization. Soil Sci. Soc. Am. J. 55, 1020–1025.

Bandaranayake, W.M., Butters, G.L., Hamdi, M., Prieksat, M., Ellsworth, T.R., 1998. Irrigation and tillage management effects on solute movement. Soil Tillage Res. 46, 165–173.

Bhardwaj, A.K., Jasrotia, P., Hamilton, S.K., Robertson, G.P., 2011. Ecological management of intensively cropped agro-ecosystems improves soil quality with sustained productivity. Agric. Ecosyst. Environ. 140, 419–429. https://doi.org/10.1016/j.agee.2011.01.005.

Brainard, D.C., Peachey, R.E., Haramoto, E.R., Luna, J.M., Rangarajan, A., 2013. Weed ecology and nonchemical management under strip-tillage: Implications for Northern U.S. vegetable cropping systems. Weed Technol. 27, 218–230. https://doi.org/10.1614/WT-D-12-00068.1.

Cavigelli, M.A., Teasdale, J.R., Conklin, A.E., 2008. Long-term agronomic performance of organic and conventional field crops in the Mid-Atlantic region. Agron. J. 100, 785–794.

Clark, M.S., Horwath, W.R., Shennan, C., Scow, K.M., Lantni, W.T., Ferris, H., 1999. Nitrogen, weeds and water as yield-limiting factors in conventional, low-input, and organic tomato systems. Agric. Ecosyst. Environ. 73, 257–270.

Constantin, J., Mary, B., Laurent, F., Aubrion, G., Fontaine, A., Kerveillant, P., Beaudoin, N., 2010. Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. Agric. Ecosyst. Environ. 135, 268–278.

Cook, J.C., Gallagher, R.S., Kaye, J.P., Lynch, J., Bradley, B., 2010. Optimizing vetch nitrogen production and corn nitrogen accumulation under no-till management. Agron. J. 102, 1491–1499.

Crum, J.R., Collins, H.P., 1995. KBS Soils [Online], W. K. Kellogg Biological Station Long-Term Ecological Research Project, Michigan State University, Hickory Corners, MI. http://lter.kbs.msu.edu/research/site-description-and-maps/soil-description.

Dinnes, D.L., Karlen, D.L., Jaynes, D.B., Kaspar, T.C., Hatfield, J.L., Colvin, T.S., Cambardella, C.A., 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agron. J. 94, 153–171.

Doane, T.A., Horwath, W.R., Mitchell, J.P., Jackson, J., Miyao, G., Brittan, K., 2009. Nitrogen supply from fertilizer and legume cover crop in the transition to no-tillage for irrigated row crops. Nutr. Cycl. Agroecosyst. 85, 253–262.

Dou, Z., Fox, R.H., Toth, J.D., 1994. Tillage effect on seasonal nitrogen availability in corn supplied with legume green manures. Plant Soil 162, 203–210.

Dou, Z., Fox, R., Toth, J.D.J., 1995. Seasonal soil nitrate dynamics in corn as affected by tillage and nitrogen source. Soil Sci. Soc. Am. J. 59, 858–864.

Drinkwater, L., Janke, R., Rossoni-Longnecker, L., 2000. Effects of tillage intensity on nitrogen dynamics and productivity in legume-based grain systems. Plant Soil 227, 99–113.

Drury, C.F., Reynolds, W.D., Tan, C.S., Welacky, T.W., Calder, W., McLaughlin, N.B., 2006. Emissions of nitrous oxide and carbon dioxide. Soil Sci. Soc. Am. J. 70, 570–581.

Franzluebbers, A.J., 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Tillage Res 66, 197–205.

Gebhardt, M.R., Daniel, T.C., Schweizer, E.E., Allmaras, R.R., 1985. Conservation tillage. Science 230, 625–630.

Gelderman, R.H., Beegle, D., 1998. Nitrate-nitrogen. NC Regional Res. Publ. no. 221. In: Brown, J.R. (Ed.), Recommended Chemical Soil Test Procedures for the North Central Region, 221. Missouri Agricultural Experiment Station, Columbia, MO, pp. 17–20.

Groffman, P.M., Holland, E.A., Myrold, D.D., Robertson, G.P., Zou, X., 1999. Denitrification. In: Robertson, G.P., Coleman, D.C., Bledsoe, C.S., Sollins, P. (Eds.), Standard soil methods for long-term ecological research. Oxford University Press, New York, NY, pp. 272–284.

Haramoto, E., 2014. Weed Population Dynamics, Profitability, and Nitrogen Loss in Strip-tilled Cabbage and Sweet Corn (PhD Dissertation). Michigan State University.

Haramoto, E.R., Brainard, D.C., 2012. Strip tillage and oat cover crops increase soil moisture and influence N mineralization patterns in cabbage. HortScience 47, 1596–1602.

Izaurralde, R.C., Feng, Y., Robertson, J.A., McGill, W.B., Juma, N.G., Olson, B.M., 1995. Long-term influence of cropping systems, tillage methods, and N sources on nitrate leaching. Can. J. Soil Sci. 75, 497–505. https://doi.org/10.4141/cjss95-071.

Johnson, A.M., Hoyt, G.D., 1999. Changes to the soil environment under conservation tillage. Horttechnology 9, 380–393.

Jokela, D., Nair, A., 2016. Effects of reduced tillage and fertilizer application method on plant growth, yield, and soil health in organic bell pepper production. Soil Tillage Res 163, 243–254.

Kalra, Y.P., 1998. Hand Book of Reference Methods for Plant Analysis. CRC Press, Boca Raton, FL, USA, pp. 75–92.

Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S., Jordahl, J.L., 1994. Long-term tillage effects on soil quality. Soil Tillage Res. 32, 313–327.

Kennedy, T., Decock, C., Six, J., 2013. Assessing drivers of $N_2O$ production in California tomato cropping systems. Sci. Total Environ. 465, 36–47.

Kuo, S., Sainju, U.M., 1998. Nitrogen mineralization and availability of mixed leguminous and non-leguminous cover crop residues in soil. Biol. Fertil. Soils 26, 346–353.

Lascano, R.J., Baumhardt, R.L., Hicks, S.K., Heilman, J.L., 1994. Soil and plant water evaporation from strip-tilled cotton: Measurement and simulation. Agron. J. 86, 987–994.

Licht, M.A., Al-kaisi, M., 2005. Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Tillage Res. 80, 233–249.

Logan, T.J., Lal, R., Dick, W.A., 1991. Tillage systems and soil properties in North America. Soil Tillage Res. 20, 241–270.

Lowry, C.J., Brainard, D.C., 2016. Strip-intercropping of rye–vetch mixtures affects biomass, carbon/ nitrogen ratio, and spatial distribution of cover crop residue. Agron. J. 108, 2433–2443.

Luehmann, M.D., Peter, B.G., Connallon, C.B., Schaetzl, R.J., Smidt, S.J., Liu, W., Kincare, K.A., Walkowiak, T.A., Thorlund, E., Holler, M.S., 2016. Loamy, two-storied soils on the outwash plains of southwestern lower Michigan: pedoturbation of loess with the underlying sand. Ann. Am. Assoc. Geogr. 106, 551–572.

Luna, J.M., Staben, M.L., 2002. Strip tillage for sweet corn production: yield and economic return. HortScience 37, 1040–1044.

Luo, J., Tillman, R.W., White, R.E., Ball, P.R., 1998. Variation in denitrification activity with soil depth under pasture. Soil Biol. Biochem. 30, 897–903.

Mahmood, T., Ali, R., Malik, K. a, Shamsi, S.R. a, 1997. Denitrification with and without maize plants (*Zea mays* L.) under irrigated field conditions. Biol. Fertil. Soils 24, 323–328. https://doi.org/10.1007/s003740050251.

Malhi, S.S., O'Sullivan, P.A., 1990. Soil temperature, moisture and penetrometer resistance under zero and conventional tillage in central Alberta. Soil and Tillage Res. 17, 167–172.

Mirsky, S.B., Ryan, M.R., Curran, W.S., Teasdale, J.R., Maul, J., Spargo, J.T., Moyer, J., Grantham, A.M., Weber, D., Way, T.R., Camargo, G.G., 2012. Conservation tillage issues: cover crop-based organic rotational no-till grain production in the mid-Atlantic region, USA. Renew. Agric. Food Syst. 27, 31–40.

Mohler, C.L., Teasdale, J.R., 1993. Response of weed emergence to rate of *Vicia villosa* and *Secale cereale* L. residue. Weed Res. 33, 487–499.

Mulvaney, M.J., Wood, C.W., Balkcom, K.S., Shannon, D.A., Kemble, J.M., 2010. Carbon and nitrogen mineralization and persistence of organic residues under conservation and conventional tillage. Agron. J. 102, 1425–1433.

Ogden, C.B., van Es, H.M., Wagenet, R.J., Steenhuis, T.S., 1999. Spatial-temporal variability of preferential flow in a clay soil under no-till and plow-till. J. Environ. Qual. 28, 1264–1273.

Omonode, R.A., Vyn, T.J., 2019. Tillage and nitrogen source impacts on relationships between nitrous oxide emission and nitrogen recovery efficiency in corn. J. Environ. Qual. 48, 421–429.

Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., Grace, P., 2014. Conservation agriculture and ecosystem services: an overview. Agric. Ecosyst. Environ. 187, 87–105. https://doi.org/10.1016/j.agee.2013.10.010.

Paustian, K., Andren, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noord- wijk, M., 1997. Agricultural soils as a sink to mitigate $CO_2$ emissions. Soil Use Manag. 13, 230–244.

Phillips, R., Blevins, R., Thomas, G., Frye, W., Phillips, S., 1980. No-tillage agriculture. Science 208, 1108–1113.

Pisani, O., Strickland, T.C., Hubbard, R.K., Bosch, D.D., Coffin, A.W., Endale, D.M., Potter, T.L., 2017. Soil nitrogen dynamics and leaching under conservation tillage in the atlantic coastal plain, georgia, united states. J. Soil Water Conserv 72, 519–529.

Poudel, D.D., Horwath, W.R., Lanini, W.T., Temple, S.R., van Bruggen, A.H.C., 2002. Comparison of soil N availability and leaching potential, crop yields and weeds in organic, low-input and conventional farming systems in northern California. Agric. Ecosyst. Environ. 90, 125–137. https://doi.org/10.1016/S0167-8809(01)00196-7.

Prade, K., Trolldenier, G., 1988. Effect of wheat roots on denitrification at varying soil air-filled porosity and organic-carbon content. Biol. Fertil. Soils 7, 1–6. https://doi.org/10.1007/BF00260723.

Quisenberry, V.L., Phillips, R.E., 1976. Percolation of surface-applied water in the field. Soil Sci. Soc. Am. J. 40, 484–489. https://doi.org/10.2136/sssaj1976.03615995004000040013x.

Ranells, N.N., Wagger, M.G., 1996. Nitrogen release from grass and legume cover crop monocultures and bicultures. Agron. J. 88, 777–782.

Robertson, G.P., 2000. Denitrification. In: Sumner, M.E. (Ed.), Handbook of Soil Science. CRC Press, Boca Raton, Florida, USA, pp. C181–C190.

Robertson, G.P., Groffman, P.M., 2015. Nitrogen transformations. In: Paul, E.A. (Ed.), Soil Microbiology, Ecology and Biochemistry, fourth ed. Academic Press, Burlington, Massachusetts, USA, pp. 421–446.

Robertson, G.P., Vitousek, P.M., 2009. Nitrogen in agriculture: balancing the cost of an essential resource. Annu. Rev. Environ. Resour. 34, 97–125. https://doi.org/10.1146/annurev.environ.032108.105046.

Rochette, P., 2008. No-till only increases N2O emissions in poorly-aerated soils. Soil Tillage Res. 101, 97–100. https://doi.org/10.1016/j.still.2008.07.011.

Ruffo, M.L., Bollero, G.A., 2003. Modeling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. Agron. J. 95, 900–907.

Sainju, U.M., Singh, B.P., Whitehead, W.F., Wang, S., 2007. Accumulation and crop uptake of soil mineral nitrogen as influenced by tillage, cover crops, and nitrogen fertilization. Agron. J. 99, 682–691. https://doi.org/10.2134/agronj2006.0177.

Syswerda, S.P., Basso, B., Hamilton, S.K., Tausig, J.B., Robertson, G.P., 2012. Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. Agric. Ecosyst. Environ. 149, 10–19.

Syswerda, S.P., Corbin, A.T., Mokma, D.L., Kravchenko, A.N., Robertson, G.P., 2011. Agricultural management and soil carbon storage in surface vs. deep layers. Soil Sci. Soc. Am. J. 75, 92–101.

Thomas, G.W., Blevins, R.L., Phillips, R.E., McMahon, R.L., 1973. Effect of a killed Sod Mulch on nitrate movement and corn yield. Agron. J. 65, 736–739.

Triplett, G.B., Dick, W.A., 2008. No-tillage crop production: a revolution in agriculture! Agron. J. 100 (Suppl 3). S-153.

Tyler, D., Thomas, G., 1977. Lysimeter measurements of nitrate and chloride losses from soil under conventional and no-tillage corn. J. Environ. Qual. 6, 63–66.

Unger, P.W., Vigil, M.F., 1998. Cover crop effects on soil water relationships. J. Soil Water Conserv 53, 200–207.

Varco, J.J., Frye, W.W., Smith, M.S., MacKown, C.T., 1993. Tillage effects on legume decomposition and transformation of legume and fertilizer nitrogen-15. Soil Sci. Soc. Am. J. 57, 750–756.

Wander, M.M., Bollero, G.A., 1999. Soil quality assessment of tillage impacts in Illinois. Soil Sci. Soc. Am. J. 63, 961–971.

Weier, K.L., Doran, J.W., Power, J.F., Walters, D.T., 1993. Denitrification and the dinitrogen/nitrous oxide ratio as affected by soil water, available carbon, and nitrate. Soil Sci. Soc. Am. J. 57, 66–72. https://doi.org/10.2136/sssaj1993.03615995005700010013x.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci. Soc. Am. J. 66, 1930–1946.

Wu, L., Swan, J.B., Paulson, W.H., Randall, G.W., 1992. Tillage effects on measured soil hydraulic properties. Soil Tillage Res. 25, 17–33.

Supplement

Supplemental Table 1. Results from a repeated measures ANOVA analyzing the effects of tillage (full-width and strip-tillage), cover crop (Rye-Vetch and No Cover Crop), and date as a repeated measure on whole plot (weighted average of WR and BR) soil inorganic N in With Corn subplots throughout the sweet corn growing season in 2012, 2013, and 2014.

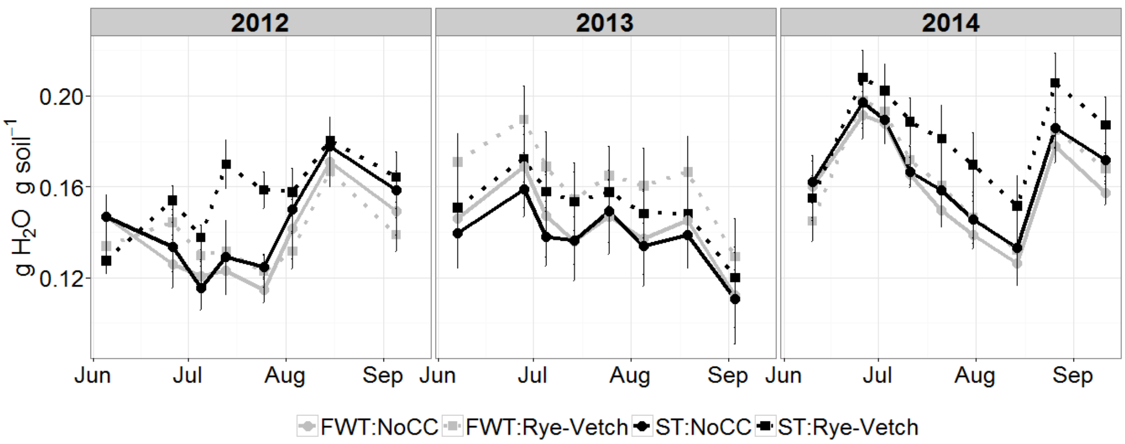
| | 2012 | | 2013 | | 2014 | |
|---|---|---|---|---|---|---|
| **Effect** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** |
| Till (T) | $0.37_{(1,12)}$ | 0.552 | $11.17_{(1, 3.6)}$ | 0.033 | $4.45_{(1, 9.4)}$ | 0.063 |
| Cover (C) | $0.45_{(1,12)}$ | 0.515 | $6.53_{(1,3.6)}$ | 0.069 | $0.06_{(1, 9.4)}$ | 0.813 |
| Date (D) | $163.79_{(7, 34)}$ | <0.001 | $72.43_{(7, 22.5)}$ | <0.001 | $36.6_{(8, 74.7)}$ | <0.001 |
| C*T | $0.18_{(1,12)}$ | 0.678 | $0.5_{(1,3.6)}$ | 0.521 | $0.03_{(1, 9.4)}$ | 0.874 |
| T*D | $0.32_{(7, 34)}$ | 0.941 | $3.37_{(7, 22.5)}$ | 0.013 | $2.59_{(8, 74.7)}$ | 0.015 |
| C*D | $1.28_{(7, 34)}$ | 0.291 | $1.49_{(7, 22.5)}$ | 0.221 | $2.7_{(8, 74.7)}$ | 0.011 |
| C*T*D | $0.97_{(7, 34)}$ | 0.471 | $2.53_{(7, 22.5)}$ | 0.045 | $0.88_{(8, 74.7)}$ | 0.535 |

Supplemental Table 2. Results from a repeated measures ANOVA analyzing the effects of tillage (full-width and strip-tillage), cover crop (Rye-Vetch and No Cover Crop), zone (Within-Row and Between-Row), and date as a repeated measure on soil inorganic N in Bare Soil subplots in 2012, 2013, and 2014.

| | 2012 | | 2013 | | 2014 | |
|---|---|---|---|---|---|---|
| **Effect** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** |
| Till (T) | $8.98_{(1, 9.3)}$ | 0.015 | $16.58_{(1, 9)}$ | 0.003 | $8.04_{(1, 9)}$ | 0.02 |
| Cover (C) | $5.44_{(1, 9.3)}$ | 0.044 | $0.9_{(1, 9)}$ | 0.368 | $0.03_{(1, 9)}$ | 0.865 |
| Date (D) | $50.02_{(7, 147)}$ | <0.001 | $309.4_{(7, 61)}$ | <0.001 | $271.9_{(8, 134)}$ | <0.001 |
| Zone (Z) | $0.65_{(1, 48.6)}$ | 0.423 | $7.91_{(1, 17)}$ | 0.012 | $2.86_{(1, 12)}$ | 0.116 |
| C*T | $1.91_{(1, 9.3)}$ | 0.199 | $1.79_{(1, 9)}$ | 0.214 | $0.08_{(1, 9)}$ | 0.786 |
| T*D | $3.45_{(7, 148)}$ | 0.002 | $6.99_{(7, 61)}$ | <0.001 | $5.72_{(8, 134)}$ | <0.001 |
| C*D | $0.83_{(7, 148)}$ | 0.564 | $5.38_{(7, 61)}$ | <0.001 | $4.3_{(8, 134)}$ | <0.001 |
| Z*D | $0.96_{(7, 148)}$ | 0.464 | $1.39_{(7, 61)}$ | 0.226 | $1.88_{(8, 134)}$ | 0.068 |
| T*Z | $0.83_{(1, 48.6)}$ | 0.367 | $5.77_{(1, 17)}$ | 0.028 | $1.23_{(1, 12)}$ | 0.289 |
| C*Z | $0.34_{(1, 48.6)}$ | 0.561 | $0.07_{(1, 17)}$ | 0.801 | $0.05_{(1, 12)}$ | 0.828 |
| C*T*Z | $0.15_{(1, 48.6)}$ | 0.703 | $0.17_{(1, 17)}$ | 0.689 | $0.01_{(1, 12)}$ | 0.939 |
| C*T*D | $0.87_{(7, 148)}$ | 0.535 | $3.22_{(7, 61)}$ | 0.006 | $0.58_{(8, 134)}$ | 0.796 |
| T*Z*D | $0.65_{(7, 148)}$ | 0.714 | $1.33_{(7, 61)}$ | 0.251 | $1.74_{(8, 134)}$ | 0.094 |
| C*Z*D | $0.22_{(7, 148)}$ | 0.981 | $0.43_{(7, 61)}$ | 0.882 | $0.55_{(8, 134)}$ | 0.813 |
| C*T*Z*D | $0.38_{(7, 148)}$ | 0.914 | $0.55_{(7, 61)}$ | 0.793 | $0.71_{(8, 134)}$ | 0.68 |

Supplemental Table 3. Results from a repeated measures ANOVA analyzing the effects of tillage (full-width and strip-tillage), year, and date as a repeated measure on leachate N concentration in With Corn subplots with a rye-vetch mixture in 2012, 2013, and 2014.

| Effect | *F* | *p* |
|---|---|---|
| Till (T) | $7.48_{(1, 24.9)}$ | 0.011 |
| Year (Y) | $0.74_{(2, 12)}$ | 0.498 |
| Date (D) | $20.68_{(11,160)}$ | <0.001 |
| Y*T | $1.26_{(2, 31)}$ | 0.299 |
| T*D | $1.26_{(11,160)}$ | 0.2513 |
| Y*D | $9.15_{(10, 166)}$ | <0.001 |
| Y*T*D | $1.56_{(10, 166)}$ | 0.1218 |




Supplemental Figure 1. Mean (+/- SEM) gravimetric soil moisture in the top 20 cm of soil across the whole subplot (weighted average of WR and BR) in With Corn subplots present in 2012, 2013, and 2014. Gravimetric soil moisture comparisons include full-width tillage (FWT) and strip-tillage (ST) combined with either no cover crop (NoCC) or a rye and vetch mixture (Rye-Vetch).