Rye-vetch spatial arrangement and tillage: Impacts on soil N and sweet corn roots

C.J. Lowry*[1] and D.C. Brainard[2]
[1]Department of Natural Resources and the Environment, University of New Hampshire, Durham, NH 03824.
[2] Department of Horticulture, Michigan State University, East Lansing, MI 48824.
*Corresponding author (Carolyn.Lowry@unh.edu)

ABSTRACT

Strip-intercropping of functionally diverse cover crops, such as cereal rye (*Secale cereal* L.; “rye”) and hairy vetch (*Vicia villosa* Roth; “vetch”), may enhance N use efficiency in reduced-tillage systems by concentrating N-rich vetch residue within the subsequent crop row, thereby increasing root access to pools of organic N. We established a field study in southwest Michigan between 2011 and 2014 to compare the effects of rye-vetch spatial arrangement and tillage on soil N, soil moisture, sweet corn (*Zea mays* L.) above- and belowground biomass, and root morphology. The experiment consisted of a 2 X 2 factorial with two levels of rye-vetch spatial arrangement: segregated into strips (SEG) and full width mixture (MIX), and two levels of tillage: strip-tillage (ST) or full width tillage (FWT). Strip-tillage reduced soil inorganic N compared to FWT in two out of three years, but increased soil moisture and sweet corn shoot biomass in two out of three years. Segregating rye and vetch into strips increased inorganic N within the crop row, but had minimal impact on sweet corn biomass or yield. In contrast, sweet corn roots were responsive to relatively small changes in the distribution of soil N or moisture resulting from strip-tillage and segregated plantings. Strip-tillage and strip-intercropping show promise in adapting reduced-till systems for

organic production, but future research should evaluate the response of other crops, and adjustments in cover crop species and termination methods to help optimize these practices.

ABBREVIATIONS: BR, between-row zone; WR, zone within the crop row; ST, strip-tillage; FWT, full-width tillage; MIX, rye-vetch full-width mixture; SEG, rye-vetch segregated into strips; C:N, carbon:nitrogen; ; N, nitrogen; GDD, growing degree days.

Intensive tillage practices have been associated with a decline in soil quality, including the loss of soil organic matter and increased erosion (Karlen et al 1994, Triplett and Dick, 2008). Reducing or eliminating tillage can improve soil quality compared to conventional tillage practices, and by increasing soil water holding capacity and infiltration (Malhi and O'Sullivan, 1990; Franzluebbers, 2002), no-till agriculture may buffer against the potential increase in erratic precipitation predicted by climate change models (Hayhoe et al. 2010). Despite the potential benefits of no-till, adoption has been limited due to reduced crop yields in many climates and cropping systems (Pittelkow et al., 2015). Lower yields in reduced tillage are in part due to N deficiency, resulting from slower decomposition and N mineralization from incorporated plant residues or soil organic matter (Dou et al. 1994; Grandy and Robertson, 2006).

Currently, there is growing interest in developing hybrid systems that optimize the benefits provided by both tilled and un-tilled soils by targeting soil disturbance both spatially (e.g. zonal-tillage) and temporally (e.g. rotational tillage) (Brainard et al., 2013;

Williams et al., 2016). These approaches aim to integrate the soil quality benefits of conservation tillage with the improved seedbed and increased N mineralization that result from tillage (Williams et al., 2016). Zonal-tillage practices, such as ridge-tillage or strip-tillage (ST), isolate soil disturbance to the crop row, resulting in a greater level of control over organic matter turnover and N mineralization (Müller et al., 2009; Kane et al., 2015).

Strip-tillage utilizes a combination of narrowly placed disks and rotary baskets (often attached to a shank), to confine tillage to a narrow strip within the crop row while leaving the zone between crop rows untilled (Luna and Staben, 2002). When combined with a preceding cover crop, ST preserves residue on the soil surface of the untilled zone and provides benefits such as suppressing weed germination, reducing soil erosion and conserving soil moisture (Mohler and Teasdale, 1993; Unger and Vigil, 1998). Additionally, without unnecessarily releasing N between crop rows, ST may decrease the amount of inorganic N inaccessible to crop roots early in the growing season, thereby decreasing N losses. However, lower N availability (Haramoto and Brainard, 2012) and increased potential for N losses (Lowry, 2015) have been observed in ST compared to full-width tillage.

To improve the performance of strip-tillage systems, and address N management challenges, this study investigates targeted placement of labile and recalcitrant cover crop residues. Strip-intercropping of low C:N cover crops (e.g. legumes) in the future planting row, and high C:N cover crops (e.g. grasses) between rows is one approach for increasing N use efficiency. Recalcitrant (high C:N) cover crops, such as cereal rye, conserve soil moisture and are helpful for weed suppression when used as a mulch in organic reduced-tillage systems (Wells et al., 2014), but also are likely to immobilize N (Rosecrance et al., 2000). However, when sown between crop rows, cereal rye may create a zone initially deficient in N that serves as a reservoir of late-releasing N. In contrast, legume cover crops, such as hairy vetch, sown in the zone of the subsequent crop will increase the proximity of mineralized N to crop roots and increase N capture.

Targeted placement of N-rich legume residue to the crop row is analogous to banded applications of N fertilizer within conventional cropping systems, and may share many of its documented benefits. For example, banding of N fertilizers can increase crop N uptake efficiency and yields (Maddux et al., 1991) and may reduce N losses (Nash et al., 2012; Haramoto, 2014). However, the targeted placement of an organic form of N may be more likely to reduce N deficiency compared to banding inorganic N by: 1) reducing immobilization of N by microorganisms (Korsaeth et al., 2001; Ettema and Wardle, 2002); and 2) enhancing root foraging in response to heterogeneously distributed decomposing organic material (Hodge, 1999).

Microorganisms often outcompete plants for soil organic and inorganic N, resulting in available N being immobilized into microbial biomass (Rosswall, 1982; Kaye and Hart, 1997). However, when N-rich organic material is aggregated or heterogeneously distributed, soil microbes become saturated and plants are able to intercept a greater quantity of the recently mineralized N (Korsaeth et al., 2001; Ettema and Wardle, 2002). In fact, previous studies have found that heterogeneously distributed or patchy resources result in an increase in N uptake and plant biomass (Hodge et al., 1999; Loecke and Robertson, 2009). Therefore, banding organic sources of N may reduce N deficiency in legume-based organic systems because of its potential to increase overall N availability by decreasing immobolization.

Concentrating N-rich legume residue within the crop row means that crop roots are well positioned to absorb mineralized N as it is released, thereby decreasing the time and energy required for crop roots to access N pools. However, the extent to which N use efficiency increases in response to targeted N placement in the crop root zone, depends in part on the phenotypic plasticity of crop roots. To more effectively capture nutrients from heterogeneously distributed resources, many plant species exhibit morphological plasticity through the proliferation of roots (e.g. increase in root length density) within nutrient patches (Hodge, 2004). By diverting energy for root growth away from nutrient poor regions and into regions of the soil with concentrated reserves of nutrients, an individual plant may receive a larger return on carbon investment in root growth (Robinson, 1994). This reduces the energy required by the plant for acquisition of the limiting nutrient and allows more energy to be diverted to aboveground productivity (Bloom et al., 1985; Shipley and Meziane, 2002).

Our primary objective was to evaluate whether strip tillage in combination with strip-intercropping of cereal rye and hairy vetch could increase soil N availability and productivity of organic sweet corn. We hypothesized that ST would reduce inorganic N availability, especially in the untilled zone between crop rows (BR), but that targeting vetch in the crop root zone (WR) would increase N availability, N uptake, and sweet corn biomass compared to the standard full-width rye and vetch mixture. A secondary objective was to investigate the role of sweet corn root plasticity in overcoming patchy distribution of N resources. We hypothesized that ST and segregated rye and vetch would result in a greater proportion of root length and biomass allocated to the N-rich WR zone.

MATERIALS AND METHODS

Site Description and Experimental Design

The experiment was conducted between 2011-2014 on Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, mesic Typic Hapludalfs) loam (Crum and Collins, 1995), at the Kellogg Biological Station in Hickory Corners, MI ($85^0$24'W, $42^0$24' N). The fields used for the study had been organically managed between 5-7 years, depending on the field, and the experiment was moved to a different field each year. Crops grown prior to initiation of the experiment included cereal rye harvested for grain in July in 2011 and 2013, and wheat harvested for grain in 2012. Each year, prior to cover crop establishment, the field was chisel plowed and managed with frequent shallow tillage to minimize perennial weed and volunteer crop growth. The entire experimental area was disked and harrowed prior to cover crop establishment. No N fertilizer was applied, and soil tests in all years indicated sufficient P and K for cover crop growth.

In both 2013 and 2014, treatments were arranged as a split-plot randomized complete block design with four replicates. Main plots consisted of a 2 X 2 factorial with two levels of tillage (FWT and ST) and two levels of rye and vetch spatial arrangement: mixed biculture (MIX) and segregated into strips (SEG). The split plot factor was crop: with a sweet corn crop (CORN) or bare soil (BARE-SOIL). The bare-soil treatments enabled us to observe patterns in soil inorganic N due solely to rye-vetch spatial arrangement and tillage, without sweet corn N uptake. In 2012 the experiment was arranged in a split-split plot design with four replicates, with tillage as the main plot, rye-vetch spatial arrangement as the split plot, and crop as the split-split plot. Plot sizes were adjusted each year based on availability of organically certified land. Subplot areas with sweet corn (CORN) were 27.3, 37.2, and 41.0 m^2 in 2012, 2013, and 2014 respectively. Subplots without sweet corn were 9.0 in 2012 and 2013, and 20.3 m^2 in 2014.

Field operations are listed in Table 1. Both cereal rye and hairy vetch seeds were organically certified and “Variety Not Stated” in all three years. Hairy vetch was inoculated with N-DURE inoculant *Rhizobium leguminosarum* (INTX Microbials LLC, Kentland, IN). Spatial arrangements included a full-width mixture (MIX) in which rye and vetch were sown together in the same rows; and a segregated mixture (SEG) in which two rows of hairy vetch were alternated with two rows of rye. Both spatial arrangements had the same seed rate on a per plot basis (62.7 kg ha^{-1} rye; 22.4 kg ha^{-1} vetch), with seeds of each species in the SEG treatments concentrated in their respective zones at twice their MIX rates. In both rye and vetch spatial arrangements, between-row spacing for rye and vetch rows was 19.1 cm. Cereal rye was planted with a grain drill and every two drop tubes were blocked within SEG to prevent seeding rye in the vetch rows (Lowry and Brainard, 2016). Between the rows of rye, hairy vetch was planted with a push-seeder (Jang Clean Seeder, Jang Automation Co., Ltd., Korea).

Cover crops were flail mowed twice when vetch had reached approximately 50% flowering in mid- to late- May of 2012, 2013, and 2014. Organic forms of P and K were added prior to tillage in the spring according to soil tests, and consisted of: 34 kg K and P ha^{-1} of NOP certified Potassium Sulfate Plus and Tennessee Brown Phosphate in

2012 and 34 kg K ha^{-1} of Potassium Sulfate Plus in 2013. Full-width tillage treatments were chisel plowed to a depth of approximately 20 cm, and then rototilled to a depth of approximately 10 cm to break up and incorporate cover crop residue. A two-row strip tiller (Hiniker Model 6000, Mankato, MN) that was equipped with cutting-coulter, shank point assembly, berming discs, and rolling basket was used for WR tillage in ST treatments. To improve soil tilth for planting in ST, a walk behind rototiller was used for WR secondary-tillage. The resulting WR zone was approximately 25 cm wide and 20 cm deep.

Two weeks after tillage, sweet corn (*Zea mays* L. var "Luscious") was planted using a high residue planter (Monosem vacuum seeder, Monosem Inc., Edwardsville, KS) at a between-row spacing of 76 cm and in-row spacing of 10 cm. High seeding rates were used to control for possible treatment differences in sweet corn emergence and density; once sweet corn emerged, population density was thinned to 5 plants/ m row (or 7 plants/m^2). In BARE-SOIL subplots, all sweet corn plants were removed by hoeing approximately 10 days after emergence. Weeds were controlled through a combination of hand weeding and hoeing once a week for the first 5 weeks, and every other week thereafter. Sweet corn was irrigated during low-rainfall periods in 2012 and 2014, totaling 62.2 and 46.8 mm of irrigated water, respectively throughout the sweet corn season (Table 2). In 2013, we did not apply any additional irrigation.

Soil Inorganic N and Gravimetric Moisture

Soil samples were collected every 7 to 14 days (8 sampling times in 2012, 2013, and 9 sampling times in 2014) throughout the growing season in all treatments and subplots in both the WR and BR. At each sampling date, 10-12 cores (2.5 cm diameter

X 20 cm deep) were composited and homogenized. Two 10 g subsamples of moist soil were dried at 100°C and reweighed to measure calculate gravimetric moisture. The remaining soil was dried at 38°C and ground. To extract soil inorganic N, 50 mL of 1M KCl were used on 10 g of dry soil and samples were analyzed according to Gelderman and Beagle (1998) on a QuikChem 8500 Flow Injection Analyzer (Lachat Instruments, Loveland, CO). Total inorganic N was calculated by adding NH_4-N with NO_3-N.

To calculate the soil inorganic N and gravimetric moisture across the whole plot, we used weighted means of the measured values from the WR and BR zones adjusted by their respective areas. For example, for soil inorganic N we used:

$$N_{\text{whole plot}} = N_{WR}*1/3 + N_{BR}*2/3 \quad [1]$$

Where the within-row (WR) zone is the 25 cm zone where the crop is planted (and where tillage occurs within strip-tilled treatments), and the between-row (BR) zone is the 50 cm zone between crop rows and also is untilled in strip-tilled treatments.

Sweet Corn Sampling and Data Collection

At physiological maturity, we removed all primary ears from sweet corn plants in a designated harvest area of 9.3, 14, and 22.3 m^2 in 2012, 2013, and 2014, respectively. Harvest areas were adjusted each year based on available plot size. Secondary ear weight was grouped with nonreproductive biomass and consisted of no more than 5% of nonreproductive biomass. To obtain plant dry weight, we collected the nonreproductive aboveground portion of 5 randomly sampled plants from each plot, and 5 random harvested ears. We removed a 2.5 cm thick cross-section from each corn ear (2.5 cm from base of 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 nonreproductive biomass and sweet corn ear sections were dried at 60˚C and ground through a 1 mm screen.

To compare tillage and rye-vetch spatial arrangement effects on sweet corn root growth and morphology, three cores (5 cm diameter X 25 cm depth) were excavated from both the WR and BR zones at sweet corn harvest. A meter stick was laid adjacent to a randomly selected sweet corn plant and perpendicular to the sweet corn row, and root cores were excavated 7.5 cm (WR) and 25 cm (BR) from the plant; samples thus represented the mid-point between the edge and center of each zone. Samples were sieved twice through a 4 mm sieve and roots were collected, thoroughly washed, and scanned with an EPSON (V800) scanner. We used the WinRHIZO (Régent Instruments Inc. Québec, Canada) image analysis system to analyze root images for root length and average root diameter. Roots were dried at 60°C for 72 hours and weighed. Root data was used to calculate specific root length (root length per unit root dry weight [m g^{-1}]) and root length density (root length per unit of soil volume [cm cm^{-3}]).

Statistical Analysis

All data were analyzed using mixed models ANOVA with PROC MIXED procedures in SAS (SAS Institute, 2011). Year was initially treated as a fixed factor to determine if treatment effects interacted with year to affect response variables, and in the absence of an interaction, the data were pooled across years. In all cases, block was nested in year, and block and the interactions of block with fixed factors were treated as random effects. Zones (WR and BR) within the cropping system were treated as subplots. The zone within the crop row (WR) is the 25 cm zone where the crop is planted (and where tillage occurs within strip-tilled treatments), and the between-row

(BR) zone is the 50 cm zone between crop rows and also is untilled in strip-tilled treatments.

The fixed effects of tillage (FWT vs ST), rye-vetch spatial arrangement (MIX vs SEG), and zone (WR vs BR) were analyzed for their effect on inorganic N, and gravimetric moisture. For both soil inorganic N and gravimetric moisture, the BARE-SOIL and CORN subplots were analyzed separately, and data were analyzed using repeated measures mixed models with date included as a repeated factor, and AIC and BIC values were compared to determine the best model fit. The WR and BR zones were analyzed separately for the fixed effects of tillage and rye-vetch spatial arrangement on sweet corn root mass and morphology.

The data were checked for assumptions of normality and equal variance, and when necessary, unequal variance models were selected based on AIC values. To increase normality, we log transformed soil inorganic N, specific root length, and sweet corn root mass. When significant treatment effects were detected, means were separated using Fisher's protected LSD $P < 0.05$. In cases where P-values were between 0.05 and 0.10, differences are reported as “marginal” with the P-value presented parenthetically. All figures were made using the GGPLOT2 package in R (Wickham, 2009).

RESULTS AND DISCUSSION

GDD and Precipitation

Temperature, growing degree days (GDD, base 10˚C accumulation), and precipitation during sweet corn growth varied considerably during the three years of this study (Table 2). In 2012, total GDD accumulation was 17% and 29% higher than 2013 and 2014, respectively. Average daily temperatures during the month of July in 2012 were 3.4˚C higher than 2013 and 5.9˚C than 2014. Precipitation in 2012 was 128 mm and 138 mm lower than in 2013 and 2014, but with irrigation this difference was reduced to 66 mm in 2013 and 122 mm in 2014. Warm temperatures and low precipitation in 2012 likely resulted in droughty conditions, especially during the month of July.

Rye and Vetch Biomass and N Content

Detailed information on the effects of spatial arrangement on rye and vetch biomass, N content, and C:N ratio is provided in Lowry and Brainard (2016). In brief, segregating rye and vetch into strips decreased rye-vetch total shoot biomass in 2012 (from 8 Mg ha^{-1} in MIX to 7 Mg ha^{-1} in SEG), but had no effect on total shoot biomass in 2013 or 2014. Averaged across spatial arrangements, total shoot biomass was 5.5 Mg ha^{-1} in 2013 and 7.5 Mg ha^{-1} in 2014. Strip-intercropping of rye-vetch mixtures increased vetch shoot biomass in the WR zone in 2 out of 3 years, and decreased rye shoot biomass in the WR zone in all three years compared to the MIX, resulting in a lower C:N ratio of cover crop residue within the crop row. On a whole plot basis, total shoot N did not differ by rye-vetch spatial arrangement and was approximately 130, 100, and 160 kg N ha^{-1} in 2012, 2013 and 2014, respectively.

Strip-tillage Effects on Soil Inorganic Nitrogen and Gravimetric Moisture

As we expected, ST reduced soil inorganic N compared to FWT, however only in two out of three years (Table 3, Figure 1). Within CORN subplots, ST decreased N by 24% and 28% compared to FWT in 2013 and 2014, respectively, but had no effect on soil inorganic N in 2012 (Figure 1a). This effect may not have been observed in 2012 because of higher overall temperatures (Table 2), which may have accelerated decomposition regardless of tillage. Lower soil inorganic N within ST was likely not due to greater N uptake by sweet corn, because results within the BARE-SOIL subplots (Figure 1b) mirrored those with sweet corn present, in which we found ST reduced N across the whole plot in two (2013 and 2014) out of three years.

Incorporating crop residues into the soil typically enhances decomposition and mineralization due to increased residue-soil contact, and when residues remain on the soil surface decomposition may be slowed resulting in lower inorganic N availability within legume-based reduced-till systems (Dou et al., 1994; Mulvaney et al., 2010). Therefore, we had expected that within BARE-SOIL subplots, where N uptake from corn plants was excluded, we would have found greater inorganic N within the tillage zone (WR) compared to the untilled zone (BR). However, this was true only in 2014, in which ST-WR contained 20% greater soil inorganic N compared to ST-BR (Table 3, Figure 2), but was still 25% lower than FWT-WR and BR.

In two out of three years (2012 and 2014), ST increased whole-plot soil moisture within CORN subplots by an average of 10% across the sweet corn season, with the greatest difference occurring in mid-July, as well as early September in 2014 (Table 4, Figure 3). In contrast, in 2013 we found greater soil moisture in FWT, but this difference only occurred at planting in late June, approximately one week after tillage. Higher soil moisture in ST compared to FWT in 2012, may have enhanced N mineralization in ST relative to FWT (Guntiñas et al., 2012).

Strip-tillage Effects on Sweet Corn

Despite lower soil inorganic N in ST compared to FWT, ST increased sweet corn aboveground biomass in two out of three years (Figure 4). In 2012, ST increased total shoot biomass by 19% (*P*=0.02), resulting from a 37% increase in nonreproductive biomass, while sweet corn ear dry weight and yield (Table 5) were unaffected. In 2014, ST increased total shoot biomass by 16% (*P*=0.01), resulting from an 18-19% increase in both nonreproductive biomass and ear dry weight; sweet corn yield was also marginally increased. In contrast, in 2013, ST resulted in a marginal reduction of total shoot biomass of approximately 10% compared to FWT (*P*=0.09), and a marginal decrease in sweet corn yield. This suggests that factors other than N—such as soil moisture—may have accounted for differences in sweet corn aboveground biomass. In fact, the years with greater biomass in ST, 2012 and 2014, were also the years that ST had higher soil moisture than FWT (Figure 3).

Strip-tillage reduced sweet corn root mass WR by 30% compared to FWT across both rye-vetch spatial arrangements, and reduced root mass within the BR but only in the SEG spatial arrangement (Table 6, Figure 5a). Additionally, ST decreased root length density in both WR and BR in 2014, but not 2013 (Table 6, Figure 6), suggesting that sweet corn plants allocated less carbon to resource acquisition within the top 0.25 m compared to FWT. Plants generally increase root growth and root length density when nutrients or water are limiting (Bloom et al., 1985; Fageria and Moreira, 2011). Difference in root mass and root length density in our study were likely due to tillage-induced differences in soil moisture and soil bulk density, and not to soil inorganic N which was lower in ST. Root length density was greater in FWT in 2014, the year in which FWT decreased soil moisture compared to ST, but not in 2013, when tillage had little effect on soil moisture (Figure 4).

ST decreased specific root length and increased diameter within the BR of the MIX, but not SEG, spatial arrangement (Table 6, Figure 7). Greater bulk density observed within the BR zone of ST (Lowry, 2015) likely contributed to the increase in diameter and decrease in specific root length within the MIX spatial arrangement. Previous studies have found that in soils with greater bulk density, roots must be stronger and denser to penetrate the soil (Unger and Kaspar, 1994; Chassot et al., 2001). However, if this is the case it is not clear why we did not see the same effect within the SEG spatial arrangement.

Rye-Vetch Spatial Arrangement Effect on Soil N and Sweet Corn

Rye-vetch spatial arrangement had no effect on whole plot soil inorganic N within either FWT or ST in any of the three years (Table 3, Figure 1). However, the data supported our hypothesis that segregating rye and vetch into strips increased soil inorganic N within the crop row. Within the BARE-SOIL of ST, SEG rye-vetch increased soil inorganic N by approximately 11% compared to MIX (Figure 2; SA*Zone, *P*=0.002, the three years pooled). Additionally the WR of SEG had on average 23% greater inorganic N compared to the SEG between-row. Rye-vetch spatial arrangement effects on soil inorganic N may have been smaller than expected due in part to movement of cover crop shoot tissue across zones prior to sweet corn planting. While we anticipated some lateral mixing of rye and vetch, lateral growth of vetch, cover crop lodging (in 2012 and 2014) and flail-mowing resulted in greater movement of shoot tissue across zones than anticipated.

Given the relatively small differences in soil N availability due to spatial arrangement observed in our study, it is not surprising that we found no effect of rye-vetch spatial arrangement on sweet corn aboveground biomass, ear dry weight, or yield in any of the three years (Figure 4, Table 5). However, sweet corn root growth was surprisingly responsive to soil differences via variations in rye-vetch spatial arrangement. For example, concentrating the N-rich vetch residue within the crop row of SEG spatial arrangements reduced sweet corn root mass WR by 34% (compared to MIX) regardless of tillage (Table 6, Figure 5a). It is likely that the lower root biomass WR resulted from a more efficient uptake of soil resources (e.g. nitrogen and water), because sweet corn allocated less carbon for roots within the top 25 cm of soil to support relatively equal shoot growth and sweet corn yield. In contrast, between the crop rows, SEG rye and vetch increased root biomass by 43% in FWT, but had no measurable effect on root biomass in ST.

Resource absorption is directly proportional to root length and surface area, so increasing specific root length indicates a higher resource absorption per carbon investment in root growth (Ryser, 2006). Sweet corn roots in the WR of SEG spatial arrangements exhibited a trend for greater specific root length (P=0.08) across both tillage systems, and a marginal (P=0.09) decrease in root diameter WR in ST (Table 6, Figure 7). The increased specific root length (and decreased diameter within ST) suggests that sweet corn plants within SEG spatial arrangement exhibited signs of more efficient resource uptake due to a higher proportion of finer roots with a greater absorption capacity. This morphological difference in root growth enables roots to exploit greater soil volumes, and may have been a response to increased N availability

WR resulting from the concentration of N rich vetch residue. This is consistent with other studies that have found an increase in specific root length within nutrient enriched patches (Hodge et al., 1998; Yu et al., 2015). For example, Yu et al. (2015) found both primary and shoot-borne corn roots increased specific root length in response to localized nitrogen enrichment, while other studies have found N fertilization increases specific root length across the whole root system of field corn (Anderson, 1988; Bonifas and Lindquist, 2009).

We had expected that the greatest difference between the WR and BR zones in root mass and morphology would be in the ST+SEG, the treatment with the greatest zonal differences in soil resources and physical properties. Therefore, it was surprising that the root WR/BR mass ratio was greatest in the most homogenous treatment, FWT+MIX. FWT+MIX had 4 times greater root biomass WR compared to BR, while FWT+SEG and both ST rye-vetch spatial arrangements had only roughly 1.7 times greater root biomass WR compared to BR (Table 6, Figure 5b). One potential explanation for this result is that our root sampling method cannot account for potential differences in root growth below our 25 cm sampling depth. Compared to no-till, tillage sometimes results in a more vertical orientation of root development (Ball-Coelho et al., 1998). It is possible that the lower root growth BR in the FWT+MIX is the result of a more vertical orientation of roots that penetrate more deeply but less laterally within the soil. Less available water in FWT treatments (Figure 3), may have also contributed to reduced lateral root proliferation and more vertical root orientation that would not have been detected through our methods (Trachsel et al., 2013; Zhan et al., 2015). However, it is unclear why such an effect would be enhanced with the MIX spatial arrangement.

Potential for Targeted Placement of Organic N

Corn has a large and extensive root system (Amos and Walters, 2006), which also exhibits a high degree of architectural and morphological plasticity (Bonifas and Lindquist et al., 2009; Trachsel et al., 2013; Yu et al., 2015). This plasticity in root foraging traits may have minimized any potential effects on shoot biomass or yield that could have resulted from an increase in inorganic N within the crop row. For example, sweet corn roots have been shown to grow to greater than a 1 to 1.5 m depth, and expand almost 1 m laterally (Weaver and Bruner, 1927), and would therefore be likely to access mineralized N between crop rows. Corn has also been shown to exhibit considerable architectural plasticity by increasing the steepness of lateral root angles under low N conditions, enabling the root system to access deeper N pools when topsoil N is limiting (Trachsel et al., 2013). Crop species with less plastic, narrower, or shallow root systems (e.g. potato or pea) are unable to access both deeper and further N pools (Weaver and Bruner, 1927; Lynch, 2013), and placing N within close proximity to their limited root system would likely result in a greater benefit of N uptake and productivity.

Reducing the lateral movement of cereal and legume shoots in a segregated cover crop planting system would likely increase differences in N availability between the WR and BR zones. Several adaptations to cover crop strip-intercropping might enhance its effectiveness at targeting mineralized N to the crop row, including: 1) use of non-vining legume species with less lateral growth; 2) strategies to minimize lodging including earlier termination, lower seeding rates or different choice of cover crop species; and 3), roller crimping rather than a flail mowing to terminate the cover crops. However, each of these management choices entail significant tradeoffs that must be weighed against their potential benefits for improving N use efficiency. A “cut and carry” approach, in which cover crop biomass is grown in one field and then harvested and translocated to a different field, may also be an effective strategy for targeted placement of cover crop residues. Alternative options for targeted N placement within organic reduced tillage systems include banding of manure, compost, or other organic N amendments (ie. feathermeal, blood meal, etc.) within the crop row. But more work is needed to evaluate other approaches to banding organic N, and their potential for increasing nitrogen use efficiency in reduced-till systems.

SUMMARY AND CONCLUSION

Our results demonstrate that ST entails tradeoffs between soil moisture and nitrogen management. In two of three years, ST resulted in reduced soil inorganic N compared to FWT (Figure 1). However, these reductions in soil N did not consistently impact sweet corn ear dry weight or yield, and resulted in lower total above ground biomass in only one of three years (2013), when soil moisture was non-limiting (Figure 3). In contrast, in dry years (e.g. 2012 and 2014), total sweet corn shoot biomass was greater under ST compared to FWT (Figure 4), presumably due to increased soil moisture retention (Figure 3).

The data supported our hypothesis that segregated plantings of rye and vetch increase soil inorganic N within the crop row of ST systems (Figure 2). However this increase was not sufficient to match overall soil inorganic N levels found in FWT (Figure 1). Additionally, the differences in soil inorganic N due to segregating rye and vetch was not sufficient to impact sweet corn shoot growth (Figure 4). This lack of above-ground response to spatial arrangement suggests that N from vetch was either sufficient to be non-limiting (especially in dry years), or that differences in soil N were too small to lead to detectable differences in shoots. In contrast, sweet corn roots were responsive to relatively small differences in the distribution of soil N or moisture within the soil (Figures 5 and 7). This plasticity may limit the potential benefits of nitrogen placement strategies such as segregated cover cropping. To the extent that other crops exhibit less root plasticity than sweet corn, segregated rye-vetch plantings might provide greater benefits than those observed in our study. Segregated plantings of less sprawling legume species, or adjustments in management strategies to minimize lateral movement of cover crop residue may also enhance the benefits of this approach.

ACKNOWLEDGEMENTS

This research was supported in part through funding from the USDA Sustainable Agriculture Research and Education (SARE) program (Project no. GNC10-141), MSU AgBioResearch Project GREEEN (Project no.GR12-387), the Ceres Trust Organic Research Initiative and the USDA-OREI program (Proposal no. 2014-05381). Weather data at the experimental site was provided by the NSF Long-Term Ecological Research Program at the Kellogg Biological Station. We thank Corey Noyes, Joe Simmons, Todd Martin, Erin Haramoto, and Zack Hayden for technical advice and assistance. We also thank Alexis Snyder, Heather Eifert, Sam Peck, Nate Robinson, Frank Horton, Hannah Gray, and Max Kokmeyer for assistance with data collection and field maintenance. Finally, we thank Mathieu Ngouajio, Alexandra Kravchenko, and G.Phil Robertson for guidance, as well as four reviewers for comments on the manuscript.

REFERENCES

Amos, B., and D.T. Walters. 2006. Maize root biomass and net rhizodeposited carbon. Soil Sci. Soc. Am. J. 70: 1489–1503.

Anderson, E.L. 1988. Tillage and N fertilization effects on maize root growth and root:shoot ratio. Plant Soil 108:245–251.

Ball-Coelho, B.R., R.C. Roy, and C.J. Swanton. 1998. Tillage alters corn root distribution in coarse-textured soil. Soil Tillage Res. 45:237–249.

Bloom, A.J., F.S. Chapin, and H.A. Mooney. 1985. Plants-an Economic Analogy. Annu. Rev. Ecol. Syst. 16: 363–392.

Bonifas, K.D., and J.L. Lindquist. 2009. Effects of nitrogen supply on the root morphology of corn and velvetleaf. J. Plant Nutr. 32: 1371–1382.

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

Chassot, A., P. Stamp, and W. Richner. 2001. Root distribution and morphology of maize seedlings as affected by tillage and fertilizer placement. Plant Soil 231: 123–135.

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

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

Ettema, C.H., and D.A. Wardle. 2002. Spatial soil ecology. Trends Ecol. Evol. 17: 177–183.

Fageria, N.K., and A. Moreira. 2011. The role of mineral nutrition on root growth of crop plants. Adv. Agron. 110: 251–331.

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

Gelderman, R.H., and D. Beegle. 1998. Nitrate-nitrogen. In Recommended Chemical Soil Test Procedures for the North Central Region, ed. Brown, J.R., pp.17-20. NC

Regional Res. Publ. no. 221. Columbia, MO: Missouri Agricultural Experiment Station.

Grandy, A.S., and G.P. Robertson. 2006. Aggregation and organic matter protection following tillage of a previously uncultivated soil. Soil Sci. Soc. Am. J. 70: 1398–1406.

Guntiñas, M.E., M.C. Leirós, C. Trasar-Cepeda, and F. Gil-Sotres. 2012. Effects of moisture and temperature on net soil nitrogen mineralization: A laboratory study. Eur. J. Soil Biol. 48: 73–80.

Haramoto, E. 2014. Weed population dynamics, profitability, and nitrogen loss in strip-tilled cabbage and sweet corn. Ph.D. dissertation. Michigan State University. East Lansing, MI.

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

Hayhoe, K., J. VanDorn, T. Croley, N. Schlegal, and D. Wuebbles. 2010. Regional climate change projections for Chicago and the US Great Lakes. J. Great Lakes Res. 36: 7–21.

Hodge, A. 2004. The plastic plant: root responses to heterogeneous supplies of nutrients. New Phytol. 162: 9–24.

Hodge, A., D. Robinson, B.S. Griffiths, and A.H. Fitter. 1999. Why plants bother: root proliferation results in increased nitrogen capture from an organic patch when two grasses compete. Plant, Cell Environ. 22: 811–820.

Hodge, A., J. Stewart, D. Robinson, B.S. Griffiths, and A.H. Fitter. 1998. Root proliferation, soil fauna and plant nitrogen capture from nutrient-rich patches in soil. New Phytol. 139: 479–494.

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

Kane, D.A., S.S. Snapp, and A.S. Davis. 2015. Ridge tillage concentrates potentially mineralizable soil nitrogen, facilitating maize nitrogen uptake. Soil Sci. Soc. Am. J. 79: 81–88.

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

Kaye, J.P., and S.C. Hart. 1997. Competition for nitrogen between plants and soil microorganisms. Trends Ecol. Evol. 12: 139–143.

Korsaeth, A., L. Molstad, and L.R. Bakken. 2001. Modelling the competition for nitrogen between plants and microflora as a function of soil heterogeneity. Soil Biol. Biochem. 33: 215–226.

Lahlou, O., and J.F. Ledent. 2005. Root mass and depth, stolons and roots formed on stolons in four cultivars of potato under water stress. Eur. J. Agron. 22: 159–173.

Loecke, T.D., and G.P. Robertson. 2009. Soil resource heterogeneity in the form of aggregated litter alters maize productivity. Plant Soil 325: 231–241.

Lowry, C.J. 2015. Adapting reduced tillage systems for organic production: Utilizing strip-tillage and alternative cover crop spatial arrangements to address farmers' perceived barriers to adoption. Ph.D. dissertation. Michigan State University. East Lansing, MI.

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

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

Lynch, J.P. 2013. Steep, cheap and deep: an ideotype to optimize water and N acquisition by maize root systems. Ann. Bot. 112: 347–357.

Maddux, L.D., C.W. Raczkowski, D.E. Kissel, and P.L. Barnes. 1991. Broadcast and subsurface-banded urea nitrogen in urea ammonium nitrate applied to corn. Soil Sci. Soc. Am. J. 55: 264–267.

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

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

Müller, E., Wildhagen, H., Quintern, M., Heß, J., Wichern, F., and Joergensen, R. G. 2009. Spatial patterns of soil biological and physical properties in a ridge tilled and a ploughed Luvisol. Soil Tillage Res. 105: 88–95.

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

Nash, P.R., P.P. Motavalli, and K.A. Nelson. 2012. Nitrous oxide emissions from claypan soils due to nitrogen fertilizer source and tillage/fertilizer placement practices. Soil Sci. Soc. Am. J. 76: 983–993.

Pittelkow, C.M., B.A. Linquist, M.E. Lundy, X. Liang, K.J. van Groenigen, J. Lee, N. van Gestel, J. Six, R.T. Venterea, and C. van Kessel. 2015. When does no-till yield more? A global meta-analysis. Field Crop. Res. 183: 156–168.

Robertson, G.P., D. Wedin, P.M. Groffman, J.M. Blair, E.A. Holland, K.J. Nadelhoffer, D. Harris. 1999. Soil Carbon and Nitrogen Availability: Nitrogen mineralization, nitrification, and soil respiration potentials. In Robertson, G.P., C.S. Bledsoe, D.C. Coleman and P. Sollins, editors. Standard Soil Methods for Long Term Ecological Research. New York: Oxford University Press, New York.

Robinson, D. 1994. The responses of plants to non-uniform supplies of nutrients. New Phytol. 127: 635–674.

Rosecrance, R.C., G.W. McCarty, D.R. Shelton, and J.R. Teasdale. 2000. Denitrification and N mineralization from hairy vetch (*Vicia villosa* Roth) and rye (*Secale cereale* L.) cover crop monocultures and bicultures. Plant Soil 227: 283–290.

Rosswall, T. 1982. Microbiological regulation of the biogeochemical nitrogen cycle. Plant Soil 67: 15–34

Ryser, P. 2006. The mysterious root length. Plant Soil 286: 1–6.

SAS Institute. 2011. The SAS system for windows version. Version 9.3. SAS Inst., Cary, NC.

Shipley, B., and D. Meziane. 2002. The balance-growth hypothesis and the allometry of leaf and root biomass allocation. Funct. Ecol. 16: 326–331.

Trachsel, S., S.M. Kaeppler, K.M. Brown, and J.P. Lynch. 2013. Maize root growth angles become steeper under low N conditions. F. Crop. Res. 140: 18–31.

Triplett, G.B., and W.A. Dick. 2008. No-tillage crop production: A revolution in agriculture! Agron. J. 100(Supplement_3): S153–165.

Unger, P.W., and T.C. Kaspar. 1994. Soil compaction and root growth: A review. Agron. J. 86: 759–766.

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

Weaver J.E. and W.E. Bruner. 1927. Root Development of Vegetable Crops. McGraw-Hill Book Co., Inc. New York.

Wells, M.S., S.C. Reberg-Horton, and S.B. Mirsky. 2014. Cultural strategies for managing weeds and soil moisture in cover crop based no-till soybean production. Weed Sci. 62: 501–511.

Wickham, H. 2009. ggplot2: Elegant graphics for data analysis. Springer, New York.

Williams, A., D.A. Kane, P.M. Ewing, L.W. Atwood, A. Jilling, M. Li, Y. Lou, A.S. Davis A.S. Grandy, S.C. Huerd, M.C. Hunter, R.T. Koide, D.A. Mortensen, R.G. Smith, S.S. Snapp, K.A. Spokas, A.C. Yannarell, and N.R. Jordan. 2016. Soil functional zone management: a vehicle for enhancing production and soil ecosystem services in row-crop agroecosystems. Front. Plant Sci. 7: 1–15.

Yu, P., F. Hochholdinger, and C. Li. 2015. Root-type-specific plasticity in response to localized high nitrate supply in maize (*Zea mays*). Ann. Bot. 116: 751–762.

Zhan, A., H. Schneider, and J.P. Lynch. 2015. Reduced lateral root branching density improves drought tolerance in maize. Plant Physiol. 168: 1603–1615.

Table 1. Dates of key field activities and data collection.

	Dates of Operation		
Activity	**2011-2012**	**2012-2013**	**2013-2014**
Planted cover crops	8/31/2011	9/10/2012	9/6/2013
Terminated cover crops	6/5/2012	6/4/2013	6/10/2014
Primary tillage	6/13/2012	6/19/2013	6/16/2014
Secondary tillage	6/15-6/18/2012	6/19/2013	6/17/2014
Planted sweet corn	6/19/2012	6/21/2013	6/27/2014
Installed PMN-Early Season	6/25/2012	6/24/2013	6/27/2014
Installed PMN-Late Season	7/27/2012	7/30/2013	7/31/2014
Collected root samples	9/17/2012	8/30/2013	8/26/2014
Harvested corn	9/4/2012	9/4/2013	9/11/2014

Table 2. Average temperature, GDD, and precipitation during sweet corn growth in 2012, 2013, and 2014 at the Kellogg Biological Station in Hickory Corners, MI.

	Average Temperature (°C)			**GDD (base 10°C)**			**Precipitation + Irrigation (mm)**		
Month	**2012**	**2013**	**2014**	**2012**	**2013**	**2014**	**2012**	**2013**	**2014**
June	22.6	22.5	23.7	145.7	128.9	55.4	4.3	48.8	32.0
July	25.1	21.7	19.2	461.4	360.1	277.9	77.5	82.6	102.4
August	20.8	20.1	20.3	337.2	320.5	334.0	89.9	117.1	119.9
September	21.6	19.6	19.3	47.8	39.4	102.9	10.9	0.0	50.3
Cumulative	–	–	–	992.1	849.0	770.3	182.6	248.4	304.5

Table 3. *P*-values from analysis of inorganic N from CORN and BARE-SOIL subplots in 2012, 2013, and 2014. Across the whole plot of CORN and BARE-SOIL, inorganic N was analyzed as a weighted average of WR and BR, with a three-way ANOVA in which fixed effects include tillage (full-width and strip-tillage), rye-vetch spatial arrangement (mixed and segregated), and date as a repeated measure. In BARE-SOIL, inorganic N was also analyzed with a four-way ANOVA in which fixed effects include tillage, rye-vetch spatial arrangement, zone (WR and BR), and date as a repeated measure.

Effects Across the Whole Plot	**CORN**			**BARE-SOIL**		
	2012	**2013**	**2014**	**2012**	**2013**	**2014**
Till (T)	NS	0.001	0.087	NS	<0.001	0.036
Spatial Arrangement (SA)	NS	NS	NS	NS	NS	NS
SA*T	NS	NS	NS	NS	NS	NS
Date (D)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
T*D	NS	0.026	0.004	NS	<0.001	<0.001
SA*D	NS	NS	NS	NS	NS	NS
SA*T*D	NS	NS	NS	NS	NS	NS
Effects By Zone						
Zone (Z)	–	–	–	0.098	0.085	0.003
T*Z	–	–	–	NS	NS	0.046
SA*Z	–	–	–	0.064	NS	NS
SA*T*Z	–	–	–	NS	NS	NS
Z*D	–	–	–	NS	NS	NS
T*Z*D	–	–	–	NS	NS	0.008
SA*Z*D	–	–	–	NS	NS	NS
SA*T*Z*D	–	–	–	NS	NS	NS

Table 4. *P*-values from a three-way ANOVA for gravimetric soil moisture across the whole plot (weighted average of WR and BR) of CORN subplots. Fixed effects include tillage (full-width and strip-tillage) and rye-vetch spatial arrangement (mixed and segregated), and date as a repeated measure.

Effect	**2012**	**2013**	**2014**
Till (T)	NS	NS	NS
Spatial Arrangement (SA)	NS	0.046	NS
T*SA	NS	NS	NS
Date (D)	<0.001	<0.001	<0.001
T*D	<0.001	NS	<0.001
SA*D	NS	NS	NS
T*SA*D	NS	NS	NS

Table 5. Mean (+/-SEM) sweet corn marketable ear fresh weight in 2012, 2013, and 2014. Fixed effects include tillage (full-width and strip-tillage) and rye-vetch spatial arrangement (mixed and segregated).

			2012		2013		2014	
<u>Main Effect</u>			Mg ha^{-1}					
Tillage								
	FWT		11.8	(0.6)	10.6	(1.1)	6.5	(0.2)
	ST		12.4	(0.4)	8.0	(1.5)	7.8	(0.5)
Rye-Vetch Spatial Arrangement								
		MIX	12.5	(0.5)	9.5	(1.5)	7.2	(0.5)
		SEG	11.8	(0.6)	9.2	(1.3)	7.1	(0.4)
<u>Interactive Effects</u>								
	FWT	MIX	12.4	(0.8)	10.9	(2.0)	6.5	(0.3)
	FWT	SEG	11.3	(0.9)	10.4	(1.3)	6.5	(0.2)
	ST	MIX	12.5	(0.7)	8.1	(2.3)	7.9	(0.9)
	ST	SEG	12.4	(0.6)	8.0	(2.2)	7.7	(0.6)
Significance of Fixed Effects								
	Till (Till)		NS		0.059		0.054	
	Spatial Arrangement (SA)		NS		NS		NS	
	Till * SA		NS		NS		NS	

Table 6. *P*-values from a three-way ANOVA for sweet corn root mass and morphology from soil cores taken at the 7.5 cm (WR) and 25 cm (BR) position from a sweet corn plant, along a transect perpendicular to corn rows. Root morphological data includes specific root length (SRL), average root diameter (ARD) and root length density (RLD). Main effects include tillage (full-width and strip-tillage), rye and vetch spatial arrangement (mixed and segregated), and year (2013 and 2014).

	Root Mass			Root Morphology					
	Mass		Mass Ratio	SRL		Diameter		RLD	
Effect	WR	BR	WR/BR	WR	BR	WR	BR	WR	BR
Till (T)	0.01	NS	0.043	NS	<0.001	NS	0.021	<0.001	0.002
Spatial Arrangement (SA)	0.032	NS	0.049	0.077	NS	NS	NS	NS	NS
T*SA	NS	0.025	0.027	NS	0.025	0.095	0.024	NS	NS
Year (Y)	NS	NS	NS	NS	NS	NS	NS	NS	NS
T*Y	NS	NS	NS	NS	0.058	NS	NS	0.001	NS
SA*Y	NS	NS	NS	NS	NS	NS	NS	NS	NS
T*SA*Y	NS	NS	NS	NS	NS	NS	NS	NS	NS

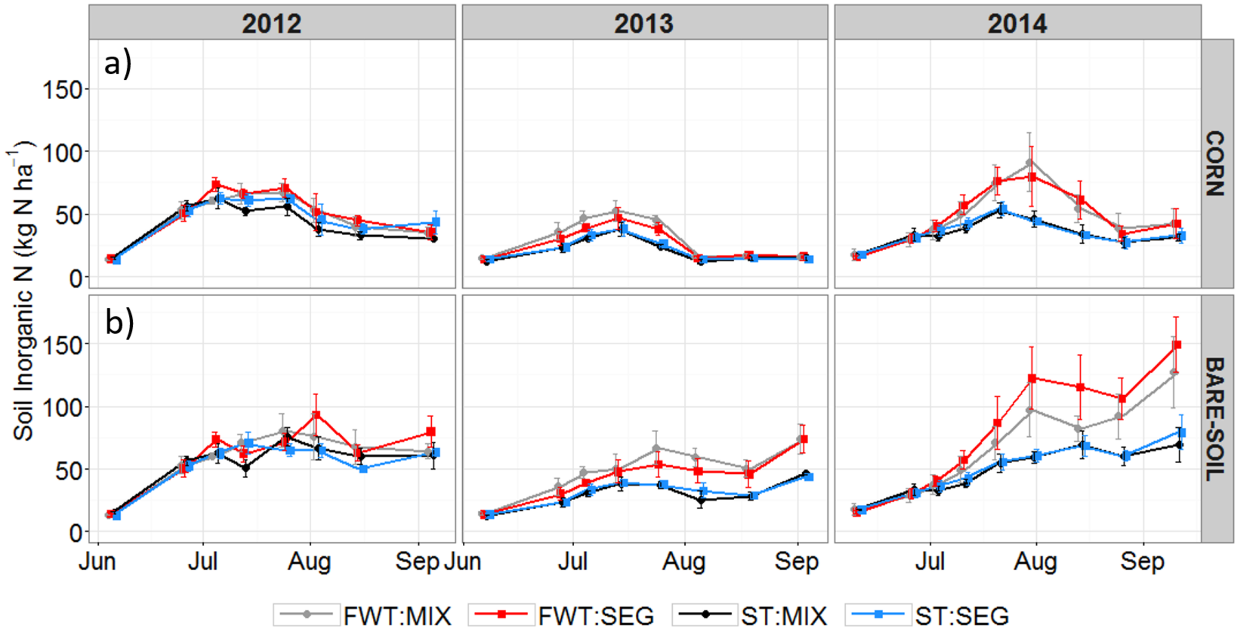

Figure 1. Mean (+/- SEM) soil inorganic N sampled to a depth of 20 cm across the whole plot (weighted average of WR and BR) of CORN (a) and BARE-SOIL (b) subplots in 2012, 2013, and 2014. Soil inorganic N comparisons include full-width tillage (FWT) and strip-tillage (ST) combined with either a mixed (MIX) or segregated (SEG) rye and vetch spatial arrangement. Data points are jittered to reduce overlap.

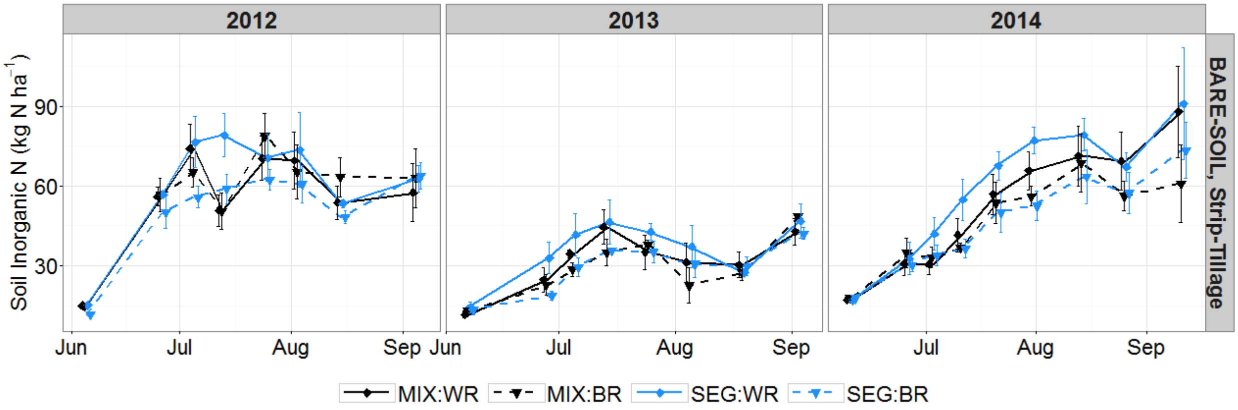

Figure 2. Mean (+/- SEM) inorganic N in the top 20 cm of soil within strip-tillage BARE-SOIL treatments (without sweet corn plants present) in 2012, 2013, and 2014. Bare-soil treatments allowed patterns in soil inorganic N to be observed within zones without sweet corn N uptake. Soil inorganic N comparisons include the within-row (WR) and between-row (BR) zones of mixed (MIX) or segregated (SEG) rye and vetch spatial arrangement. Data points are jittered to reduce overlap.

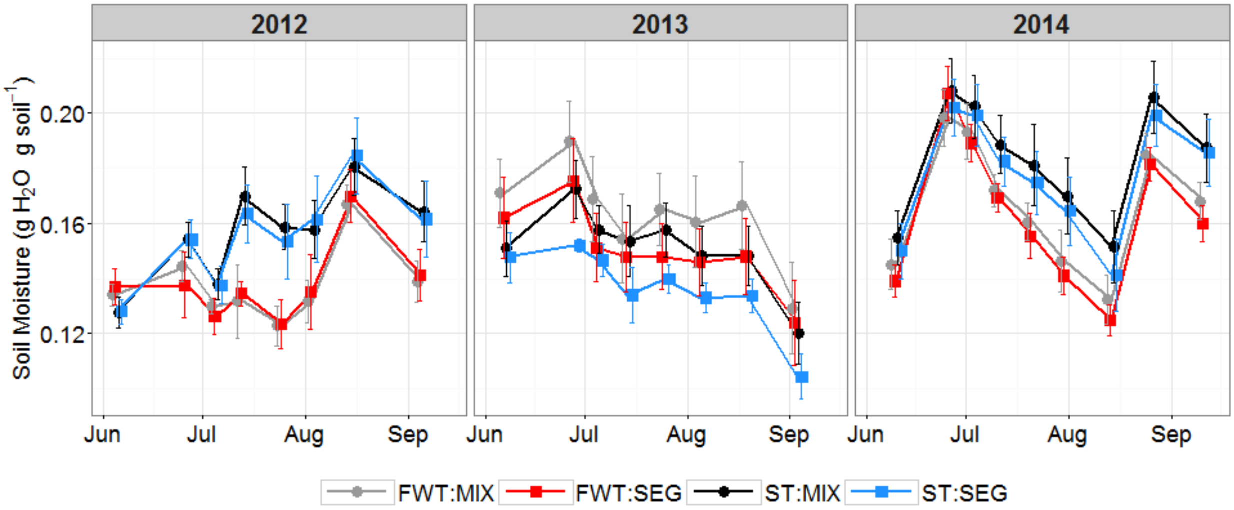

Figure 3. Mean (+/- SEM) gravimetric soil moisture sampled to a depth of 20 cm across the whole plot (weighted average of WR and BR) of CORN subplots in 2012, 2013, and 2014. Gravimetric soil moisture comparisons include full-width tillage (FWT) and strip-tillage (ST) combined with either a mixed (MIX) or segregated (SEG) rye and vetch spatial arrangement. Data points are jittered to reduce overlap.

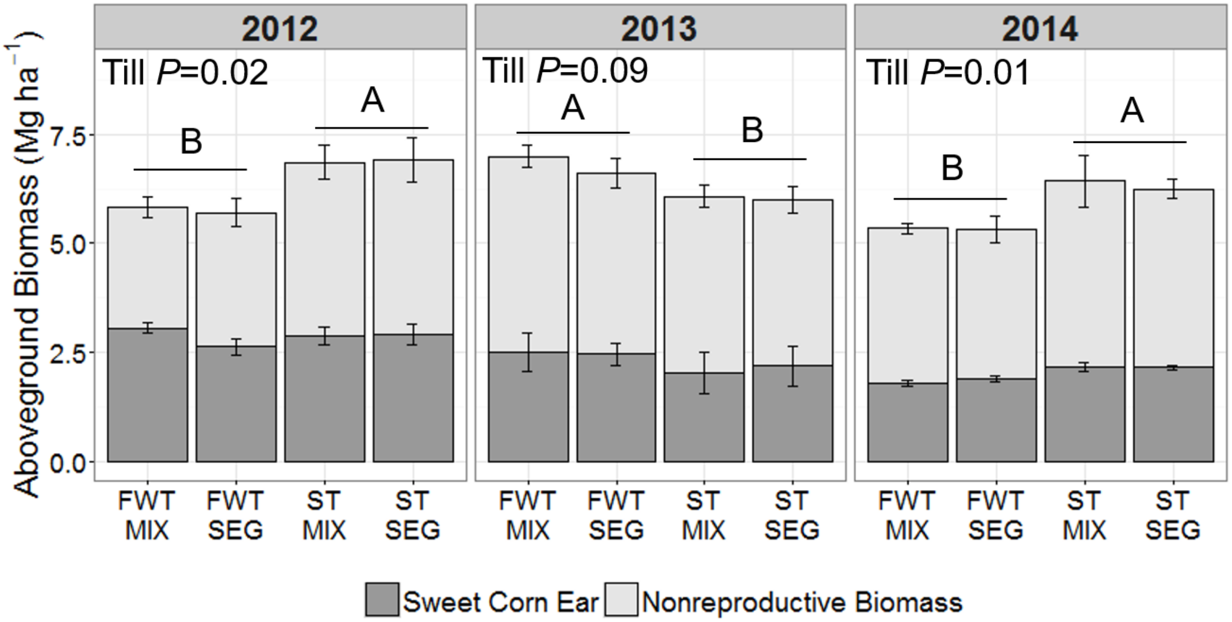

Figure 4. Mean (+/- SEM) sweet corn shoot biomass within nonreproductive biomass and corn ear dry weight in 2012, 2013, and 2014. Comparisons of fixed effects include full-width tillage (FWT) and strip-tillage (ST) combined with either a mixed (MIX) or segregated (SEG) rye and vetch spatial arrangement. Bars with different letters indicate differences between means at the *P* value listed in the top of each panel.

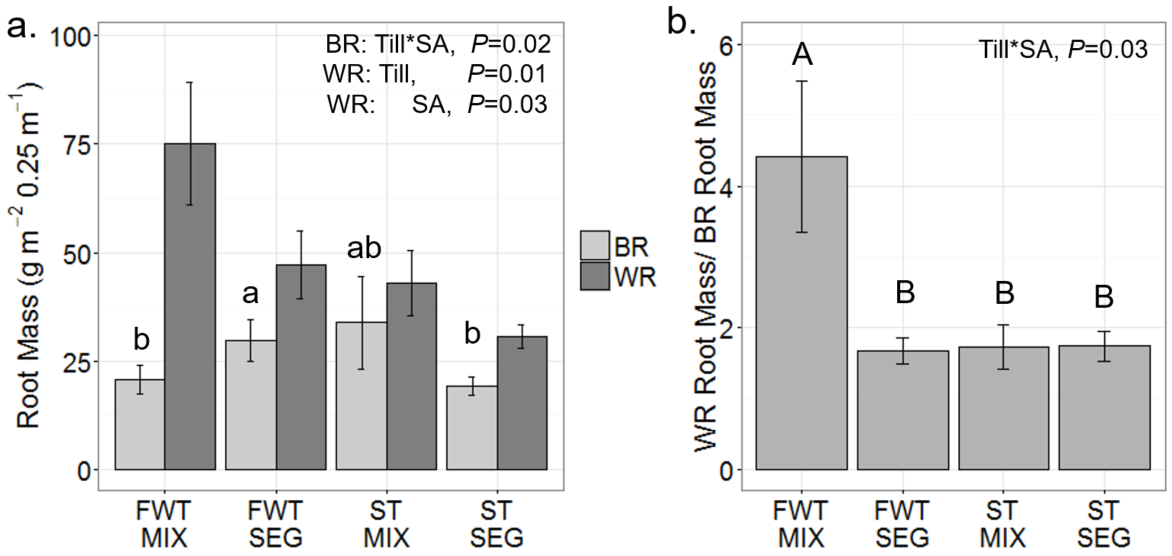

Figure 5. A) Mean (+/-SEM) sweet corn root mass to a depth of 0.25 m in 2013 and 2014 combined. Samples were collected from soil cores taken at the 7.5 cm (WR) and 25 cm (BR) position from a sweet corn plant, along a transect perpendicular to corn rows. B) The ratio of WR/BR root mass in 2013 and 2014 combined. Comparisons of fixed effects include full-width tillage (FWT) and strip-tillage (ST) combined with either a mixed (MIX) or segregated (SEG) rye and vetch spatial arrangement. Bars with different letters indicate differences between treatment means (with zones analyzed separately) at the *P* value listed in the top of each panel.

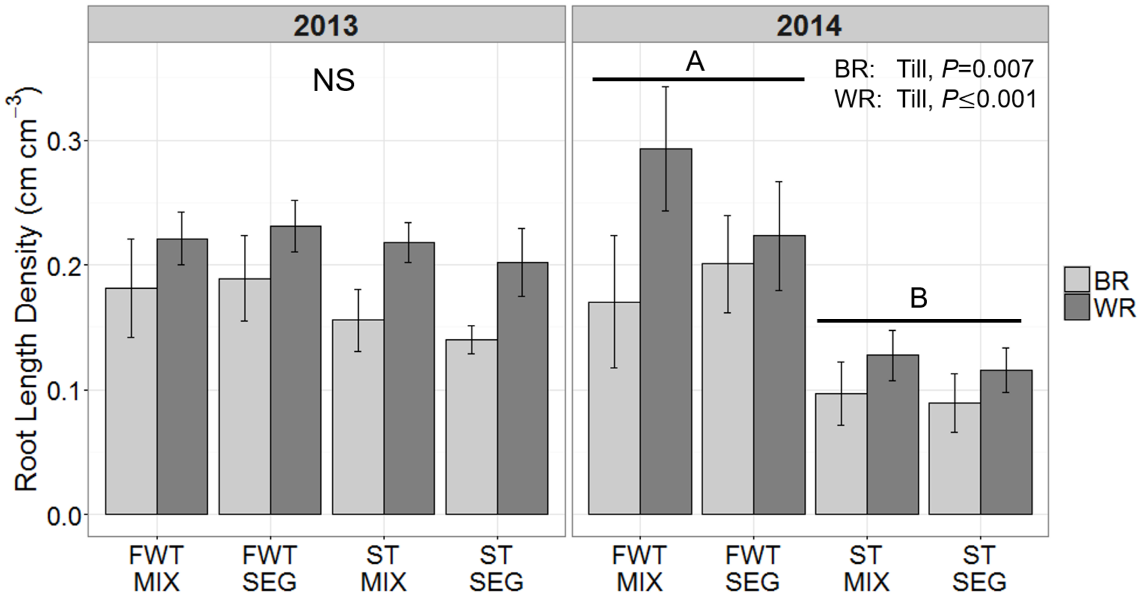

Figure 6. Mean (+/-SEM) sweet corn root length density (RLD) in 2013 (left) and 2014 (right). Samples were collected from soil cores taken at the 7.5 cm (WR) and 25 cm (BR) position from a sweet corn plant, along a transect perpendicular to corn rows. Comparisons of fixed effects include full-width tillage (FWT) and strip-tillage (ST) combined with either a mixed (MIX) or segregated (SEG) rye and vetch spatial arrangement. Bars with different letters indicate differences between means at the *P* value listed in the top of each panel.

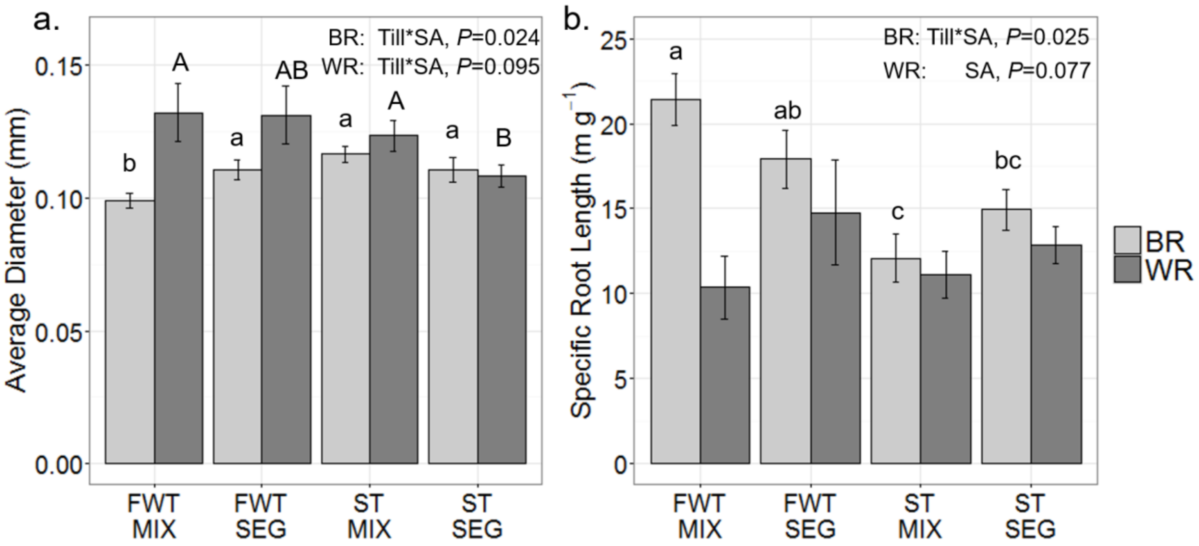

Figure 7. Mean (+/-SEM) sweet corn A) average root diameter (ARD) and B) specific root length (SRL) in 2013 and 2014 combined. Samples were collected from soil cores taken at the 7.5 cm (WR) and 25 cm (BR) position from a sweet corn plant, along a transect perpendicular to corn rows. Comparisons of fixed effects include full-width tillage (FWT) and strip-tillage (ST) combined with either a mixed (MIX) or segregated (SEG) rye and vetch spatial arrangement. Bars with different letters indicate differences between means at the *P* value listed in the top of each panel.