WEED POPULATION DYNAMICS, PROFITABILITY, AND NITROGEN LOSS IN STRIP-TILLED CABBAGE AND SWEET CORN

By

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ABSTRACT

WEED POPULATION DYNAMICS, PROFITABILITY, AND NITROGEN LOSS IN STRIP-TILLED CABBAGE AND SWEET CORN

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In strip tillage (ST), tillage is limited to the crop rows while soil between the rows remains undisturbed. ST offers multiple potential benefits compared to full-width tillage (FWT), including preventing erosion and reducing the number of operations required for soil preparation. However, weed management may be complicated by the lack of soil disturbance in ST. We conducted field experiments and a partial budget analysis to study tradeoffs associated with ST within cabbage and sweet corn production.

In order to understand and address weed management challenges associated with ST, field studies were evaluated the impacts on emergence, growth, and reproduction of Powell amaranth (*Amaranthus powellii*), a widespread problem weed in vegetable cropping systems. Weed emergence in cabbage was examined in ST and FWT, with and without a cover crop. We manipulated soil moisture and nitrogen, and planted fungicide-treated seeds to elucidate mechanisms that affect weed emergence. Emergence was often lower in ST compared to FWT, though this effect diminished over time. Cover crop residues also reduced early emergence of weeds but in some cases led to increased emergence later in the season. This suppression was often alleviated by fungicides, suggesting that fungal pathogens may mediate this cover crop effect. In another set of experiments, plots without cabbage were included to assess the relative importance of crop competition and soil moisture and nitrogen on weed growth and reproduction. ST was often associated with higher soil moisture while the oat cover

crop also reduced soil nitrogen in many cases. Weed growth, however, was often influenced more by the cabbage than by soil moisture and nitrogen. Yield of weedy and weed-free cabbage was not affected by ST or the cover crop.

To evaluate the economic impact of ST adoption in sweet corn, we conducted a partial budget analysis with various assumptions regarding prices, yield, and weed management costs to examine changes in profitability. Tillage-related costs were estimated using an economic engineering approach. Sweet corn yields with a small grain cover crop were similar in ST and FWT across nine site years of experiments suggesting that yields, and thus revenue, will be maintained with ST. ST adoption resulted in increased profits of $26-34/acre depending on the level of investment.

To evaluate potential environmental impacts of ST, we compared the effects of FWT and ST with deep-banded N fertilizer on potentially leachable nitrate (PLN) and nitrous oxide flux (NOF) in a cabbage and sweet corn rotation. Two ST treatments varying the strip position from year to year were included. PLN after harvest was assessed using 1 m deep soil cores. Compared to FWT, ST had little effect on PLN in four of five crop-years. In 2012, following drought conditions with poor sweet corn growth, ST reduced PLN by 44-62 kg/ha compared to FWT. NOF in the cabbage field was lower in ST than in FWT. Relative strip placement had no effect on these losses, though sweet corn yield was 10-18% higher when strips were moved from year to year.

ST can reduce production costs and weed emergence, and has the potential to reduce nitrogen loss while maintaining cabbage and sweet corn yields.

This work is dedicated to my mother, Vicki Haramoto, who passed away in 2010. Growing up on an Allis Chalmers farm, she always thought we used the wrong color equipment but nonetheless was proud of my contributions to agriculture.

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KEY TO ABBREVIATIONS

ST: Strip tillage

FWT: Full-width tillage

IR: In row

BR: Between row

N: Nitrogen

NO_3^-: nitrate

NH_4^+: ammonium

AMAPO: Powell amaranth

CHEAL: common lambsquarters

N_2O: nitrous oxide

NOF: nitrous oxide flux

INTRODUCTION

The use of extensive tillage for agricultural production contributes to soil erosion, loss of soil organic matter (Lal et al., 2004), and a decoupling of nutrient cycling from organic matter pools (Drinkwater and Snapp, 2007). Eliminating tillage, or reducing the frequency and intensity of tillage can mitigate these effects. For vegetable growers in northern areas, complete elimination of tillage is often not feasible because relatively short growing seasons, combined with cool, wet, and unpredictable spring weather underscores the importance of timely plantings. Tillage warms and dries soil in the spring, helping to ensure good crop emergence, establishment, and early growth (Kaspar et al., 1990). In addition, tillage is used to manage weeds prior to planting and also for in-season weed management (Brainard et al., 2013).

While common in many agronomic crops like field corn, cotton, and sugar beets, strip tillage (ST) remains relatively uncommon in vegetable production (Hoyt 1999). In ST, narrow strip (15-30 cm wide depending on equipment and crop) is tilled into otherwise undisturbed soil and a crop is planted into this strip. This targets the benefits of tillage to the crop in-row zone (IR) where they are most useful; these benefits include warming and drying the soil in the spring, ensuring good seed-to-soil contact, and contributing to nitrogen mineralization (Kaspar et al., 1990). As ST eliminates tillage between the rows (BR), some of the benefits of no-till are realized, including maintaining organic matter, protecting soil from erosion, and improving soil water holding capacity (Overstreet and Hoyt, 2008). For these reasons in particular, ST is a form of reduced tillage that is well-suited to vegetable growers wishing to reduce tillage intensity but unable to give tillage up completely. Many vegetable crops perform well in ST; yields of potato (*Solanum tuberosum* L.) and sweetpotato (*Ipomoea batatas* (L.) Lam) (Hoyt and Monks, 1996), pumpkin in one year (*Cucurbita pepo* L.) (Rapp et al., 2004), sweet corn (*Zea mays* L.) (Luna and Staben, 2002), carrots (Brainard and Noyes, 2012) and cabbage (*Brassica oleracea* L. var *capitata*) (Haramoto and Brainard, 2012; Mochizuki et al., 2007) produced with ST were similar to, or greater than, yields produced with conventional, full-width tillage (FWT). Yields of organic broccoli, however, were lower following ST than following FWT (Luna et al., 2012). ST also offers the capability to deep band fertilizers directly into the crop rows, potentially improving N uptake by the crop and reducing the amount of excess N in the soil that is vulnerable to loss.

Because of the more flexible entry points and harvest dates, strip tilled vegetable fields offer more opportunities to integrate cover crops into rotations as well. Cover crop residues remain on the soil surface in the untilled BR zone between the strips. Over the short term, these residues can increase soil water holding capacity by lowering soil temperatures and further protect against erosion (Dahiya et al., 2007). Over the long term, cover crops may help ameliorate some of the negative effects of disturbance in the tilled strips by adding organic matter and helping to re-couple nutrient cycling with organic matter cycling (Drinkwater and Snapp, 2007), thus increasing nutrient storage in soil and better syncing nutrient supply from low but steady OM mineralization with crop demand.

Weed management in ST may be more complicated. Without soil disturbance to incorporate pre-emergence herbicides, growers must rely on irrigation or timely precipitation for optimal efficacy (Banks and Robinson, 1986; Locke and Bryson, 1997). In addition, plant residues on the soil surface BR in ST may intercept these herbicides, reducing their effectiveness. However, there are many factors within ST systems, particularly those with cover crops, that can be exploited to improve weed management (Brainard et al., 2013). Tillage itself promotes the germination and emergence of weed seeds, so eliminating tillage from the BR zone may result in lower weed emergence (Myers et al., 2005). Surface cover crop residues can further reduce emergence in this zone through their effects on soil moisture and N (Bernstein et al., 2014), and by providing habitat for seed predators and seed and seedling decay agents (Shearin et al., 2008). Reductions in emergence will lead to lower weed density in crops, reducing competitive losses. Even if these only occur in the BR zone, weed management efforts can then be targeted to the other zone (e.g. banded herbicides, zone-specific cultivation equipment), reducing costs and potentially herbicide use.

Through its zonal nature, and its effects on soil N and moisture, ST can also affect the growth and reproduction of weeds that do successfully establish. For example, availability of broadcast fertilizers is typically reduced without tillage to incorporate them (Maddux et al., 1991). Weeds growing in the BR zone then may be less able to use these fertilizers, reducing their growth. However, soil moisture in this undisturbed zone may be higher, leading to improved weed growth in this area. Impacts of tillage and incorporated or surface cover crop residues on soil N and moisture are likely stronger immediately after tillage and then diminish through time. For example, incorporation of relatively high C:N residues from non-legume cover crops typically results in an initial immobilization of N in the soil as these residues decay (McSwiney et al., 2010). However, as residue decomposition proceeds, there may be a net mineralization of N from these residues, increasing soil N. Likewise, the longer a soil remains undisturbed, the more soil water holding capacity likely increases. These changes may be observed within a growing season or over longer time scales.

Crop competition adds an additional layer of complexity to weeds growing in ST fields. Successful crop establishment and good crop growth are critical to maximizing crop competitive ability against weeds and minimizing yield loss (Patterson 1995; Blackshaw et al., 2002). Thus factors in ST that improve cabbage performance, like improved soil moisture and nutrient status of the BR zone if cabbage can access that zone, will also contribute to weed management.

The use of ST combined with deep fertilizer banding can also contribute to reducing the amount of N lost from agroecosystems (Malhi et al., 2001). Placing all N fertilizers directly in the crop row puts them closer spatially to where demand is highest—near the crop roots. This can improve crop N uptake, resulting in higher yields combined with less N loss that can result from having excess N in the soil. In particular, this practice may lower the amount of residual N left in the soil after harvest—this N is at risk of being leached over winter in temperate climates with summer annual crop growth. Excess soil N throughout the season has been linked with increased nitrous oxide flux (NOF; McSwiney and Robertson, 2007). While untilled soils have many properties that could increase NOF, like higher soil moisture and larger soil organic N pools, NOF is not typically higher in untilled, well drained soils (Rochette 2008). NOF plays a minor role in determining the total amount of N that can be lost from agroecosystems, but is important due to its effect as a greenhouse gas.

If ST is adopted over the long term, relative strip placement from year to year can influence yields and N utilization and loss. GPS guidance and RTK technologies can be used to place tilled strips in the same location from year to year. In this situation the BR zone would remain perpetually untilled, likely leading to improved soil quality, moisture holding capacity, and nutrient cycling—all of which could potentially influence plants growing IR. However, accumulation of crop residues in the tilled strips could interfere with seedbed preparation and crop establishment. If strip location is offset from year to year, crops are planted into soil that was undisturbed the previous year. Mineralization of labile organic matter pools that developed during this undisturbed period could increase crop yields and, overall, disturbing the soil only every 2-3 years likely results in some improvements in soil quality. Relative strip placement may also influence weed population dynamics. For example, non-creeping perennial species may be favored when strips are in the same location each year (Brainard et al., 2013).

Farmers may be more likely to adopt strip tillage and cover cropping if multiple benefits can be demonstrated. Thus, the objectives of this research were to examine the horticultural, economic, and environmental costs and benefits of ST. Specifically, field experiments were used to study the impacts of ST with and without cover crops on weed emergence and growth, cabbage and sweet corn yield, potential nitrogen loss through leaching, and nitrous oxide flux. In addition, we constructed partial budgets for ST adoption to examine profitability of sweet corn production and potential changes in profitability with adoption of ST on a scale relevant to Michigan vegetable growers.

LITERATURE CITED

LITERATURE CITED

Banks, P. A. and E. L. Robinson. 1986. Soil reception and activity of acetochlor, alachlor, and metolachlor as affected by wheat (*Triticum aestivum*) straw and irrigation. Weed Science 34:607–611.

Bernstein, E.R., D.E. Stoltenberg, J.L. Posner, and J.L. Hedtcke. 2014. Weed Community Dynamics and Suppression in Tilled and No-Tillage Transitional Organic Winter Rye–Soybean Systems. Weed Science 62: 125-137

Blackshaw, R.E., G. Semach, and H.H. Janzen. 2002. Fertilizer application method affects nitrogen uptake in weeds and wheat. Weed Science 50: 643-641.

Brainard, D.C. and D.C. Noyes. 2012. Strip-tillage and compost influence carrot quality, yield and net returns. HortScience 47:1073-1079.

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 Technology 27:218-230.

Dahiya, R., J. Ingwersen, and T. Streck. 2007. The effect of mulching and tillage on the water and temperature regimes of a loess soil: Experimental findings and modeling. Soil Tillage and Research 96: 52-63.

Drinkwater, L.E., and S.S. Snapp. 2007. Nutrients in agroecosystems: Rethinking the management paradigm. Advances in Agronomy 92: 163-186.

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

Hoyt, G.D. and D.W. Monks. 1996. Weed management in strip-tilled Irish potato and sweetpotato systems. HortTechnology 6: 238-240.

Hoyt, G.D. 1999. Tillage and cover residue affects on vegetable yields. HortTechnology 9: 351-358.

Kaspar, T.C., D.E. Erbach, and R.M. Cruse. 1990. Corn response to seed-row residue removal. Soil Science Society of America Journal 554:1112-1117.

Lal, R., M. Griffen, J. Apt, L. Lave, and M. G. Morgan. 2004. Managing soil carbon. Science 304:393.

Locke, M. A. and C. T. Bryson. 1997. Herbicide–soil interactions in reduced tillage and plant residue management systems. Weed Science 45:307–320

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

Luna, J. M., J. P. Mitchell, and A. Shrestha. 2012. Conservation tillage in organic agriculture: evolution toward hybrid systems in the Western USA. Renewable Agriculture and Food Systems 27:21–30.

Malhi, S.S., C.A. Grant, A.M. Johnston, and K.S. Gill. 2001. Nitrogen fertilization management for no-till cereal production in the Canadian Great Plains: a review. Soil and Tillage Research 60: 101-122.

Maddux, L.D., P. L. Barnes, C. W. Raczkowski, and D. E. Kisse. 1991. Broadcast and subsurface-banded urea nitrogen in urea ammonium nitrate applied to corn. Soil Science Society of America Journal 55: 264-267.

McSwiney, C.P., and G.P. Robertson. 2005. Nonlinear response of N2O flux to incremental fertilizer addition in a continuous maize (*Zea mays* L.) cropping system. Global Change Biology 11: 1712-1719.

McSwiney,C.P., S. S.Snapp, and L.E. Gentry. 2010. Use of N immobilization to tighten the N cycle in conventional agroecosystems. Ecological Applications 20: 648-662.

Mochizuki, M. J., A. Rangarajan, R. R. Bellinder, T. N. Bjorkman, and H. M. Van Es. 2007. Overcoming compaction limitations on cabbage growth and yield in the transition to conservation tillage. Hortscience 42:1690–1694.

Overstreet, L. F. and G. D. Hoyt. 2008. Effects of strip-tillage and production inputs on soil biology across a spatial gradient. Soil Science Society of America Journal 72:1454–1463.

Patterson, D. T. 1995. Effects of environmental stress on weed/crop interactions. Weed Science 43:483–490.

Rapp, H.S., R.R. Bellinder, H.C.Wien, and F.M. Vermeylen. 2004. Reduced tillage, rye residues, and herbicides influence weed suppression and yield of pumpkins. Weed Technol. 18:953–961.

Rochette, P. 2008. No-till only increases N_2O emissions in poorly-aerated soils. Soil and Tillage Research 101: 97-100.

Shearin, A.F., S.C. Reberg-Horton, and E.R. Gallandt. 2008. Cover crop effects on the activity-density of the weed seed predator *Harpalus rufipes* (Coleoptera: Carabidae). Weed Science 56:442–450.

CHAPTER ONE

Impacts of tillage, cover crops, and crop competition on the emergence of Powell amaranth (*Amaranthus powellii*) and common lambsquarters (*Chenopodium album*)

Abstract

In strip tillage (ST), tillage is limited to strips where the crop will be planted and the area between crop rows remains undisturbed. ST contributes to soil conservation and improved soil quality in the untilled zone. More information about the mechanisms by which tillage and cover crops influence weed emergence will be helpful in designing ST systems to improve weed management. The objectives of this experiment were to understand how ST and oat cover crop residue impact weed emergence and to evaluate the potential role of fungal pathogens, nitrogen and soil moisture in mediating these effects. Fully-factorial field trials were established with tillage (ST vs. conventional, full-width tillage (FWT)), cover crop (oat or none), and crop competition (cabbage or no cabbage) factors. Powell amaranth and common lambsquarters seeds were sown both in the crop row (IR) and between rows (BR) immediately following tillage (early) and again at the time of cabbage transplanting (late). In 2011 and 2012, subplot treatments manipulating soil nitrogen, soil moisture, and with fungicide-treated seeds were included to elucidate mechanisms responsible for regulating emergence. Emerged seedlings were counted and pulled daily. We hypothesized that emergence would be lower in the BR zone due to the lack of germination-stimulating tillage, particularly with oat residue. We anticipated that the residue would conserve soil moisture, contributing to more favorable conditions for fungal pathogens that could

cause seed or seedling mortality, and temporarily immobilize nitrogen, which could reduce emergence of nitrogen-sensitive species. We also hypothesized that any suppression from lack of tillage and oat residue would be relatively short-lived. In most cases, ST resulted in lower early emergence than FWT. IR emergence was consistently lower in ST compared to FWT; BR emergence was also lower in ST than in FWT in two of the three years though only with oats in one of those years. Few tillage effects on late emergence were detected and these were often contradictory. In both zones, oat residue either reduced early emergence or had no effect, though oats did increase late emergence in one year. In several cases, Powell amaranth emergence following oat residue was increased by fungicide seed treatments, suggesting that fungal pathogens played a role in reducing emergence in oat residue. When water was withheld, oats also increased early Powell amaranth emergence in one zone*year combination, suggesting that residue may also have retained soil moisture in the driest conditions. As with tillage, the effects of oat residue on early emergence were stronger than on later emergence. The cabbage crop affected late BR emergence more than IR emergence, despite closer proximity to the IR emergence quadrats. Practically, ST may result in reduced early weed emergence, particularly BR with oats. Fungal pathogens may be responsible for observed suppression by oat residue. However, these impacts are fleeting and likely not sufficient to provide satisfactory levels of weed management in a cabbage crop.

1.1 Introduction

In strip tillage, crops are planted directly into tilled strips, while the soil between these strips is left undisturbed. This form of reduced tillage has the potential to reduce erosion, maintain or improve soil quality in untilled zones (Lemke et al., 2012), and reduce input costs through lower fuel and labor use (Luna and Staben, 2002). ST offers a compromise for vegetable growers in cooler climates who are trying to reduce tillage intensity, but require some of the benefits of tillage for crop establishment including warming and drying the soil in cool, wet springs and providing a fine seedbed for smaller-seeded crops. Without soil disturbance to physically disrupt weeds, weed management is more challenging. Learning more about how weed emergence behaves in these reduced tillage systems, and potential mechanisms responsible for regulating weed emergence, will help with the design of improved management tools and practices.

Weed seeds in ST fields face very different environments depending on whether they are in the tilled in-row zone (IR) or the untilled between-row zone (BR). Weed emergence is typically stimulated by tillage which aerates the soil, creates good seed-soil contact, and exposes seeds to light (Mohler 2001). Emergence of velvetleaf (*Abutilon theophrastii* Medik), for example, declined as tillage intensity declined—emergence in no-till was approximately 30% of that found in chisel plowed plots (Buhler and Daniel, 1988). However, emergence of common lambsquarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.) in response to changing tillage intensity was much more variable (Buhler 1995).

In addition, tillage impacts soil temperature, moisture, and nitrogen—all important factors in determining the success of weed seedling emergence (Myers et al., 2005). Untilled soils, as found in the BR zone in ST, generally have higher soil moisture than tilled soils (Hares and Novak, 1992; Dahiya et al., 2007) and higher BR soil moisture in

ST relative to FWT has been noted (Wilhoit et al., 1990; Hendrix et al., 2004). Tillage also typically causes a flush of nitrate to be released from the oxidation of organic matter, which can stimulate the germination and emergence of nitrophilic weeds like common lambsquarters (Blackshaw et al., 2003).

Differences between the IR and BR zones in ST are greater when cover crops are used; residues are incorporated in the IR zone and left on the soil surface as a mulch layer in the BR zone, adding to the differences between these two zones in factors that can influence weed emergence. Emergence is typically decreased by incorporated residues, though the magnitude of this effect is variable. For example, incorporated oat residue decreased hairy galinsoga (*Galinsoga ciliata* (Raf.) Blake) emergence by 50% in one year, but had no effect in another (Kumar et al., 2009).

These residue-mediated effects may act through nitrogen immobilization, allelopathy, or by fostering seed decay or seedling disease organisms (Mohler et al., 2012). Red clover (*Trifolium pretense* L.) extracts increase the incidence of pythium on wild mustard (*Sinapis arvensis* L.) seedlings (Conklin et al., 2002). Both *Fusarium oxysporum and F. chlamydosporum,* pathogens of both seeds and seedlings, were isolated from seeds buried with fresh green manure residues; emergence of many weed species was also decreased by these residues in unsterilized soil, but not in sterilized soil suggesting a biological mechanism behind this suppression (Mohler et al., 2012). However, Kumar et al. (2008) were not able to demonstrate that residue-mediated effects on some species were reversed by adding fungicides. Their work with buckwheat (*Fagopyrum esculentum* Moench) suggests that nitrogen (N) immobilization plays a role in suppressing weed emergence. Residues of many cover crops, including oats, also have demonstrated allelopathic potential that may impact emerging seedlings (Grimmer and Masiunas, 2005).

Surface cover crop residues present under reduced tillage can have large impacts on weed emergence (Davis 2010; Mirsky et al., 2011; Bernstein et al., 2014). These cumulative effects can result through reductions in seed germination, increases in post-germination seedling mortality below the residue surface, or both. Several mechanisms contribute to reduced emergence. Light penetration to the soil surface is reduced, decreasing germination of light-sensitive species (Teasdale and Mohler, 1993). Thick residues can also physically obstruct weed emergence, and prevent seedlings from reaching sunlight before seed reserves are depleted, thus increasing post germination seed mortality (Teasdale and Mohler, 2000). Surface residues may also influence weed emergence through reductions in soil temperature and increases in soil moisture. Germination is usually favored by higher soil moisture, which is commonly found under surface residues (Dahiya et al., 2007).

Crop competition can also reduce weed germination and emergence through competition for light. This is often exploited to reduce weed management intensity for an entire growing season—weed management efforts are concentrated in the early part of the season before crop canopy closer effectively shades the soil surface. This phenomenon, however, cannot be exploited before canopy closure, and small crop plants often do not affect weed emergence (Oryokot et al., 1997; Roman et al., 1999).

Characterizing weed emergence (i.e. how weeds behave in ST) is important because emerged weeds compete directly with the crop and increase weed management costs; each emerging seedling also represents a withdrawal from the soil seed bank. Emerged weeds are easier to control than seeds in the soil, so promoting emergence in areas where control of emerged individuals is possible is a good way to mitigate future weed problems (Gallandt 2006). However, if weeds are difficult to control through the use of herbicides and/or tillage (e.g. between rows in a strip till vegetable system with limited herbicide options) then reducing weed emergence is an important goal. In addition, improved understanding of the mechanisms responsible for the impact of residues on weed emergence (i.e. why weeds behave the way they do in ST) may help farmers manipulate tillage and cover crop residues to suit their management goals. Thus, the objectives of this experiment were two-fold: 1) characterize the effects of tillage, cover crops and crop competition on IR and BR emergence of Powell amaranth (*Amaranthus* powellii S.Wats.) and common lambsquarters, and 2) evaluate the role of fungal pathogens, soil moisture and soil nitrogen on suppression of emergence.

1.2 Materials and Methods

1.2.1 Plot establishment This experiment was conducted in three different sections of a 1.6 ha field in 2010, 2011, and 2012 at the Kellogg Biological Station in Hickory Corners, MI (lat 42.4058, lon -85.3845). Prior to use in this experiment, the field was no-till soybean or no-till chemical fallow (prior to use in 2012).   We examined eight treatments, a fully-factorial combination of two tillage levels (ST and FWT), two cover crop levels (oats or none), and two crop competition levels (cabbage crop (*Brassica oleracea* var. capitata) or none). These treatments were assigned to main plots that were 3.1 m wide by 4.3 m long, with four rows of cabbage per plot.

Field operations are summarized in Table 1. The oat cover crop was sown at 93.1 kg ha-1 with a no-till drill (John Deere 750). Glyphosate was applied prior to oat planting in 2011 and 2012, but not in 2010 as few emerged weeds were observed in this year. All plots were fertilized in mid-May (2010: 19-19-19 provided 42.6 kg each of N, P, and K per ha; 2011: 46.8 kg N/ha with urea; 2012: 10.4 kg N/ha with urea). Weeds were not controlled in the oat cover crop plots, however glyphosate was applied and/or hand weeding was used to control weeds in the bare soil plots. Cover crop and/or weed biomass was sampled prior to termination with glyphosate by clipping all biomass at the soil surface from two 0.25 m^2 quadrats in each plot, including small untreated areas in bare soil plots. Oat residue was flail mowed 7-12 days after glyphosate application.

Additional fertilizer was broadcast by hand prior to tillage in all plots, with rates based on soil test recommendations for cabbage (Warncke et al., 2004). In 2010, 81.3 kg N ha^{-1}, 100 kg P ha^{-1}, and 69.4 kg K ha^{-1} were applied as a combination of monoammonium phosphate, triple super phosphate, potash, and urea. In 2011 and 2012, 78.3 kg N ha^{-1}, 28.4 kg P ha^{-1}, and 112.5 kg K ha^{-1} were applied as 19-19-19, potash, and urea. Tillage occurred immediately after fertilization. For ST plots, tillage was accomplished with one pass of a Hiniker Model 6000 two-row strip tiller, equipped with cutting disks, a shank, berming disks, and a rolling basket. In FWT plots, one pass with a chisel plow was used for primary tillage, followed by two passes with a field cultivator for secondary tillage.

The first set of weed seeds were planted immediately after tillage (0 days after tillage (DAT)). Seeds of Powell amaranth and common lambsquarters were collected from adjacent fields in the fall preceding each experiment, separated from chaff using a rub board and seed cleaner, and stratified under moist conditions at 4°C for four months. Due to low germination rates in the laboratory, seeds used in 2011 were pre-conditioned by soaking in 2 mM gibberillic acid to break dormancy (Buhler and Hoffman, 1999). Seeds were sown into 0.093 m^2 quadrats located both IR and BR. All BR quadrats were located in non-tire track areas. Approximately 600 seeds of Powell amaranth and 500 seeds of common lambsquarters were sown per quadrat.

Cabbage (“Blue Dynasty”) was transplanted by hand into rows without seed quadrats between 8-13 DAT. Transplants were started in the greenhouse and had 3-5 leaves at transplanting. Flaming was used to control ambient weeds (in non-quadrat areas) that had emerged by this time. Another set of weed seed quadrats were planted immediately after cabbage transplanting as described above.

1.2.2 Fungicide, N, and water subplots In 2011 and 2012, subplot treatments were included to test mechanisms that might be responsible for suppressing emergence. In addition to untreated controls, these included fungicide-treated weed seeds, additional irrigation water, withholding all irrigation and precipitation. In 2011 only, subplots with three different nitrogen rates (no additional N, 78 kg N/ha, and 156 kg N/ha) were also included. The fungicide-treated seeds were coated with captan (71 mg ai/100 g seed), trifloxystrobin (10 mg ai/100 g seed), and metalaxyl (15 mg ai/100 g seed). These were selected to provide protection against a broad range of fungal pathogens (Kumar et al., 2011) and did not affect germination of either species in petri dish assays. Additional irrigation water was supplied with a backpack sprayer calibrated to apply 5 mm of water at low pressure (68 kilopascals) to avoid washing seeds out of the quadrats; a total of 15 mm of extra water was applied to these quadrats over six days at the beginning of each trial. Precipitation and irrigation was excluded from a set of quadrats using plastic sheeting over a flexible plastic frame; these were open on the sides to minimize temperature shifts and were only put in the field while irrigating or when rain was imminent. For additional N, 0.11M and 0.22M urea solutions were prepared and applied to the quadrats using a backpack sprayer that applied 5 mm of solution to each quadrat; this was repeated three times over six days. The quadrats with no additional N received the same amount of water without urea.

1.2.3 Data collection Emerged seedlings were counted and pulled daily for approximately four weeks until less than two seedlings were emerging per quadrat per day for at least five days. Emergence was summed over the entire period.

1.2.4 Statistical analysis Emergence data were square root transformed as necessary prior to analysis to improve normality. Data were grouped according to their variances when variances were heterogeneous; the best model was selected based on Akaiki's Information Criterion. The proportion of emerged seedlings relative to number of seeds sown was the dependent variable. For the early emergence timing, this proportion was subjected to a three way analysis of variance using SAS PROC MIXED (version 9.2; SAS Institute, Cary, NC) with tillage and cover as the main plot factors and the N, fungicide, and water treatments as the subplot factor. The late emergence timing was analyzed similarly, but with the addition of crop as a main plot factor. In both cases, replicate was considered a random factor. Emergence was analyzed separately by zone and by year as initial testing with year indicated significant year by treatment interactions. Single degree of freedom contrasts, slicing, and Tukey's test were used to separate significant interactions where appropriate. P values less than α=0.1 were considered significant; this significance level was chosen to allow detection of effects with high levels of variability typically found in these types of experiments.

1.3 Results and Discussion

1.3.1 Weather conditions During the period of cover crop growth (mid April-late June), 2010 was relatively warm and wet compared to the ten-year average (Table 2). April and May 2010 were 2.5°C and 1.7°C warmer and May and June had 23 and 99 mm of additional precipitation. April 2011 was 1.8°C cooler than the ten-year average and also wetter, receiving double the average precipitation. May and June 2011 temperatures were similar to the ten-year average, while May was wetter (30 mm additional precipitation) and June was drier (38 mm less precipitation). In 2012, May was 2.8°C warmer than average, while both May and June received much less precipitation—only 23-30 mm in June and May, respectively, compared to averages of 85 and 112 mm.

During the weed emergence trials (July through early August), temperatures were higher than the ten-year average in July in all years (1.4°C, 2.0°C, and 3.2°C higher in 2010, 2011, and 2012, respectively) and 1.5°C higher than normal in August 2010 but similar to average in August 2011 and 2012 (Table 2). Precipitation continued to be low in 2012, averaging 45 mm in July and 70 mm in August, compared to ten-year averages of 94 and 101 mm. Precipitation was also very low in August 2010 (34 mm) but higher than the ten year average in July 2010 and throughout 2011.

1.3.2 Cover crop and weed biomass Cover crop and weed biomass are summarized in Table 3. Oats produced approximately 2800 kg/ha in 2010 and 2011. Oat growth was poor in 2012, likely because of low precipitation during May and June 2012 (Table

2), producing on average 1800 kg/ha. As a result, oat residue was raked from areas adjacent to the plots and spread into plot areas to increase biomass to 2800 kg/ha. Weed biomass within the oat cover crop was variable and ranged from 100-1100 kg/ha. Higher weed biomass was observed in 2010, when glyphosate was not applied prior to cover crop planting. Low weed biomass was observed in 2011 with average rainfall, suggesting that oats are more successful in out-competing weeds in years with adequate moisture (Ateh and Doll, 1996). Dominant weed species within the cover crop were shepherd's purse (*Capsella bursa-pastoris* (L.) Medik), mouse-ear cress (*Arabidopsis thaliana* (L.) Heynh), and common chickweed (*Stellaria media* L.)

1.3.3 Early in row emergence Three-way ANOVA results for tillage, cover crop, and subplot treatment effects on early (planted 0 DAT) weed emergence are presented in Table 4, with effects slicing of significant tillage*subplot and cover crop*subplot interactions shown in Table 5. Results and discussion below are separated into main effects of tillage and cover crop, with interactions between these factors discussed if appropriate. Subsequent results and discussion focus on the interactions between main plot factors and the subplot factors to help clarify mechanisms responsible for observed changes in emergence associated with tillage and cover crop treatments.

1.3.3.1 *Tillage effects* At the early timing, ST consistently reduced IR Powell amaranth emergence relative to FWT. Compared to FWT, IR Powell amaranth emergence in ST was 40%, 25%, and 33% lower in 2010, 2011, and 2012, respectively (Figure 1A). In contrast, tillage did not influence early IR common lambsquarters emergence in 2010 or 2011. Common lambsquarters emergence in this zone in 2012 was lower in ST compared to FWT, but only without oats (0.8% and 1.8% emerged for ST and FWT, respectively).

The explanation for consistently lower early IR Powell amaranth emergence in ST compared to FWT is unclear, as we did not observe any interactions between tillage and the fungicide, water, or nitrogen subplot factors. Other factors that may have influenced Powell amaranth emergence include physical differences in seedbeds or temperature effects that were not measured in this study. Others have demonstrated lower temperatures in ST (Mochizuki et al., 2007) though temperature effects are often small, especially in the IR zone (e.g. Haramoto and Brainard, 2012).

1.3.3.2 ***Oat cover crop effects*** In cases where oat cover crop residue affected IR emergence at the early timing, it was usually as an interaction with the subplot factors (Table 4); these cases will be discussed below. Aside from these, the effect of oats on early IR weed emergence depended on tillage and this effect was observed in only one of six year*species combinations. This occurred for IR common lambsquarters in 2012, when oats reduced emergence by 54% compared to no oats but only in FWT ($p<0.0001$). Common lambsquarters emergence was very low in this zone and year—oats reduced emergence to 0.8% compared to 1.8% emergence without oats.

1.3.3.3 ***Mechanisms of oat effects*** In three out of four cases (year*species) in which we included mechanistic N, fungicide, and water subplot treatments, the effect of oat cover crops on early weed emergence varied with subplot treatments (Table 4). Specifically, the effect of oats on IR Powell amaranth depended on water and fungicide manipulations in both 2011 and 2012, and the effect of oats on IR common lambsquarters emergence depended on fungicide manipulations but only in 2012 (Table 5).

For Powell amaranth in 2012, oats reduced emergence of untreated seeds by 36% (Figure 2A; p=0.028) but did not affect emergence of fungicide-treated seeds (Figure 2A; p=0.518). This result suggests that fungal pathogen effects may be an important mechanism explaining oat residue suppression of Powell amaranth. Mohler et al. (2012) also found that fungal pathogens may be responsible for suppressing weed emergence following incorporation of fresh cover crop residues. In 2011, emergence of untreated IR Powell amaranth seeds was similar with and without oats (Figure 2A; p=0.553), but emergence of fungicide-treated seeds was greater with oats than without oats (p=0.006). This result demonstrates that fungal pathogens played an important role in suppressing Powell amaranth emergence in the presence of oats, but suggests that other stimulative mechanisms offset this suppressive fungal-mediated effect of oats in 2011. A similar effect was also observed by Kumar et al. (2011)—buckwheat residues did not affect emergence of Powell amaranth and barnyardgrass (*Echinochloa crus-galli* (L.) Beauv) relative to non-buckwheat controls, but within buckwheat treatments, emergence of fungicide-treated seeds of these species was increased.

The effect of oats on IR Powell amaranth emergence also depended on water manipulations in one year (Table 5). In the driest subplots in 2011, where water was withheld, oats increased emergence relative to no oats (Figure 3; p=0.0014). With additional water, however, oats did not affect emergence (Figure 3; p=0.987). This suggests that the incorporated oats residue promoted emergence by relieving some of the moisture limitation in these dry conditions. In 2012, however, oats suppression of

Powell amaranth emergence only occurred under wet conditions, and the addition of water resulted in lower emergence regardless of whether oats residue was present (Figure 3; p<0.0001). We did not, however, observe a similar effect of supplemental water on emergence of IR common lambsquarters in 2012. Several explanations may account for these results. First, additional moisture may have promoted fungal pathogens that promote decay of Powell amaranth seeds, but not those of common lambsquarters. For example, soil moisture promotes damping-off agents such as *Pythium*, to which *Amaranthus* species are known to be particularly sensitive (Sealy et al., 1988). Alternatively, additional water that we applied evaporated quickly in this hot, dry year and may have been sufficient for germination but insufficient for successful emergence. Soil crusting following supplemental irrigation was also observed in some places, which may have further inhibited successful emergence.

In 2012, we also observed a significant interaction between the cover crop and the subplot treatments on common lambsquarters emergence (Table 4). As with 2012 IR Powell amaranth, oats suppressed IR common lambsquarters emergence by 34% in the untreated quadrats (1.2% and 1.9% for oats and no oats, respectively; p=0.05). However, unlike the IR Powell amaranth in this year, the fungicide treatment did not alleviate this effect as oats also suppressed emergence of the fungicide-treated common lambsquarters seeds in this zone and year (1.6% and 2.6% for oats and no oats, respectively; p=0.003). This significant interaction suggests that the fungicide treatment stimulated emergence without oats, but did not affect emergence with oats. The fungicide treatment did not affect germination of common lambsquarters in laboratory assays. This result could suggest that common lambsquarters, unlike Powell amaranth, was affected by a fungal pathogen in the absence of oats but not where oats residue was present. Regardless, this result suggests that oat suppression of common lambsquarters emergence was not due to the presence of fungal pathogens.

1.3.3.4 ***Mechanistic treatments alone*** We only detected a main effect of the subplot treatment (not interacting with cover crop) in 2011 IR common lambsquarters (Table 4). Both rates of additional N increased emergence beyond that with no additional N (2.3%). However, we did not observe an increasing dose-response; in fact, emergence at the 2N rate (3.3%) was marginally lower than emergence at the 1N rate (4.1%, $p=0.078$). Increases in emergence with more N is consistent with previous studies showing that common lambsquarters germination can be stimulated by nitrates (Sweeney et al., 2008) and this occurred with and without oats as there was no interaction with the cover crop.

1.3.4 Early between row emergence

1.3.4.1 ***Tillage effects*** Early emergence of BR Powell amaranth and common lambsquarters was lower in ST than in FWT in two of the three years (Table 4). In 2010, BR Powell amaranth emergence in ST was 78% lower than in FWT (Figure 1B). In 2011, BR Powell amaranth emergence was 72% lower in ST compared to FWT with oats ($p<0.0001$) and 32% lower in ST compared to FWT without oats ($p=0.029$; Figure 1B). In 2012, in contrast, BR Powell amaranth emergence in ST was greater in most cases than in FWT—these cases will be discussed later in the tillage mechanisms section.

As with Powell amaranth, BR common lambsquarters emergence was 54% lower in ST than in FWT in 2010 (Figure 1B). In 2011, BR common lambsquarters emergence was lower in ST than FWT but only when oats were present (Figure 1B; p=0.007). In 2012, ST had higher BR common lambsquarters emergence (2.0%) than in FWT (0.57%) with oats (p=0.0003), but emergence between tillage types was similar without oats (p=0.425).

1.3.4.2 ***Mechanisms of tillage effects*** There were no significant tillage*subplot interactions in 2011. In 2012, however, the effect of tillage on early BR emergence of both species varied with subplot treatment in both Powell amaranth and common lambsquarters (Table 4). BR Powell amaranth emergence was greater in ST than in FWT in untreated subplots (p=0.0004), but not in subplots where water was excluded (Figure 4; p=0.500). For BR common lambsquarters, early emergence between the two tillage types in untreated subplots was similar (Figure 4; p=0.131), but FWT resulted in lower emergence where water was withheld (p=0.002). Emergence in ST was greater for subplots with additional water (not shown; p<0.0001) and from which water was withheld (Figure 4; p=0.002). These results suggest that the FWT was conserving soil moisture relative to ST—a conclusion that is inconsistent with the observation that soil moisture is generally higher in the untilled BR zone in ST (Hendrix et al., 2004). In addition, for common lambsquarters, single df contrasts within FWT showed that emergence from these dry subplots (water withheld) was actually greater than from untreated subplots (Figure 4; p=0.046) and subplots with additional water (not shown; p<0.0001).

Lower BR emergence with additional water compared to drier conditions was similar to IR results with similar potential explanations including fungal pathogen interactions or soil crusting (see discussion in section 1.3.3.3). Also in this year, there was a non-significant trend of greater soil moisture in ST than in FWT, particularly in the first two weeks after tillage, but variability precluded detection of significant differences (data not shown). It is possible that the lack of tillage in the BR zone in ST contributed to greater moisture loss through increased capillarity of the soil. In dry areas, no till can lead to increased soil moisture loss through evaporation due to the increase in macropore connectivity. The slight differences in soil moisture may have been enough to increase BR emergence in ST in this year. Surface soil at this time was very dry, despite having more soil moisture at greater depths. It is likely that our samples to 20 cm were too deep to assess surface soil moisture conditions.

It is not surprising that we observed more interactions with tillage BR compared to IR. The BR zone is not tilled in ST but is tilled in FWT, thus this zone is more different between tillage types than the IR zone. Our mechanistic subplot treatments, however, did not provide evidence to explain why ST was associated with lower emergence in two of our three years with or without the surface mulch of cover crop residue (78% lower in 2010 averaged over cover crop and no cover crop, 72% lower in 2011 with oats, and 32% lower in 2011 without oats).

1.3.4.3 *Oat cover crop effects* In all cases, oats either had no effect or reduced emergence of BR weeds compared to no oats (Table 4). In 2010, for BR Powell amaranth, emergence with oats was 51% lower than emergence without oats (Figure 5). Oats also reduced early emergence of BR Powell amaranth in 2011, but only in ST

(Figure 5; p=0.003). Oats did not influence BR Powell amaranth emergence in 2012 (Table 4). In 2010, oats also did not influence BR common lambsquarters emergence. In 2011, BR common lambsquarters emergence was reduced by oats, but only within ST (Figure 5; p=0.029). In 2012, oats reduced BR common lambsquarters emergence but only in FWT (Figure 5; p=0.013).

Reductions in BR emergence in ST with oats are consistent with observations from other studies that weed emergence is lower under rye cover crop residue mulches (De Bruin et al., 2005; Nord et al., 2011; Smith et al., 2011; Bernstein et al., 2014). However, some of these studies have noted that this effect can be inconsistent, especially with low cover crop biomass production (<4000 kg/ha; De Bruin et al., 2005), and later in the season (Mirsky et al., 2011). Oats biomass in our study was less than 3000 kg/ha in all years (Table 3), which could explain why we did not consistently observe lower emergence in the BR zone of ST with oats.

1.3.4.4 ***Mechanisms of oat effects*** For BR emergence, the cover crop*subplot interaction only affected one of four cases—BR Powell amaranth emergence in 2011. In this case, oats reduced emergence in the untreated subplots (Figure 2a; p=0.0002), but not emergence of the fungicide-treated seeds (Figure 2a; p=0.97). In other words, the fungicide treatment alleviated the suppressive effect of the oat residue mulch in a similar manner to IR Powell amaranth in 2012. Therefore, fungal pathogens appear to have regulated Powell amaranth emergence through surface oat residue.

Oats also reduced 2011 BR Powell amaranth emergence in subplots where extra water was added (18.3% and 30.7% for oats and no oats, respectively; p=0.002).

Fungal pathogens could also explain these results—this moister environment could have harbored more fungal pathogens. Planting fungicide-treated seeds into these quadrats with additional water could test this hypothesis.

1.3.5 Late in row emergence

1.3.5.1*Tillage effects* In most years, tillage had minimal impact on late (sown 8-13 DAT) emergence in the IR zone of both species—tillage did not affect IR Powell amaranth emergence alone or in combination with other factors in 2011 or 2012, nor IR common lambsquarters emergence in 2010 or 2011, but did impact IR Powell amaranth in 2010 and common lambsquarters emergence in 2012 (Table 6). In 2010, ST had lower IR Powell amaranth emergence than FWT but only where neither oats nor cabbage were present (5.2% and 9.4% for ST and FWT, respectively; p=0.05); where oats were present (and cabbage absent), ST had higher Powell amaranth emergence compared to FWT (16.1% and 4.5% for ST and FWT, respectively; p=0.003). The reason for this differential impact of tillage is unclear as no mechanistic subplot treatments were applied in 2010.

1.3.5.2 *Mechanisms of tillage effects* IR common lambsquarters emergence in 2012 was reduced by approximately 46% in ST compared to FWT in untreated treatments, but fungicide treatment alleviated this suppression (Table 7). In addition, where water was withheld, emergence in FWT was greater than emergence in ST (Table 7).

The observation in this study that tillage effects in the IR zone were smaller at the late timing compared to the early timing is consistent with previous studies showing diminished impacts of tillage over time (Myers et al., 2005; Schutte et al., 2013). The lack of tillage impacts on the IR zone at the late timing is not surprising, as it is tilled in both tillage types.

1.3.5.3 *Oat cover crop effects* The oat cover crop influenced late IR Powell amaranth and IR common lambsquarters emergence in two out of the three years, but in different ways (Table 6). Oats reduced emergence of IR Powell amaranth in 2010 from 9.4% to 4.5% in FWT without cabbage (p=0.05) but oats increased emergence from 5.2% to 16.1% in ST without cabbage (p=0.002). In 2011, oats did not affect IR Powell amaranth emergence. In 2012, oats influenced Powell amaranth emergence, but effects varied by mechanistic subplots and will be discussed in the next section. For IR common lambsquarters, results varied by year: in 2010, oats increased emergence but only when cabbage was present (Figure 6); in 2011, oats suppressed emergence by 32% but only without cabbage; and in 2012, oats reduced emergence from 2.5% to 1.5% in 2012 (Table 6).

1.3.5.4 *Mechanisms of oat effects* In 2012, oats reduced late emergence of IR Powell amaranth in the untreated subplots by 32% compared to no oats but oats had no effect on emergence of fungicide-treated seeds (Table 6). This is similar to the pattern we observed for early emergence of IR Powell amaranth in 2012 (Figure 2a), suggesting that the fungicide treatment was still conferring protection to seedlings at this later time. Others have noted that potential pathogen attack on seedlings occurs soon after fresh residue incorporation (1-4 days; Mohler et al., 2012); initial dry conditions followed by increased precipitation towards the end of our study in 2012 (Table 2) could have slowed cover crop decomposition and prolonged any potential interactions with soil-borne pathogens.

In 2012, oats also reduced late IR Powell amaranth emergence in subplots with additional water (13.7% and 22.6% for oats and no oats, respectively). This finding is consistent with the observation that oats reduced emergence with water at the earlier planting of this species in 2012; continued dry conditions may have led to more moisture tie-up by the oats residue.

1.3.5.5 *Cabbage effects* The cabbage crop had minimal impact on late emergence (planted 8-13 DAT) of IR Powell amaranth and common lambsquarters (Table 6) with significant effects occurring in only three instances. In 2010, cabbage reduced emergence of IR Powell amaranth in ST with oats from 16.1% to 7% (p=0.008); in 2011, cabbage reduced emergence of IR common lambsquarters without oats from 8.1% to 6.4% (p=0.041) but increased emergence of IR Powell amaranth in FWT with oats from 4.5% to 11.8% (p=0.044). These cabbage effects were not influenced by N, fungicide or water subplots (Table 6), so results cannot be easily explained by these factors.

In cases where cabbage suppressed emergence, it is possible that shade from cabbage may have inhibited germination and emergence of these species through reductions in the ratio of red:far red wavelength light or soil temperature. Both of these factors have previously been shown to influence emergence of both Powell amaranth (Gallagher and Cardina, 1998; Steckel et al., 2004) and common lambsquarters (Myers et al., 2004). However, possible mechanisms for the observed stimulation of emergence by cabbage for IR Powell amaranth in FWT with oats are unclear.

1.3.6 Late between row emergence

1.3.6.1 ***Tillage effects*** As expected, tillage generally had a stronger influence on emergence in the BR zone than in the IR zone, but tillage effects were inconsistent across years, and often involved complex interactions with cover crop and crop factors (Table 6). For example, compared to FWT, ST resulted in increased BR Powell amaranth emergence in 2010 without oats residue and without cabbage but resulted in lower emergence in 2012 with cabbage (not shown). BR common lambsquarters emergence was lower overall in ST compared to FWT in 2011, but greater in ST compared to FWT in 2010 with oats and with cabbage (not shown).

1.3.6.2 ***Mechanisms of tillage effects*** The effect of tillage on late BR Powell amaranth in 2011 was affected by the interaction between subplot treatment and cover crop (Table 6, 7). ST resulted in lower emergence than FWT where water was withheld but only with oats, and with additional water but only without oats. The former would suggest that FWT with oats may have had more available moisture than ST with oats. However, this seems unlikely given the relatively high amount of precipitation during this period (Table 2).

1.3.6.3 ***Oat cover crop effects*** The effects of the oat residue on BR emergence were consistently affected by the subplot treatments and are discussed in the next section (Table 6).

1.3.6.4 ***Mechanisms of oat effects*** As with tillage, complex interactions between tillage, the cover crop, and subplot factors make generalizations about the oat effects difficult. In 2010 and 2011, when oats affected late BR Powell amaranth emergence, it was generally stimulatory, while any oat effects noted in 2012 were generally inhibitory.

Also noteworthy, in 2011, oats increased emergence relative to no oats in many of the subplot treatments within ST but not within FWT. For example, in untreated subplots, emergence with oats (37%) was much higher than emergence without oats (7%) but emergence in FWT was similar (23% and 15% for oats and no oats, respectively). This could suggest that there was higher soil moisture under the surface oat mulch. However, no differences were observed between these treatments where water was withheld, suggesting that this was not the case.

Oats also reduced late emergence of BR Powell amaranth in 2012; an effect that was alleviated by fungicide (Table 7). This was the only case in which we detected potential suppression from fungal pathogens on late emergence in the BR zone.

1.3.6.5 *Cabbage effects* Surprisingly, the cabbage crop influenced BR emergence more than it did IR emergence (Table 6); cabbage effects were mostly inhibitory. For BR Powell amaranth, the cabbage reduced emergence in 2010 in ST with oats (but increased emergence in FWT with oats), in 2011 without oats, and in 2012 in ST. For BR common lambsquarters, the cabbage reduced emergence in FWT without oats in 2010 (but increased emergence in FWT with oats), decreased emergence without oats in 2011, and had no effect in 2012.

1.3.6.6 *Mechanisms of cabbage effects* No cabbage*subplot interactions were detected, suggesting that the effects of cabbage on emergence were not related to nitrogen, moisture, or fungal pathogens. It also seems unlikely that cabbage plants, which were still relatively small over the course of this experiment, would have a shading effect on BR weed seeds. Thus, another mechanism is likely responsible for emergence suppression by cabbage.

1.4 Summary and Conclusions

Results from this study indicate that tillage has significant but inconsistent and short-lived effects on emergence of Powell amaranth and common lambsquarters. For early emergence, ST consistently resulted in lower emergence than FWT in the IR zone and typically reduced emergence in the BR zone as well. For emergence beginning 8-13 DAT, fewer tillage effects were detected and those that were detected were small and inconsistent. In cases where tillage influenced emergence, neither nitrogen, fungal pathogens, nor soil moisture were clearly responsible.

Our results demonstrate that oat residue can have both suppressive and stimulative effects on weed emergence and that fungal pathogens and soil moisture can play an important role in mediating these effects. Oats typically resulted in lower early emergence than no oats in the BR zone, often only in ST suggesting that surface residue mulches were important. The fungicide treatment often alleviated this oat effect, or increased emergence further if oats didn't suppress emergence in untreated subplots. In one year, oats also appeared to suppress emergence by contributing soil moisture both IR and BR. In contrast with early emergence, oats often increased late emergence of BR Powell amaranth and decreased late emergence of BR common lambsquarters, though again inconsistent oat effects were often noted. Practically, soon after tillage, ST may result in reduced weed emergence, particularly BR with oats.

However, these impacts are fleeting and likely not sufficient to provide satisfactory levels of weed management in a cabbage crop.

These results suggest several lines of useful future research to improve emergence suppression in ST systems with cover crops: 1) identify specific fungal pathogens responsible for inhibition of germination and emergence; 2) evaluate their selectivity with respect to both weeds and crops; 3) if they are found to be selective for key weeds, assess the impact of different cover crop species on these specific pathogens as well as management practices that might enhance effects. Learning more about the interactions between tillage, cover crop residues, and these pathogens can also be used to further enhance the stale seed bed technique used to minimize weed emergence in crops.

Table 1.1 Timeline for field operations in 2010-2012.

Operation	2010	2011	2012
Glyphosate application	--	4/13	4/6
Oat cover crop established—variety Ida	4/20	4/13	4/18
Oat and weed biomass measured	6/17	6/16	6/20
Cover crop terminated with glyphosate	6/17	6/17	6/22
Residue flail mowed	6/29	6/24	6/29
Fertilizer applied, plots tilled, first timing planted	7/1	6/30	7/3
Cabbage transplanted, second timing planted	7/8 (7 DAT[1])	7/13 (13 DAT)	7/11 (8 DAT)

[1] DAT=days after tillage

Table 1.2 Monthly average temperature and monthly total precipitation (plus supplemental irrigation) for April to August in 2010, 2011, and 2012 at the Kellogg Biological Station in Hickory Corners, MI. Ten year average monthly temperature and average total monthly precipitation from 2002-2011 is also provided.

	Average temperature (°C)				Total precipitation and irrigation (in parentheses) (mm)			
	2010	2011	2012	10 year average [1]	2010	2011	2012	10 year average
April	11.9	7.6	8.8	9.4	71	246	109	73
May	16.1	15.1	17.2	14.4	135	142	30	112
June	20.2	20.2	21.0	20.1	184	47	23 (38)	85
July	23.5	24.1	25.3	22.1	149	187[2] (18)	45 (14)	94
August	22.5	20.7	20.7	21.0	34 (20)	96	70	101

[1] 2002-2011

[2] rainfall in July 2011 was scattered, with 59 mm falling prior to July 6 and 117 mm falling within 3 days (July 27-29). Supplemental irrigation added on July 15 and 19.

Table 1.3 Cover crop and weed biomass prior to termination. Biomass was collected from two 0.25 m^2 quadrats per plot. Averages and standard errors (in parentheses) are presented.

	2010	2011	2012
	--------------------------------kg/ha--------------------------------		
Cover crop	2,728 (380)	2812 (208)	2752[1] (552)
Weeds	1,084 (312)	108 (28)	392 (196)

[1] includes supplemental residue raked into plot areas

Table 1.4 Results of a three-way ANOVA for in row (IR) and between row (BR) emergence of Powell amaranth (AMAPO) and common lambsquarters (CHEAL) beginning 0 days after tillage (early emergence). Main plot factors were tillage and cover crop, with subplot treatment (fungicide-treated (F), untreated (U), additional water (+W), water withheld (-W), and three different nitrogen rates (0N, 1N, 2N)) as the subplot factor. Results of single degree of freedom contrasts separating significant subplot main effects are also shown. See Table 5 for separation of tillage*subplot and cover crop*subplot interactions. † denotes p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

	IR						BR					
	2010		2011		2012		2010		2011		2012	
factor	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL
Tillage (T)	*	NS	**	NS	**	**[1]	***	*	***	NS	***	**
Cover (C)	NS	NS	†	NS	*	**	*	NS	NS	NS	NS	NS
T*C	NS	NS	NS	NS	NS	**	NS	NS	**	*	NS	*
Subplot (S)	--	--	***	**	***	***	--	--	*	*	***	***
T*S	--	--	NS	NS	NS	†	--	--	NS	NS	**	†
C*S	--	--	*	NS	*	*	--	--	***	NS	NS	NS
T*C*S	--	--	NS	NS	NS	NS	--	--	NS	NS	†	NS
single df contrasts separating subplot main effects[2]												
fungicide (F) vs. untreated (U)				NS						NS		F>U***
+ water (+W) vs. - water (-W)				NS						+W>-W***		†
0N vs 1N[3]				1N>0N*						1N > 0N***		--[4]
0N vs 2N				2N>0N*						2N > 0N***		--
1N vs 2N				†						NS		--

[1] grey background indicates that this main effect was not separated because interactions were also significant

[2] single df contrasts used to separate significant subplot main effect

[3] 0N is no additional nitrogen; 1N is 90 kg N/ha; 2N is 180 kg N/ha

[4] Nitrogen subplots were not evaluated in 2012

Table 1.5 Results of effects slicing on in row (IR) and between row (BR) emergence of Powell amaranth (AMAPO) and common lambsquarters (CHEAL) beginning 0 days after tillage (early emergence). Significant tillage*subplot and cover crop*subplot interactions from three-way ANOVA (Table 4) are separated here. Entries denote which factor level (i.e. ST or FWT for tillage and oats (O) or no oats (NO) for cover crop) had higher emergence, and the significance of each effects slice. † denotes p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

	IR						BR					
	2010		2011		2012		2010		2011		2012	
factor	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL
*Effects slicing for subplot*tillage interactions*												
0N											--[1]	
1N											--	
2N											--	
untreated											ST>FWT***	
fungicide											ST>FWT***	
- water											NS	
+ water											ST>FWT***	
*Effects slicing for subplot*cover interactions*												
0N			NS		NS	--			NS			
1N			NS		NS	--			NS			
2N			NS		NS	--			NS			
untreated			NS		NO>O[2]*	NO>O*			NO>O***			
fungicide			O>NO**		NS	NO>O**			NS			
- water			O>NO**		NS	NS			NS			
+ water			NS		NO>O***	NS			NO>O**			

[1] Nitrogen subplot treatments were not evaluated in 2012

[2] NO=no oats; O=oats

Table 1.6 Results of a four-way ANOVA for in row (IR) and between row (BR) emergence of Powell amaranth (AMAPO) and common lambsquarters (CHEAL) beginning 8-13 days after tillage (late emergence). Main plot factors were tillage, cover crop, and cabbage crop, with subplot treatment (fungicide-treated (F), untreated (U), additional water (+W), water withheld (-W), and three different nitrogen rates (0N, 1N, 2N)) as the subplot factor. Results of single degree of freedom contrasts separating significant subplot main effects are also shown. See Table 7 for separation of tillage*subplot and cover crop*subplot interactions. † denotes p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

	IR						BR					
	2010		2011		2012		2010		2011		2012	
factor	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL
Tillage (T)	NS	NS	†	NS	NS	*[1]	†	NS	NS	**	*	NS
Cover crop (CC)	†	NS	†	*	**	**	***	*	NS	**	NS	NS
Cabbage crop (CR)	NS	NS	NS	NS	NS	NS	†	NS	NS	†	NS	NS
T*CC	†	NS	NS	NS	NS	NS	***	NS	NS	NS	NS	†
T*CR	†	NS	NS	NS	NS	NS	**	NS	NS	NS	*	NS
CC*CR	NS	*	NS	*	NS	NS	NS	NS	**	*	NS	NS
T*CC*CR	**	NS	†	NS	NS	NS	**	*	NS	NS	NS	NS
Subplot (S)	-[2]	-	**	**	***	***			**	NS	***	***
T*S	-	-	NS	NS	NS	*	-	-	NS	NS	NS	NS
CC*S	-	-	NS	NS	**	NS	-	-	***	*	*	NS
CR*S	-	-	NS	NS	NS	NS	-	-	NS	NS	NS	NS
T*CC*S	-	-	NS	NS	NS	NS	-	-	**	NS	NS	NS
T*CR*S	-	-	NS	NS	NS	NS	-	-	NS	NS	NS	†
CC*CR*S	-	-	NS	NS	NS	NS	-	-	NS	NS	NS	NS
T*CC*CR*S	-	-	NS	NS	NS	NS	-	-	NS	NS	NS	NS
subplot main effects[3]												
fungicide (F) vs untreated (U)			F>U*	NS								NS
+ water (+W) vs - water (-W)			+W>-W**	+W>-W***								+W>-W***
0N vs 1N			†	†								-[4]
0N vs 2N			NS	NS								-
1N vs 2N			NS	NS								-

[1] grey background indicates that this main effect was not separated because interactions were also significant

[2] subplot treatments were not included in 2010

[3] single df contrasts used to separate significant subplot main effects where appropriate

[4] Nitrogen subplot treatments not evaluated in 2012

Table 1.7 Results of effects slicing on in row (IR) and between row (BR) emergence of Powell amaranth (AMAPO) and common lambsquarters (CHEAL) beginning 8-13 days after tillage (late emergence). Significant tillage*subplot and cover crop*subplot interactions from four-way ANOVA (Table 6) are separated here. Entries denote which factor level (i.e. ST or FWT for tillage and oats (O) or no oats (NO) for cover crop) had higher emergence, and the significance of each effects slice. † denotes p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

	IR						BR					
	2010		2011		2012		2010		2011		2012	
factor	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL	AMAPO	CHEAL
*Effects slicing for subplot*tillage*												
0N						--[1]			NS			
1N						--			NS			
2N						--			NS			
Untreated						FWT>ST*			NS			
Fungicide						NS			NS			
- water						FWT>ST***			FWT>ST[2] *			
+ water						NS			FWT>ST[3] **			
*Effects slicing for subplot*cover interactions*									(all only in ST)			
0N					--				NO>O*	NO>O***	--	
1N					--				NO>O*	NO>O*	--	
2N					--				NO>O*	NO>O***	--	
Untreated					NO>O***				O>NO***	NS	NO>O*	
Fungicide					†				NS	NS	NS	
- water					NS				NS	NO>O*	NS	
+ water					NO>O***				O>NO***	NS	†	

[1] Nitrogen subplot treatments not evaluated in 2012

[2] only with oats

[3] only without oats

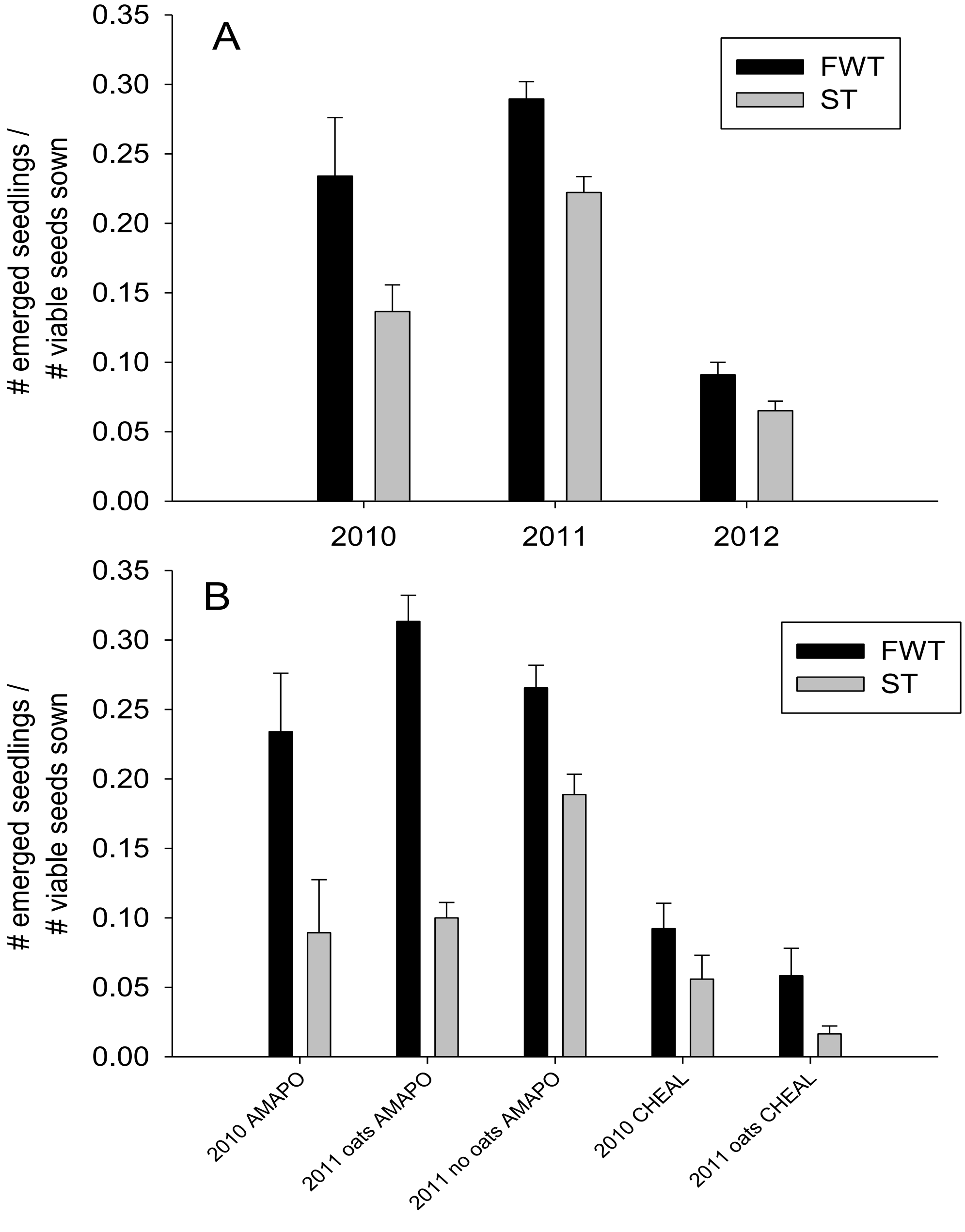


Figure 1.1 Average early IR Powell amaranth (AMAPO) emergence in 2010, 2011, and 2012 in ST and FWT (A) and BR Powell amaranth and common lambsquarters (CHEAL) emergence in 2010 and 2011 in ST and FWT (B). In B, only cover crop levels with significant differences between tillage types are shown. Error bars represent +/- 1 SEM. Within each year and year*cover crop*species combination, emergence between ST and FWT was significantly different at α=0.10.

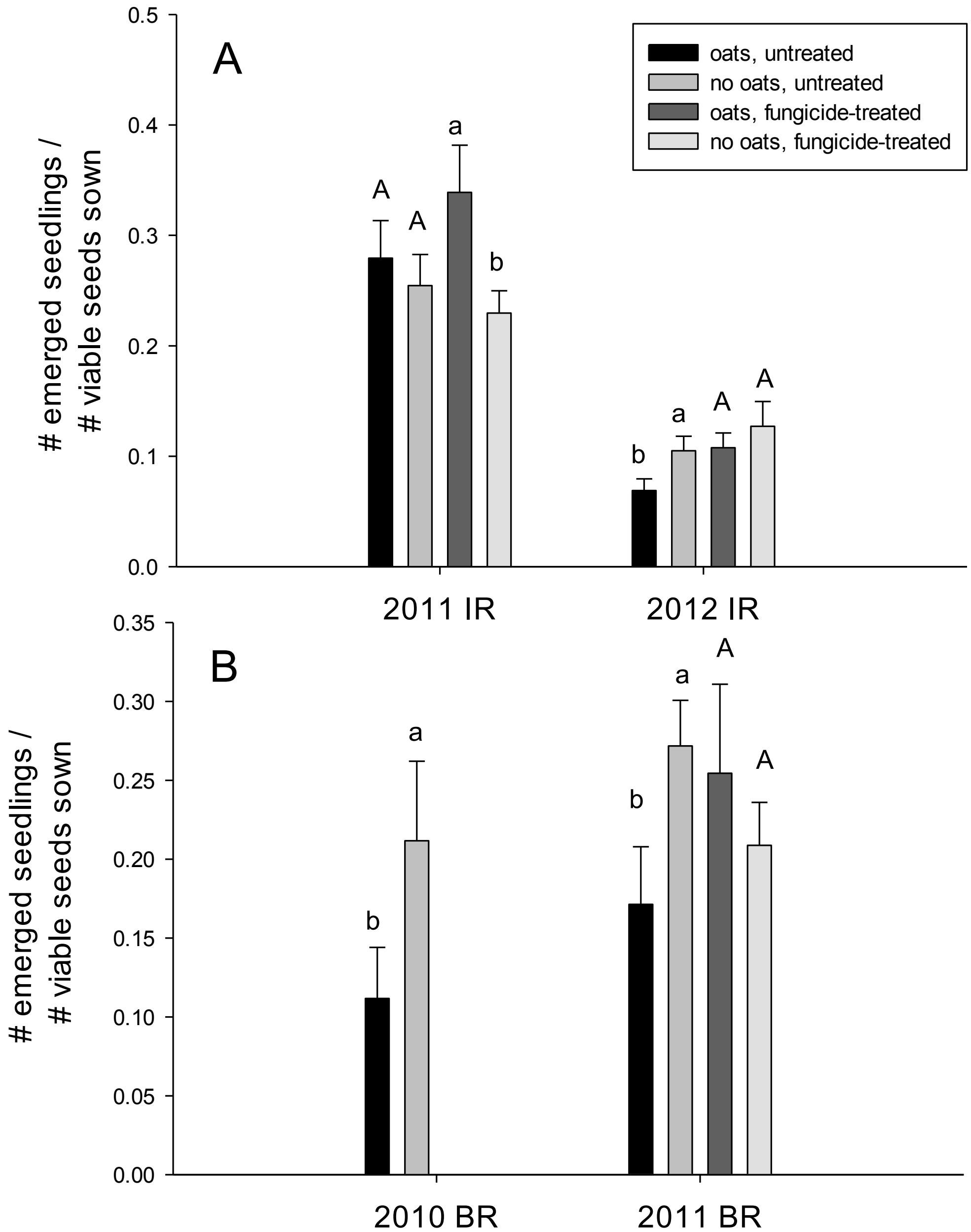


Figure 1.2 Average early emergence of IR (A) and BR (B) Powell amaranth, with and without oats and fungicide treatment. Fungicide treatment was not used in 2010. Error bars represent +/- 1 SEM. Within each year*zone combination, bars with the same uppercase or lowercase letter are not significantly different at α=0.10.

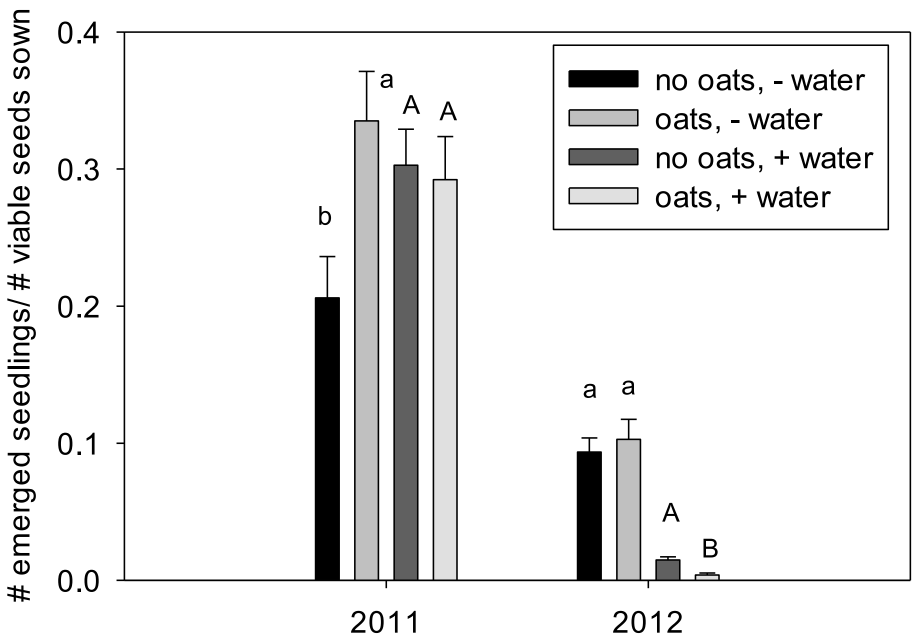


Figure 1.3 Average early IR Powell amaranth emergence in subplots with and without additional water, both with and without oats. Error bars represent +/- 1 SEM. Within each year*zone combination, bars with the same uppercase or lowercase letter are not significantly different at α=0.10.

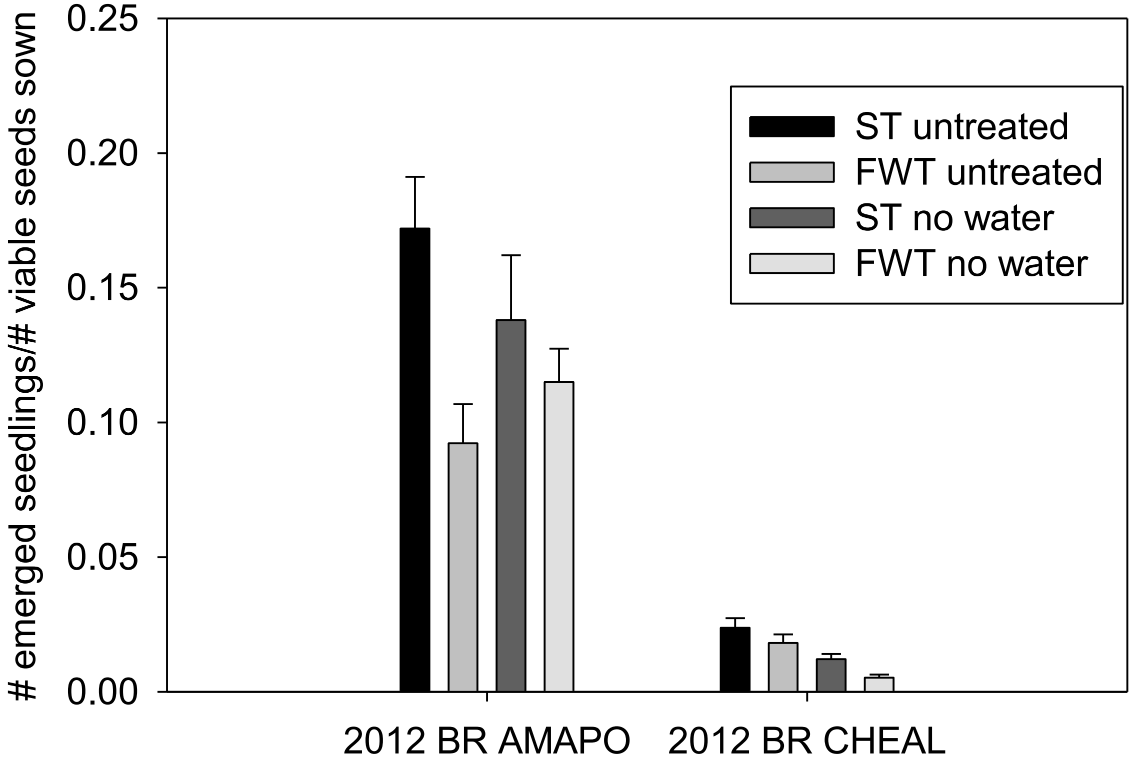


Figure 1.4 Average early BR Powell amaranth (AMAPO) and common lambsquarters (CHEAL) emergence in untreated subplots and in those from which water was withheld, in ST and FWT (2012). Error bars represent +/- 1 SEM. Within each year*zone combination, bars with the same uppercase or lowercase letter are not significantly different at α=0.10.

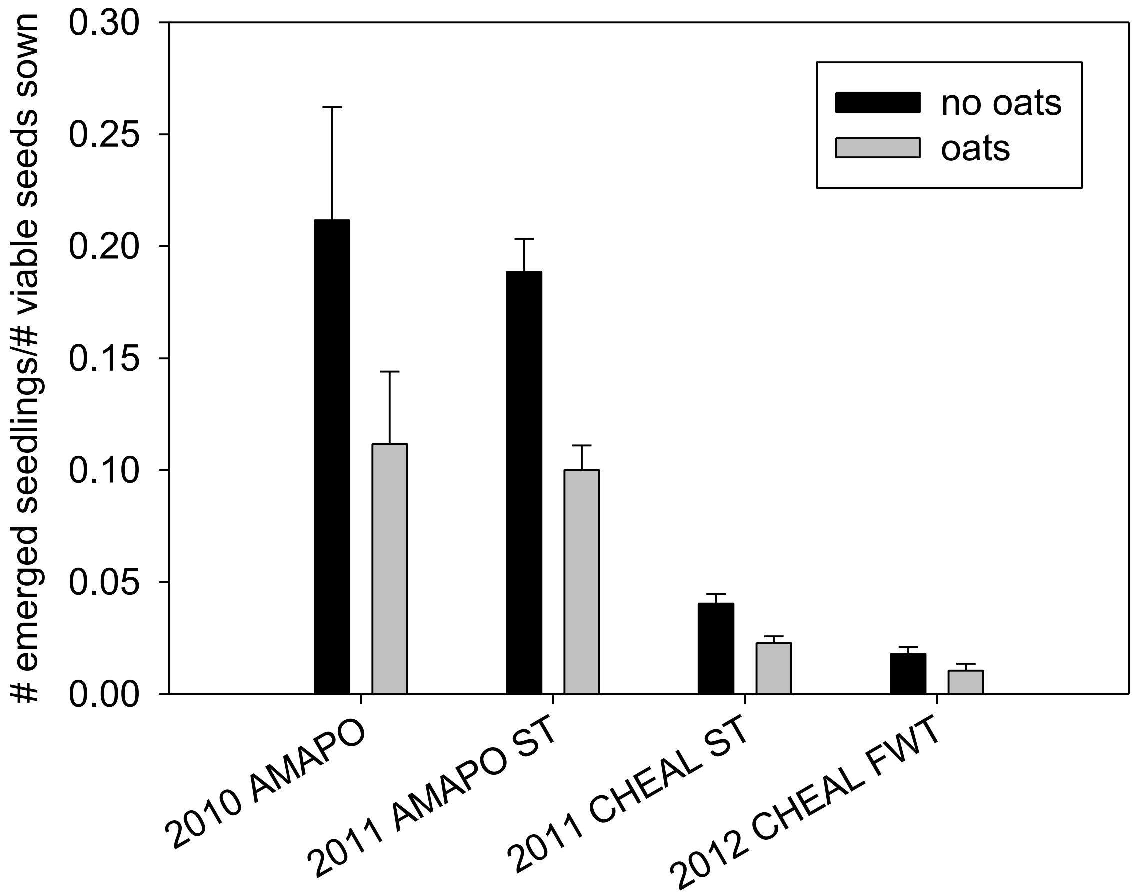


Figure 1.5 Average early BR Powell amaranth (AMAPO) and common lambsquarters (CHEAL) emergence with and without oats. Error bars represent +/- 1 SEM. Within each year and tillage type (if applicable), emergence was reduced in oats relative to no oats at α=0.05.

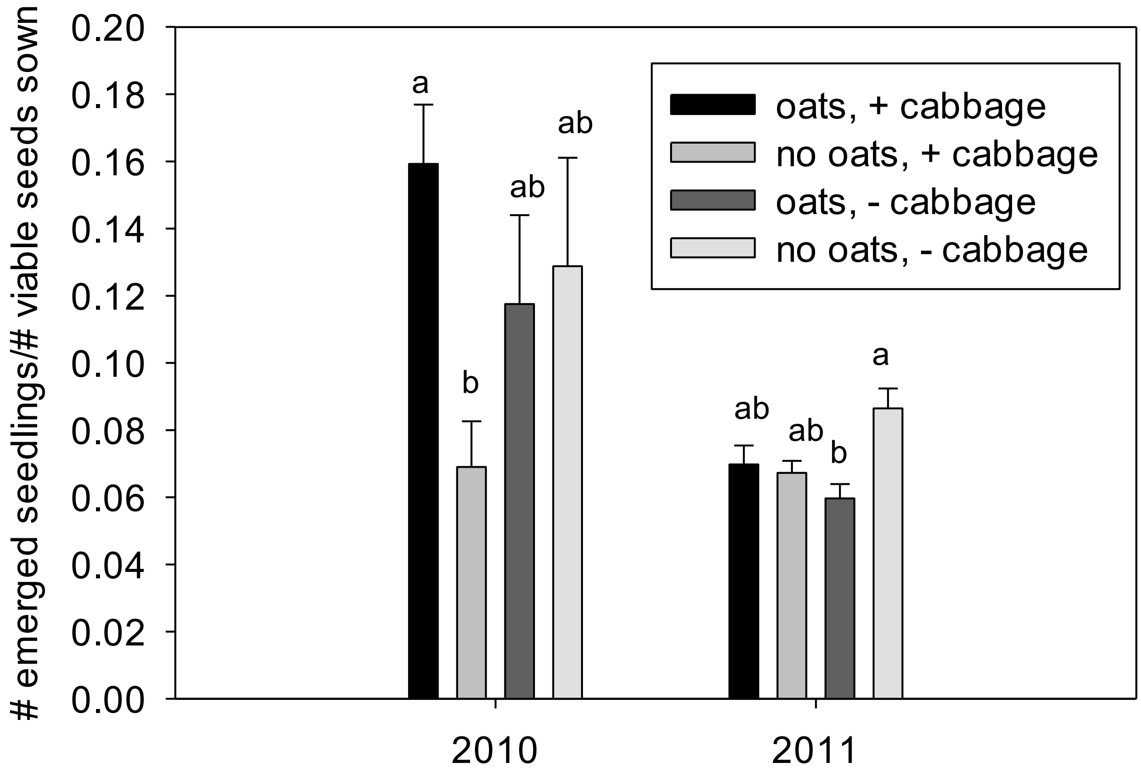


Figure 1.6 Average late BR common lambsquarters emergence, with and without oats and cabbage. Error bars represent +/- 1 SEM. Results of Tukey test indicate that, within each year, bars with the same uppercase or lowercase letter are not significantly different at $\alpha=0.05$.

LITERATURE CITED

LITERATURE CITED

Ateh, C. M. and J. D. Doll. 1996. Spring-planted winter rye (*Secale cereale*) as a living mulch to control weeds in soybean (*Glycine max*). Weed Technol. 10:347–353.

Bernstein, E.R., D.E. Stoltenberg, J.L. Posner, and J.L. Hedtcke. 2014. Weed Community Dynamics and Suppression in Tilled and No-Tillage Transitional Organic Winter Rye–Soybean Systems. Weed Science 62: 125-137.

Blackshaw, R. E., R. N. Brandt, H. H. Janzen, T. Entz, C. A. Grant, and D. A. Derksen. 2003. Differential response of weed species to added nitrogen. Weed Sci. 51:532–539

Buhler, D.D., and T.C. Daniel. 1988. Influence of tillage systems on giant foxtail, *Setaria faberi*, and velvetleaf, *Abutilon theophrasti*, density and control in corn, *Zea mays*. Weed Science 36: 642-647.

Buhler, D.D. 1995. Influence of tillage systems on weed population dynamics and management in corn and soybean in the Central USA. Crop Science 35: 1247-1258.

Buhler, D.D., and M.L. Hoffman. 1999. Andersen's Guide to Practical Methods of Propagating Weeds and Other Plants, 2nd edition. Weed Science Society of America.

Conklin, A.E., M.S. Erich, M. Liebman, D. Lambert, E. Gallandt, and W.A. Halteman . 2002. Effects of red clover (*Trifolium pratense*) green manure and compost soil amendments on the growth and health of wild mustard (*Brassica kaber*) seedlings. Plant and Soil. 238: 245–256.

Dahiya, R., J. Ingwersen, and T. Streck. 2007. The effect of mulching and tillage on the water and temperature regimes of a loess soil: Experimental findings and modeling. Soil Tillage and Research 96: 52-63.

Davis, A.S. 2010. Cover-crop roller-crimper contributes to weed management in no-till soybean. Weed Science 58:300–309.

De Bruin, J.L., P.M. Porter, and N.R. Jordan. 2005. Use of a rye cover crop following corn in rotation with soybean in the upper Midwest. Agronomy Journal 97:587–598.

Franczuk J, E. Kosterna, A. Zaniewicz-Bajkowska. 2010. Weed-control effects on different types of cover-crop mulches. Acta Agriculturae Scandinavica Section B- Soil and Plant Science 60: 472-479.

Gallagher, R. S. and J. Cardina. 1998. Phytochrome-mediated *Amaranthus* germination I: effect of seed burial and germination temperature. Weed Science 46: 48-52.

Gallandt, E. 2006. How can we target the weed seedbank? Weed Science 54: 588–596.

Grimmer, O.P. and J.B. Masiunas. 2005. The weed control potential of oat cultivars. HortTechnology 15: 140-144.

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

Hares, M.A., and M.D. Novak. 1992. Simulation of surface energy balance and soil temperature under strip tillage: II. Field test. Soil Science Society of America Journal 56: 29-36.

Hendrix, B.J., B.G. Young, and S. Chong. 2004. Weed management in strip tillage corn. Agronomy Journal 96: 229-235.

Hoyt, G.D. and T.R. Konsler. 1988. Soil water and temperature regimes under tillage and cover crop management for vegetable culture. pp. 697-702. Proc. of the 11th International Conference, ISTRO. Edinburgh, Scotland.

Hoyt, G.D., A.R. Bonanno, and G.C. Parker. 1996. Influence of herbicides and tillage on weed control, yield, and quality of cabbage (*Brassica oleracea* L. var. *capitata*). Weed Technology 10: 50-54.

Hoyt, G.D. and D.W. Monks. 1996. Weed management in strip-tilled Irish potato and sweetpotato systems. HortTechnology 6: 238-240.

Hoyt, G.D. 1999. Tillage and cover residue affects on vegetable yields. HortTechnology 9: 351-358.

Kumar, V., D.C. Brainard, and R.R. Bellinder. 2008. Suppression of Powell amaranth (*Amaranthus powellii*), shepherd's-purse (*Capsella bursa-pastoris*), and corn chamomile (*Anthemis arvensis*) by buckwheat residues: role of nitrogen and fungal pathogens. Weed Science 56: 271-280.

Kumar, V., D.C. Brainard, and R.R. Bellinder. 2009. Effects of spring-sown cover crops on establishment and growth of hairy galinsoga (*Galinsoga ciliata*) and four vegetable crops. HortScience 44: 730-736.

Kumar, V., D.C. Brainard, R.R. Bellinder, and R.R. Hahn. 2011. Buckwheat Residue Effects on Emergence and Growth of Weeds in Winter-Wheat (*Triticum aestivum*) Cropping Systems. Weed Science 59: 567-573.

Lemke, R.L., A.J. VandenBygaart, C.A. Campbell, G.P. Lafond, B.G. McConkey, and B.Grant. 2012. Long-term effects of crop rotations and fertilization on soil C and N in a thin Black Chernozem in southeastern Saskatchewan. Canadian Journal of Soil Science 92: 449-461.

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

Manici, L.M., F. Caputo, and V. Babini. 2004. Effect of green manure on *Pythium* spp. population and microbial communities in intensive cropping systems. Plant Soil 263: 133–142.

Mirsky, S.B., W.S. Curran, D.A Mortensen, M.R. Ryan, and D.L. Shumway. 2011. Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller-crimper. Weed Science 59:380–389.

Mochizuki, M.J., A. Rangarajan, R.R. Bellinder, T.Bjorkman, and H.M. van Es. 2007. Overcoming compaction limitations on cabbage growth and yield in the transition to reduced tillage. HortScience 42:1690–1694.

Mohler, C.L. 2001. Weed life history: identifying vulnerabilities. Pages 40-98 in Ecological Management of Agricultural Weeds, M. Liebman, C.L. Mohler, and C.P. Staver, eds. New York: Cambridge University Press.

Mohler, C.L., C. Dykeman, E.B. Nelson, and A. DiTommaso. 2012. Reduction in weed seedling emergence by pathogens following the incorporation of green crop residue. Weed Research 52: 467–477.

Myers, M.W., W.S. Curran, M.J. VanGessel, B.A. Majek, D.A. Mortensen, D.D. Calvin, H.D. Karsten, and G.W. Roth. 2005. Effect of soil disturbance on annual weed emergence in the Northeastern United States. Weed Technology 19: 274-282.

Nord, E.A., W.S. Curran, D.A. Mortensen, S.B. Mirsky, and B.P. Jones. 2011. Integrating multiple tactics for managing weeds in high residue no-till soybean. Agronomy Journal 103:1542–1551

Oryokot, J.O.E., S.D. Murphy, and D.J. Swanton. 1997. Effect of tillage and corn on pigweed (*Amaranthus* spp.) seedling emergence and density. Weed Science 45: 120-126.

Overstreet, L.F. and G.D. Hoyt. 2008. Effects of strip-tillage and production inputs on soil biology across a spatial gradient. Soil Science Society of America Journal 72: 1454-1463.

Roman, E.S., S.D. Murphy, and C.J. Swanton. 1999. Effect of tillage and *Zea mays* on *Chenopodium album* seedling emergence and density. Weed Science 47: 551-556.

Schutte, B.J., B.J. Tomasek, A.S. Davis, L. Andersson, D.L. Benoit, A Cirujeda, J. Dekker, F. Forcella, J.L. Gonzalez-Andujar, F. Graziani, A.J. Murdoch, P. Neve, I.A. Rasmussen, B. Sera, J. Salonen, F. Tei, KS. Torresen, and J.M Urbano. 2014. An investigation to enhance understanding of the stimulation of weed seedling emergence by soil disturbance. Weed Research 54: 1-12.

Sealy, R.L., C.M. Kenerley, and E.L. McWilliams. 1988. Evaluation of *Amaranthus* accessions for resistance to damping-off by *Pythium myriotylum*. Plant Disease 72: 985-989.

Smith, A.N., C.S. Reberg-Horton, G.T. Place, A.D. Meijer, C. Arellano, and J.P. Mueller. 2011. Rolled rye mulch for weed suppression in organic no-tillage soybeans. Weed Science 59:224–231.

Steckel, L.E., C.L. Sprague, E.W. Stoller, and L.M. Wax. 2004. Temperature effects on germination of nine *Amaranthus* species. Weed Science 52:217–221.

Sweeney, A.E., K.A. Renner, C.Laboski, and A. Davis. 2008. Effect of fertilizer nitrogen on weed emergence and growth. Weed Science 56: 714-721.

Teasdale, J.R. and C.L. Mohler. 1993. Light transmittance, soil-temperature, and soil-moisture under residue of hair vetch and rye. Agronomy Journal 85: 673-680.

Teasdale, J.R. and C.L. Mohler. 2000. The quantitative relationship between weed emergence and the physical properties of mulches. Weed Science 48: 385-392.

Warncke, D., J. Dahl, and B. Zandstra. 2004. Nutrient recommendations for Michigan vegetable crops. MSU Extension Bulletin Publication E2934. East Lansing, MI.

Wilhoit, J.H., R.D. Morse, and D.H. Vaughan. 1990. Strip-tillage production of summer cabbage using high residue levels. Applied Agricultural Research 5:338–342.

CHAPTER TWO

Growth of Powell amaranth (*Amaranthus powellii*) in different tillage systems as affected by cover crop residues and crop competition.

Abstract

In strip till (ST), tillage is limited to the crop rows resulting in more spatial heterogeneity than found in conventional, full-width tillage (FWT), particularly where cover crops are used. Weeds growing in different locations in ST thus face different environments—in crop rows (IR), the soil is tilled, cover crop residues are incorporated, and crop competition is stronger while the area between the crop rows (BR) is untilled, has a surface mulch of cover crop residue, and is less impacted by crop competition. Differences in soil moisture and nitrogen content in these distinct zones are likely important in determining the success of weed growth. Understanding how weeds respond to these different environments is important to optimize tillage and cover cropping strategies for weed suppression. A field experiment was conducted over two years in central Michigan to separate the effects of three different factors on weed growth—tillage [ST or FWT (chisel plow followed by field cultivation)], cover crop (spring-planted oat or none), and crop competition (cabbage or no cabbage). Powell amaranth seedlings were transplanted IR and BR and sampled both at mid-season and at cabbage maturity. Soil samples were collected biweekly from planting to harvest to measure moisture and nitrate content. We hypothesized that the undisturbed BR zone in ST would have higher soil moisture and decreased nitrogen availability and that the interaction between these would regulate weed growth. Surface mulch of oats was

expected to enhance these effects by immobilizing N and reducing evaporation. IR, we expected that cabbage would have a dominant role in regulating weed growth, and that ST would improve the weed-suppressive ability of cabbage compared to FWT. In the BR zone, ST and oats increased soil moisture and decreased soil N in several cases, but did not suppress Powell amaranth growth as expected. In the IR zone, ST and oats had inconsistent effects on soil N, soil moisture and Powell amaranth biomass; as expected, cabbage exerted the strongest and most consistent effects on Powell amaranth biomass in this zone. These findings demonstrate strong spatial and often temporal variability in edaphic conditions and weed growth that should be considered when developing weed-crop competition models and integrated weed management strategies.

2.1 Introduction

Reducing tillage intensity can result in lower fuel and management costs (Luna and Staben, 2002), retain or increase soil organic matter (Lal et al., 2004; Lemke et al., 2012), and improve organic nutrient cycling within agroecosystems. Strip tillage (ST) is a type of conservation tillage in which crops are sown into tilled strips while the rest of the soil remains undisturbed. It offers advantages over no-till, especially in areas with cool, wet springs—in-row (IR) tillage helps to warm and dry soil before planting and offers a better seedbed, which is an important consideration for vegetable farmers often planting smaller-seeded crops. ST also offers advantages over conventional, full-width tillage (FWT)—soil between rows (BR) remains undisturbed, maintaining soil quality and reducing the potential for erosion. Yields of potato (*Solanum tuberosum* L.) and sweet potato (*Ipomoea batatas* (L.) Lam) (Hoyt and Monks, 1996), pumpkin in one year

(*Cucurbita pepo* L.) (Rapp et al., 2004), sweet corn (*Zea mays* L.) (Luna and Staben, 2002), carrots (Brainard and Noyes, 2012) and cabbage (Haramoto and Brainard, 2012, Hoyt et al., 1996, Wilhoit et al., 1990) produced with ST were similar to, or greater than, yields produced with FWT, suggesting that ST can be a viable option for maintaining or improving yields of many vegetable crops.

Since tillage is limited to rows, ST results in more heterogeneous fields than FWT with distinct zones differing in soil moisture content and rates of nitrogen mineralization and immobilization—all factors expected to influence weed growth and reproduction in these zones (Overstreet and Hoyt, 2008; Luna et al, 2012; Haramoto and Brainard, 2012). Since the IR zone is tilled in both ST and FWT, smaller differences in moisture and N availability might be expected compared to the BR zone. Soil moisture is typically higher in the BR zone in ST and this zone may act as a soil moisture reservoir for the IR zone, increasing moisture available to crops and weeds (Wilhoit et al., 1990; Haramoto and Brainard, 2012; Brainard et al., 2013). However, there is likely lower initial N availability in the untilled BR zone as lower temperatures and reduced aeration from tillage result in lower N mineralization rates. As the season progresses, however, this low but steady mineralization may result in better synchrony between N availability and crop demand.

In systems that include cover crops, this heterogeneity is accentuated. Cover crop residue is incorporated in the crop rows (IR) but is left as a surface residue BR. Such cover crop mulches may help to retain soil moisture (Wilhoit et al., 1990, Mochizuki et al., 2007; Dahiya et al., 2007), prevent germination and emergence of weed seeds (Teasdale and Mohler, 1993), and further protect against erosion. While decomposition is slower when they are not incorporated, non-legume surface mulches tend to immobilize less N than incorporated residues (Mulvaney et al., 2010). Incorporating the carbon-rich residue from non-legume cover crops tends to increase nitrogen immobilization, at least temporarily making less N available to the following crop (Cheshire et al., 1999; McSwiney et al., 2010). However, if cover crops with relatively low C:N ratios are utilized, like oats prior to reproduction, this has the potential to improve synchrony of N release with crop demand—N is unavailable early when crops are small and demand is low but mineralization increases N availability later when crop demand is high. This phenomenon may be enhanced in ST as early-season BR immobilization is stronger with unincorporated residues, but soil moisture is higher; improved N synchrony, along with improved soil moisture, may help to explain higher yields under ST (Wilhoit et al., 1990).

Understanding the effects of tillage, both with and without cover crops, on the growth and fecundity of weeds is useful for predicting shifts in weed species' abundance and diversity and for identifying efficient practices for managing weeds in reduced tillage systems. Studies that evaluate the impact of tillage on specific phases in weed life cycles can be used to identify weak points that may be targeted for management. Inclusion of cover crops can complicate these studies as tillage can exert direct and indirect effects on different weed stages—thus studies with full factorial designs are desirable. In addition to parsing out relative direct and indirect effects of tillage and cover crops, distinguishing how these effects may be mediated through changes in soil properties like inorganic nitrogen content and moisture retention would be valuable. Most studies of reduced tillage systems do not include a crop-free control, and therefore cannot distinguish direct tillage effects from indirect crop-mediated effects of tillage on weeds. For example, observed increases in weed growth in reduced tillage systems may have been caused purely by reductions in crop growth. Conversely, observed decreases in weed growth could be due to improved synchrony of nutrient release with crop demand—leading to lower nutrient availability for weeds. In order to separate such direct and indirect effects of tillage on weeds, experiments must include both cover crop-free and crop-free controls, and measure soil properties that are expected to change with reduced tillage.

Even fewer studies have examined the effects of tillage or cover crops on fecundity of weeds. In many situations, through effects on emergence and growth, weeds may be suppressed sufficiently to avoid yield losses, but may still produce seeds that will ultimately reduce yields in subsequent crops (Swinton and King, 1994; Brainard and Bellinder, 2004). Therefore, long-term effects of management practices and optimal decisions about the appropriate level of weed management depend on estimates of fecundity.

In ST, growth and fecundity of individual weeds that successfully establish and escape any POST control are likely to be regulated by many factors—soil moisture, nitrogen mineralization, and nutrient availability (Haramoto and Brainard, 2012). For example, higher soil moisture in the untilled BR zone, particularly with surface cover crop residue, may promote growth and fecundity of weeds in those areas. On the other hand, lower rates of N mineralization in the BR zone under ST systems may put nitrophilic species, including common lambsquarters (*Chenopodium album* L.) and white mustard (*Sinapis alba* L.) (Blackshaw et al., 2004) at a competitive disadvantage relative to the same weed growing in the BR zone of a FWT system. Knowing how the growth and fecundity of weeds is affected by these factors will help better predict their competitive ability against the crop. Small decreases in weed growth, particularly in early stages, may lead to a competitive advantage for the crop. In addition, elucidating the mechanisms behind growth suppression may lead to new ways to manage weeds in these systems. If cover crop residues contribute to BR weed management in ST systems but do not impact IR weeds, farmers may choose to selectively seed cover crops into the BR zone to mitigate potential negative impacts on crops that are sensitive to residues. If synergistic effects of cover crops and reduced tillage on reducing weed growth are demonstrated, it may provide more impetus for farmers to adopt both practices.

Powell amaranth (*Amaranthus powellii* S. Wats.) is a summer annual weed of increasing importance in annual cropping systems. It has developed resistance to multiple herbicides including some triazines (Eberlein et al., 1992) and ALS-inhibitors (McNaughton et al., 2005). Species in this genus, including redroot pigweed (*Amaranthus retroflexus* L.), tall waterhemp (*Amaranthus tuberculatus* (Moq.) J.D.Sauer), and Palmer amaranth (*Amaranthus palmeri* S. Wats), are known to hybridize which each other, which may contribute to resistance to additional modes of action in this species (though it is important to note Gaines et al. (2011) did not observe Powell amaranth x glyphosate-resistant Palmer amaranth hybridization). Germination of Powell amaranth seeds is responsive to tillage, with 50-87% fewer seedlings emerging in no-till vegetable plantings compared to FWT (Peachey et al., 2004). Seed germination is also sensitive to certain cover crop residues—buckwheat residues, for example, reduced Powell amaranth germination and emergence (Kumar et al., 2009). Germination rates increased in response to higher N rates (Brainard et al., 2006), suggesting that practices like tillage and cover cropping that influence soil inorganic nitrogen content may have greater impacts on the growth and development of this species.

The objective of this experiment was to characterize the effects of tillage, a spring-planted oat (*Avena sativa* L.) cover crop, and cabbage (*Brassica oleracea* L. var. 'capitata') competition on soil N and moisture dynamics and on Powell amaranth growth and reproduction. We hypothesized that IR Powell amaranth growth would be affected most by the cabbage crop. We anticipated that higher soil moisture and improved synchrony of N availability in ST would increase cabbage growth relative to FWT, resulting in improved suppression of IR weeds. The larger transplanted cabbage crop would be better able to capitalize on these resources than the smaller Powell amaranth seedlings. We also hypothesized that Powell amaranth growth in the undisturbed BR zone in ST, compared to that in all tilled zones, would be regulated more by the interaction between higher soil moisture and lower initial nitrogen availability resulting from the lack of soil disturbance; oat cover crop residue acting as surface mulch was expected to enhance these effects.

2.2 Materials and Methods

2.2.1 Plot establishment These trials were conducted in 2010 and 2011 at the Kellogg Biological Station in Hickory Corners, MI (lat 42.4058, lon -85.3845). Prior to the onset of these trials, the fields used were in no-till soybean. Eight treatments were examined—a fully factorial combination of two tillage levels (ST and FWT), two cover crop levels (a spring-planted oat cover crop and none), and two crop levels (transplanted cabbage and none). Plots were 3.1 m wide by 21.9 m long; each treatment was replicated four times within a randomized complete block design. Plots were divided into subplots (4.3-4.7 m long in 2011 and 2010, respectively) with different harvest dates—one was harvested mid-season while another was harvested prior to the first frost. A third contained only cabbage and was maintained weed-free to examine the impact of strip tillage and the oat cover crop on cabbage growth and yield (Haramoto and Brainard, 2012).

Field operations are summarized in Table 1. The oat cover crop was sown at 93.1 kg ha-1 on April 20, 2010 and April 13, 2011 using a no-till drill (John Deere 750). Glyphosate was applied prior to oat planting in 2011 but not in 2010 as few emerged weeds were observed in this year. All plots were fertilized with 19-19-19 (42.6 kg each of N, P, and K/ha) on May 18, 2010, and with urea only (46.8 kg N/ha) on May 19, 2011. Weeds were not controlled in the cover crop plots during oat growth; weeds in all bare soil plots were controlled by either glyphosate application or hand removal. Cover crop and/or weed biomass was sampled prior to burndown on June 17 in both years; two 0.25 m^2 quadrats were sampled in each plot, including small untreated areas in bare soil plots. After oats were desiccated from the glyphosate application, they were flail mowed on June 29 and June 24 in 2010 and 2011, respectively.

Additional fertilizer was broadcast by hand across all plots immediately before tillage on July 1, 2010 and June 30, 2011. Rates were based on soil test recommendations for cabbage (Warncke et al., 2004). In 2010, 81.3 kg N/ha, 100 kg

P/ha, and 69.4 kg K/ha were applied as a combination of monoammonium phosphate, triple super phosphate, potash, and urea. In 2011, 78.3 kg N/ha, 28.4 kg P/ha, and 112.5 kg K/ha were applied as 19-19-19, potash, and urea. Tillage was performed immediately after fertilization. In ST plots, a Hiniker® Model 6000 two-row strip-tiller (equipped with notched trash-cleaning discs, cutting-coulter, shank-point assembly, berming disks and rolling basket) was used to create 25 cm wide by 25 cm deep strips at 76.2 cm between-strip spacing (center to center). Conventional tillage was accomplished with a 3.1 m wide chisel plow followed by two passes with a field cultivator.

After 8-13 days (July 8, 2010 and July 13, 2011), cabbage (variety Blue Dynasty) was transplanted by hand. These transplants were established and grown to the 4-5 leaf stage in the greenhouse, then hardened off before transplanting. Plants were established with 38.1 cm IR spacing with a target density of 28,700 plants/ha. Flaming was used to control weeds that had emerged by this time. Immediately after cabbage transplanting, Powell amaranth seeds were sown IR and BR in all subplots (except weed-free). IR seeds were sown equidistant between cabbage plants; BR seeds were also sown equidistant between cabbage plants in the center of the BR zone (Figure 1). Seedlings were thinned after emergence to establish one plant in these areas. Where seedlings did not successfully establish, similarly sized Powell amaranth individuals were transplanted from other similar plot areas so they experienced the same conditions prior to transplanting. Final Powell amaranth density, including IR and BR plants, was approximately 56,400 plants/ha. Adjacent subplots were planted to cabbage on the same day and maintained weed-free throughout the season to assess yield loss from the Powell amaranth plants.

For the remainder of the season, weed management was accomplished with a combination of flame-weeding and hand weeding. All plots were sidedressed with 45 kg/ha nitrogen (applied as urea) on August 15, 2010 and August 12, 2011. Bt (as Dipel®) was applied as needed for insect management in the cabbage (on August 10 and September 17, 2010, and August 22, 2011) as a 0.25% v:v solution with a sticker/spreader adjuvant.

2.2.2 Data collection Weather data was collected from the KBS weather station. We estimated actual evapotranspiration as:

Estimated evapotranspiration = (potential evapotranspiration * crop coefficient)

The moisture deficit for each year was then calculated as the difference between estimated evapotranspiration and irrigation + precipitation.

Soil samples were collected biweekly for gravimetric soil moisture determination and extraction for inorganic N. Eight to ten soil cores to a depth of 20 cm were collected from IR and BR zones in each plot except FWT plots without cabbage—since there were no distinct IR and BR zones in these plots, only one set of cores was collected at each date. Gravimetric soil moisture was determined by weighing approximately 10 g of wet soil, drying at 100°C, and weighing again. Gravimetric water content (GWC) was calculated as follows:

GWC = [(wet soil weight)-(dry soil weight) / dry soil weight] *100

Ten grams of dry soil was extracted in 50 mls of 1M KCl following Gelderman and Beegle (1998) for inorganic N determination; extracts were analyzed for NO_3^- and NH_4^+ at the Michigan State University Soil and Plant Nutrient Laboratory. Soil inorganic nitrogen content is presented here as the sum of NO_3^--N and NH_4^+-N and is presented below separately by zone and by whole plot.

To determine mid-season biomass, Powell amaranth and cabbage plants from one subplot were harvested on August 18, 2010 and August 23, 2011 by clipping all above-ground biomass. Fresh biomass was obtained for all plants in the subplot; the plants were then dried at 60ºC for 5-7 days and dry biomass was determined. The remaining subplot with Powell amaranth was harvested in a similar manner prior to the first frost on October 1, 2010 and September 22, 2011. All plants in the subplot were weighed. Fresh weight of a subsample was also determined; this subsample was then dried and dry biomass was determined. Reproductive material was separated from a subset of plants and dried at 30ºC. Seeds were separated by rubbing the material with a rough surface and then cleaned with an air column separator (South Dakota seed blower model 757, Seedburo Equipment Company, Des Plaines, IL). All seeds were weighed and a 0.5 g subsample was counted to determine the number of seeds in the sample. Viability was assessed through germination testing; non-germinable seeds were then tested with tetrazolium. The percentage of viable seeds was calculated as:

(number of germinable seeds + number of TZ viable seeds) /

number of seeds tested *100.

Cabbage was hand harvested from weed-free subplots and subplots with Powell amaranth in October of each year. After discarding the individuals closest to the plot edges, all heads in the center two rows of the plots were cut and separated into marketable or non-marketable categories based on head diameter (>10 cm was considered marketable). Total fresh weight of all marketable and non-marketable heads was obtained and divided by the number of plants in each category to obtain average yield per plant. Head diameter was determined for a subsample of five marketable heads. The proportion of plants producing a marketable head was determined by dividing the number of plants that produced a marketable head by the total number of plants in the subplot. Plant biomass remaining after head harvest was also collected, dried, and weighed; this is also expressed on a per-plant basis.

2.2.3 Statistical analysis Mid-season and final Powell amaranth biomass was analyzed separately using PROC MIXED in SAS version 9.2 (SAS Institute, Cary, NC) with treatment factors as fixed factors and blocks as random factors. Significant interactions were separated using Tukey's test. Years were analyzed separately as models would not converge when this factor was included.

Soil nitrogen and moisture data were also analyzed separately by year with PROC MIXED using repeated measures analysis; the best covariance structure was chosen to minimize Akaike's Information Criterion (AIC). In all repeated measures analyses, sampling time was considered a fixed factor along with treatment factors; blocks were treated as random factors. For all dependent variables, natural log or square root transformations were used to improve normality when necessary; all data presented are back-transformed. When data failed the heterogeneity of variances assumption, data were separated into different groups based on treatment- or factor-level variability and analyzed using heterogeneous variances. AIC was also used to select the best grouping in these cases. When ANOVA indicated significant differences for a sampling date, effects slicing was used to separate means.

2.3 Results

2.3.1 Weather During the period of cover crop growth (mid April-mid June), 2010 was relatively warm and wet compared to the ten year average (Table 2). Compared to the ten year average, April and May 2010 were 2.5°C and 1.7°C warmer and May and June had 23 and 99 mm more precipitation. April 2011 was 1.8°C cooler and also wetter than average—receiving double the average precipitation. May and June 2011 temperatures were similar to average, while May was wetter (30 mm additional precipitation) and June was drier (38 mm less precipitation) than average.

During the period of Powell amaranth and cabbage growth (July through October), temperatures were fairly similar between years, differing by less than 1.1°C (Table 2). August was an exception, as 2010 was 1.8°C warmer than 2011 and 1.5°C warmer than average. July temperatures were 1.4°C and 1.9°C warmer than average in 2010 and 2011, respectively. September was 1.7°C cooler than average in 2011, while October was 1.3 °C warmer than average in 2010. Precipitation was variable between years. Both July 2010 and 2011 were wetter than average—receiving 55 and 94 mm more precipitation, respectively. August 2010 was much drier than normal, receiving 67 mm less precipitation; supplemental irrigation contributed some additional moisture but not enough to cover estimated evapotranspiration for the cabbage.

2.3.2 Cover crop biomass production Oat cover crop biomass in 2010 averaged 2728 kg/ha (+/- 380 kg) and averaged 2812 kg/ha (+/- 208 kg) in 2011 (not shown).

2.3.3 Powell amaranth growth and reproduction

2.3.3.1 ***In row*** Mid-season IR Powell amaranth biomass was 43 and 80% smaller with cabbage than without cabbage in 2011 and 2010, respectively (Table 3). Tillage and the oat cover crop did not affect IR mid-season Powell amaranth biomass in either year.

In 2010, in the absence of crop competition, the final dry weight of Powell amaranth growing IR was 46% lower under ST compared to FWT, though tillage did not affect final plant biomass when cabbage was present (Table 3). Fecundity of IR plants was also reduced in ST in this year, with ST plants producing 31% fewer seeds than FWT plants (Table 4). Fecundity was also reduced by the presence of cabbage—IR plants grown with cabbage produced 60% fewer seeds than IR plants grown without cabbage (Table 4). The oat cover crop did not affect final IR Powell amaranth biomass (Table 3).

In 2011, we detected only a significant main effect of crop competition on final plant biomass—final plant biomass was 44% lower with cabbage compared to Powell amaranth grown without cabbage (Table 3). Neither tillage nor the oat cover crop affected final IR Powell amaranth biomass in this year (Table 3), but the oats did affect fecundity (Table 4). With oats residue, plants grown with cabbage produced less than half the seeds produced by plants grown without cabbage; without oats residue, seed production was similar in plants grown with and without cabbage (Table 4). Seed viability was similar in all treatments and averaged 96% in 2010 and 88% in 2011.

2.3.3.2 ***Between row*** In 2010, neither tillage nor the cover crop affected mid-season BR Powell amaranth biomass, but cabbage competition reduced mid-season biomass of BR Powell amaranth by 26% compared to Powell amaranth grown without cabbage (Table 3). In 2011, ST resulted in a 48% reduction in mid-season BR Powell amaranth biomass but the cover crop and cabbage competition had no effect (Table 3).

In 2010, tillage affected both final BR Powell amaranth biomass (Table 3) and seed production (Table 4), with effects depending on the presence of the oat cover crop and the cabbage crop. In particular, ST resulted in similar final Powell amaranth biomass to FWT when oats were present, but an increase in Powell amaranth growth when oats were absent (Table 3). In this zone and year, ST also resulted in similar final Powell amaranth biomass to FWT when cabbage was not present. With cabbage, final Powell amaranth biomass was 41% greater in ST compared to FWT (Table 3). Seed production was also lower in Powell amaranth grown with cabbage compared to those grown without, but a significant interaction between all three factors precludes a simple comparison (Table 4). The interaction between all three factors in determining BR seed production in this year is driven by differences in FWT plots without oats—with cabbage, seed production was low (19,500 seeds/plant), while seed production was high without cabbage (52,320 seeds/plant). Seed viability did not vary between treatments and averaged 96%.

In 2011, lower midseason biomass observed in ST did not lead to reduced final biomass (Table 3). Final BR Powell amaranth biomass in this zone and year was solely affected by cabbage—plants grown with cabbage were 25% smaller than plants grown without cabbage. BR seed production in this year, however, was not affected by cabbage but was enhanced by the oat cover crop. Plants grown after oat residue produced more seeds than plants grown without oats (Table 4). Viability was similar in all treatments and averaged 88% in 2011.

2.3.4 Cabbage growth and competition with Powell amaranth

2.3.4.1 *Mid-season* Mid-season cabbage plant biomass was reduced by 26% in ST compared to FWT in 2010 (Table 5). In 2011, mid-season cabbage biomass was similar in all treatments.

2.3.4.2 *Final biomass and harvest* Marketable cabbage yield and final dry plant biomass were reduced in both years by competition with the Powell amaranth (Table 5). In 2010, final cabbage plant biomass was reduced 17% by oats, but only when weeds were not present (Table 5). Yield, however, was not affected by these differences in final cabbage plant biomass—yield was only reduced by the presence of the Powell amaranth and not by the cover crop. Final cabbage yield and plant biomass were also reduced by the oat cover crop in 2011, but only in FWT.

2.3.5 Soil moisture

2.3.5.1 *In row* In 2010, ST was associated with greater IR soil moisture than FWT (Table 6)—season-long, ST averaged 13.0% soil moisture while FWT averaged 11.7%. Oats residue was associated with higher IR soil moisture than no oats at all dates, though the first three sampling dates were associated with greater differences between oats and no oats (Figure 2a). Cabbage had greater soil moisture than no cabbage only at the first sampling date (July 27, 2010), while the opposite was observed on August

24, 2010. At all other times, cabbage plots had similar soil moisture to plots without cabbage, averaging 12.1% with cabbage and 12.5% without.

In 2011, IR soil moisture was not affected by tillage or the cabbage crop, but was influenced by oat cover crop on one sampling date (Table 6). Plots without oats had higher soil moisture than plots with oats on the 1 July sampling date; at all other times, IR soil moisture was similar (Figure 2b).

2.3.5.2 ***Between row*** The effect of tillage on BR soil moisture depended on sampling date in both years (Table 6). In 2010, soil moisture was similar with both tillage types until mid August when ST plots began to have more soil moisture than FWT plots (Figure 3a). In 2011, however, we observed the opposite trend—ST plots started with higher BR soil moisture than FWT plots but soil moisture was similar between tillage types by the end of the season (Figure 3b). There was also one intermediate date (August 4, 2011) on which soil moisture was higher in FWT than in ST (Figure 3b).

In 2010, oats increased soil moisture season-long in both tillage types, more so in ST than in FWT (Table 6). In ST, soil moisture was increased from 11.1% without oats to 13.2% with oats; in FWT, BR soil moisture was 12.2% and 11.2% with and without oats, respectively.   When oats were present, ST had greater soil moisture than FWT but soil moisture was similar between tillage types without oats. Oats did not affect BR soil moisture in 2011, either alone or interacting with other factors (Table 6).

In 2010, the presence of cabbage influenced BR soil moisture (Table 6) at two dates. Soon after planting, cabbage had more BR soil moisture than without cabbage. In late August, however, cabbage had lower BR soil moisture than no cabbage (not shown). BR soil moisture was similar between cabbage (11.8%) and no cabbage (12.1%) at all other dates. The cabbage crop did not affect BR soil moisture in 2011.

Both IR (Figure 2) and BR (Figure 3) soil moisture exhibited different patterns in 2010 and 2011, though these were not explicitly tested. Soil moisture in 2010 started relatively high, dropped to low levels (6-8%) in late August, and then increased again with rain towards the end of the season. In 2011, however, soil moisture early in the season was very low—less than 10% during July—before increasing in August and staying around 14% for the remainder of the season.

2.3.6 Soil nitrogen

2.3.6.1 *In row* As anticipated, IR soil nitrogen was not affected by tillage in 2010 (Table 7). In 2011, however, ST (26.7 mg inorganic N/kg soil) had lower soil nitrogen season-long than FWT (32.4 mg inorganic N/kg soil). The oat cover crop did not affect IR soil nitrogen in 2010 (average 20.5 vs. 23.8 mg inorganic N/kg soil for oats and no oats, respectively). Relative to no oats, the oats residue reduced soil nitrogen on one mid-season sampling date in 2011 (August 4, 14 vs 16 mg inorganic N/kg soil for oats and no oats, respectively) and on one late sampling date (September 16, 23 vs 26 mg inorganic N/kg soil for oats and no oats, respectively).

The main effect on IR soil nitrogen was from the cabbage crop. With the exception of the first sampling date when they were similar, cabbage plots had an average of 43% lower IR soil nitrogen than plots without cabbage in 2010 (Figure 4a). In-row soil nitrogen was also lower in cabbage than no cabbage in 2011 at the last two sampling dates towards the end of the season (Figure 4b).

2.3.6.2 *Between row* In the BR zone in 2010, tillage impacts on soil nitrogen depended on whether the oat cover crop was present, with trends changing through time (Table 7). Where oats were present, soil nitrogen was similar between the two tillage types at almost all sampling dates (Figure 5; exception is on August 12, when FWT N was greater than ST N). Without oats, soil nitrogen was higher in ST than in FWT at all but the first sampling date (Figure 5). Tillage did not affect BR soil nitrogen in 2011. In this year, oats reduced BR soil N relative to no oats at all sampling dates and in both tillage types (27.9 and 34.6 mg inorganic N/kg soil for oats and no oats, respectively).

In 2010, soil nitrogen levels were similar with and without cabbage (average 34.6 and 31.0 mg inorganic N/kg soil, respectively) throughout the season. Through July and August 2011, BR soil nitrogen was similar with and without cabbage, but soil with cabbage had less nitrogen than soil without cabbage at the two September sampling dates.

2.4 Discussion

2.4.1 Tillage Compared to FWT, ST resulted in higher IR soil moisture (2010) or had no effect (2011; Table 6). Increased IR soil moisture in ST could result from the BR zone acting as a soil moisture reservoir for the IR zone, as speculated by Wilhoit et al. (1990), who observed greater cabbage yields under ST compared to FWT in dry years. However, soil moisture levels were similar between zones in this year (Figures 2a, 3a); if anything, the IR zone had slightly higher moisture than the BR zone. While we didn't explicitly test for moisture movement between zones, these modest differences suggest that this mechanism is unlikely.

In addition, BR soil moisture was mostly similar between tillage types—ST only increased moisture relative to FWT at certain sampling times later during the 2010 season (Figure 3a) and early in the 2011 season (Figure 3b). Air temperature and precipitation data help to explain these observed effects of tillage on BR soil moisture. In general, strip tillage increased BR soil moisture relative to FWT during warm, dry periods when soil moisture was low (<10% gravimetric). In 2010, warm dry conditions prevailed during August (Table 2), and the estimated soil moisture deficit (estimated evapotranspiration – precipitation – irrigation) was 33 mm. Lower rainfall and drier soil conditions occurred during the early part of the season in 2011, coincident with greater BR soil moisture in ST.

We anticipated that ST would initially result in lower BR soil nitrogen as broadcast fertilizers were not incorporated and there was no tillage to stimulate nitrogen mineralization from soil organic matter. In no-till (NT), broadcasting fertilizer often results in lower soil N content (Kaspar et al., 1987; Vetsch and Randall, 2000); this is often alleviated by deep banding or injecting fertilizers and has been attributed to the combination of lack of incorporation and lack of mineralization. We did not observe this, as ST had either no effect on BR soil nitrogen (2011; Table 7), or increased this relative to FWT (in 2010 without oats; Table 7, Figure 5). Greater BR soil moisture in ST relative to FWT later in the 2010 season may have increased mineralization rates. It is also possible that this field had developed larger pools of organic matter as it was in NT prior to initiation of this experiment; slow mineralization of these pools could then release inorganic N into the soil, increasing N to sufficient levels to mask any effect of not incorporating fertilizer. An increase in soil N in the IR zone over both tillage types without cabbage (Figure 4a) could support this explanation, though an increase from tillage-induced mineralization likely would have occurred sooner after tillage (Thomsen and Sorensen, 2006). If this was the case, it is unclear why it was only observed in 2010 and not in 2011, which was conducted in an adjacent site with a similar management history but one additional year in NT.

Not surprisingly, since tillage resulted in few discernable differences in soil moisture or nitrogen in the earlier part of the season, tillage had little effect on mid-season Powell amaranth biomass. Tillage only affected mid-season BR Powell amaranth biomass in 2011; biomass was 48% lower in ST than in FWT (Table 3). This finding contradicts our hypothesis that BR plants growing in ST in dry years would have an advantage—BR plants were smaller in ST despite having more soil moisture available during this dry period (Figure 3b). These effects on mid-season biomass were short lived, as we did not detect any effect of tillage on final BR Powell amaranth biomass in 2011. Mid-season cabbage plant biomass was reduced by 26% in ST compared to FWT in 2010 (Table 5), though the mechanism for this is unclear.

Tillage had significant yet small impacts on final Powell amaranth biomass in certain cases (Table 3). For example, ST resulted in 46% lower final biomass of IR Powell amaranth in 2010 but only without cabbage. The soil moisture data do not help explain why we observed this tillage effect interacting with the cabbage crop as IR soil moisture in 2010 was consistently higher in ST than in FWT (Table 6) and similar with and without cabbage at most dates (Figure 3a). The modest reduction on August 24, 2010, is likely not sufficient to explain differences in final Powell amaranth biomass.

Soil nitrogen was not affected by tillage in this zone and year and thus also cannot explain these differences in final IR Powell amaranth biomass in 2010.

ST resulted in 24% greater BR Powell amaranth biomass compared to FWT in 2010 but only without oats. Soil nitrogen might explain differences these differences. Soil nitrogen was also higher in ST without oats in this zone and year (Figure 5). BR soil moisture was also greater in ST than in FWT, but only with oats (Table 6) so it is unlikely then that soil moisture was responsible for increased Powell amaranth biomass in ST without oats.

2.4.2 Cover crop We expected oat residue to increase both IR soil moisture and BR soil moisture, more so in the BR zone in ST where oats were present as a surface mulch (Dahiya et al., 2007). IR soil moisture was typically higher following oats compared to no oats in 2010 (Figure 2a), but, other than the first sampling date, oats had little effect in 2011 (Figure 2b). Lower soil moisture with oats at the first sampling date in 2011 (July 1) is consistent with observations that soil moisture removal by cover crops exacerbates soil moisture deficits in dry conditions (Mitchell et al., 1999). The month prior to this first sampling date (June 2011) only had 47 mm of precipitation (Table 2) and soil moisture was very low (1-2.6%). We did not observe soil moisture levels this low in 2010.

In 2010, oats increased BR soil moisture in both ST and FWT season-long, more so in ST (Table 6). Oats as a surface mulch layer could have increased soil moisture through lowering soil temperature and thus evaporative losses (Dahiya et al., 2007), particularly during hotter than normal conditions in 2010 (Table 2). However, oats did not affect BR soil moisture in 2011. Other than the first two sampling dates, soil moisture was higher in 2011 than 2010, and it is possible that soil moisture was high enough in this year that any contribution of the surface mulch was minimal.

As with tillage, we hypothesized that the oat residue would initially immobilize N in both tillage types, but that the net effect would be last longer in the BR zone of ST where residues were not incorporated (Zibilske and Makus, 2009; McSwiney et al., 2010; Mulvaney et al., 2010). Since the oats were terminated prior to reproducing, we did not anticipate that this effect would be strong or prolonged in FWT (Kumar et al., 2004). However, we did not observe this temporal effect either zone. Oats reduced BR nitrogen by 19% season-long in 2011 compared to no oats (Table 7), but in both tillage types. In 2010, surface oat residue did reduce BR nitrogen in ST (Figure 6). This result may have been due to N immobilization from oats, or due to indirect effects of oats on soil moisture. Moisture may have played a role in determining the amount of N mineralized and immobilized from the fertilizer and cover crop residues, though there was no interaction between tillage and cover crop in determining soil moisture in this year and zone (Table 6).

Despite these impacts on soil moisture and nitrogen, the oat residue had little effect on Powell amaranth biomass accumulation. Oat residue did, however, affect seed production in 2011 in both zones—30-45% more seeds were produced with oat residue compared to no residue overall in the BR zone and with cabbage in the IR zone, respectively. This may be a result of plants allocating more resources to reproduction in conditions of N stress, such as found BR with either incorporated or surface oat residue in 2011, but we did not detect any differences in harvest index (not shown) which suggests this was not the case.

2.4.3 Cabbage Cabbage plants were expected to draw down both IR soil moisture and nitrogen, resulting in lower availability particularly later in the season. During the dry part of 2010 at the end of the season, we observed lower IR soil moisture in cabbage compared to no cabbage (not shown)—low soil moisture during this period, combined with dry conditions (Table 2), likely resulted in a moisture deficit for the cabbage. Dry conditions occurred earlier in 2011, and it is possible that soil moisture content was sufficient for the remainder of the season to mask any uptake from cabbage plants. We expected any effect of the cabbage on BR soil moisture and nitrogen to be modest, though, as in the IR zone, cabbage did reduce BR soil moisture at the end of the season in 2010 (Table 6). Since soil moisture in this year was greater IR than BR at all sampling dates, moisture was unlikely to move from BR to IR so it is possible that cabbage roots were penetrating the BR zone. BR nitrogen was lower with cabbage compared to without cabbage towards the end of the season in 2011, providing further evidence that cabbage roots were able to access resources in the BR zone.

Overall, the cabbage crop exerted the largest influence on both IR and BR Powell amaranth biomass of all experimental factors. Not surprisingly, cabbage reduced mid-season IR Powell amaranth biomass by 43 and 80% in 2011 and 2010, respectively; final IR Powell amaranth biomass was 44 and 74% lower with cabbage than without cabbage in 2011 and 2010 only in FWT, respectively (Table 3). Why the cabbage crop did not affect final IR biomass in ST in 2010 is unclear. Soil moisture in this zone and year was lower overall in FWT, which may have led to more competition for moisture between cabbage and Powell amaranth. However, we did not observe this implied interaction between tillage and the cabbage crop on IR soil moisture (Table 6), nor did the cabbage crop lower IR soil moisture at most dates (not shown). Further evidence that soil moisture was not responsible for this large difference in FWT weed biomass is found in other treatments—Powell amaranth biomass was not affected by the oat cover crop in this zone and year, despite these treatments having higher soil moisture (Table 6).

Cabbage competition resulted in larger reduction in IR Powell amaranth biomass in 2010 compared to 2011—weeds grown with cabbage were smaller and weeds grown without cabbage were larger in 2010. This difference in weed suppression by cabbage could result from differences in soil N content in these years—in-row N in 2010 with cabbage was below 15 mg inorganic N/kg soil for most of the season (Figure 4a) while it remained above 20 mg inorganic N/kg soil for most of the 2011 season (Figure 4b). Cabbage begins to suffer N stress under 24 mg IN/kg soil (Heckman et al., 2002). We cannot assess if cabbage fared relatively better with Powell amaranth in this year as we did not harvest weed-free cabbage plants at this time, but the differences in N content suggest that cabbage was successfully outcompeting Powell amaranth for N in this year.

Due to our relatively wide row spacing (76 cm), we expected less competition from the low-growing cabbage for BR Powell amaranth plants, particularly for plants harvested mid-season before achieving their maximum size. Cabbage competition did reduce mid-season BR Powell amaranth biomass in 2010 by 26% (Table 4), and reduced final BR Powell amaranth biomass by 48% in FWT in 2010 and 25% overall in

2011—for the most part, cabbage reduced BR Powell amaranth biomass to a lesser extent than IR Powell amaranth biomass, which is not surprising given the closer proximity between IR weeds and the cabbage plants.

Typically, seed production and final Powell amaranth biomass was affected by the treatments in a similar manner. For example, IR seed production in 2010 was reduced by 31% in ST compared to FWT and reduced by 60% with cabbage compared to no cabbage. Final IR plant biomass in this year was affected by the interaction between tillage and the crop—final plant biomass was 46% lower in ST than in FWT when cabbage was not present but similar between tillage types with cabbage. Conversely, the cabbage crop reduced BR plant biomass by 25% in this year, but did not influence seed production

2.5 Conclusions

Predictably, the cabbage crop exerted a large influence on weeds growing in the rows. The presence of cabbage reduced IR weed growth by 43-80%. This suppression was likely due in part to competition for N, which was 11-43% lower IR where cabbage was present, and not due to competition for water, which, despite being lower at the end of the drier 2010 season, was similar for most of the growing season in both years. In addition, competition for light cannot be ruled out as another major factor.

BR weed growth was also reduced by cabbage in one year (by 26%), but not in the other. For most of the season, cabbage had minimal impact on N or soil moisture in the BR zone in each year. The fact that cabbage suppressed BR Powell amaranth despite having little detectable effect on N or soil moisture in the BR zone, suggests that

1) Powell amaranth can more readily access N across zones than can cabbage (and was therefore influenced by depletion of N in the IR zone), and/or 2) competition for light across zones played a role in cabbage suppression of Powell amaranth BR. Surprisingly, tillage and the cover crop had small impacts on weed growth. ST often resulted in greater soil moisture, though this often did not lead to impacts on cabbage or weed growth. When oats had an effect, they generally increased soil moisture (in the drier year of our study) and lowered soil nitrogen but only affected weed growth in one zone in one year in one tillage type.

Overall, our results did not support the idea that ST systems could help shift weed-crop competition in favor of the crop by reducing N availability between crop rows. Nor did our results support the alternative hypothesis that weed competition might be exacerbated under ST by providing higher soil moisture between crop rows. The most pronounced effect of ST occurred BR in 2010, when both N availability and Powell amaranth growth were elevated.

Observed effects of cabbage on N, water and Powell amaranth in this study provide important information on the nature of weed-crop competition that could not have been documented without a crop-free control. Further studies elucidating differential access of crops and weeds to soil N may be useful for designing targeted N practices that reduce weed management costs.

Table 2.1 Dates of field operations.

Operation	2010	2011
Glyphosate application	--	4/13
Oat cover crop established	4/20	4/13
Oat and weed biomass sampled	6/17	6/16
Cover crop terminated with glyphosate	6/17	6/17
Residue flail mowed	6/29	6/24
Fertilizer applied and plots tilled	7/1	6/30
Cabbage transplanted; Powell amaranth sown	7/8	7/13
Nitrogen side dress application	8/12	8/15
Cabbage and Powell amaranth mid-season harvest	8/18	8/23
Cabbage and Powell amaranth final harvest	10/29	10/18

Table 2.2 Weather summary for April-October in 2010 and 2011at the Kellogg Biological Station in Hickory Corners, MI.

	Average temperature (°C)			Total precipitation and irrigation (in parentheses) (mm)			Estimated evapotranspiration for cabbage crop (mm)	
	2010	2011	10-yr avg	2010	2011	10-yr avg	2010	2011
April	11.9	7.6	9.4	71	146	73	--	--
May	16.1	15.1	14.4	135	142	112	--	--
June	20.2	20.2	20.1	184	47	85	--	--
July	23.5	24.0	22.1	149	187 (18)	94	31	24
August	22.5	20.7	21	34 (20)	96	101	87	79
September	16.5	15.4	17.1	67	83	94	74	66
October	11.6	10.5	10.3	48	90	82	--	--
planting-mid season harvest	23.4	22.6	21.8-22.0	178	211	127.4-127.5	90	65
planting-final harvest	20.7	20.5	20.0-20.5	249.4	253.0	224.8-270.7	202	165

[a] irrigation provided an additional 20 and 18 mm of water in 2010 and 2011, respectively

[b] estimated as potential evapotranspiration multiplied by crop coefficient for cabbage

[c] 2002-2011

[d] July 8, 2010 to August 18, 2010 and July 13, 2011 to August 23, 2011

[e] July 8, 2010 to October 1, 2010 and July 13, 2011 to September 22, 2011

Table 2.3 Mid-season and final Powell amaranth biomass, IR and BR, in 2010 and 2011 and results of the three-way ANOVA[1]. ANOVA main effects were tillage, cover crop, and cabbage crop. Only values for significant main effects and interactions are provided.

	IR								BR							
	2010				2011				2010				2011			
	mid-season		final		mid-season		final		mid-season		final		mid-season		final	
	---------------------g/plant------------------------								---------------------g/plant------------------------							
tillage																
ST	13.3		42.1		8.5		49.5		14.6		87.7		11.5	a	63.7	
FWT	12.0		70.0		12.8		60.4		17.3		81.9		21.9	b	67.2	
crop																
+cabbage	4.3	b	26.5		7.8	b	39.4	b	13.6	b	67.5	b	15.0		55.9	b
-cabbage	21.1	a	82.9		13.5	a	70.5	a	18.4	a	102.1	a	18.4		75.0	a
tillage*cover crop																
FWT oats	11.8		82.6		12.3		71.6		18.2		95.16	a	23.2		75.3	
ST no oats	11.1		43.8		8.4		50.9		14.1		90.67	a	13.9		66.1	
ST oats	15.5		40.4		8.6		48.1		15.1		84.68	ab	9.1		61.4	
FWT no oats	12.3		59.0		13.4		49.2		16.5		68.59	b	20.5		59.1	
tillage*crop																
FWT no cabbage	19.7		107.8	a	13.6		71.5		19.7		107.8	a	22.7		75.5	
ST no cabbage	22.5		57.9	b	13.4		69.5		17.0		96.4	a	14.0		74.5	
ST cabbage	4.2		26.2	b	3.6		29.5		12.2		79.0	ab	8.9		53.0	
FWT cabbage	4.4		27.7	b	12.0		49.2		15.0		56.0	b	21.1		58.9	

Table 2.3 (cont'd)

	IR				BR			
	2010		2011		2010		2011	
	mid-season	final	mid-season	final	mid-season	final	mid-season	final
tillage (T)	NS	**[2]	NS	NS	NS	NS	**	NS
cover crop (CC)	NS	NS	NS	NS	NS	NS	NS	NS
crop (CR)	***	***	*	*	*	***	NS	*
T*CC	NS	NS	NS	NS	NS	*	NS	NS
T*CR	NS	**	NS	NS	NS	*	NS	NS
CC*CR	NS	NS	NS	NS	NS	NS	NS	NS
T*CC*CR	NS	NS	NS	NS	NS	NS	NS	NS

[1] † $p<0.1$; * $p<0.05$; ** $p<0.01$; *** $p<0.001$

[2] significant results shaded in gray in ANOVA table were not separated because higher order interactions were also significant

Table 2.4 Seed production by IR and BR Powell amaranth in 2010 and 2011, with results of the three-way ANOVA[1]. ANOVA main effects were tillage, cover crop, and cabbage crop. Only values for significant main effects and interactions are provided.

	IR				BR			
	2010		2011		2010		2011	
	------------------------seeds per plant------------------------							
Tillage								
ST	21942	b	21637		42919		29656	
FWT	31794	a	30405		38104		35770	
Cover crop								
+ oat	27401		21927		40576		38421	a
- oat	26620		19878		40281		27005	b
Crop								
+cabbage	15218	b	19877		33004		29521	
-cabbage	38518	a	32165		48358		35905	
CC*CR								
+ oats, - cabbage	36113		41585	a	45465		43266	
- oats, - cabbage	40922		22745	b	51664		28544	
- oats, + cabbage	12318		21109	b	30321		25465	
+ oats, + cabbage	17443		18645	b	35687		33576	
T*CC*CR								
FWT - oats, - cabbage	52320		23653		52320	a	27238	
ST + oats, - cabbage	29442		30931		48145	a	34293	
ST - oats, - cabbage	29524		21836		47167	ab	29850	
FWT + oats, - cabbage	42785		52239		42785	ab	52239	
ST - oats, + cabbage	15408		14641		41143	ab	25383	
FWT + oats, + cabbage	22841		18151		37809	ab	38054	
ST + oats + cabbage	13395		19139		33565	ab	29099	
FWT - oats, + cabbage	9223		18151		19500	b	25548	

Table 2.4 (cont'd)

	IR		BR	
	2010	2011	2010	2011
tillage (T)	*	†	NS	NS
cover crop (CC)	NS	†	NS	*
crop (CR)	***	*	**[2]	NS
T*CC	NS	NS	NS	NS
T*CR	†	NS	NS	NS
CC*CR	NS	*	NS	NS
T*CC*CR	NS	†	*	NS

[1] † p<0.1; * p<0.05; ** p<0.01; *** p<0.001

[2] significant results shaded in gray in ANOVA table were not separated because higher order interactions were also significant

Table 2.5 Mid-season cabbage plant biomass and marketable yield, with results of three-way ANOVA[1]. Marketable head yield per plant was calculated as total fresh wt of marketable heads divided by number of marketable heads. Only values for significant main effects and interactions are provided.

	Mid-season plant biomass			Marketable yield				Final plant biomass [1]			
	2010		2011	2010		2011		2010		2011	
	-----------g/plant-------			----------kg/plant------------				----------kg/plant---------			
Tillage											
ST	35.9	b	42.6	1.10		1.15		89.9		94.9	
FWT	48.5	a	42.6	0.98		1.22		95.8		85.7	
Weediness											
with AMAPO	--[2]		--	0.82	b	0.93	b	78.9		105.20	a
weed free	--		--	1.28	a	1.43	a	107.4		75.39	b
Tillage*cover crop											
ST oats	34.8		39.5	1.06		1.15	ab	86.4		95.7	
ST no oats	37.0		45.8	1.16		1.14	ab	93.3		94.1	
FWT oats	50.2		41.2	0.99		1.09	b	85.5		78.8	
FWT no oats	46.8		44.0	0.97		1.35	a	107.7		92.6	
Cover crop* weediness											
- Oats, weed free	--		--	0.86		1.48		120.2	a	110.5	
+ oats, weed free	--		--	1.27		1.38		96.0	b	99.9	
- oats, + AMAPO	--		--	1.29		1.01		82.0	bc	76.2	
+ oats, + AMAPO	--		--	0.78		0.86		75.9	c	74.6	
Tillage (T)	*		NS	NS		NS		†		**	
Cover crop (CC)	NS		NS	NS		†		**		†	
Weediness (W)	--[2]		--	***		***		***		***	
T*CC	NS		NS	NS		*		†		*	
T*W	--		--	†		NS		NS		NS	
CC*W	--		--	NS		NS		*		NS	
T*CC*W	--		--	NS		NS		†		NS	

[1] Biomass of unharvested portion of the cabbage plant
[2] mid-season cabbage plant biomass not assessed in weed-free plots

Table 2.6 Results of three-way repeated measures ANOVA for gravimetric soil moisture[1]. All treatment factors (tillage, cover crop, and cabbage crop), as well as sampling time, were considered fixed factors. Effects with p<0.05 were considered significant.

	IR		BR	
Effect	2010	2011	2010	2011
Tillage (T)	***	NS	*	NS
Cover crop (CC)	***[2]	NS	***	NS
Cabbage crop (CR)	NS	NS	NS	NS
Time	***	***	***	***
T*CC	NS	NS	*	NS
T*CR	NS	NS	NS	NS
T*time	NS	NS	*	***
CC*CR	NS	†	NS	NS
CC*time	*	**	NS	NS
CR*time	***	NS	***	NS
T*CC*CR	NS	†	NS	NS
T*CC*time	NS	NS	NS	NS
T*CR*time	NS	NS	NS	NS
CC*CR*time	NS	NS	NS	NS
T*CC*CR*time	†	NS	NS	NS

[1] † p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

[2] Significant results shaded in gray in ANOVA table were not separated because higher order interactions were also significant

Table 2.7 Results of three-way repeated measures ANOVA for soil inorganic N content (nitrate + ammonium)[1]. All treatment factors (tillage, cover crop, and cabbage crop), as well as sampling time, were considered fixed factors. Effects with $p<0.05$ were considered significant.

	IR		BR	
Effect	2010	2011	2010	2011
T	NS	*	NS	NS
CC	NS	**	***	***
CR	***	*	NS	NS
time	***	***	***	***
T*CC	NS	NS	***	NS
T*CR	NS	NS	NS	NS
T*time	NS	NS	NS	NS
CC*CR	NS	NS	NS	NS
CC*time	NS	*	***	NS
CR*time	*	*	†	*
T*CC*CR	NS	NS	NS	NS
T*CC*time	†	NS	*	NS
T*CR*time	NS	NS	NS	NS
CC*CR*time	NS	NS	NS	NS
T*CC*CR*time	NS	NS	NS	NS

[1] † p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

[2] Significant results shaded in gray in ANOVA table were not separated because higher order interactions were also significant

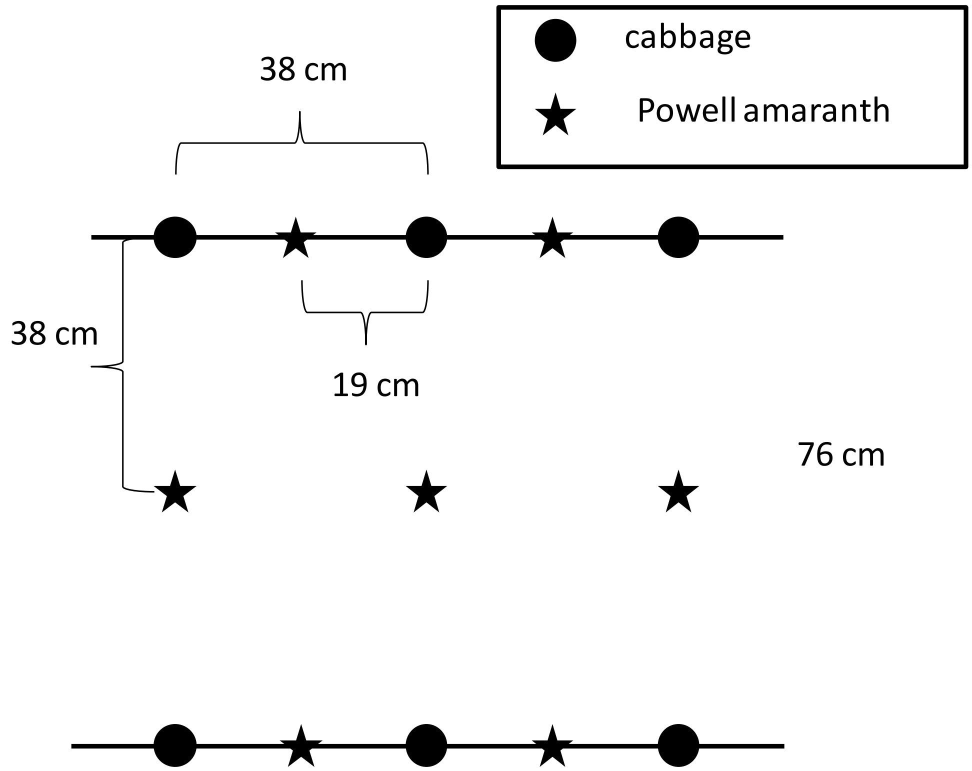


Figure 2.1 Cabbage and Powell amaranth planting diagram, describing spatial arrangement of plants in and between cabbage rows.

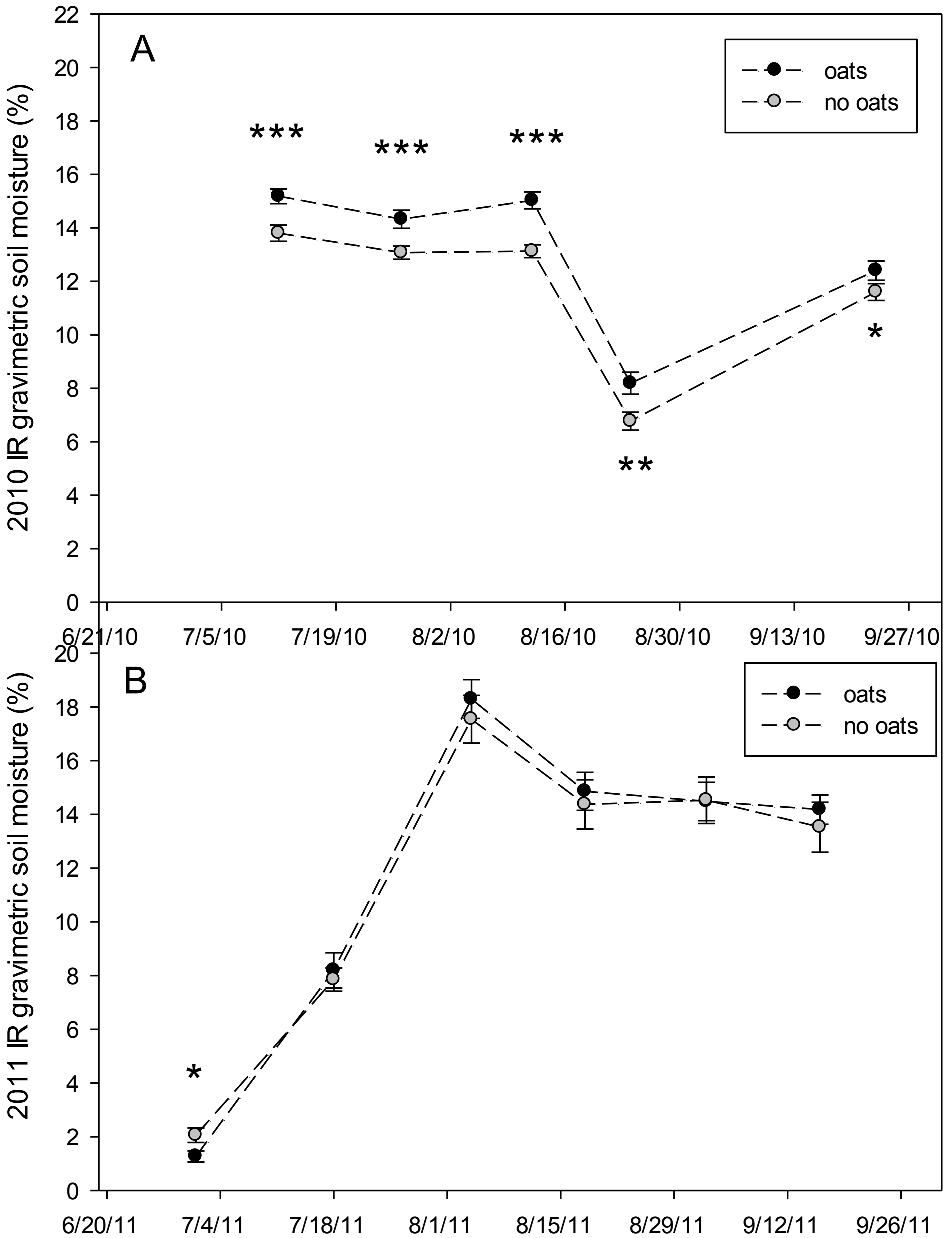


Figure 2.2 In-row (IR) gravimetric soil moisture (%) in oats and no oats in 2010 (A) and 2011 (B). Three-way repeated measures ANOVA indicated that oats affected IR soil moisture in each year. * denotes significant differences at that date as determined by effects slicing (* p<0.05; ** p<0.01; *** p<0.001).

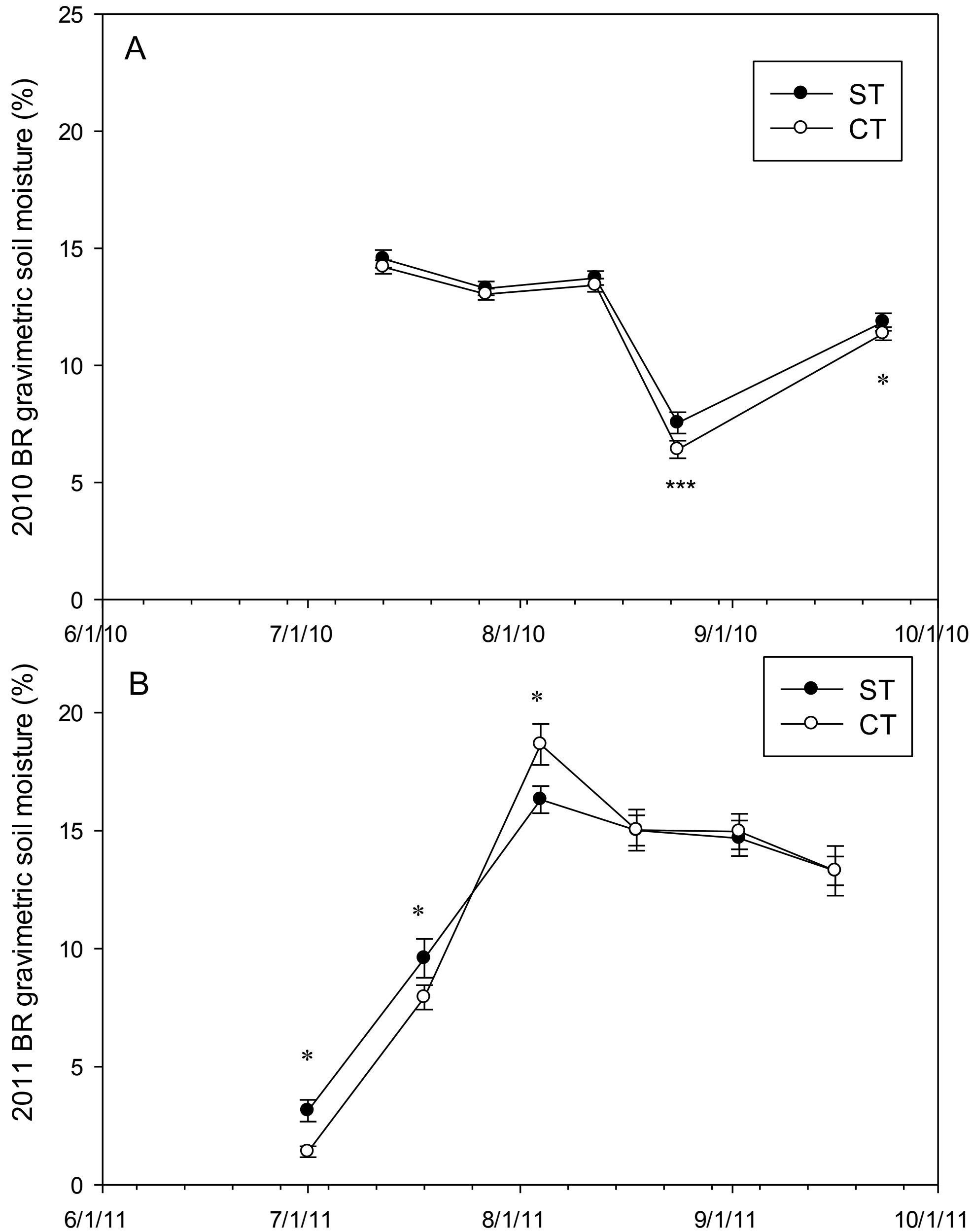


Figure 2.3 Between-row (BR) gravimetric soil moisture (%) in ST and FWT in 2010 (A) and 2011 (B). Three-way repeated measures ANOVA indicated that tillage affected IR soil moisture in each year. * denotes significant differences at that date as determined by effects slicing (* $p<0.05$; ** $p<0.01$; *** $p<0.001$).

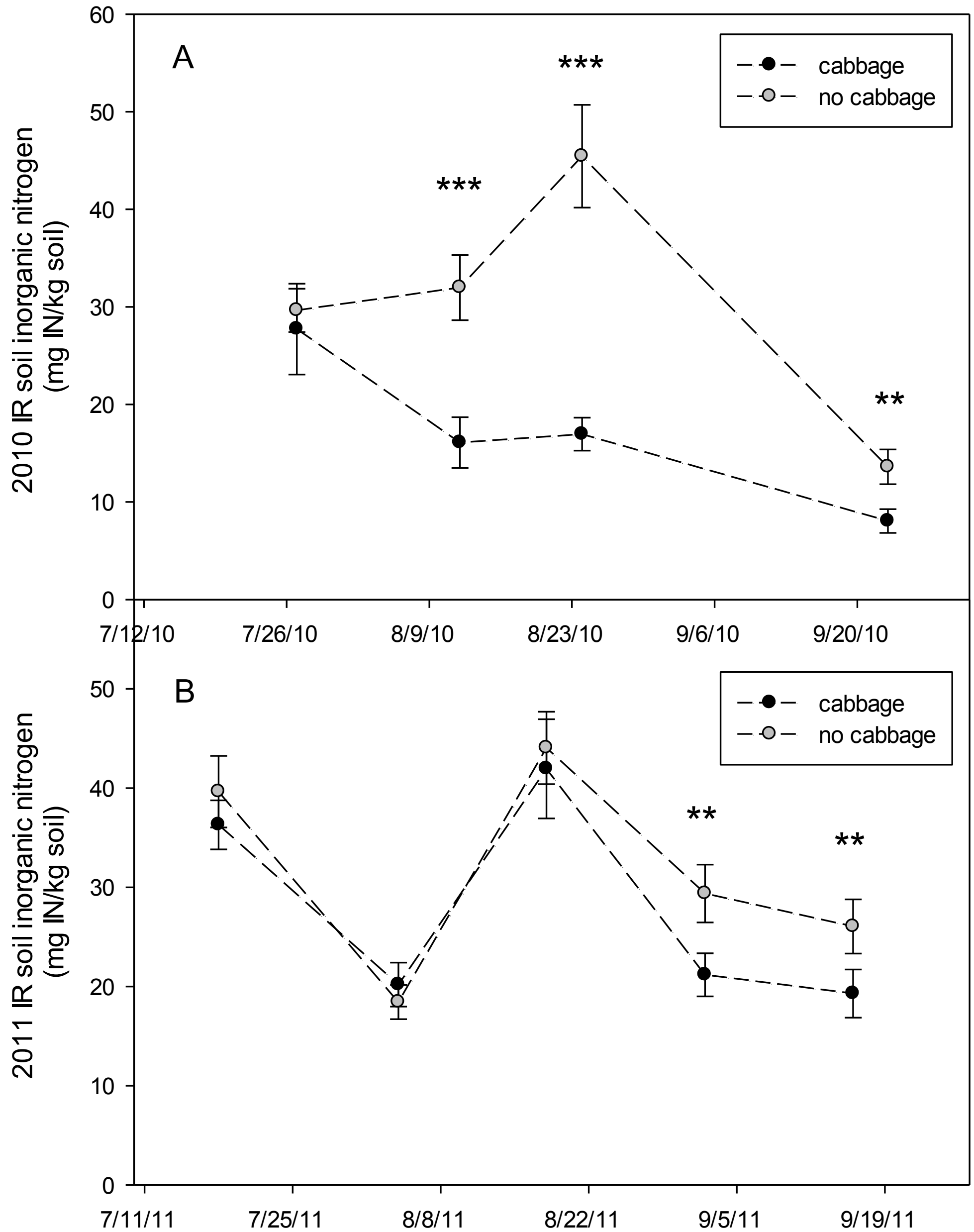


Figure 2.4 In row (IR) inorganic soil nitrogen (mg IN/kg soil) with and without cabbage in 2010 (A) and 2011 (B). Three-way repeated measures ANOVA indicated that the cabbage affected IR soil nitrogen in each year. * denotes significant differences at that date as determined by effects slicing (* $p<0.05$; ** $p<0.01$; *** $p<0.001$).

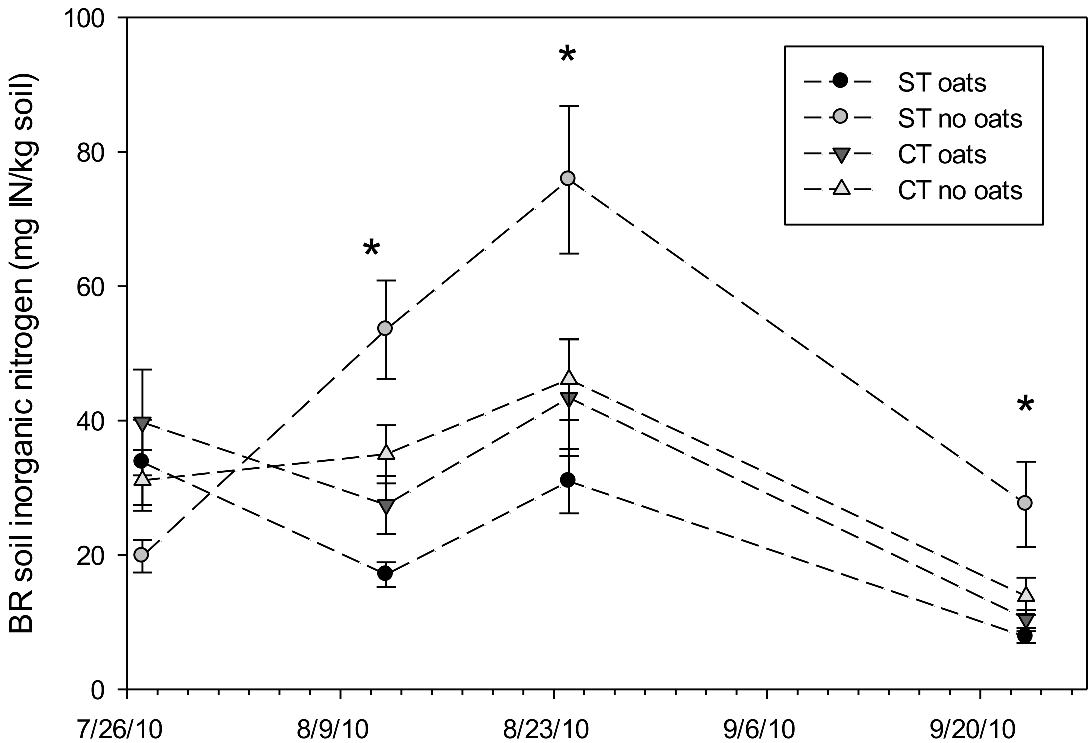


Figure 2.5 Between row (BR) inorganic soil nitrogen (mg IN/kg soil) in ST and FWT, with and without oat residue, in 2010. Three-way repeated measures ANOVA indicated a significant interaction between tillage and cover crop. * denotes significant differences (at $\alpha=0.05$) at that date as determined by effects slicing. Please see the text for explanation of these differences.

LITERATURE CITED

LITERATURE CITED

Blackshaw, R.E., L.J. Molnar, and H.H. Janzen. 2004. Nitrogen fertilizer timing and application method affect weed growth and competition in spring wheat. Weed Science 52: 614-622.

Brainard, D.C., and R.R. Bellinder. 2004. Weed suppression in a broccoli–winter rye intercropping system. Weed Science 52: 281–290.

Brainard, D.C, A. DiTommaso, and C.L. Mohler. 2006. Intraspecific variation in germination response to ammonium nitrate of Powell amaranth (*Amaranthus powellii*) seeds originating from organic vs. conventional vegetable farms. Weed Science 54: 435-442.

Brainard, D. C. and D. C. Noyes. 2012. Strip-tillage and compost influence carrot quality, yield and net returns. Hortscience 47:1073–1079.

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 Technology 27: 218-230.

Cheshire, M.V., C.N. Bedrock, B.L. Williams, S.J. Chapman, I. Solntseva, and I. Thomsen. 1999. The immobilization of nitrogen by straw decomposition in soil. European Journal of Soil Science 50:320–341.

Dahiya, R., J. Ingwersen, and T. Streck. 2007. The effect of mulching and tillage on the water and temperature regimes of a loess soil: Experimental findings and modeling. Soil Tillage and Research 96: 52-63.

Eberlein., C.V., K. Al-Khatib, M.J. Guttieri, and E.P. Fuerst. 1992. Distribution and characteristics of triazine-resistant Powell amaranth (*Amaranthus powellii*) in Idaho. Weed Science 40: 507-512.

Gaines, T.A., S.M. Ward, B. Bukun, C. Preston, J.E. Leach, and P. Westra. 2011. Interspecific hybridization transfers a previously unknown glyphosate resistance mechanism in *Amaranthus* species. Evolutionary Applications 5: 29-38.

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

Heckman, J.R., T. Morris, J.T. Sims, J.B. Sieczka, U. Krogmann, P. Nitzsche, and R. Ashley. 2002. Presidedress soil nitrate test is effective for fall cabbage. HortScience 37:113–117.

Hoyt, G. D., A. R. Bonnano, and G. C. Parker. 1996. Influence of herbicides and tillage on weed control, yield and quality of cabbage (*Brassica oleracea* L. Var. *capitata*). Weed Technology 10:50–54.

Hoyt, G.D. and D.W. Monks. 1996. Weed management in strip-tilled Irish potato and sweetpotato systems. HortTechnology 6:238–240.

Kaspar., T.C., T.M. Crosbie, R.M. Cruse, D.C. Erbach, D.R. Timmons, and K.N. Potter. 1987. Growth and productivity of four corn hybrids as affected by tillage. Agronomy Journal 79: 477-481.

Kumar, V., D.C. Brainard, R. Bellinder. 2009. Suppression of Powell amaranth (*Amaranthus powellii*) by buckwheat residues: role of allelopathy. Weed Science 57: 66-73.

Lal, R., M. Griffen, J. Apt, L. Lave, and M. G. Morgan. 2004. Managing soil carbon. Science 304:393.

Lemke, R.L., A.J. VandenBygaart, C.A. Campbell, G.P. Lafond, B.G. McConkey, and B.Grant. 2012. Long-term effects of crop rotations and fertilization on soil C and N in a thin Black Chernozem in southeastern Saskatchewan. Canadian Journal of Soil Science 92: 449-461.

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

Luna, J. M., J. P. Mitchell, and A. Shrestha. 2012. Conservation tillage in organic agriculture: evolution toward hybrid systems in the Western USA. Renewable Agriculture and Food Systems 27:21–30.

McNaughton, K.E., J. Letarte, E.A. Lee, and F.J. Tardif. 2005. Mutations in *ALS* confer herbicide resistance in redroot pigweed (*Amaranthus retroflexus*) and Powell amaranth (*Amaranthus powellii*). Weed Science 53: 17-22.

McSwiney,C.P., S.S. Snapp, and L.E. Gentry. 2010. Use of N immobilization to tighten the N cycle in conventional agroecosystems. Ecological Applications 20: 648–662.

Mitchell, J.P., D.W. Peters, and C. Shennan. 1999. Changes in soil water storage in winter fallowed and cover cropped soils. Journal of Sustainable Agriculture 15: 19–31.

Mochizuki, M.J., A. Rangarajan, R.R. Bellinder, T.Bjorkman, and H.M. van Es. 2007. Overcoming compaction limitations on cabbage growth and yield in the transition to reduced tillage. HortScience 42:1690–1694.

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. Agronomy Journal 102:1425–1433.

Overstreet, L. F. and G. D. Hoyt. 2008. Effects of strip-tillage and production inputs on soil biology across a spatial gradient. Soil Science Society of America Journal 72:1454–1463.

Peachey, R.E., R. William, and C. Mallory-Smith. 2004. Effect of no-till or conventional planting and cover crops residues on weed emergence in vegetable row crops. Weed Science 18: 1023-1030.

Rapp, H.S., R.R. Bellinder, H.C. Wien, and F.M. Vermeylen. 2004. Reduced tillage, rye residues, and herbicides influence weed suppression and yield of pumpkins. Weed Technology 18:953–961.

Swinton, S. M. and R. P. King. 1994. A bioeconomic model for weed management in corn and soybean. Agricultural Systems 44:313–335.

Teasdale, J.R. and C.L. Mohler. 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agronomy Journal 85:673–680.

Thomsen, I.K, and P. Sorensen. 2006. Tillage-induced N mineralization and N uptake in winter wheat on a coarse sandy loam. Soil and Tillage Research 89: 58-69.

Turan, M. and F. Sevimli. 2005. Influence of different nitrogen sources and levels on ion content of cabbage (*Brassica oleracea* var. *capitata*). New Zealand Journal of Crop and Horticultural Science 33:241–249

Vetsch, J.A., and G.W. Randall. 2000. Enhancing no-tillage systems for corn with starter fertilizers, row cleaners, and nitrogen placement methods. Agronomy Journal 92: 309-315.

Warncke, D., J. Dahl, and B. Zandstra. 2004. Nutrient recommendations for Michigan vegetable crops. MSU Extension Bulletin Publication E2934. East Lansing, MI.

Wilhoit, J.H., R.D. Morse, and D.H. Vaughan. 1990. Strip-tillage production of summer cabbage using high residue levels. Applied Agricultural Research 5:338–342.

Zibilske, L.M., and D.J. Makus. 2009. Black oat cover crop management effects on soil temperature and biological properties on a Mollisol in Texas, USA. Geoderma 149: 379-385.

CHAPTER THREE

Strip tillage and oat cover crops increase soil moisture and influence N mineralization patterns in cabbage

Abstract

Strip tillage (ST) is a form of conservation tillage in which disturbance is limited to the crop rows while the rest of the soil remains undisturbed. Compared to conventional, full-width tillage (FWT), ST may reduce tillage costs, protect soil from erosion, and benefit cool season crops including cabbage (*Brassica oleracea* L. var. 'capitata') by improving water retention, reducing soil temperatures, and improving the synchrony of inorganic nitrogen (IN) supply with crop demand. Field experiments were conducted in 2010 and 2011 in Central Michigan to assess the effects of tillage (FWT vs. ST) and a preceding cover crop (none vs. oats, *Avena sativa* L. var. 'Ida'), on soil temperature, moisture, N dynamics, and yields in transplanted cabbage. Oats were sown in April and terminated 2-3 weeks prior to cabbage transplanting in early July. In-row (IR) soil moisture, temperature, and IN content were assessed from transplanting until cabbage harvest in October. In 2010, IR soil moisture was higher season long in ST compared to FWT, and in oat compared to non-oat treatments, but these effects were not detected in 2011. Tillage and oat residue had little or no effect on IR soil temperature. Shortly after tillage in both years, soil IN availability was greater in FWT treatments without oats compared to both ST treatments and FWT with oats. However, these differences dissipated after 3-4 weeks, and hypothesized improvements in N release patterns under ST were not observed. No differences in cabbage marketable yield were detected in

either year, although the proportion of plants that produced a marketable head was lower in cover cropped plots in 2010. These findings suggest that soil conservation and input savings potentially associated with ST production systems may be attained without a yield penalty. More research is needed to understand and optimize cover crop management in ST systems in order to realize potential benefits in N use efficiency, moisture retention, and soil temperature moderation.

3.1 Introduction

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

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

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

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

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

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

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

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

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

3.2 Materials and Methods

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

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

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

Cabbage (variety Blue Dynasty) transplants were grown to the 4-5 leaf stage in the greenhouse and hardened off prior to transplanting. On 8 July 2010, and 13 July 2011, transplants were hand-planted into the field with 76.2 cm center to center row spacing and 38.1 cm in row spacing between plants. Weed management was accomplished with a combination of flame-weeding and hand weeding after transplanting, both IR and BR. Sidedressing (45 kg/ha nitrogen applied as urea) occurred on 15 August 2010 and 12 August 2011. Bt (as Dipel®) was applied as needed for insect management (on 10 August and 17 September 2010, and 22 August 2011) as a 0.25% v:v solution with a sticker/spreader adjuvant.

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

After cabbage transplanting, soil samples were collected biweekly to 20 cm depth for gravimetric soil moisture determination and extraction for inorganic N. Samples were drawn from a composite of 8-10 soil cores from an area within each plot that contained both cabbage and a fixed density of the weed Powell amaranth (*Amaranthus powellii* L.) as part of a larger experiment with multiple objectives. For moisture determination, approximately 10 g of wet soil was weighed, dried at 100°C, and weighed again. Gravimetric water content (GWC) was calculated as follows:

GWC = [(wet soil weight)-(dry soil weight) / dry soil weight] *100

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

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

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

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

3.3 Results and Discussion

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

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

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

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

In 2010, IR soil moisture was higher in ST plots compared to FWT plots (Figure 1B). The 2010 data suggest that BR areas may be acting as a soil moisture reservoir, contributing to higher IR soil moisture. This is consistent with previous results that have shown higher soil moisture both IR and BR in ST fields (Hoyt and Konsler, 1988). Another possibility is that cabbage in FWT plots had greater rates of transpiration than cabbage in ST plots due to greater biomass accumulation. However, this is unlikely since total above ground cabbage weight did not vary between ST and FWT treatments in 2010 (Table 4).

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

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

3.3.5 Soil nitrogen As cabbage can use both ammonium and nitrate as an N source (Turan and Sevimli, 2005), total soil IN content is presented as the sum of nitrate, nitrite, and ammonium. Ammonium represented approximately 10-40% of total IN depending on the date (data not shown). After side-dressing and during cooler periods, ammonium represented a higher fraction of total IN.

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

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

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

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

Yields in 2011 were greater than those in 2010 (Table 4), and may have been due in part to lower rainfall in late summer of 2010 compared to 2011 (Table 1). Irrigation during that period was not sufficient to overcome periods of low soil moisture in August 2010 that were not present in 2011 (Figure 1). However, higher soil moisture observed in the cover cropped plots and in the ST plots (Figure 1) during late August and early September 2010 did not result in higher yields. Lower yields in 2010 may also have been due in part to lower N availability throughout the growing season in 2010 compared to 2011 (Figure 3). In 2010, soil IN levels for the entire growing season were under 24 mg NO_3^- - N and NH_4^+ - N kg^{-1} soil, the level at which N is considered to be limiting for cabbage growth (Heckman et al., 2002). Again, however, higher yields were not observed in the FWT treatment without oats, despite initially higher soil IN in this treatment. In 2010, the proportion of plants that produced a marketable head was lower in plots with cover crops compared to plots without cover crops; this effect was not observed in 2011. Average plant fresh biomass also did not differ between treatments in either year.

3.4 Conclusions

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

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

Table 3.1 Weather summary for April to October 2010 and 2011 at the Kellogg Biological Station in Hickory Corners, MI. Irrigation provided an additional 20 and 18 mm of water in 2010 and 2011, respectively.

	Average temperature (°C)			Total precipitation and irrigation (in parentheses) (mm)			Estimated evapotranspiration (mm) [1]	
	2010	2011	10 year average [2]	2010	2011	10 year average [2]	2010	2011
April	11.9	7.6	9.4	71	246	73	--	--
May	16.1	15.1	14.4	135	142	112	--	--
June	20.2	20.2	20.1	184	47	85	--	--
July	23.5	24.1	22.1	149	187[3] (18)	94	31	24
August	22.5	20.7	21.0	34 (20)	96	101	87	79
September	16.5	15.6	17.1	67	83	94	74	66
October	11.6	10.5	10.3	48	90	82	25	27
During cabbage growth[4]	19.0	19.1	18.1	295	306	321		

[1] estimated as potential evapotranspiration multiplied by crop coefficient for cabbage

[2] 2002-2011

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

[4] while cabbage was in the ground, from 7 July to 29 October 2010, and 13 July to 18 October 2011.

Table 3.2 Timeline for field operations in 2010 and 2011.

Operation	2010	2011
Soil sampled for nutrient recommendations	4/20	4/13
Glyphosate application	--	4/13
Oat cover crop established—variety Ida	4/20	4/13
Oat and weed biomass measured	6/17	6/16
Cover crop terminated with glyphosate	6/17	6/17
Residue flail mowed	6/29	6/24
Fertilizer applied and plots tilled	7/1	6/30
Cabbage transplanted—variety Blue Dynasty	7/8	7/13
Nitrogen side dress application	8/12	8/15
Mid-season growth measured on cabbage	8/18	8/23
Bt application	8/10, 9/17	8/22
Cabbage harvested	10/29	10/18

Table 3.3 Weed and cover crop biomass prior to termination. Weeds were chemically or physically controlled in bare soil plots, but quadrats were left untreated to allow biomass collection. Biomass was collected from two 0.25 m^2 quadrats per plot. Averages and standard errors (in parentheses) are presented. Within each year, means followed by the same letter were not significantly different at α=0.05.

	Cover crop dry biomass (average (SE))		Weed dry biomass (average (SE))		Weed final density (average (SE))	
	-------------------------g 0.25 m^{-2}		------------------------		-----number 0.25 m^{-2}------	
	2010	2011	2010	2011	2010	2011
bare soil	---	---	40.8 a (8.9)	20.6 a (3.2)	400.9 a (122.3)	181.4 a (12.5)
cover crop	68.2 (9.5)	70.3 (5.2)	27.1 a (7.8)	2.7 b (0.7)	333.9 b (104.1)	108.5 b (13.8)

Table 3.4 Mean and standard error of marketable yield, proportion of plants yielding marketable head, and average fresh plant biomass of cabbage harvested in 2010 and 2011. ANOVA results based on α=0.05.

treatment	average marketable head biomass (kg/head)[1]				marketable yield (T/ha)[2]				proportion of plants yielding marketable head[3]				average plant fresh biomass (kg/plant)[4]			
	-----2010------		------2011-------		-----2010------		------2011-------		-----2010------		------2011-------		-----2010------		------2011-------	
	mean	se	mean	se	mean	se	mean	se	mean	se	mean	se	mean	se	mean	se
ST oat	1.33	0.04	1.43	0.19	28.27	3.37	44.95	7.53	0.91	0.03	0.94	0.02	1.79	0.06	2.31	###
ST none	1.49	0.08	1.36	0.04	36.06	2.82	43.24	2.43	1.00	0.00	0.90	0.07	2.24	0.08	2.19	###
CT oat	1.16	0.12	1.32	0.12	25.74	2.27	41.05	7.01	0.95	0.02	0.91	0.09	1.72	0.15	2.12	###
CT none	1.09	0.23	1.60	0.04	27.16	5.77	53.20	1.69	1.00	0.00	0.98	0.03	1.79	0.22	2.50	###
ANOVA results																
tillage	NS		NS		NS		NS		NS		NS		NS		NS	
CC	NS		NS		NS		NS		*		NS		NS		NS	
tillage*CC	NS		NS		NS		NS		NS		NS		NS		NS	

[1] total fresh mass of marketable heads divided by the number of marketable heads

[2] fresh mass of marketable heads per plot area, extrapolated to T/ha

[3] number of plants producing a marketable head / total number of plants per plot

[4] average fresh per plant biomass (head plus vegetative material)

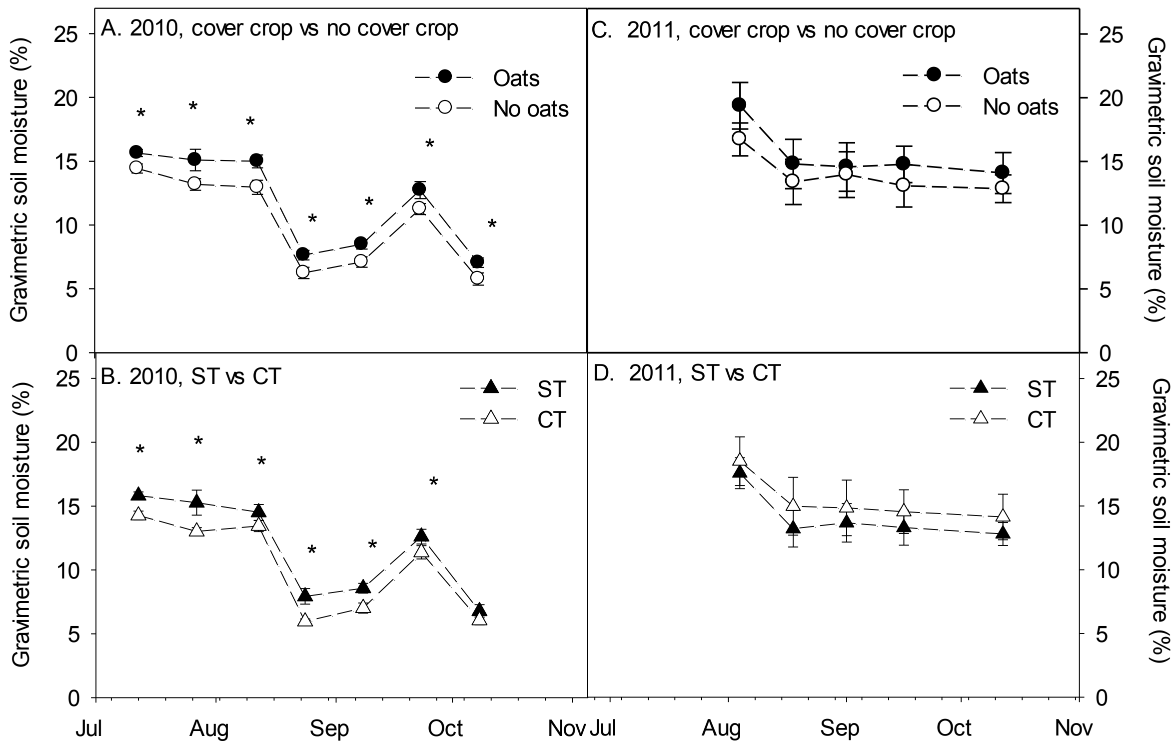


Figure 3.1 In row gravimetric soil moisture in 2010 and 2011. Error bars represent standard error. Soil moisture was measured to 20 cm using soil cores. Each date was analyzed separately using a two-way ANOVA with cover crop and tillage as the main factors. No significant interactions between cover crop and tillage were detected for any date in either year, so main effects of tillage and cover crop are shown. For dates in 2010, significant main effects of cover crop and tillage at $\alpha=0.05$ are shown with *. In 2011, there were no significant differences at any date.

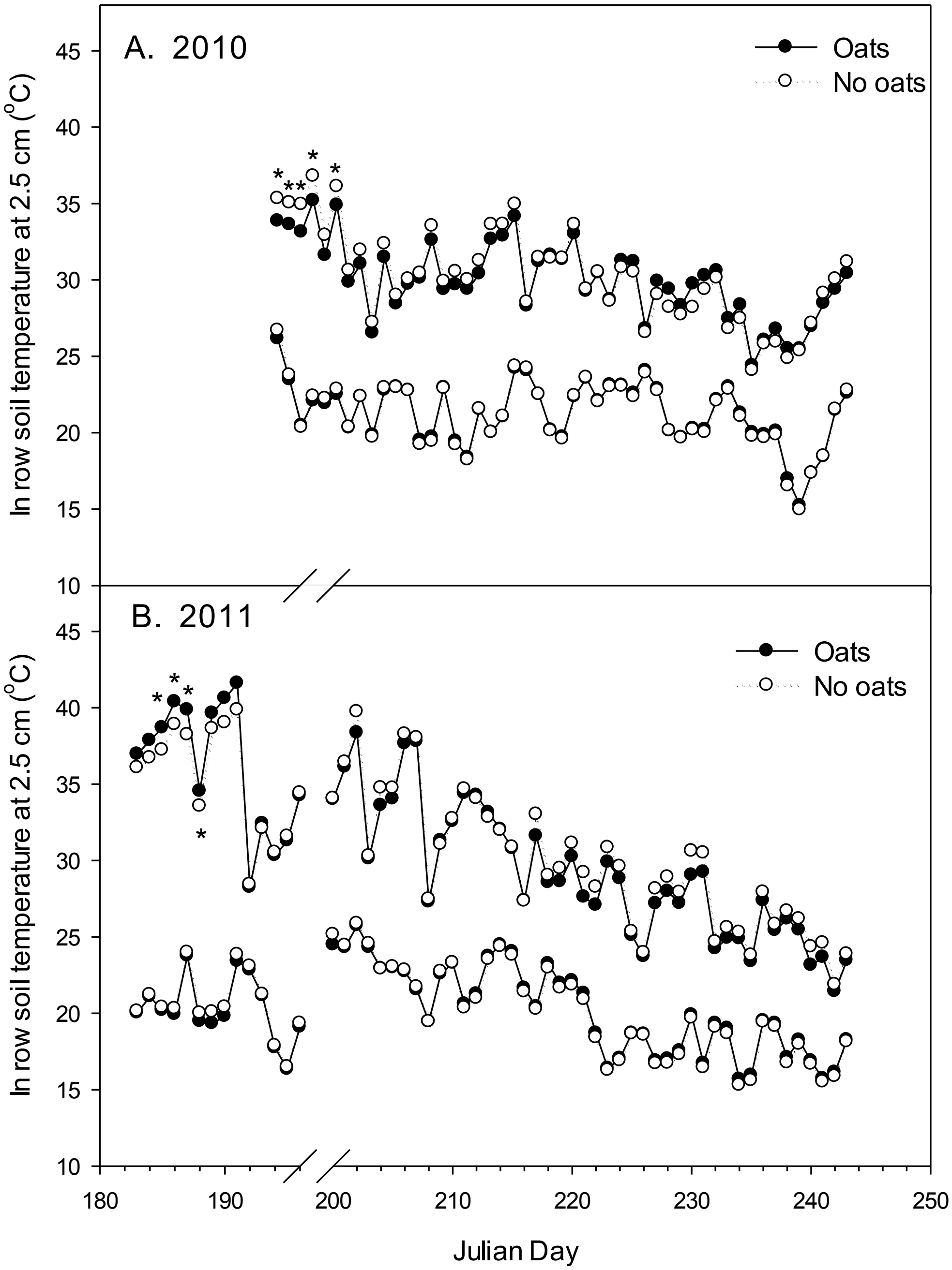


Figure 3.2 Average daily maximum and minimum soil temperature at 2.5 cm in °C in 2010 (A) and 2011 (B). Data collection started on JD 195 (14 July) in 2010. A break is shown in 2011 after dataloggers were moved. At dates noted with a *, there was a significant cover crop effect at α=0.05, with oat treatments having lower temperature in 2010 and higher temperature in 2011. There were no main effects of tillage, and no significant cover crop by tillage interactions in either year so data are shown averaged over tillage levels.

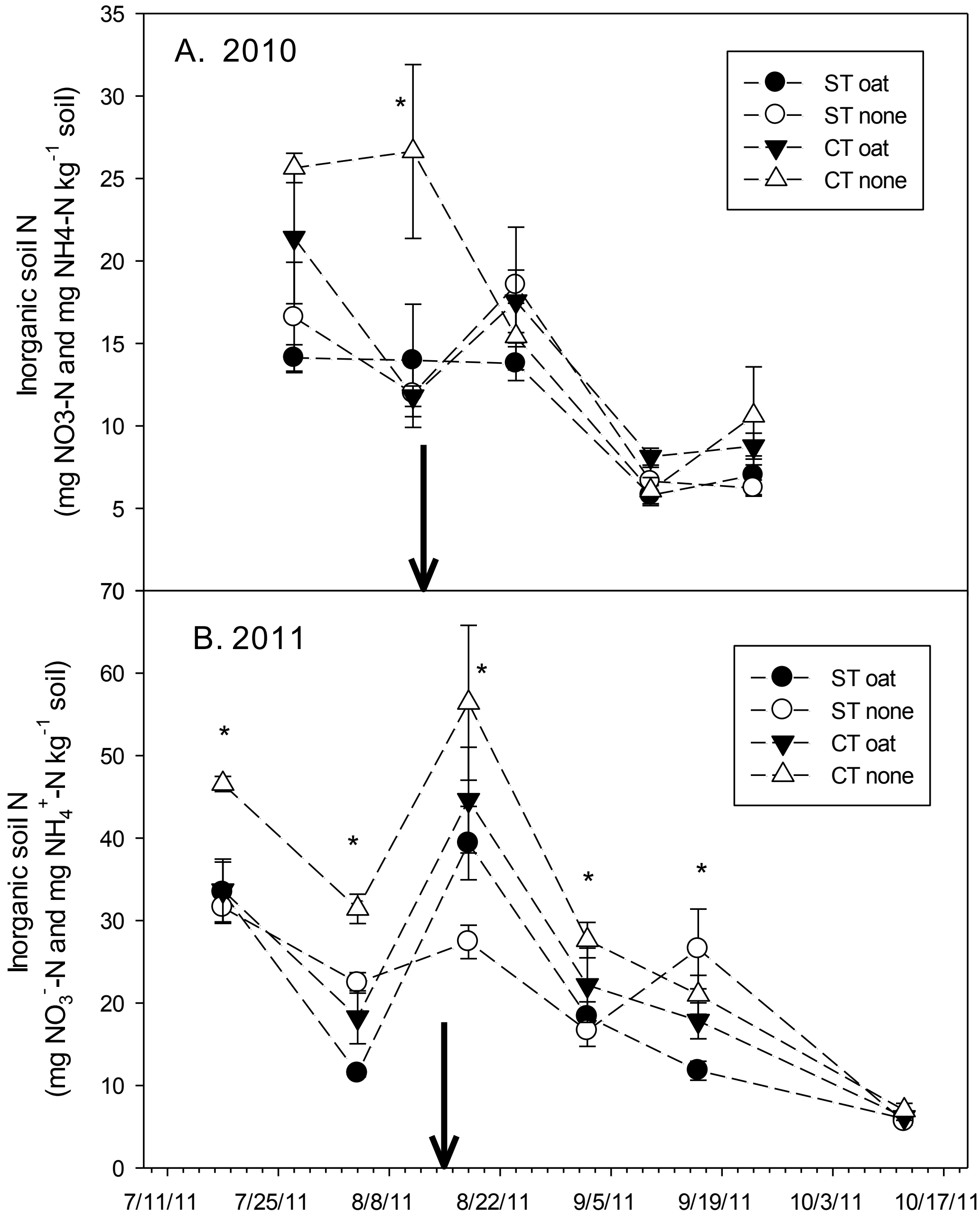


Figure 3.3 In row inorganic soil nitrogen (sum of mg NO3--N and mg NH4+-N kg-1 soil) in 2010 (A) and 2011 (B). Error bars represent standard error. Soils were sampled to 20 cm depth and NO3- and NH4+ were measured using a 1M KCl extract. ANOVA were performed separately for each date. At dates signified with a *, there were significant differences in soil IN between the treatments at α=0.05; specific differences are discussed in the text. Arrows note when side dressing occurred.

LITERATURE CITED

LITERATURE CITED

Al-Kaisi, M. and M.A. Licht. 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.

Calderon, F.J., L.E. Jackson, K.M. Scow, and D.E. Rolston. 2000. Microbial responses to simulated tillage in cultivated and uncultivated soils. Soil Biol. and Biochem. 32: 1547-1559.

Carter, M.R and D.A. Rennie. 1984. Soil temperature under zero tillage systems for wheat in Saskatchewan. Can. J. Soil. Sci. 65: 329-338.

Cheshire, M.V., C.N. Bedrock, B.L. Williams, S.J. Chapman, I. Solntseva, and I. Thomsen. 1999. The immobilization of nitrogen by straw decomposition in soil. Eur. J. Soil Sci. 50:320–341.

Finney, D.M., N.G. Creamer, J.R. Schultheis, M.G. Wagger, and C. Brownie. 2009. Sorghum sudangrass as a summer cover and hay crop for organic fall cabbage production. Renewable Agr. and Food Systems 24: 225-233.

Franczuk J, E. Kosterna, A. Zaniewicz-Bajkowska. 2010. Weed-control effects on different types of cover-crop mulches. Acta Agriculturae Scandinavica Sec. B- Soil and Plant Sci. 60: 472-479.

Gallandt, E. 2006. How can we target the weed seedbank? Weed Sci. 54: 588–596.

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.

Heckman, J.R., T. Morris, J.T. Sims, J.B. Sieczka, U.Krogmann, P. Nitzsche, and R. Ashley. 2002. Presidedress soil nitrate test is effective for fall cabbage. HortScience. 37:113-117.Hoyt, G.D. 1999. Tillage and cover residue effects on vegetable yields. HortTechnol. 9: 351-358.

Hoyt, G.D. and D.W. Monks. 1996. Weed management in strip-tilled Irish potato and sweetpotato systems. HortTechnol. 6: 238-240.

Hoyt, G.D., A.R. Bonanno, and G.C. Parker. 1996. Influence of herbicides and tillage on weed control, yield, and quality of cabbage (*Brassica oleracea* L. var. capitata). Weed Technol. 10:50-54.

Hoyt, G.D. and T.R. Konsler. 1988. Soil water and temperature regimes under tillage and cover crop management for vegetable culture. pp. 697-702. In C. Van Ouwerkerk (ed.) Proc. ISTRO Int. Conf, 11th, Edinburgh, Scotland. 11-15 July 1988. Elsevier, Amsterdam.

Krueger, E.S, T.E. Ochsner, P.M. Porter, and J.M. Baker. 2011. Winter rye cover crop management influences on soil water, soil nitrate, and corn development. Agron. J. 103: 316-323.

Kruidhof, H.M., E.R. Gallandt, E.R. Haramoto, and L. Bastiaans. 2011. Selective weed suppression by cover crop residues: effects of seed mass and timing of speciessensitivity. Weed Res. 51: 177–186.

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

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

Luna, J.M., J.P. Mitchell, and A. Shrestha. 2012. Conservation tillage in organic agriculture: evolution toward hybrid systems in the Western USA. Renew. Agric. and Food Syst. 27:21-30.

Mochizuki, M.J., A.Rangarajan, R.R. Bellinder, T. Bjorkman, and H.M. van Es. 2007. Overcoming compaction limitations on cabbage growth and yield in the transition to reduced tillage. HortSci. 42: 1690-1694.

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.

Overstreet, L.F. and G.D. Hoyt. 2008. Effects of strip tillage and production inputs on soil biology across a spatial gradient. Soil Sci. Soc. Am. J. 72: 1454-1463.

Power, J.E., W. Wilhelm and J.W. Doran. 1986. Crop residue effects on soil environment and dryland maize and soya bean production. Soil and Tillage Research 8: 101-111.

Rapp, H.S., R.R. Bellinder, H.C. Wien, and F.M. Vermeylen. 2004. Reduced tillage, rye residues, and herbicides influence weed suppression and yield of pumpkins. Weed Technol. 18: 953-961.

Sainju, U.M. and B.P. Singh. 2008. Nitrogen storage with cover crops and nitrogen fertilization in tilled and nontilled soils. Agron. J. 100:619-627.

SAS 9.2 (2002-2010) SAS Institute, Cary, NC, USA.

Teasdale, J.R. and C.L. Mohler. 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron. J. 85: 673-680.

Turan, M. and F. Sevimli. 2005. Influence of different nitrogen sources and levels on ion content of cabbage (*Brassica oleracea* var. capitata). New Zealand J. of Crop and Hort. Sci. 33: 241-249.

Wagner-Riddle, C., T. J. Gillespie, L.A. Hunt, and C.J. Swanton. 1997. Modeling a rye cover crop and subsequent soybean yield. Agron. J. 89: 208-218

Warncke, D., J. Dahl and B. Zandstra. 2004. Nutrient recommendations for Michigan vegetable crops. MSU Extension Bulletin Publication E2934. East Lansing, MI.

Wilhoit, J.H., R.D. Morse, and D.H. Vaughan. 1990. Strip-tillage production of summer cabbage using high residue levels. App. Agricul. Res. 5: 338-34.

CHAPTER FOUR

Strip tillage increases profitability in sweet corn

Abstract

While more common in agronomic crops like field corn, cotton, and sugarbeets, strip tillage (ST) is still an emerging practice for vegetable production. In ST, crops are planted into tilled strips while the soil between the strips remains undisturbed. This may offer a good compromise for vegetable growers who wish to reduce tillage for soil conservation benefits, but require some of the benefits of tillage for crop establishment. Integration of small-grain cover crops into ST vegetable production systems may have environmental benefits, but be associated with economic tradeoffs in the short term. Reductions in fuel usage are often cited as a reason to adopt ST, and ST has been associated with lower tillage costs than full-width tillage (FWT). However, these cost savings are rarely put into context of total production costs and revenues, particularly for more diverse vegetable operations. The objectives of this chapter were to determine the total production costs for a representative sweet corn operation in Michigan; and to evaluate changes in profitability associated with adoption of ST and small grain cover crops. A focus group and interviews with Michigan sweet corn growers were used to outline a typical season of sweet corn production; costs for inputs and field operations other than tillage were determined from the growers, input dealers, and regional extension publications. An economic engineering approach was used to estimate FWT and ST costs representing three different investment scenarios. We concluded that it costs approximately $1,580 to produce one acre of sweet corn yielding 200 crates/acre.

Nine site years of field trials with a small grain cover crop and five site years with and without cover crops showed that sweet corn yields were similar between ST and FWT, though the small grain cover crops reduced yield by approximately 10%. Relative to FWT, ST resulted in increased profits of $26-34/acre. These changes are only 1.6-2.2% of the total production costs. Averaged over a number of experiments in Michigan, integration of small grain cover crops resulted in reductions in profits of $238/acre due to the combined effects of higher management costs, and reduced yields.

4.1 Introduction

Eliminating tillage has many economic (Archer and Reicosky, 2009) and environmental benefits (Syswerda et al., 2012), but is not always feasible particularly for vegetable growers in northern regions with cool, wet springs (Brainard et al, 2013). In strip till (ST), the future crop rows are tilled while the rest of the soil remains undisturbed. This offers many potential benefits including tillage-induced warming and drying of the soil in the crop rows and maintenance of soil quality between the rows (Kaspar et al., 1990). ST may be a good option for vegetable growers in northern regions who want to reduce tillage intensity but still require some of the benefits of tillage for good crop establishment and early growth, and for whom early yields can receive a price premium. Yields of many vegetable crops have been improved or maintained with ST including potato (*Solanum tuberosum* L.) and sweetpotato (*Ipomoea batatas* (L.) Lam) (Hoyt and Monks, 1996), pumpkin in one year (*Cucurbita pepo* L.) (Rapp et al., 2004), sweet corn (*Zea mays* L. var *rugosa*) (Luna and Staben, 2002), carrots (Brainard and Noyes, 2012), and cabbage (*Brassica oleracea* L. var *capitata*)

(Haramoto and Brainard, 2012; Mochizuki et al., 2007; Hoyt et al., 1996; Wilhoit et al., 1990). ST can also be used to band fertilizers, which can contribute to improved plant N uptake (Maddux et al., 1991) and may reduce losses to the environment (Malhi et al., 2001).

The use of cover crops with ST can provide additional benefits and there is growing interest among farmers in Michigan and in the North Central US (CTIC 2013) on their use for protecting soil during the winter and adding organic matter. Incorporating cover crop residues in the tilled strips can help replace organic matter lost during the tillage operation, helping to maintain soil quality and, over the long-term, contribute to improved moisture retention and nutrient cycling (McSwiney et al., 2010). Residue mulches in the undisturbed area between crop rows can help stabilize soil during rain and wind events and contribute to weed management (Haramoto and Brainard, 2013). However, cover crop residues can interfere with good crop establishment and reduce crop yield (Luna et al. 2012; Mochizuki et al., 2007; Gallagher et al., 2003) so their effects on yield in combination with ST should be examined in multiple settings and for multiple crops.

Additional weed management may be necessary under ST in the absence of cultivation, particularly for growers who do not use herbicides (Brainard et al., 2013). For those that do, weed management may not present a problem in ST since herbicide efficacy is often similar regardless of tillage (Hoyt et al., 1996; Hoyt and Monks, 1996; Luna and Staben, 2002; Rapp et al., 2004). However, some herbicides are less effective under ST systems either because they rely on soil incorporation or because residue present on the soil surface interferes with their movement or activity (Hoyt et al., 1994; Locke and Bryson, 1997; Banks and Robinson, 1986). ST with deep fertilizer banding (4-6") may provide a competitive advantage to the crop by placing fertilizers (especially nitrogen) out of reach of weeds emerging from the top 0.5-1" of the soil. Anderson (2008) found that compared to weed-free corn, corn yield loss in weedy conditions was lower in ST with deep fertilizer banding (15%) compared to full-width tillage (FWT) with broadcast fertilizer (40% yield loss), attributing this result to improved corn competitiveness from the deep fertilizer band. Weed density and biomass in ST were 51% and 38%, respectively, that of FWT (Anderson 2008). However, such effects may change with repeated years of ST as weed communities shift towards domination by perennials, bienniels, and annual grasses (Brainard et al., 2013). The latter in particular can be problematic in sweet corn as there are few herbicide control options.

In addition to potential agronomic and environmental benefits, reduced fuel and labor costs are often cited as another reason to adopt ST. The main savings associated with ST are expected to come from reduced fuel and labor use due to fewer required tractor-passes for field preparation and planting. Relatively few studies have examined the economics of ST and how this can affect profitability. In Oregon, ST reduced tillage costs by 50% ($8-19/acre) without affecting revenue from processing sweet corn (Luna and Staben, 2002). Machinery operating time was also reduced by 0.2 hours/acre as one pass with a ST accomplished the same tillage as three passes with FWT equipment. No information was provided about other costs, so these savings cannot be put into a broader context of total production costs.

Archer and Reicosky (2009) compared tillage costs on a 1000 acre farm in a field corn/soybean rotation. Relative to chisel plowing (CP; a form of FWT), ST saved only

$2/acre in operating costs (labor, fuel, and repairs for the implement plus power unit) but increased ownership costs (depreciation and overhead for the implement plus power unit) by $3/acre (Archer and Reicosky, 2009). Equipment operating costs were $37/acre in ST and $39/acre in CP, while equipment ownership costs were $50/acre in ST and $47/acre in CP; the changes between tillage types then were less than 10%. In soybeans rotated with field corn, ST offered slightly higher savings relative to CP. For this crop, ST operating costs were $8/acre less than CP operating costs, while ownership costs were also $4.50/acre less in ST than in CP (Archer and Reicosky, 2009). Equipment operating costs were $34/acre for ST and $42/acre for CP, while ownership costs were $43/acre in ST and $47.50/acre in CP. In soybeans, the reported cost savings with ST represented almost 15% of the CP cost. In addition, these authors note that these operating costs were small compared to input costs (seed, herbicides, and fertilizers), so changes in input use could be much larger than any change in machinery costs (Archer and Reicosky, 2009).

Cost of production estimates for sweet corn have been developed with various levels of detail for several production regions including Michigan (Dartt et al., 2002) and Pennsylvania (Orzolek et al., 2011). Typically these estimates are compiled from a combination of published sources on costs, combined with grower focus groups and interviews to determine typical grower practices. The most recent estimates for sweet corn in MI were published in 2002 (Daart et al., 2002). Since then many factors influencing sweet corn profitability have changed including fertilizer and diesel fuel costs, availability of new technologies (e.g. genetically modified seed), and changing farm size. Therefore, there is a need to update cost estimates and to provide growers with this information.

Because production costs, including machinery costs, are sensitive to farm size and type of operation, and because the size and operational complexity differ among Michigan vegetable growers, determining detailed cost estimates relevant to Michigan vegetable growers is crucial to a better understanding of the potential profitability of using ST in this region. Economic decisions require a good measurement of how these practices affect sweet corn yield, and thus revenue, in different locations and in different years. To better inform grower decision making about tillage options, we wanted to explore the potential economic benefits of ST for sweet corn production. We chose sweet corn because it is grown throughout southern Michigan (and the US), compared to other vegetable crops there is relatively more information about its production, and, because of its large seed and relative ease of planting, it is well-adapted to ST. To compare costs and revenues associated with different tillage types, a partial enterprise budgeting approach is useful. In this approach, only those costs and revenues that vary between different tillage types are included (CIMMYT, 1988) and all others that are the same regardless of tillage type are excluded.

The objectives of this study were to:

1. Produce an updated cost of production budget for sweet corn growers in Michigan

2. Use a partial budget approach to analyze profitability of using ST for soil preparation instead of conventional full-width tillage, under different weed management systems and with integration of a small grain cover crop.

4.2 Materials and Methods

4.2.1 Production costs Nine growers, representing eight different operations, were queried about their production practices. We conducted one focus group with four growers (representing three different operations) in Macomb County, Michigan and individual interviews with five additional growers in Monroe, Berrien, and Kent counties. These counties are the top four fresh market sweet corn producing counties in Michigan (NASS 2007) and, at the time of the 2007 Census of Agriculture, represented 32% of the sweet corn acreage in the state.

In both the focus group and individual interviews, growers were asked to outline the timeline of a typical sweet corn production season. Each task, and the number of times it was performed, was recorded. This information was used to compile practices used and the frequency of use during a “typical” production season for fresh market sweet corn.

Prices for seed, fertilizers, and pesticides were obtained from local input suppliers; volume pricing was used where appropriate. The growers were used as sources for some prices, including those for soil testing, labor, and some harvest-related costs. Custom work rates used for field operations outside of tillage (applying lime, fertilizers, and pesticides) were obtained from recent surveys conducted in Ohio and Indiana (Ward 2012, Miller 2013).

Harvest costs in the budget are dependent on yield; these costs were estimated using a yield of 200 crates/acre, with one crate holding 5 dozen ears. This yield was considered representative of an average year by the interviewed growers. Since revenue is highly dependent on yield and price received by the grower, revenues were forecast for a range of yields and prices based on grower interviews.

4.2.2 Field experiments Three sets of experiments at different locations in Michigan were used to assess sweet corn yield responses to ST and provide information about potential changes in revenue (Table 1). Two of these sets were on research stations (SW=Southwest Michigan Research and Extension Center in Benton Harbor, MI; KBS=Kellogg Biological Station in Hickory Corners, MI) and a third set was conducted on production farms in Milan (Monroe County in southeast Michigan; Z7) and Romeo (Macomb County in east central Michigan; Z8). All of these experiments compared ST to FWT, with the FWT operations depending on the experiment. For example, in the SW experiments, FWT was one pass of a moldboard plow followed by a disk followed by a field cultivator. At KBS, FWT was one pass of a chisel plow followed by two passes of a field cultivator. Some of these experiments included both a small grain cover crop and a no cover crop control (SW, Z7 in 2012, and Z8), while others only had small grain cover crops (KBS, Z7 in 2013). All but SW in 2010 and 2012 included deep N banding in ST and broadcast N fertilizers in FWT (in 2010 and 2012 SW, all fertilizers were broadcast). Lastly, supplemental irrigation was used at the research stations, but not for the on-farm trials.

All experiments followed the same general timeline of field operations. The cover crop was terminated in mid-May (rye), late May (oats for on-farm trials), or early June (oats at KBS) with a glyphosate application. Residues were flail mowed at all the research stations but not at the on-farm sites; we intentionally terminated oats early at the on-farm sites to prevent high biomass accumulation. Fertilizer application, tillage, and planting occurred approximately 1-2 weeks after cover crop termination, between May 25 and June 21. A sidedress application of 40-50 lbs N/acre was applied when the sweet corn was approximately stage V6-V8. Sweet corn was harvested at the end of August or in early September. All ears were removed from a given harvest area and sorted into marketable or non-marketable categories based on ear size and insect or animal damage. Ears in each category were counted and weighed.

4.2.3 Yield data analysis Sweet corn growers measure yield by the number of ears produced, so we analyzed the number of marketable ears produced in each experiment. This was expressed as the number of crates (5 dozen ears) produced per acre. We used a subset of the experiments to assess the impact of ST on yield with and without cover crops (SW, Z8, Z7 in 2012). The number of crates per acre was subjected to a three-way ANOVA with site year combinations, tillage, and cover crop as fixed factors and replicate within each experiment as a random factor. We used data from plots with cover crops from all experiments to assess how ST affected yield with a small grain cover crop. This was analyzed with a two-way ANOVA with site year combination and tillage as fixed factors and replicate as a random factor. All data met normality and equality of variance assumptions and thus were not transformed. We considered p values less than α=0.01 to be significant. This more conservative significance level was chosen to lower the chance of concluding that tillage or other experimental factors affected yield when in fact yields were similar. In cases with significant interactions between treatments, either effects slicing or contrasts were used to separate significant effects.

4.2.4. Estimating machine costs Tillage costs were estimated using the Farm Machinery Economic Cost Estimation Spreadsheet (Machdata.XLSM; Lazarus 2014), a spreadsheet that determines ownership and operating costs for equipment using an economic engineering approach. Local dealers provided cost estimates for different types of new ST equipment, while websites selling used farm equipment were surveyed for these prices. Six-row equipment with 30” row spacing was priced out; this size is flexible enough to be used by both larger and smaller Michigan sweet corn growers and is the equipment size of some of the growers we interviewed (other interviewed growers use 4-10 row equipment). Power requirements for these strip tillers were based on equipment specifications and dealer recommendations (25-35 HP per shank), while those provided by Lazarus (2014) were used for the conventional tillage options analyzed. Tillage was assumed to use 20% of the hours operated by the power unit; other potential uses include spraying, fertilizing, mowing, etc. An operational speed of 5.5 mph and field efficiency of 85% was assumed. We assumed growers would use the ST equipment on 200 acres, with one pass per year. This acreage was chosen by considering the range of sweet corn acreage of interviewed growers (35-750 acres) and the crops for which this equipment could be used (those not grown on raised beds or with different row spacing). Other general assumptions were chosen to reflect current costs in Michigan and included $20/hour for skilled labor and $3.60 for a gallon of diesel fuel (Stein 2014), as well as a 4% interest rate and 0% inflation rate.

Cost per acre for ST was determined for three scenarios: 1) a high cost scenario with a new 6 row pull-type strip tiller with attached fertilizer cart and capability to band fertilizers (STH); 2) a medium cost scenario with six new row units mounted on a toolbar (STM); and 3) low cost scenario with the least expensive used strip tiller (STL). Each row unit on the high and medium cost strip tillers is equipped with trash cleaners, cutting disks, a shank, berming disks, and a rolling basket. Given the wide range of available used ST equipment, the low cost option may have all of these components. To add fertilizer banding capability to the two lower cost scenarios, $2000 for a fertilizer tank or hopper, tubes, and metering unit was added to the purchase price. All scenarios assumed an eight-year-old 200 HP tractor for the associated power unit. For comparison, we also priced new and used conventional tillage equipment with appropriate used power units—a 15' chisel plow (CP) with a 130 HP tractor and 18' field cultivator (FC) with a 105 HP tractor. Because ownership and operating costs are highly dependent on the number of acres on which the implement is used, and on the number of years of use before the implement is sold or traded, we also conducted a sensitivity analysis to see how changes in these parameters would affect the total cost for the medium cost scenario. Two different inflation rates were also considered.

Costs expected to change upon adoption of ST were selected from the sweet corn cost of production budget for use in the partial budget analysis. These included costs related to soil preparation, fertilization passes, herbicide products and applications, and cultivation. Because all of our ST scenarios included the capability to band fertilizers, the cost of an additional broadcast fertilization pass used with full-width tillage was eliminated. We also eliminated the cultivation pass in the ST partial budget.

The partial budgets included four parts—additional revenue, additional costs, reduced revenue, and reduced costs. These were summed together for each scenario in the partial budget to produce changes in profit. These changes were compared to the total production costs.

4.2.5 Additional considerations for ST partial budget To examine how profitability might change in the face of increased weed pressure in ST, we developed two different POST weed management scenarios and constructed costs using the medium cost ST option. These scenarios assume that growers are proactive about managing weeds and will add additional management practices if they feel that weeds are becoming problematic, rather than waiting for yield loss to occur. These additional scenarios considered costs associated with: 1) using one additional POST herbicide application on all acreage, including additional chemical costs, and 2) using one hand-weeding pass. This type of hand-weeding, or rogue-weeding is a common practice among Michigan vegetable growers in other crops and is designed to remove large weeds that escape PRE and POST emergence control measures. It is relatively uncommon in sweet corn production, however, due to the high efficacy of PRE emergence herbicides in this crop. We considered it as an alternative to cultivation and POST herbicide control in the case of poor control with PRE emergence herbicides. It is not intended to remove all weeds, but just those large individuals likely to cause inordinate competitive losses, interfere with harvest, and contribute to the soil seed bank. We determined the time needed to hand-weed one acre of ST sweet corn that had been treated with PRE herbicides used by the growers in a subset of the research experiments outlined above (KBS in 2012 and 2013). Unskilled labor costs were provided by growers. Since we were assuming that growers would use one of these practices proactively, before yield loss resulted from increasing weed pressure, we did not forecast any loss in revenue from yield reduction.

We also used our medium cost ST option to examine profitability of cover crop use. Additional costs related to establishment and termination of cover crops were added to a partial budget. As with the weed management scenarios, changes in revenue were determined by measuring how yield was affected by winter rye cover crops in a subset of the experiments outlined above. Custom work rates for cover crop drilling and termination via glyphosate application were used (Ward 2012).

4.3 Results and Discussion

4.3.1 Grower interviews and cost of production budget Total farm size for these growers ranged from 45-1500 acres, with 35-750 acres devoted annually to sweet corn. Other vegetable crops produced include cole crops, green beans, winter and summer squash, peppers, tomatoes, and potatoes, in addition to soybeans. Additional details of these growers' operations are not given to address privacy concerns. Most growers are planting sweet corn multiple times throughout the season—approximately every 3-6 days starting in mid-April, weather permitting, and ending in early July. This allows them to harvest sweet corn every 1-3 days starting ideally around July 4 and ending in September. Three of the growers we interviewed were selling primarily to larger chain stores. Another three produced primarily for their own retail operations, while also providing some to other smaller retail and food service operations. The remaining two produced for other wholesale markets, with one providing larger quantities (selling by bins, which hold approximately 60 dozen ears) and the other providing smaller quantities (selling by the crate, which holds 5 dozen ears).

The cost of production budget, relating all costs to one acre of sweet corn produced, is presented in Table 2. This includes different inputs (i.e. seed, fertilizers) and practices used (i.e. planting, fertilizer applications) in the left-most column, followed by the units applicable to that practice. The number of units was derived from interviews with the growers. In most cases, the weighted averaged was used—the average number of units reported after removing the highest and lowest value. Price information from sources described above was then used to calculate the total cost of each input and practice per acre.

All growers reported the use of soil testing to determine nutrient application rates; testing occurred ever 1-5 years. Though some reported an interest in reducing tillage, all growers interviewed still use one primary tillage pass and two or three secondary tillage passes for spring soil preparation before sweet corn. The primary tillage pass would often occur in the fall prior to sweet corn, particularly for early plantings or in heavier ground. Fertilizer rates and application timing were variable throughout the state. One larger grower reported using grid sampling and custom applications for phosphorus and potassium. Growers in the eastern part of Michigan tended to not use much of these fertilizers, other than the phosphorus present in starter fertilizers. Nitrogen (N) rates ranged from 110-180 lbs N/acre. Typically, one extra fertilization pass was used in addition to fertilizer applied at planting and at sidedress.

All but one grower reported planting at least some genetically engineered (GE) seed containing the Bt (*Bacillus thuringensis*) gene (that confers insect resistance to the plant) in their later plantings; only one grower reported significant use of glyphosate resistant (GR) seed. Future use of these technologies in sweet corn production is uncertain as one anonymous grower reported that, as of 2014, some larger chain grocery stores will no longer accept GE sweet corn. Thus, this cost of production budget includes costs for non-GE varieties. The use of GE seed will entail an increase in seed costs ($270 and $700 more for 100K seeds for Bt and GR, respectively), but likely decreases in pesticide costs. We estimate growers using Bt seed will save $55/acre ($21 by reducing the number of insecticide spray passes to two and $34 in reduced chemical purchases). Cost changes from the use GR seed are harder to quantify as this technology is still relatively new (released in 2012). Changes in weed management costs will likely result with the use GR seed as growers move towards reliance on POST glyphosate applications; the grower that has used this seed reported interest in this technology because increased reliance on glyphosate for POST weed management would allow him to use less of the residual PRE products, and allow him to rotate sensitive crops back into this land more readily.

Insect, weed, and fungal pest management was surprisingly similar among the growers. Most reported one application of methomyl in a typical season for aphid management. For plantings of Bt sweet corn, growers would also use one insecticide application for earworm management; plantings of non-Bt seed would typically receive 4-6 insecticide applications for earworm management while fresh silks were present. Products used include bifenthrin (Capture®), chlorothalonil (Bravo®), cyhalothrin

(Warrior®), esfenvalerate (Asana®), and zeta-cypermethrin (Mustang MAX®). All growers also used one PRE herbicide application, typically s-metolachlor + atrazine (Bicep II Magnum®) or s-metolachlor + atrazine + mesotrione (Lumax®). Three growers reported using a POST application of bentazon (Basagran®), but only if weed infestation was heavy. Six growers also reported that they use cultivation for weed management in most or all of their sweet corn; this is typically timed to coincide with the sidedress nitrogen pass. All growers also reported one application of propiconazole (Tilt) for rust later in the season. Additionally, growers reported different ways of managing bird and raccoon pests; costs related to this are found in "other pest management". This entailed trapping for raccoons and buying shotgun shells for either paid labor or volunteers to shoot at regular intervals to scare away birds.

Only two of the growers interviewed use mechanical harvesters for their sweet corn; the remaining six growers hand-harvest and costs related to this are presented in Table 2. These costs include both labor for the picking, sorting, and packing crew, and fuel costs for tractors and trucks used to transport sweet corn from the field to the main farm. Crew size varied depending on the operations' size, how often sweet corn was harvested, and the market for the ears which varied widely among growers. Growers selling to chain stores would hydrocool their sweet corn; this practice was not used among the other growers. Icing individual crates or boxes was used only by one grower and is not included in this cost of production budget.

Given the different markets for sweet corn produced by these growers, trucking, management, and marketing costs varied widely. One grower who sold larger quantities into the wholesale market had relatively high trucking expenses (driving produce to Detroit and other market locations), as did a grower who sold to a number of small, local grocery and food service operations and delivered corn to these daily. Some growers reported no trucking costs, as their customers picked up sweet corn crates and bins at their farms. Management and marketing costs were difficult to quantify. For this budget, we considered these mainly in two different forms—the fee a grower would pay to a broker to sell their produce and a portion of the cost for maintaining retail operations. Dartt et al. (2002) included a vehicle for the manager in this cost; we did not include this cost in our budget which lowered our management costs compared to theirs.

Growers reported yields ranging from 125-280 crates/acre (625-1400 dozen ears/acre); most agreed that yielding 200 crates/acre represented an average year while 300 crates/acre represented an exceptionally good year and 100 crates/acre represented an exceptionally bad year. Prices received for the sweet corn varied widely depending on the growers' primary market. For those with retail operations selling smaller quantities, $4.75/dozen ($23.75/crate) was an average price. Those selling into wholesale markets sold by larger quantities and receive a lower price for their corn, typically around $13-15/crate. We projected profits per acre for yields ranging from 175-275 crates/acre and prices from $11-17/crate (Table 2).

4.3.2 Sweet corn yield In our field experiments, tillage did not affect sweet corn yield (crates/acre) in experiments with and without cover crops (Figure 1) or in experiments solely with a small grain cover crop (Figure 2). These findings are consistent with others who have demonstrated similar field corn yields with ST compared to FWT (Nash et al., 2013; Halvorson and Del Grosso 2013; Viswakumar et al., 2008).

Averaged over all site years, the small grain cover crop (either winter rye at SW or oats at Z7 and Z8) reduced yield by 10% (Figure 1); average yield without a cover crop was 309 crates/acre while yield with the cover crop was only 278 crates/acre. In the SW trials, winter rye reduced yield by 13.5% relative to no cover ($p=0.0034$), from 348 crates/acre without cover to 301 crates/acre with winter rye. Small grain cover crops have reduced field corn yields when supplemental N is not added to account for potential N immobilization by the cover crop (Clark et al., 2007; Clark et al., 1997). While soil nitrogen immobilization is often temporary (McSwiney et al., 2010), soil nitrate levels can be lower after incorporation of carbon-rich residues (Rosecrance et al., 2000; Burger and Jackson, 2003).

In two of these studies, Z7 2012 and Z8 2012, we used a spring-planted oat cover crop that was terminated early, when the oats were 6-10" tall. At this stage, prior to reproduction, cover crop C:N content is lower and the risk of N immobilization is lessened. While the interaction between site year and cover crop was not significant (Figure 1), sweet corn yields following the oat cover crop at one of these sites (Z8) was similar to yields without cover. This site had lower cover crop biomass than the Z7 site ($p=0.003$; data not shown). Of the three years at SW, 2013 had lower rye cover crop biomass than the other two years ($p<0.0001$; data not shown) and was the only year at this site to utilize deep fertilizer banding (Table 1); this year also had lower yield reduction from the cover crop than the other years (Figure 1). While analysis of these data as a whole shows that cover crop residue does reduce sweet corn yield in both ST and FWT, these site years suggest that early termination of cover crops, while biomass and the C:N ratio is still relatively low, might help alleviate some of the deleterious effects on yield.

We also detected significant differences between site years for yield with and without cover crops. At the research stations, yields throughout 2012, a droughty year (Table 1), were lower than yields in 2013, a year with adequate rainfall (see single degree of freedom contrasts, Figure 2). The research station trials consistently yielded more than the on-farm trials (Figures 1, 2). All of our research stations were irrigated—an important factor particularly in droughty 2012 (Table 1).

4.3.3 Partial budget for ST adoption Using Machdata.xlsm (Lazarus 2014), we determined that one pass from an 8-year-old chisel plow cost a total of $11.40/acre, while one pass from a similar age field cultivator cost $10.60. Our high cost ST scenario cost $25.60/acre, the middle cost scenario was $18.00/acre, while the low cost scenario was $17.30/acre (Table 3). The high cost option was $7.60 and $8.30 more per acre than the medium and low cost options, respectively. Implement ownership costs for the STH option are more than double those for the STM option—a reflection of the higher purchase price for the STH option. Since fuel, lubrication, and labor costs were the same for all ST options, differences in operating costs are tied to repairs and maintenance. These are linked to equipment age so are higher for the STL option that purchases used equipment than for the STM option that purchases new equipment; they are also linked to the purchase price so are higher for the more expensive STH option and this is mostly responsible for cost differences. The difference of $0.30/acre in repair and maintenance costs between the STL and STM options translates to $68 in annual costs assuming the equipment is used on 200 acres.

A survey of growers in Ohio indicated that custom ST rates ranged from $15.80-22.30/acre with an average of $19.00 (Ward 2012); our values are slightly higher than these, but in good accordance with costs in a nearby state. Costs per acre increase as the acreage on which the equipment is used decreases, so costs for smaller-scale sweet corn growers are expected to be higher than those operating at larger scales (see sensitivity analysis below). Researchers in North Dakota (Nowatzki et al., 2011) have estimated a total cost of only $7.98/acre for six row strip tillers, though with different assumptions than ours. They spread the cost of the implement over 400 acres, twice our assumed acreage of use, and also assume lower fuel ($3/gallon) and labor rates ($12/hour). More importantly, they assume a purchase price of $6000 for a six row strip tiller; we were unable to find used equipment for this price.

The sensitivity analysis (Table 4) shows how changing the operation size, as well as the number of years the ST equipment is kept influence the total cost per acre (ownership and operating) of the medium cost ST option. With 0% inflation, using the strip tiller on 400 acres instead of the 200 acres assumed for our budget lowers the total cost per acre by $1.90, while using it on only 100 acres raises the total cost per acre by $3.10. Keeping the ST equipment for 30 years instead of 20 years, assuming it is used on 200 acres/year, lowers the total cost by $1.10/acre. With 1.5% inflation, the total operating cost increases to $18.80/acre; using on 400 acres decreases the cost by $2.40 and using on 100 acres increases the cost by $4.60. With 3% inflation, the total operating cost increases to $19.80; using on 400 acres decreases the cost by $3.10 and using on 100 acres increases the cost by $6.60.

The partial budget for changing tillage from FWT to ST, with the three different ST cost scenarios, is presented in Table 5. Given the amount of tillage done by interviewed growers (Table 2) and cost estimates per acre (Table 3) we estimate total tillage costs to be $32.60/acre in FWT (Table 5). In all ST scenarios, $18.80/acre was saved by eliminating an additional broadcast fertilizer application and the cultivation pass (Table 5). Assuming weed management costs stay the same, this represents a total savings of $25.80, $33.40, and $34.10 for the high, medium, and low cost ST options, respectively, relative to FWT (Table 5). As yields were not affected by ST, there is no change in revenue, so these savings represent increased profit.

The partial budget for the alternative weed management scenarios is included in Table 6. Scenario 1—in which and additional POST application of bentazon is assumed to be required for ST—increased weed-management associated costs by $39 relative to the standard practice (Table 2), while Scenario 2—in which additional rogue weeding is used—increased weed-management associated costs by $63.10. These increases reflect 2.5% and 4.1% of total production costs with the medium-cost ST option (Table 5). Again, since we assume that these measures are used proactively before weeds cause yield loss, we assume no change in revenue and these additional costs represent reduced profits. If these tactics increased yield, increased revenues would result and the net economic returns would change.

The partial budget for using cover crops is found in Table 7. This includes costs related to sowing and terminating cover crops ($73.40/acre), as well as reduced revenue from yield loss as determined by our field experiments ($164.60/acre). The net effect is to reduce profits by $238/acre.

4.4 Conclusions

Full-width tillage costs represented a small fraction, 2.1%, of the total sweet corn production costs that we estimated. Strip tillage costs were $26-34 per acre lower than those for full-width tillage, but savings upon adoption of ST reflected only 1.6-2.2% of total production costs. As sweet corn yields were unaffected by tillage in nine site years of field trials, revenue was unchanged and these reduced costs thus represent increased profit to growers.

We, and others, have observed good weed management with herbicides in ST, though this may not always be the case. Community shifts towards more perennial weeds and also grass weeds that can accompany reduced tillage adoption may entail additional weed management efforts. However, two research trials failed to detect any yield benefit to the use of a POST herbicide or a hand-weeding pass. Thus, additional costs incurred for these practices ($39/acre for an additional POST application and $63/acre for hand-weeding) are not accompanied by increased revenue in the short term and represent decreased profits. However, it should be noted that weeds which have no impact on short-term yield, may produce seeds that contribute to yield and revenue losses in future crops (Swinton and King, 1994). Long term studies with strip tillage suggest that additional applications of herbicides in ST sweet corn may be necessary to avoid future yield losses in subsequent crops in the rotation including winter squash (Brainard, unpublished).

The use of small grain cover crops (both fall-planted winter rye and spring-planted oats) reduced yield over five site years by an average of 10% compared to yield without cover crops. Winter rye alone reduced yields by 13.5% compared to no cover crop. Additional costs for cover crop seed, planting, and termination are thus associated with reduced revenues, at least in the short term. These losses can be mitigated through early cover crop termination, lengthening the window between incorporation and planting, and through adjustments in N fertilization rates and timing. It is important to note that the use of cover crops may, over the long term, contribute to improved nutrient cycling (Drinkwater and Snapp, 2007), which has the potential to lower fertilizer inputs and improve yields. These cover crops may also help buffer crops from risks associated with extreme weather including soil erosion and yield reductions due to drought stress. Although not examined in our study, cover crops may also provide benefits for insect and disease suppression that help reduce pesticide costs and/or reduce the risk of yield losses from pests. Thus growers must balance numerous short and long-term management goals, as well as their risk aversion, with potential yield reductions in early years.

It is ultimately up to growers to decide whether the short-term increase in profits estimated for ST in this study, or the short-term decrease in profits incurred with the use of cover crops, fit into their management objectives. For some growers, the environmental benefits of ST and cover crops may be attractive as well. While not considered in this analysis, time savings can also result from ST adoption as one ST pass can accomplish fertilization and primary and secondary tillage—these tasks may take four or more passes using FWT. This may be an important consideration for growers who perform these operations themselves. Thus, the economic considerations presented here may contribute to farmer decision-making, though other factors are likely important as well.

Table 4.1 Summary of research trials used to assess how ST affects sweet corn yield. Site and year characteristics, and factors differing between the different trials are presented here. Total precipitation and average temperature for the growing season were measured at nearby weather stations.

Name	Location[1]	predominant soil type	year	cover crop type	no cover control[2]	FWT practice[3]	Precipi-tation	Tempe-rature	N in deep band?	N rate	additional weed management treatment[4]
							in	°F		(lbs/ acre)	
SW	SW MI	fine sand	2010	rye	yes	MBP fb D fb FC	10.7	72.0	no	120	no
SW	SW MI	fine sand	2012	rye	yes	MBP fb D fb FC	6.1	72.9	no	135	POST
SW	SW MI	fine sand	2013	rye	yes	MBP fb D fb FC	6.9	68.9	yes	120	HW[5]
KBS	SW MI	loam	2011	rye	no	CP fb FC	11.9	71.6	yes	120	no
KBS	SW MI	loam	2012	rye	no	CP fb FC	4.6	73.6	yes	120	no
KBS	SW MI	loam	2013	rye	no	CP fb FC	11.8	68.5	yes	120	HW
Z7	SE MI	sandy loam	2012	oats	yes	CP fb FC	5.2	72.0	yes	120	no
Z8	EC MI	sandy loam	2012	oats	yes	CP fb FC	8.7	72.1	yes	120	no
Z7	SE MI	sandy loam	2013	wheat	no	MBP fb FC	12.1	69.6	yes	120	no

[1] SW=southwest; SE=southeast; EC=east central; MI=Michigan

[2] “yes” indicates that data from this experiment were used to test cover crop effect on sweet corn yield

[3] MBP=moldboard plow; fb=followed by D=disk; FC=field cultivator; CP=chisel plow

[4] POST=POST emergence herbicide application; HW=one hand-weeding pass

[5] Hand-weeding was used at this site in this year, but typical sweet corn PRE herbicides were not used, so yield loss due to weeds was not considered.

Table 4.2 Cost of production budget for sweet corn in Michigan. Expenses listed are used in a typical production season as determined by grower interviews and a focus group. Number of units was derived from these growers, while costs were primarily from input dealers and custom work rates. Soil preparation costs were determined using an economic engineering approach (machdata.xlsm; Lazarus 2014).

EXPENSES	unit	number of units	cost, $/unit	cost, $/acre
Soil testing	acre/year	0.6	$7.67	$4.70
Soil preparation				
primary	acre	1.0	$11.37	$11.40
secondary	acre	2.0	$10.59	$21.20
Planting	acre	1.0	$15.60	$15.60
Seed				
non GE[1]	100,000 seeds	0.2	$627.00	$125.40
Fertilizer				
N (from urea)	lb N	134.0	$0.12	$16.10
P (from DAP)	lb P2O5	58.0	$0.15	$8.60
K (from potash)	lb K2O	74.7	$0.19	$14.40
lime	ton	0.5	$28.00	$15.20
fertilization passes	acre	1.0	$6.00	$6.00
liming pass	acre	0.3	$7.20	$2.20
Pest management				
scouting	acre	1.0	$5.00	$5.00
herbicides				
PRE	acre	1.0	$35.00	$35.00
POST	acre	0.1	$23.50	$2.90
insecticides	acre	1.0	$57.82	$57.80
fungicides	acre	1.0	$3.00	$3.00
spray passes				
herbicides	acre	1.1	$6.10	$6.90
insecticides	acre	5.0	$7.30	$36.50
fungicides	acre	1.0	$7.30	$7.30
cultivation	acre	1.0	$12.84	$12.90
other pest management[2]	acre	2.9	$5.22	$15.00
Irrigation	acre-inch	1.9	$6.40	$12.30

Table 4.2 (cont'd)

EXPENSES	unit	number of units	cost, $/unit	cost, $/acre
Hand harvest				
labor	$/crate	240	$0.74	$178.30
fuel	$/crate	240	$0.46	$110.10
hydrocooling	$/crate	200	$0.55	$110.70
crates	$/crate	200	$1.37	$273.30
trucking	$/crate	200	$1.00	$199.10
land rental rate	acre	1.0	$150.00	$150.00
insurance	acre	1.0	$3.08	$3.10
Interest (4%)	acre			$7.00
TOTAL EXPENSES				$1,580.60

[1] seed not genetically engineered

[2] other pest management includes controlling birds and rodents

Expected profit (revenue-expenses) with selected yield and price combinations:

price	yield (number of 5 dozen crates)						
($/crate)	125	150	175	200	225	250	275
11	$164	$316	$468	$620	$771	$923	$1,075
12	$289	$466	$643	$820	$996	$1,173	$1,350
13	$414	$616	$818	$1,020	$1,221	$1,423	$1,625
14	$539	$766	$993	$1,220	$1,446	$1,673	$1,900
15	$664	$916	$1,168	$1,420	$1,671	$1,923	$2,175
16	$789	$1,066	$1,343	$1,620	$1,896	$2,173	$2,450
17	$914	$1,216	$1,518	$1,820	$2,121	$2,423	$2,725

Table 4.3 Total cost estimates ($/acre) including ownership (fixed) and operating (variable) costs for different tillage equipment. Costs determined using machdata.xlsm (Lazarus 2014). Please refer to the methods for the numerous assumptions used in this analysis.

				implement cost			tractor cost			
	age	list price/ value[1]	tractor size[2]	Owner.[3]	Oper.[4]	sum	Owner.	Oper.	sum	Total costs
Type[5]	years	-----$----	--HP--	---------------------------------$/acre--------------------------------						
CP	8	$8,505	130	$3.20	$5.70	$8.90	$2.00	$0.60	$2.60	$11.50
FC	8	$9,922	105	$3.70	$5.30	$9.00	$1.30	$0.40	$1.70	$10.70
STH	0	$42,175	200	$13.80	$7.40	$21.20	$3.40	$1.00	$4.40	$25.60
STM	0	$22,347	200	$6.70	$6.90	$13.60	$3.40	$1.00	$4.40	$18.00
STL	8	$13,500	200	$5.70	$7.20	$12.90	$3.40	$1.00	$4.40	$17.30

[1] List price is given for new equipment, while estimated remaining value given for used equipment. Purchase price is assumed to be 90% of the list price. For medium and low cost ST options, $2000 is added here to purchase fertilizer tank/hopper, tubes, metering system, and clamps to add fertilizer banding capability.

[2] . An 8 year old tractor was assumed for all tillage equipment. HP determined from Lazarus (2014) for CP and FC and from dealer recommendations for ST options.

[3] Denotes ownership costs, including depreciation, interest, and insurance

[4] Denotes operation costs, including fuel, lube, repairs and maintenance, and labor. Fuel, lube, and labor costs are included with the implement operating costs.

[5] CP=chisel plow; FC=field cultivator; STH=high cost strip till; STM=medium cost ST; STL=low cost ST

Table 4.4 Sensitivity analysis for the medium cost ST option, changing the acres on which the implement is used (rows), the hours it is operated until it is sold (columns), and the inflation rate. 480 hours until trade-in represents 20 years of 24 hours of annual use. Costs represent total cost per acre (ownership and operating) for the ST implement and associated power unit and were determined using machdata.xlsm (Lazarus 2014). Please see the methods for the assumptions used in this analysis.

		Hours to trade in								
Annual acres of use	Annual hours of use	240	480	720	240	480	720	240	480	720
		0% inflation			1.5% inflation			3% inflation		
100	12	$24.60	$21.10	$19.50	$25.30	$23.40	$23.40	$25.90	$26.40	$29.50
150	18	$22.20	$19.10	$17.90	$22.40	$20.40	$20.20	$22.60	$21.90	$23.20
200	24	$20.80	$18.00	$16.90	$20.90	$18.80	$18.50	$21.00	$19.80	$20.40
300	36	$19.30	$16.80	$15.80	$19.30	$17.20	$16.80	$19.30	$17.70	$17.80
400	48	$18.50	$16.10	$15.20	$18.40	$16.40	$15.90	$18.40	$16.70	$16.50

Table 4.5 Partial budget components for changing tillage type from full-width tillage to strip tillage. With this change in tillage, cultivation and one fertilization pass are also eliminated; these are shown in "reduced costs". Tillage costs for three different strip tillage cost options are presented in "additional costs". No change in revenue is anticipated based on research findings.

	STH[1]	STM	STC		STH	STM	STC
Additional revenue	-----------$/acre-----------			**Additional costs**	-----------$/acre-----------		
none	0	0	0	Strip till, 1x	$25.60	$18.00	$17.30
SUBTOTAL	0	0	0		$25.60	$18.00	$17.30
Reduced cost				**Reduced revenue**			
Chisel plow, 1x	-$11.40	-$11.40	-$11.40	none	0	0	0
Field cultivator, 2x	-$21.20	-$21.20	-$21.20				
Cultivation	-$12.80	-$12.80	-$12.80				
Fertilization pass	-$6.00	-$6.00	-$6.00				
SUBTOTAL	-$51.40	-$51.40	-$51.40		$25.60	$18.00	$17.30
NET							
change in tillage-associated cost[2]	-$25.80	-$33.40	-$34.10				
total production cost[3]	$1,554.80	$1,547.20	$1,546.50				
% change in total production cost[4]	-1.63	-2.11	-2.16				

[1] STH=high cost, STM=medium cost, STL=low cost strip till options

[2] equals reduced costs + additional revenue + additional costs + reduced revenue

[3] equals total production cost with FWT ($1580.60) + change in tillage-associated costs

[4] change in tillage costs as a percent of the total production costs

Table 4.6 Partial budget for two different weed management scenarios using the medium cost ST option. Additional costs for these two different scenarios are presented in “additional costs”. No change in revenue is anticipated based on research findings.

	add one POST application	add one hand weeding		add one POST application	add one hand weeding
Additional revenue	--------$/acre--------		**Additional costs**	--------$/acre--------	
none	0	0	POST herbicides ($23.50/acre)	$25.90	$2.40
			herbicide pass ($6.10/acre)	$12.80	$6.70
			hand weeding ($54/person/acre)	$0.00	$54.00
SUBTOTAL	0	0		$38.70	$63.10
Reduced costs			**Reduced revenue**		
none	0	0	None	0	0
SUBTOTAL	0	0		0	0
NET					
change in weed-management associated cost [1]	$38.70	$63.10			
total production cost [2]	$1,619.30	$1,643.70			
% change in total production cost [3]	+2.50	+4.08			

[1] equals reduced costs + additional revenue + additional costs + reduced revenue

[2] equals total production cost with no additional weed management + change in weed management costs

[3] change in weed management costs as a percent of the total production costs

Table 4.7 Partial budget for cover crop adoption using the medium cost ST option. Additional costs related to cover crop establishment and termination are presented in "additional costs". A 13.5% reduction in revenue from lower yields is anticipated based on research findings.

	fall-planted winter rye cover crop		fall-planted winter rye cover crop
Additional revenue	---$/acre--	**Additional costs**	-$/acre-
none	0	planting	$15.40
		seed [1]	$40.00
		burndown pass	$6.10
		burndown prod	$11.90
SUBTOTAL	0		$73.40
Reduced costs		**Reduced revenue**	
none	0	13.5% yield reduction [2]	-$164.60
SUBTOTAL	0		-$238.00
NET			
change in total production cost ($/acre)[3]	$238.00		
total production cost ($/acre)[4]	$1,785.10		
change in total production cost (%)[5]	-15.39		

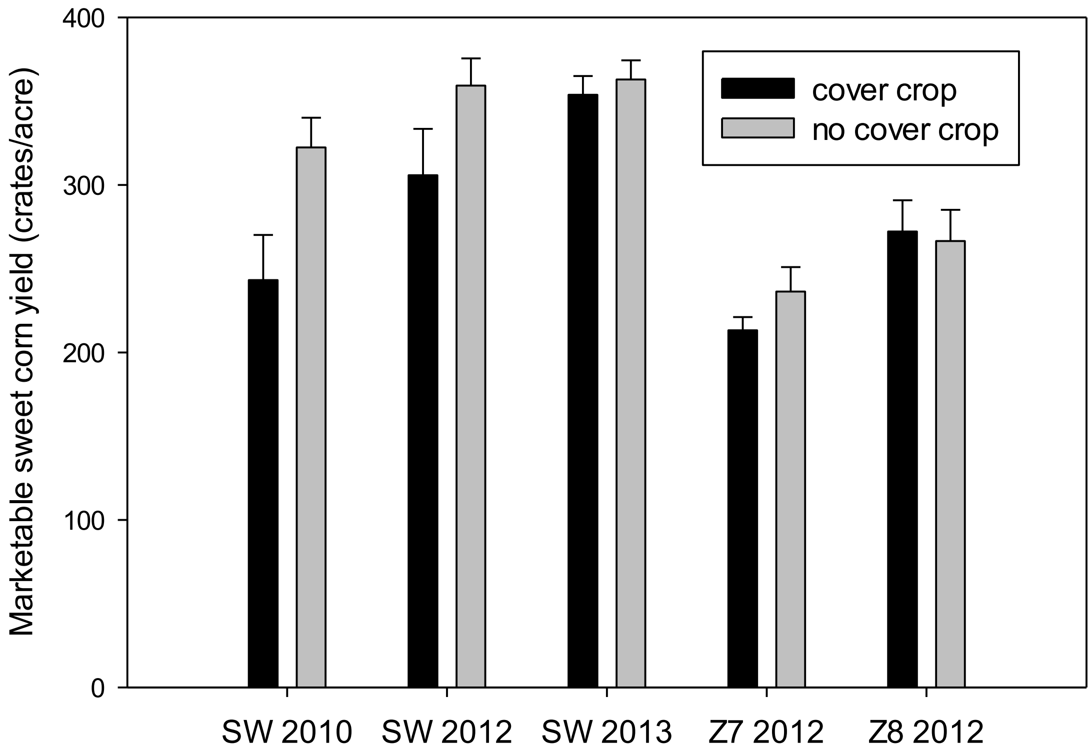
[1] assumes planting rate of 2 bushels/acre and cost of $20/bushel

[2] Average reduction by rye cover crop compared to no cover crop at SW, 2010, 2012, 2013

[3] equals reduced costs + additional revenue + additional costs + reduced revenue

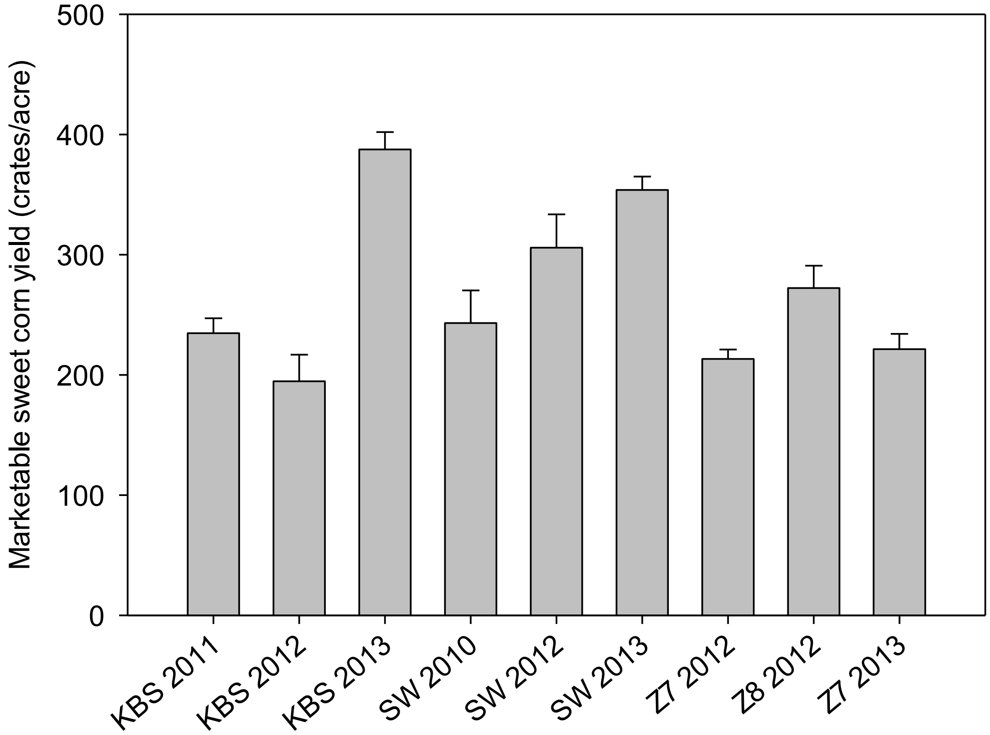
[4] equals total production cost with ST and no cover crop +change in costs associated with cover crop use

[5] change in costs with cover crop as a percent of the total production costs



Effect	F Value	Pr > F
Site year	16.04	<.0001
tillage	0.93	0.3403
Site year*tillage	1.15	0.3434
Cover	7.63	0.0078
Site year*cover	1.86	0.1303
tillage*cover	0.71	0.4024
Site year *tillage*cover	1.28	0.2883

Figure 4.1 Average marketable sweet corn yield at five site*year combinations (site year) throughout Michigan, with and without small grain cover crops. Error bars show plus one SE. Results of a three-way ANOVA with site year (i.e. a site within a given year—SW in 2010, SW in 2012, etc.), tillage type (ST or FWT), and cover (small grain or none) are also shown. Data presented here are averaged over tillage type since tillage did not affect yield. Contrasts for the site year main effect indicated that the three research station site years (SW) outyielded the on-farm trials (p<0.0001) and that Z8 outyielded Z7 (p=0.022).



Effect	F Value	Pr > F
Site year	29.13	<.0001
tillage	0.11	0.7449
Site year*tillage	1.7	0.117

Single degree of freedom contrasts

	F Value	Pr > F
SW vs KBS	4.7	0.034
Z7 vs Z8	5.33	0.0243
2012 vs 2013 for KBS, SW	32.36	<.0001
research vs onfarm	15.29	0.0002

Figure 4.2 Average marketable sweet corn yield at nine site*year combinations (site year) throughout Michigan, all with small grain cover crops (SW, KBS in 2013 was rye; Z7 in 2013 was wheat; the remainder had oats). Error bars show plus one SE. Results of a two-way ANOVA with site year (i.e. a site within a given year—SW in 2010, SW in 2012, etc.) and tillage type (ST or FWT) also shown. Data are averaged over tillage type since tillage did not affect yield.

LITERATURE CITED

LITERATURE CITED

Anderson, R.L. 2008. Residue management tactics for corn following spring wheat. Weed Technology 22: 177-181.

Archer, D.W. and D.C. Reicosky. 2009. Economic performance of alternative tillage systems in the northern Corn Belt. Agronomy Journal 10:296-304.

Banks, P. A. and E. L. Robinson. 1986. Soil reception and activity of acetochlor, alachlor, and metolachlor as affected by wheat (*Triticum aestivum*) straw and irrigation. Weed Science 34:607–611.

Brainard, D.C. and D.C. Noyes. 2012. Strip-tillage and compost influence carrot quality, yield and net returns. HortScience 47:1073-1079.

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 Technology 27:218-230.

Burger, M., and L.E. Jackson. 2003. Microbial immobilization of ammonium and nitrate in relation to ammonification and nitrification rates in organic and conventional cropping systems. Soil Biology and Biochemistry 35: 29-36.

Clark, A.J., A.M. Decker, J.J. Meisinger, F.R. Mulford, and M.S. McIntosh. 1997. Kill date of vetch, rye, and a vetch–rye mixture: II. Soil moisture and corn yield. Agron. J. 89:434–441.

Clark, A.J., J.J. Meisinger, A.M. Decker, and F.R. Mulford. 2007. Effects of a grass-selective herbicide in a vetch–rye cover crop system on corn grain yield and soil moisture. Agron J. 99:43–48

CTIC (Conservation Tillage Innovation Council). 2013. 2012-2013 Cover Crop Survey. Available online at http://www.northcentralsare.org/Educational-Resources/From-the-Field/2012-Cover-Crops-Survey-Analysis

Dartt, B., R. Black, P. Marks, and V. Morrone. 2002. Cost of fresh market sweet corn production in Monroe County, Michigan. Michigan State University Department of Agricultural Economics, Staff Paper 2002-40.

Drinkwater, L.E., and S.S. Snapp. 2007. Nutrients in agroecosystems: Rethinking the management paradigm. Advances in Agronomy 92: 163-186.

Gallagher, R.S., J. Cardina, M. Loux. 2003. Integration of cover crops with postemergence herbicides in no-till corn and soybean. Weed Science 51: 995-1001.

Halvorson, A.D. and S.J.Del Grosso. 2013. Nitrogen Placement and Source Effects on Nitrous Oxide Emissions and Yields of Irrigated Corn. Journal of Environmental Quality 42: 312-322.

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

Hoffman, M.L., E.E. Regnier, and J. Cardina. 1993. Weed and corn (*Zea mays*) responses to a hairy vetch (*Vicia villosa*) cover crop. Weed Technology 7:594-599.

Hoyt, G. D., D. W. Monks, and T. J. Monaco. 1994. Conservation tillage for vegetable production. HortTechnology 4:129–135.

Hoyt, G.D., A.R. Bonanno, and G.C. Parker. 1996. Influence of herbicides and tillage on weed control, yield, and quality of cabbage (Brassica oleracea L. var. capitata). Weed Technology 10: 50-54.

Hoyt, G.D. and D.W. Monks. 1996. Weed management in strip-tilled Irish potato and sweetpotato systems. HortTechnology 6: 238-240.

Kaspar, T.C., D.E. Erbach, and R.M. Cruse. 1990. Corn response to seed-row residue removal. Soil Science Society of America Journal 554:1112-1117.

Lazarus, W. 2014. Farm machinery economic cost estimate spreadsheet (machdata.xlsm). Available at http://faculty.apec.umn.edu/wlazarus/tools.html. Verified June 19, 2014. University of Minnesota Extension Service.

Locke, M. A. and C. T. Bryson. 1997. Herbicide–soil interactions in reduced tillage and plant residue management systems. Weed Science 45:307–320

Lockeretz, W. 1987. Establishing the proper role for on-farm research. American Journal of Alternative Agriculture 3:132:136.

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

Luna, J. M., J. P. Mitchell, and A. Shrestha. 2012. Conservation tillage in organic agriculture: evolution toward hybrid systems in the Western USA. Renew. Agric. Food Syst. 27:21–30.

Malhi, S.S., C.A. Grant, A.M. Johnston, and K.S. Gill. 2001. Nitrogen fertilization management for no-till cereal production in the Canadian Great Plains: a review. Soil and Tillage Research 60: 101-122.

Maddux, L.D., P. L. Barnes, C. W. Raczkowski, and D. E. Kisse. 1991. Broadcast and subsurface-banded urea nitrogen in urea ammonium nitrate applied to corn. Soil Science Society of America Journal 55: 264-267.

McSwiney,C.P., S. S.Snapp, and L.E. Gentry. 2010. Use of N immobilization to tighten the N cycle in conventional agroecosystems. Ecological Applications 20: 648-662.

Miller, A. 2013. 2013 Indiana Farm Custom Rates. Purdue University Extension Fact Sheet EC-130-W.

Mochizuki, M. J., A. Rangarajan, R. R. Bellinder, T. N. Bjorkman, and H. M. Van Es. 2007. Overcoming compaction limitations on cabbage growth and yield in the transition to conservation tillage. Hortscience 42:1690–1694.

Nash, P.R., K.A. Nelson, and P.P. Motavalli. 2013. Corn Yield Response to Timing of Strip-Tillage and Nitrogen Source Applications. Agronomy Journal 105: 623-630.

Nowatzki, J., G. Endres, J. DeJong-Hughes, and D. Aakre. 2011. Strip till for field crop production. North Dakota State University Extension Publication AE-1370 (revised).

Orzolek, M.D., L.F. Kime, and J.K. Harper. 2011. Agricultural Alternatives: Sweet Corn Production. Pennsylvania State University Cooperative Extension.

Rapp, H.S., R.R. Bellinder, H.C.Wien, and F.M. Vermeylen. 2004. Reduced tillage, rye residues, and herbicides influence weed suppression and yield of pumpkins. Weed Technol. 18:953–961.

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 and Soil 227: 283-290.

Swinton, S. M. and R. P. King. 1994. A bioeconomic model for weed management in corn and soybean. Agricultural Systems 44:313–335

Syswerda, S.P., B. Basso, S.K. Hamilton, J.B. Tausig, and G.P. Robertson. 2012. Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. Agriculture, Ecosystems and Environment 149: 10-19.

Viswakumar, A., R.W. Mullen, A. Sundermeier, and C.E. Dygert. 2008. Tillage and Nitrogen Application Methodology Impacts on Corn Grain Yield. Journal of Plant Nutrition 31: 1963-1974.

Ward, B. 2012. Ohio Farm Custom Rates 2012. The Ohio State University Extension Fact Sheet AEDE-11-12.

Wilhoit, J.H., R.D. Morse, and D.H. Vaughan. 1990. Strip-tillage production of summer cabbage using high residue levels. Applied Agricultural Research 5: 338-342.

CHAPTER FIVE

Strip tillage influences potentially leachable nitrate and nitrous oxide flux in a sweet corn and cabbage rotation

Abstract

Excess nitrogen (N) applied in agroecosystems is often lost to nitrate leaching and nitrous oxide flux. Both are pollutants—nitrate leaching contributes to contamination of ground and surface waters, while nitrous oxide is a potent greenhouse gas with almost 300 times the global warming potential of carbon dioxide. Combining strip tillage (ST), a form of reduced tillage, with deep N fertilizer banding has the potential to mitigate these effects by improving plant N uptake and reducing the amount of residual N remaining after crop harvest that is vulnerable to leaching loss. Additional benefits of long-term ST related to N retention may be realized if strips are located in the same position from year to year as soil quality improves in the continuously untilled zone between crop rows; this has the potential, however, to reduce yields as crop residues from one year can interfere with planting in the next. Residual soil nitrate after harvest (or potentially leachable nitrate) and nitrous oxide flux (NOF) were examined over three years in a cabbage/sweet corn rotation with three tillage treatments—conventional, full-width tillage (FWT), ST with deep fertilizer banding and strips located in the same position from year to year (ST same), and ST with deep fertilizer banding but strip location offset from year to year (ST offset). Potentially leachable nitrate was measured using 100 cm deep soil cores collected after crop harvest in the fall, while nitrous oxide flux was measured using the static chamber method. ST resulted in lower

residual soil nitrate in the 20-100 cm profile compared to FWT in two out of the five falls examined (following sweet corn in 2011 and 2012) and increased residual soil nitrate relative to FWT in one site year. Over the 0-100 cm profile, ST reduced soil nitrate relative to FWT in one site year. The most notable differences occurred under drought-stress conditions in 2012, when FWT had 60 kg NO_3^-N/ha greater residual soil nitrate compared to ST. The amount of soil nitrate remaining after crop harvest varied widely by year and was likely influenced by differences in crop and weed biomass accumulation resulting from varied temperature and rainfall. Cumulative season-long nitrous oxide flux was similar between tillage types in sweet corn in 2011, but was greater from the crop rows than the area between rows. High nitrous oxide flux from between cabbage rows led to significantly greater flux out of FWT compared to both ST treatments. The sequential location of tilled zones in ST had very little effect on either NOF or potentially leachable nitrate, but ST offset did result in greater sweet corn yields. Our findings suggest that ST with deep fertilizer banding can reduce residual soil nitrate in years in which crop growth is limited by environmental stresses, and potentially lower cumulative nitrous oxide flux in some crops. Our results also demonstrate that studies evaluating NOF and potentially leachable nitrate in row crops must consider spatial variation across zones when designing monitoring protocols.

5.1 Introduction

5.1.1 Excess nitrogen in agroecosystems Nitrogen (N) is an essential element for crop growth and N fertilizers are often applied in excess to ensure optimal yields. When N is applied in excess to crop demand, however, it can be lost from the agroecosystem. Two important environmental impacts of excess N in agroecosystems are nitrate (NO_3^-)

leaching into ground and surface waters and nitrous oxide (N_2O) flux. In surface waters, nitrate can contribute to eutrophication and excessive algal growth, resulting in hypoxic or anoxic conditions that are harmful to pelagic organisms like fish and shrimp. Nitrate contamination of surface and groundwater used as a drinking water source may also pose a threat to human health; large areas of the Midwest are at risk for exceeding the safe level of nitrate in drinking water (4 mg/L) established by the EPA (EPA, 2007; Nolan et al., 2002). Agriculture is the leading anthropogenic contributor of nitrous oxide (Smith et al., 2008), which is a potent greenhouse gas with almost 300 times the global warming potential of carbon dioxide (Robertson and Grace, 2004). In addition to causing environmental problems, N that is applied in fertilizers but is lost to either leaching or via nitrous oxide flux represents a direct cost to growers in wasted resources. Thus, agricultural practices that can mitigate nitrate leaching and nitrous oxide flux are beneficial to both growers and to society as well.

In temperate climates, nitrate remaining in the soil after summer annual crop harvest is at risk for leaching over the winter. The use of over-wintering cover crops can mitigate this risk by taking up nitrate in surface soils (Snapp et al., 2005; Gruber et al., 2012), but nitrate below the rooting zone of these cover crops can still be leached. Thus, finding ways to improve crop uptake of applied N, either through the use of reduced tillage and/or fertilizer banding, may mitigate nitrate leaching. This can be particularly important in vegetable crops like sweet corn and cabbage that are typically fertilized with well over 200 kg N/ha (Tremblay and Belec, 2006; Everaarts and De Moel, 1998).

Tillage impacts soil moisture, temperature, and gas exchange, which all influence the microbial processes that regulate nitrogen mineralization, immobilization, nitrification, and denitrification. Thus, tillage can have a large influence on nitrate leaching potential and nitrous oxide flux and reducing the intensity and frequency of tillage may help mitigate N loss through these pathways. However, complete elimination of tillage is often not possible, especially in areas with cooler and wetter springs, as tillage helps to warm and dry the soil which ensures good crop establishment. This is particularly important for vegetable growers, who may grow smaller-seeded crops that are more difficult to establish, and for whom delays in crop maturity can mean large reductions in revenue. Strip tillage (ST) is a form of reduced tillage in which the crop is planted into tilled strips, while the rest of the soil between these strips remains undisturbed. Because it combines the advantages of tillage in the crop rows (IR) and the advantages of NT between the crop rows (BR), ST is a good option for growers wishing to reduce tillage intensity but unable to give tillage up completely. Many vegetable crops perform well in ST; yields of potato (*Solanum tuberosum* L.) and sweetpotato (*Ipomoea batatas* (L.) Lam) (Hoyt and Monks, 1996), pumpkin in one year (*Cucurbita pepo* L.) (Rapp et al., 2004), sweet corn (*Zea mays* L.) (Luna and Staben, 2002), and cabbage (*Brassica oleracea* L. var *capitata*) (Haramoto and Brainard, 2012; Mochizuki et al., 2007; Hoyt et al., 1996; Wilhoit et al., 1990) produced with ST were similar to, or greater than, yields produced with FWT.

ST offers the additional benefit of making deep fertilizer banding easier to accomplish. Banding fertilizers closer to the crop roots is another way to minimize N losses—putting the N supply closer to roots with N demand helps to ensure that more of the N will be taken up by the plant and less will be lost to the environment. Concentrated fertilizer bands deeper in the soil are also less prone to volatilization and nitrification, keeping more in the form of ammonium (NH_4^+) which is less prone to loss than ammonia (NH_3) and nitrate (Malhi et al., 2001).

5.1.2 Reduced till and no till effects on leaching and nitrous oxide flux Reducing or eliminating tillage has the potential to reduce N losses through leaching. For example, nitrate leaching measured by lysimeters after 11 years in no-till (NT) annual row crops (maize (*Zea mays* L.), soybeans (*Glycine max* (L.) Merr.) and winter wheat (*Triticum aestivum* L.) was approximately 35% lower than leaching with conventional, full-width tillage (FWT) (Syswerda et al., 2012). Averaged over all crops, nitrate loss from NT was 41.6 kg NO_3^- -N/ha/year while that from FWT was 62.3 NO_3^- -N/ha/year. This represented 50% and 76% of the total N inputs from inorganic fertilizers into NT and FWT, respectively, over this period (Syswerda et al., 2012). Reduced leaching in NT occurred despite higher soil water drainage; this often occurs in NT due to increases in macropores (Shipitalo et al., 2000). Others, also using lysimeters, have noted increased nitrate leaching in NT because of higher drainage (Tyler and Thomas, 1977).

In addition to the use of lysimeters, measuring nitrate pools remaining in the soil after harvest is a commonly used method of assessing potentially leachable nitrate. In the fall following tomato production, residual soil nitrate from 0-120 cm was similar between moldboard plow, chisel plow, and NT. However, by the following spring, NT had lost over twice the nitrate in this profile compared to the other two tillage types (Sainju et al., 1999), a loss the authors attributed to leaching. In both tillage systems, soil residual nitrate was approximately 220 kg NO_3^--N/ha in the fall; by the following spring, NT had lost 129 kg NO_3^--N/ha, or 58% of the fall nitrate content, while chisel plow lost 55 kg NO_3^--N/ha, or 25% of the fall nitrate content. Both represent a significant loss of N.

In contrast to completely eliminating tillage, reducing tillage can also affect nitrate leaching potential. Relatively few studies have examined leaching potential of ST. Leaching potential from the BR zone in ST may be similar to that from NT, though this also has not been examined specifically. In an experiment comparing spring ST with spring fertilizer banding to fall chisel plowing with fall fertilizer application, less soil nitrate accumulated in the 0-120 cm profile in ST after two years compared to FWT, with differences being more pronounced for depths greater than 60 cm (Al-Kaisi and Licht, 2004). Cores were taken both IR and BR, but data were not presented separately. NT was also associated with lower nitrate accumulation in this study (Al-Kaisi and Licht, 2004). ST does not always have this effect. Soil residual nitrate remaining after cotton and sorghum harvest from 0-30 cm was similar between ST and FWT with and without a rye cover crop (Sainju et al., 2008), as was total soil N from 0-120 cm (Sainju and Singh, 2008). While inorganic soil nitrogen (combined nitrate and ammonium) in different depth sections down to 120 cm varied throughout and between seasons, few differences were detected between tillage types (Sainju et al., 2007). Similarly, reducing tillage intensity by using a chisel plow rather than a moldboard plow had either no effect or a negligible impact on soil nitrate at depths up to 90 cm (Gruber et al., 2012) in spring or fall.

Reducing or eliminating tillage can also influence nitrous oxide flux. Nitrous oxide (N_2O) is produced in the soil as a result of both nitrification (the conversion of ammonium to nitrate) and denitrification (the conversion of nitrate to dinitrogen gas); denitrification is often halted at nitrous oxide unless completely anaerobic conditions are present. Increased flux of N_2O is associated with wetter soils, increased bulk density, and lower O_2 content, all characteristics often associated with NT soils (Johnson et al., 2005). In a review of 27 studies, 14 had higher N_2O emissions in NT soils compared to tilled soils, 12 had lower, and one had no difference (Rochette 2008). Of the 12 studies that had lower flux in NT compared to FWT, eight had either good aeration and medium drainage or medium aeration with good drainage. Conversely, of the 14 studies with higher NT emissions, half had either poor aeration and poor drainage or medium aeration and medium drainage. This review concluded that N_2O flux is likely to be higher in NT than in FWT on poorly-drained soils in humid climates but that lack of tillage does not necessarily increase flux in well-drained soils or in drier areas. Nitrous oxide flux in ST is similarly variable. Generally, similar emissions are observed compared in ST and FWT (Johnson et al., 2010; Bavin et al., 2009; Nash et al., 2012), though these studies are often complicated by different fertilizer types, application methods, and residue management.

5.1.3 Deep nitrogen banding Banded fertilizers show promise for maintaining crop yields while also reducing residual N in the soil. While grain yield was similar, total corn biomass accumulation was greater with subsurface banded UAN (urea-ammonium-nitrate) fertilizer compared to broadcast and incorporated UAN (Maddux et al., 1991). Uptake of ^{15}N labeled fertilizers by corn (Maddux et al., 1991; Malhi et al., 1996) and tall fescue (Raczkowski and Kissel 1989) was greater when the fertilizer was subsurface banded compared to broadcast; increased uptake of unlabeled N in wheat has also been reported where fertilizers were injected 10 cm deep (Blackshaw et al., 2002). Uptake of unlabeled N by cabbage also increased with banded fertilizers compared to broadcast, and N content of cabbage residues after harvest was also higher, though yield was not affected (Everaarts and Booij, 2000).

In N labeling studies, more labeled N remained in the soil profile (0-90 cm) after corn harvest in a broadcast treatment compared to a subsurface banded treatment, and, in one year of the study, over three times as much N was lost with broadcast compared to banding (Maddux et al, 1991). The authors speculate that this was primarily lost to leaching in their well-drained soils. Only 1% of banded N was not accounted for after tall fescue forage production, but 23% of broadcast N was lost (Rackowski and Kissel, 1989); these authors speculate that denitrification or volatilization was responsible for this loss in their more xeric soils. However, N remaining in the soil after cabbage harvest did not differ between broadcast and banding (Everaarts and Booij, 2000).

Banded applications of urea were associated with greater N_2O flux than broadcast application in one of two years in canola (Engel et al., 2007), in cabbage (Cheng et al., 2006), and in irrigated field corn (Halvorson and Del Grosso, 2013). However, deep fertilizer bands did not affect N_2O emissions in a cauliflower and lettuce rotation (Pfab et al., 2012). The combination of deep N placement and reduced tillage may actually reduce nitrous oxide flux, particularly in humid climates (Drury et al., 2006; Van Kessel et al., 2013).

Relatively few studies have combined ST with deep N fertilizer banding; those that do exist focus on agronomic crops like field corn (Nash et al., 2013; Halvorson et al., 2013) and sugarbeets (Stevens et al., 2010) rather than vegetables and do not measure impacts this practice can have on residual soil N. Similarly, to our knowledge, no studies have examined nitrous oxide flux out of vegetables produced with the combination of ST with deep fertilizer banding. The primary objective of this chapter therefore is to examine nitrogen loss with FWT and ST with deep fertilizer banding in a sweet corn and cabbage rotation. N loss was considered via two different pathways—soil nitrate remaining after harvest that is potentially leached over the winter and nitrous oxide flux. A secondary objective is to examine how relative strip placement from year to year influences these loss pathways. N in these pathways was examined in FWT and in the two ST treatments with deep N banding—ST same and ST offset. We hypothesized that the deep N banding in ST would contribute to improved crop growth, particularly when strip location shifted between years (ST offset) because of improved nutrient cycling in the tilled planting zone that was undisturbed the previous year. Improved crop growth would lead to more N taken up by the crop, thereby decreasing N pools in the soil and leading to less loss via over-winter leaching and through denitrification to nitrous oxide.

5.2 Materials and Methods

5.2.1 Plot establishment This experiment was conducted from 2010-2014 at the Kellogg Biological Station in Hickory Corners, Michigan (lat 42.4058, lon -85.3845). The primary soil series at this site is Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) with pockets of Oshtemo series (coarse-loamy, mixed, mesic Typic Hapludalfs) (Crum and Collins 1995). Two entry points of this experiment were established in adjacent sections of the same field (Figure 1); plots were 3.1 m wide by 20.9 m long. Prior to use in this experiment, this field was in soybeans. In the spring of year 1 of each entry point (EP), an oat cover crop was established (Figure 1). This was terminated with a glyphosate application, flail mowed once desiccated, and tillage operations were performed 7-8 days later (Table 1). Immediately prior to tillage, fertilizer was broadcast in all plots (ST and FWT); 19-19-19 was used with urea for additional N. In ST plots, a Hiniker® Model 6000 two-row strip-tiller (equipped with notched trash-cleaning discs, cutting-coulter, shank-point assembly, berming disks and rolling basket) was used to create 25 cm wide by 25 cm deep strips at 76.2 cm between-strip spacing (center to center). Conventional tillage was accomplished with a 3.1 m wide chisel plow followed by two passes with a field cultivator. Cabbage (variety 'Blue Dynasty') was then transplanted 8-13 days after tillage with an IR spacing of 0.38 m. Weeds were managed in this initial year with a combination of flaming and hand-weeding; Bt was applied as needed for control of caterpillar pests. Cabbage was harvested in October of each year and the fields were fallowed the following winter.

5.2.2 Subsequent management Table 1 provides the dates of different field operations in 2011-2013. An oat cover crop was established in the spring of year two in both EPs (Figure 1). This was terminated with glyphosate in early June and residues were flail mowed.

Starting in year two, the initial pre-tillage fertilizer application (19-19-19 with additional urea) was broadcast in FWT but banded approximately 15 cm deep (for sweet corn) or 10 cm deep (for cabbage) in ST (Table 2). This pre-tillage fertilizer application also included P and K according to soil test recommendations. The two different ST treatments were also established beginning in this year—in ST same, strips were located in the same position as the previous year while in ST offset, strips were located in the previous year's BR zone (Figure 2). Tillage was accomplished as previously described for year one.

Following the initial fertilization application and tillage, sweet corn (variety 'Providence' in 2011 and 2012 and 'BC 0805', a Bt variety genetically engineered to confer protection against caterpillar feeding, in 2013) or cabbage (variety 'Blue Dynasty') was planted. In years two and four of the rotation, sweet corn was planted with 0.19 m IR spacing using a Monosem no-till vacuum planter immediately after tillage. In all plots, 45 kg/ha N as urea was banded 5 cm down and 5 cm to the side of the seed with the planter (Table 2). In year three of the rotation, cabbage was transplanted by hand 2-8 days after tillage (Table 1). Fertilization for cabbage in this year was different than that used initially in year one. In FWT, 90 kg N/ha (as urea) was broadcast prior to tillage, while this N was applied only in the IR zone in ST through a combination of deep-banding with the strip tiller (45 kg N/ha) and surface applications (Table 1).

Weeds were controlled with PRE herbicides in sweet corn and PRE plus POST in cabbage. One hand-weeding pass was also used in each crop to remove larger weed escapes; two hand weedings were performed in cabbage in 2012. Cabbage caterpillar pests were also controlled with Bt applied as needed; no insect management was used in the sweet corn.

Both crops were side-dressed with 45 kg/ha nitrogen applied as either urea or UAN (Table 1); sweet corn was side-dressed when the plants were approximately 20 cm tall and at the V6 growth stage (with six fully expanded leaves) while cabbage was side-dressed early in stage 5, the pre-cupping stage prior to head formation. This application was targeted to the IR zone in both tillage types (Table 2).

A rye cover crop, sown at 126 kg/ha, was established following crop harvest in years 2-4. The following spring, the rye was terminated with glyphosate prior to boot stage.

5.2.3 Data collection

5.2.3.1 *Aboveground biomass production* Cover crops were sampled prior to termination by clipping all aboveground biomass in two 0.25 m^2 quadrats per plot. Biomass produced by crop plants was collected in three portions. First, all sweet corn ears (including primary and secondary ears) and cabbage heads were collected from a defined harvest area (typically seven m from the center two rows of the plot). These were separated into marketable and non-marketable categories based on size and quality. Marketable diameter for sweet corn ears was defined as 5 cm and as 10 cm for cabbage heads. Undersized ears and heads were considered non-marketable based on size while ears and heads with visible rodent or insect damage or disease were also classified as non-marketable based on appearance. Fresh weight and number of all ears and heads in these three categories was recorded; dry weight of a subsample was also obtained to determine moisture content. After harvest, three plants per plot were collected to determine biomass of the unharvested portion of the crop plants. Weeds were collected at crop harvest by clipping all aboveground biomass from two 0.25 m^2 quadrats from both the IR and BR zone in each plot. All biomass was dried at 60°C until a constant weight was achieved and then weighed. Fresh weights of harvested ears and heads were converted to dry biomass using the average moisture content.

5.2.3.2 *Soil N throughout season and after harvest* During crop growth, soil samples were collected at least biweekly using a 2 cm diameter push probe. For both IR and BR zones in all plots, eight cores were taken from 0-20 cm and combined for a composite sample. Soil moisture, nitrate, and ammonium content were analyzed as described below. Deep soil cores were also collected each fall after harvest starting in year two and the following spring in both entry points (Figure 1). Three cores were collected from the between row zone (BR) in each plot; cores were also collected from the in row zone (IR) in Fall 2013 from both entry points. Cores were 3.8 cm in diameter and were collected using a hydraulic probe (Geoprobe model RS60, Geoprobe Systems, Salina, KS). After collection, they were sectioned into five 20-cm sections (0-20 cm deep, 20-40 cm deep, etc.) and these sections were consolidated across all replicate cores within a plot. Surface samples (0-20 cm) were also collected at this time from the IR zone using a push probe as described above.

Gravimetric soil moisture was measured for each deep core section and each soil sample collected throughout the season; soils were first sieved through a 4 mm mesh to remove rocks and large organic debris. A fresh soil subsample (approximately 10 g) was weighed and then dried at 100°C for 2 days; the dry subsample was then weighed. Gravimetric soil moisture (GSM), or the percent moisture in the sample by weight, was determined as:

$$GSM = (fresh\ weight - dry\ weight) / fresh\ weight * 100$$

The remaining fresh soil from each sample was dried at 60°C for 3 days until a constant weight was achieved, then ground and extracted with a 1M KCl solution to determine nitrate and ammonium content (Anonymous 2012). This analysis was conducted at the Michigan State University Soil and Plant Nutrient Laboratory.

5.2.3.3 *Nitrous oxide flux* Nitrous oxide flux was measured in the first entry point (sweet corn in 2011 and cabbage in 2012) using the static chamber method described by Kahmark and Miller (2008). Chambers were constructed by cutting the bottoms off 13.25 liter buckets (diameter 28.7 cm). Lids with o-rings allowed for an air-tight seal on the chambers; lids also had an air-tight septum that allowed headspace sampling with a needle. The chambers were installed in the field using a metal cutting ring to facilitate insertion into soil and prevent deformation of the chamber rim. Two chambers were installed in each plot—one IR and one BR. Chambers were only removed when necessary for tillage and planting operations.

At the onset of sampling, the lid was snapped on each chamber and an initial 10 ml sample of the headspace air was collected using a needle through the septum in the lid. Samples were injected into glass vials with air-tight septa for storage until analysis; three additional samples were collected at approximately 20 minute intervals to determine flux rates. Times of the four headspace samples, soil temperature, and the height of each chamber were recorded at each sampling date. Sampling occurred on approximately weekly intervals and soil samples were collected as described above at each sampling date. Samples were analyzed at the Kellogg Biological Station using a gas chromatograph equipped with a 63Ni electron capture detector operating at 350 C (Kahmark and Millar, 2008).

Flux rates (mg N_2O-N/m^2/hr) were calculated by dividing the change in N_2O concentration between the four consecutive samples by the elapsed time. These were corrected for the headspace volume, the basal area covered by each chamber, and the soil temperature. Cumulative flux (g N_2O-N/ha/growing season) was determined by summing fluxes from consecutive sampling dates; flux was assumed to be linear over these periods.

5.2.4 Data analysis All biomass data were converted to Mg/ha prior to analysis to facilitate comparison between different fractions. These fractions were added together to determine total biomass produced in the plots; marketable crop yield and weed biomass were also analyzed separately. Soil nitrate and ammonium values were converted to kg/ha using the average bulk density of soils at this site (1.6 g/cm^3; Crum and Collins, 1995). Biweekly surface soil N data were averaged over sampling dates within a season to create an aggregate value. Nitrate values from deep core samples were separated into surface (0-20 cm) and deep categories (>20 cm deep), with data being summed over the deep sections for the latter category.

A weighted average was calculated based on the relative area occupied by the BR and IR zones for the two potential N loss pathways (the BR zone is approximately twice the width of the IR zone); this area-corrected value provides plot-wide estimates of these losses. For deep soil cores, a weighted average of nitrate values from the surface soil samples (0-20 cm) was determined and added to the nitrate value from the deep samples (20-100 cm) in cases where separate zonal measurements were not made from deep cores. In fall 2013, when deep cores were taken from both the IR and BR zones, a weighted average of nitrate values from these deep samples was also determined and added to the surface value. The unit for the resulting area-corrected values is kg NO_3^--N/ha to one meter depth. Season-long soil surface (0-20 cm) nitrate and ammonium levels were also area-corrected in the same way.

All data were analyzed separately for each crop with one-, two-, or three-way analysis of variance using PROC MIXED in SAS ® version 9.3 (SAS Institute, Cary, NC). We chose α=0.1 to designate our significance level. Replicates within each experiment were considered a random factor. Year was initially included in analysis models as a fixed factor to test for year, year*treatment, and year*zone interactions (where appropriate). If year did not interact with treatment or zone, data were pooled over years. Since we were interested in making statements regarding environmental conditions within specific years, year remained a fixed factor. This was the case with biomass data, which were then pooled over one factor to analyze the effect of the other (i.e. data were pooled over treatment to consider year effects and pooled over years to consider treatment effects). In the case of significant interactions, years were analyzed separately. This was the case for all soil data, which were then analyzed separately by crop, year, and season (fall or spring for soil nitrate remaining after crop harvest). For zone-specific (IR or BR) soil nitrate data (i.e. all data collected from the surface) and nitrous oxide flux, zone was treated as a fixed subplot factor while tillage treatment was considered the fixed main plot factor.

5.3 Results

5.3.1 Environment Temperature and precipitation for the Kellogg Biological Station for May through September in 2011-2013 are shown in Table 3. Environmental conditions varied widely during this period. 2011 was a relatively warm and wet year—compared to ten year average, July was almost 2° C warmer, but September was 1.4° C cooler. Rainfall during July 2011 was almost twice the ten year average for that month. 2012, in contrast, was hot and dry—air temperature for May, June, and July 2012 was 1-3° C warmer than the ten year average, and warmer than the other two years. Precipitation in 2012 was also much lower than the ten year average, with only 227 mm of precipitation during the growing season; both high temperatures and low precipitation contributed to droughty conditions throughout 2012. 2013 was a relatively cool year, with slightly below-average temperatures in June, July, and August but, until September, had relatively normal precipitation.

5.3.2 Aboveground biomass production Results of ANOVA on total aboveground dry biomass production, marketable yield, and weed biomass are shown in Table 4. Total aboveground dry biomass production in sweet corn, including marketable and non-marketable ears, non-harvested portions of the corn plant, and weeds was not affected by tillage (Table 4; Figure 3). Biomass production was lower in 2012 than in 2011 and 2013—an average of 5.8 Mg/ha was produced in 2012 compared to 8.2 and 8.1 Mg/ha in 2011 and 2013, respectively (Table 4; Figure 3). Total aboveground dry biomass in cabbage was not affected by tillage, year, or their interaction (Figure 4).

Averaged over all years, tillage affected sweet corn marketable yield (Table 4; Figure A1). Yield in ST offset was 18% higher lower than FWT (contrast p=0.010); ST same yield was intermediate and not significantly different from either (single df contrast p=0.112 against ST offset and p=0.258 against FWT; Figure 3). Sweet corn marketable yield was also affected by year, with 2013 having the highest yields, 2012 the lowest, and 2011 having intermediate yield (Figure 3). Marketable cabbage yield was not affected by tillage or its interaction with year, but was over three-fold greater in 2013 than in 2012 (Table 4; Figures 4, A2). Fresh yield of marketable heads was 22.8 and 72.4 Mg/ha in 2012 and 2013, respectively (Figure A2).

Total weed biomass was in sweet corn was affected by the interaction between tillage and year (Table 4). In 2012, the drought year, weed biomass was lower in ST offset than in the other two treatments (slicing p=0.007; Figure 3), but similar in 2011 (p=0.705) and 2013 (p=0.421). ST offset also had lower weed biomass in 2012 and 2013 compared to 2011 (slicing p=0.001). Weed biomass in cabbage was not affected by tillage or its interaction with year, but was greater in 2012 than in 2013 (Table 4; Figure 4)

5.3.3 Season-long soil N Soil ammonium levels increased to high levels, relative to soil nitrate, after fertilizer applications. Since both sweet corn (Mills and McElhannon, 1982, 1983) and cabbage (Turan and Sevimli, 2005) can reportedly utilize ammonium as an N source, total soil inorganic N (IN, the sum of ammonium and nitrate) is presented (Table 5; see Figure B1-B3 for season-long ammonium and nitrate values).

In sweet corn, years were analyzed separately because of significant year*treatment*area interactions. In 2011, season-long average IR IN was greater than BR IN (Table 5), with no treatment effects on IN. In both 2012 and 2013, tillage effects depended on the zone. In both years, FWT had higher BR IN than the two ST treatments, while the two ST treatments had higher IR IN than in FWT (Table 5). Years were also analyzed separately for cabbage because of significant year*area interactions. The response of IN to treatment and zone, however, was similar between years. In both 2012 and 2013, FWT had greater BR IN than the ST treatments, while ST had greater IN in the IR zone. IR IN was greater than BR IN in ST in each year; the opposite was observed in FWT where BR IN was greater than IR IN.

Overall, IN values were greater in 2012 than in the other years. Averaged over all zones and treatments, IN content was 161, 191, and 135 kg NO_3^--N + NH_4^--N/ha in 2011, 2012, and 2013 following sweet corn, respectively. Following cabbage, average IN content was 152 and 103 kg NO_3^--N + NH_4^--N /ha in 2012 and 2013, respectively.

5.3.4 Residual soil nitrate after harvest Tillage effects on deep soil nitrate (20-100 cm) remaining after harvest were influenced by year, so years are presented separately for each crop. Following sweet corn harvest in 2011, ST offset had 11 kg NO_3^--N/ha less deep soil nitrate then ST same and 17 kg NO_3^--N/ha less then FWT (Table 6). In 2012 following sweet corn, FWT had 26 kg NO_3^--N/ha more deep soil nitrate than ST same; deep soil nitrate was similar between all tillage treatments following cabbage in 2012. In 2013, deep soil nitrate remaining after harvest was lower than in the two previous years and similar in all tillage treatments following both sweet corn and cabbage.

By spring of 2012 and 2013, deep soil nitrate was low in all tillage types in both crops—in most cases less than 5 kg NO_3^--N/ha—which suggests that the nitrate present in the previous fall was leached beyond the sampling depth (1 m) over the winter. In spring 2013, following the drought year when soil N remained high in the fall after harvest, FWT had more deep nitrate than the two ST treatments in sweet corn (Table 6).

There was more soil nitrate remaining after harvest in the surface layer (0-20 cm) than in the deep layer in 2012 regardless of the crop (Figure 5). Area-corrected surface nitrate averaged approximately 25, 70, and 5 kg NO_3^--N/ha following sweet corn in 2011, 2012, and 2013. Following cabbage, surface nitrate was approximately 33 and 3 kg NO_3^--N/ha in 2012 and 2013, respectively. In both years, there was consistently less residual soil nitrate in the surface and deep samples in cabbage than in sweet corn.

Whole-plot estimates of IN remaining in the top 100 cm of soil after harvest (Table 7) can be considered a “worst case scenario” of N loss in the case of poor cover crop establishment or growth. Tillage did not influence total residual soil nitrate following cabbage, but for sweet corn, tillage influenced total residual nitrate in 2 of 3 years. In 2012, ST reduced the total potential N loss compared to FWT by NO_3^--N/ha (Table 7). In 2013, the year with lowest residual soil nitrate throughout the soil profile (Figure 5), ST-same increased total potential N loss compared to FWT by NO_3^--N/ha.

5.3.5 Nitrous oxide flux (NOF) Cumulative NOF throughout each growing season is shown in the appendix (Figures C1, C2). In 2011, cumulative NOF over the sweet corn growing season was greater IR than BR ($p<0.0001$) but was not affected by tillage treatment (Figure 6). Cumulative IR NOF averaged 745 g N_2O-N/ha over 105 days, while BR NOF averaged 232 g N_2O-N /ha over this period. In 2012, cumulative NOF over the cabbage growing season was affected by the interaction between treatment and zone ($p<0.0001$; Figure 6). Cumulative IR NOF averaged 215 g N_2O-N /ha in the two ST treatments over the 156 days measured but only 156 g N_2O-N /ha in FWT. In FWT, cumulative BR NOF was much greater, 290 g N_2O-N /ha, compared to the two ST treatments which averaged just 52 g N_2O-N /ha (Figure 6). Generally, cumulative NOF was higher with higher levels of soil nitrate, expressed as the season-long average (Figure 6). Total cumulative NOF (weighted average of BR and IR NOF) in cabbage in 2012 was greater in FWT than the two ST treatments (effects slicing $p=0.008$; Table 7).

5.4 Discussion

5.4.1 Aboveground biomass production Differences in biomass production between years in both sweet corn and cabbage likely reflect differences in temperature and rainfall. For example, low biomass production in sweet corn in 2012 (Figure 3) was likely due in part to very hot and dry conditions (Table 3). While total aboveground biomass in cabbage was similar in 2012 and 2013 (Figure 4), weeds accounted for a much larger proportion of total biomass in 2012. This was likely a result of droughty conditions in 2012 that favored warm-adapted weed species like Powell amaranth relative to cool-adapted cabbage. In years with poor weed control, crop plants may suffer even greater losses due to environmental stress, further increasing the competitive ability of weeds (Patterson, 1995).

An important practical finding of this study was that sweet corn yields were highest in ST treatment in which tilled zones were offset from one year to the next (Figures 3, A1). We anticipated that biomass production and marketable yield of both crops would be higher in ST compared to FWT because of the potential direct benefits of ST on soil moisture (Wilhoit et al., 1990; Haramoto and Brainard, 2012), N retention (Sainju and Singh, 2008), and temperature moderation (Mochizuki et al., 2007), as well as indirect benefits of deep-banded N that is facilitated by ST (Maddux et al., 1991; Malhi et al., 2001). Of the two ST treatments, ST offset may have had higher yields because the tilled planting zone in one year was undisturbed the previous year, potentially allowing organic matter pools to accumulate that would contribute nutrients to the crop.

In contrast with sweet corn, tillage did not affect either marketable yield in cabbage (Fig. 4). It is possible that the more shallow-rooted cabbage was not able to utilize the deep banded N as readily as the sweet corn. Cabbage exhibited variable yields with surface N banding (Sanderson and Ivany, 1999; Everaarts and De Moel, 1998), though improved N uptake by the plant was observed with banded fertilizers (Everaarts and Booij, 2000; Cheng et al, 2006).

5.4.2 Season-long IN and residual soil nitrate after harvest Our results demonstrated heterogeneity in the distribution of IN in both FWT and ST tillage systems. In ST, the highest IN concentrations were observed in the IR zone, whereas in FWT, the highest concentrations were observed in the BR zone (Table 5). These differences are not surprising given that in ST all N fertilizer was concentrated in the IR zone whereas in FWT, only 56% or 78% of applied IN was banded in the IR zone (Table 2). In FWT, high IN in the BR zone also reflects the fact that N fertilizer applied in the BR zone was likely minimally taken up by crops since roots would only extend into this zone later in the season as the plants grew.

2012 was associated with greater IN season-long in both zones (Table 5); this is likely attributable to hot and dry conditions limiting crop growth in this year (Table 3; Figures 3, 4). In sweet corn, 2013 had the lowest levels of IN season-long, indicating that the corn was taking up more N in this year or that mineralization was limited. The latter explanation is more likely as total biomass accumulation in 2013 was similar to that in 2011 (Figure 3) and because cooler temperatures could have limited mineralization (Table 3).

Tillage effects on residual soil nitrate varied by year following sweet corn. In years with higher amounts of deep soil nitrate remaining after harvest (2011 and 2012 following sweet corn), one of the ST treatments was effective in reducing deep soil nitrate relative to FWT—ST offset in 2011 and ST same in 2012 (Table 6). However, the effect of each ST treatment was inconsistent between years. This inconsistency was also observed by Al-Kaisi and Licht (2004)—lower deep soil nitrate (15-120 cm) was observed with ST compared to FWT, but only after two years in ST at one site and not at the other. In our trial, soil nitrate remaining after sweet corn harvest represented 12-24% of N applied in 2011, 19-38% of that applied in 2012, and only 5-6% in 2013 (Table 6); residual soil nitrate in their trial represented 16-29% of N applied in FWT and 17-21% of that applied in ST (Al-Kaisi and Licht, 2004)—similar to ours in 2011 and 2012. Interestingly, residual soil nitrate amounts at this site (approximately 25-50 kg NO_3^--N/ha), were much lower compared to the site at which ST did not have an effect (approximately 85-110 kg NO_3^--N/ha).

After addition of 250 kg N/ha prior to a cabbage crop, Everaarts and Booij (2000) report 21-39 kg NO_3^--N /ha remaining after harvest in the 0-90 cm soil profile, or about

10% of that applied. Our residual nitrate values (Table 6) are similar in Fall 2012 and much lower in Fall 2013, representing approximately 5-15% of N applied in 2012 and less than 2% of that applied in 2013. Though they applied almost double the N rate, their yields (around 90 fresh Mg/ha) were much higher than ours, which accounts for similar relative amounts of nitrate remaining.

Higher amounts of soil nitrate in the surface samples were observed relative to that in the deep samples in both crops in 2012 (Figure 5). It is likely that this is a result of dry conditions in 2012—downward movement of nitrate was limited by dry soil conditions. More residual soil nitrate in both depth sections was also observed following sweet corn than following cabbage, particularly in 2012 (Figure 5). Greater biomass production in cabbage plots compared to sweet corn could explain this result. In 2012, aboveground biomass in cabbage was approximately 9 Mg/ha (Figure 4, averaged over all treatments), while aboveground biomass in sweet corn was only 5.8 Mg/ha.

Once the residual soil nitrate in the surface samples was factored in, ST reduced total residual soil nitrate relative to FWT in one of five crop*year combinations: 2012 following sweet corn. ST same also increased residual soil nitrate relative to FWT in one of five crop*year combinations, 2013 following sweet corn (Table 6). Because of the relatively large amount of soil nitrate left after harvest in 2012 (86-148 kg NO_3^--N/ha), the effect of ST in this year is important. There was also a non-significant trend towards ST reducing total residual soil nitrate relative to FWT following sweet corn in 2011. These two crop*year combinations have the highest levels of residual soil nitrate.

5.4.3 Nitrous oxide flux NOF was higher in FWT compared to ST in one out of two years in which it was evaluated (Figure 6B). In particular, NOF during the cabbage season (156 days) in 2012 was 250 g N_2O-N/ha in FWT and only 100-110 g N_2O-N/ha in ST (Table 8). Lower NOF under ST could not be explained simply by lower soil nitrate (Figure 6), nor greater crop or weed uptake of N easily explain this result, since total dry biomass was equivalent or higher in FWT compared to ST (Figures 3, 4). This difference was driven primarily by relatively large flux out of the BR zone in FWT.

As with cumulative soil IN, spatial heterogeneity in NOF was observed both within and across tillage systems, and was likely due primarily to differences in the location of IN fertilizer application. With one important exception, IR flux was greater than BR flux over all tillage treatments in both crops (Figure 6). This was expected as most of the N fertilizer was applied to the IR zone (Table 2) and N_2O flux is often correlated with increased soil nitrate content (McSwiney and Robertson, 2005). However, the exception is the BR flux in FWT cabbage in 2012. Cumulative flux out of these plots, averaging almost 300 g N_2O -N/ha over the growing season, was much higher than that in ST BR, which averaged only 51 g N_2O -N/ha (Figure 6). Soil nitrate in this zone in FWT, 60 kg NO_3^--N/ha, was higher than in ST, which averaged 33 kg NO_3^{--} -N/ha (Figure 6), though these differences are not sufficient to cause such high BR NOF.

Our results demonstrated that cumulative NOF in sweet corn in 2011 was greater than flux out of cabbage in 2012 (Figure 6; Table 8). However, these differences may be best explained by the specific environmental conditions that occurred in the two years, rather than by any intrinsic characteristics of the specific crops grown. In particular, dry conditions that occurred during cabbage growth in 2012 may have limited both microbial activity and the prevalence of anaerobic microsites that favor denitrification (Rochette 2008), resulting in lower NOF. Differences in plant IN uptake across cropping systems were likely relatively small in these crop-years, since total plant biomass was similar (Figures 3 and 4).

NOF measured in sweet corn (350-430 g N_2O -N/ha/105 days) is lower than that typically measured out of ST field corn. With ST and deep urea banding, similar to our trial, reported NOF from field corn ranges from approximately 1.7 kg N_2O-N/ha in irrigated production (Halvorson et al., 2013) to over 5 kg N_2O -N/ha in heavier, poorly drained soils (Nash et al., 2012). In irrigated sweet corn, NOF ranged from 555-668 g N_2O/ha over a 12 week period, about 80% of our season (Haile-Mariam et al., 2008). Our cumulative NOF was lower than these, though we also fertilized with a much lower N rate (135 kg N/ha compared to 225 kg N/ha).

NOF measured in cabbage (100-250 g N_2O -N/ha /156 days) is also lower than that reported for many cabbage relatives. In Chinese cabbage, a cabbage relative with a shorter growing period (80-85 days relative to 120+ days for cabbage), NOF with banded urea (250 kg N/ha) was 850 g N_2O -N/ha over an 82 day measurement period (Cheng et al., 2006), or 3.4% of the N applied. NOF as high as 5-11 kg N_2O -N/ha have been reported with broadcast urea applications of 300- 600 kg N/ha (about 1.6% of N applied) to Chinese cabbage (Bing et al, 2006). In cauliflower, NOF rates of 1.5-2.5 kg N_2O -N/ha with broadcast and deep banded urea fertilizers at 400 kg N/ha (Pfab et al., 2012), 0.37-0.62% of N applied. Our N application rates were much lower than those used in these other studies, though cumulative flux as a percentage of N applied was similar in our study to Cheng et al. (2006) and Pfab et al. (2012).

Overall, N2O flux represented only a small fraction of the nitrate remaining in the soil profile—between 0.2-1.4% over the different years and treatments (not shown). While nitrous oxide flux is important because of its impact as a greenhouse gas, it does not contribute much in the way of nitrogen loss (Halvorson et al., 2013, Haile-Merriam et al., 2013).

5.5 Conclusions

These results suggest that ST with deep N fertilizer banding, and strip placement when ST is used year after year, can influence soil N dynamics, but that these effects are also highly dependent on the crop and climatological conditions during the growing season. Weather appeared to play a larger role in determining the amount of soil nitrate remaining after harvest—both in surface and in deep samples—then did tillage system. These effects were sometimes direct and sometimes indirect. One direct effect of weather was observed in sweet corn in 2012—reduced rainfall lowered downward movement of soil nitrate, resulting in a large difference between surface and deep residual nitrate after sweet corn harvest. An indirect effect of weather, however, contributed to large amounts of residual N over the whole plot in this year as crop growth and biomass accumulation was limited by lack of available moisture.

Our study also demonstrated several important instances in which strip tillage reduced potential N losses relative to FWT. Strip tillage with deep N banding was successful in lowering potentially leachable nitrate (at the 20-100 cm depth) in two out of five crop*year combinations—this is important in systems with over-wintering cover crops to take up residual N in surface soils. However, strip tillage only reduced total residual soil nitrate that could be leached in systems (0-100 cm) without these cover crops in one of five crop*year combinations. Strip tillage also reduced total nitrous oxide flux in cabbage relative to FWT, providing modest benefits in reducing greenhouse gas emissions.

Our results suggest that the potential benefits of reduced tillage systems are likely to be greatest in years when environmental stresses limit plant uptake. This may be of increasing importance as climate change scenarios forecast increasing drought conditions in some areas.

While we did not demonstrate many benefits for ST with deep N banding in terms of reducing N loss to the environment, there are other benefits that growers may find attractive, leading to increased adoption. Though not highlighted in this chapter, it is important to note that, averaged over all years, ST offset also increased marketable sweet corn yields relative to FWT and maintained similar cabbage yields to FWT over a range of environmental conditions. ST is also associated with modest reductions in tillage costs. It should also be noted that in addition to these relatively short term effects, results from other studies suggest that ST and cover cropping may provide long-term benefits for soil health.

Table 5.1 Dates of management operations, 2011-2013.

Operation	Entry point 1			Entry point 2	
	2011 sweet corn	2012 cabbage	2013 sweet corn	2012 sweet corn	2013 cabbage
Oat planting	4-13	--	--	4-18	--
Deep core collection	--	4-4	5-3	--	5-3
Oat/rye termination	6-9	5-3	5-9	6-6	5-9
Tillage and fertilization	6-17	5-15	6-4	6-19	6-4
Planting	6-17	5-23	6-4	6-19	6-6
N sidedress application	7-25	7-11	7-11	7-23	7-11
Harvest	8-31	9-20	8-26	8-29	9-12
Deep core collection	9-12	9-25	8-29	9-11	9-17
Rye planting	10-12	9-26	8-30	9-20	9-23

Table 5.2 Summary of nitrogen applications to each crop. Urea was used as the N source for all pre-till and at-planting applications. Either urea or 28% UAN was used as the side-dress N source.

	Sweet corn		**Cabbage**	
N application	FWT	ST	FWT	ST
	------------------------kg N/ha----------------------			
Broadcast pre-till (IR and BR zones)	45	0	90	0
Deep-banded pre-till (IR zone only, 15 cm deep)	0	45	0	45
Banded with seed or transplant (IR zone only, 5 cm deep for sweet corn, surface for cabbage)	45	45	0	45
Side-dress (IR zone only)	45	45	45	45
Total N applied	135	135	135	135
Estimated N in IR zone	105	135	75	135
Estimated % N in IR zone	78%	100%	56%	100%

Table 5.3 Monthly summary of average air temperature and precipitation (with supplemental irrigation for each crop in parentheses) at Kellogg Biological Station, 2011-2013. Average temperature and average monthly rainfall from 2004-2013 are also presented.

	Average air temperature (ºC)				Total precipitation and irrigation (mm)			
Month	2011	2012	2013	2004-2013	2011	2012	2013	2004-2013
May	15.1	17.2	16.7	15.3	142	30 (38 cabb)	118	103
June	20.2	21.0	19.4	20.3	47	23 (19 cabb, 13 corn)	108	91
July	24.1	25.3	21.7	22.3	187 (13 corn)	45 (25 cabb, 25 corn)	82 (6 corn, 6 cabb)	89
August	20.7	20.7	20.1	20.8	96	70 (25 cabb, 19 corn)	117	97
September	15.6	16.5	16.7	17.0	82	58	19	87
Average	19.2	20.1	18.9	19.1				
Total					556	227	446	470
Total with irrigation				corn	568	284	452	
				cabbage	--	335	452	

Table 5.4 Results of two-way ANOVA considering year and tillage treatment effects on total aboveground plant biomass accumulation, marketable yield, and weed biomass. F is the F statistic calculated in the analysis, and p>F is the probability of rejecting the null hypothesis of no effect. P values less than α=0.10 denote significant effects.

	sweet corn						cabbage					
	total		market		weeds		total		market		weeds	
Effect	F	p > F	F	p > F	F	p > F	F	p > F	F	p > F	F	p > F
year	14.89	<0.0001	55.06	<0.0001	2.99	0.069	1.05	0.3214	218.4	<.0001	34.57	<0.0001
tillage	0.74	0.488	3.84	0.036	2.47	0.106	1.11	0.3551	0.08	0.9233	1.17	0.338
year*tillage	0.87	0.496	0.52	0.722	2.5	0.07	1.5	0.2556	1.01	0.3872	1.17	0.337

Table 5.5 Average season-long soil inorganic nitrogen (nitrate + ammonium), with standard errors in parentheses, in sweet corn and cabbage. Two-way ANOVA p values are also presented; ANOVA model analyzed treatment and zone effects separately by crop and year. Within a column, means with the same lowercase letter are not significantly different at α=0.10. Between zones within a given crop and year combination (i.e. sweet corn in 2012), means followed by the same uppercase letter are not significantly different at α=0.10.

	sweet corn						cabbage			
	2011		2012		2013		2012		2013	
	BR	IR	BR	IR	BR	IR	BR	IR	BR	IR
tillage	----------------------------kg NO_3^--N+NH_4^+-N/ha-------------------------						------------kg NO_3^--N+ NH_4^+-N/ha--------			
ST same			140 b, B (23)	221 a, A (18)	98 b, B (13)	150 ab, A (14)	85 b, B (4)	221 a, A (3)	69 b, B (8)	142 a, A (23)
ST offset			163 b, B (18)	222 a, A (18)	105 b, B (8)	178 a, A (9)	97 b, B (8)	221 a, A (27)	57 b, B (5)	131 a, A (12)
FWT			249 a, A (20)	152 b, B (14)	154 a, A (10)	125 b, B (11)	162 a, A (15)	128 b, B (19)	124 a, A (20)	83 b, B (7)
average	127 B (14)	196 A (14)								
ANOVA										
Tillage (T)	0.31		0.53		0.24		0.67		0.587	
Zone (Z)	0.003		0.25		0.001		0.0002		0.010	
T*Z	0.25		0.002		0.0005		0.0005		0.0007	

Table 5.6 Potentially leachable nitrate, or deep soil nitrate (20-100 cm), in the fall and spring following sweet corn harvest in 2011, 2012, and 2013 and following cabbage harvest in 2012 and 2013. Averages are shown, with standard errors in parentheses. One-way ANOVA p values are also presented; ANOVA model analyzed tillage treatment effects separately by crop, season (spring or fall), and year. Within a column, means with the same letter are not significantly different at α=0.10. The fraction of nitrate measured in these cores as a percent of total N applied (135 kg N/ha for both crops) is also presented.

Nitrate in deep soil samples (20-100 cm), kg NO_3^--N /ha								
	Sweet corn					Cabbage		
	F 2011	S 2012	F 2012	S 2013	F 2013	F 2012	S 2013	F 2013
ST same	26.7 a	1.42	25.7 b	0.629 b	6.95	10.9	3.41	1.24
	(2.27)	(1.02)	(3.10)	(0.52)	(2.79)	(4.0)	(0.34)	(0.74)
ST offset	15.8 b	0.93	40.5 ab	0.291 b	7.75	7.48	4.26	1.20
	(3.48)	(0.57)	(8.57)	(0.29)	(3.60)	(1.7)	(1.5)	(0.47)
FWT	33.1 a	2.76	51.5 a	6.26 a	8.59	20.0	3.51	2.20
	(12.9)	(1.10)	(7.79)	(4.97)	(3.05)	(11.1)	(1.9)	(0.85)
ANOVA tillage	0.01	0.30	0.06	0.03	0.54	0.53	0.88	0.19
	Deep soil nitrate as % of N applied							
ST same	19.8		19.0		5.1	8.1		0.92
ST offset	11.7		30.0		5.7	5.5		0.89
FWT	24.5		38.1		6.4	14.8		1.63

Table 5.7 Area corrected soil nitrate values for 0-100 cm in the fall and spring following sweet corn harvest in 2011, 2012, and 2013, and following cabbage harvest in 2012 and 2013. Averages are shown, with standard errors in parentheses. Values have been area-corrected by averaging surface samples according to the relative are occupied by each zone (BR area = 2*IR area). One-way ANOVA p values are also presented; ANOVA model analyzed treatment effects separately by crop, season (spring or fall), and year. Within a column, means with the same letter are not significantly different at α=0.10.

Area-corrected NO_3^- (0-100 cm), kg NO_3^--N /ha								
	Sweet corn					cabbage		
	F 2011	S 2012	F 2012	S 2013	F 2013	F 2012	S 2013	F 2013
ST same	51.0	3.51	86.1 b	2.43	15.9 a	43.1	9.0	2.55
	(5.52)	(1.0)	(12.0)	(1.0)	(3.89)	(7.5)	(0.24)	(0.55)
ST offset	30.5	3.53	103.8 b	1.46	12.7 ab	48.7	11.8	2.13
	(7.39)	(0.9)	(15.0)	(0.7)	(4.67)	(8.0)	(2.14)	(0.62)
FWT	67.9	5.00	147.8 a	2.83	11.0 b	45.2	10.2	3.03
	(19.2)	(1.2)	(24.4)	(1.0)	(3.72)	(17.7)	(1.45)	(0.56)
ANOVA tillage	0.19	0.56	0.08	0.36	0.05	0.95	0.46	0.48

Table 5.8 Estimated total cumulative N_2O flux for sweet corn in 2011 and cabbage in 2012. Averages are shown, with standard errors in parentheses. Values have been area-corrected by averaging flux according to the relative area occupied by each zone (BR area = 2*IR area). Two-way ANOVA p values are also presented; ANOVA model analyzed year, tillage, and interactive effects. Effects slicing indicated no tillage effects in 2011 ($p=0.124$) and a significant tillage effect in 2012 ($p=0.008$). Contrasts were then used to separate these treatment effects; within a column, means with the same letter are not significantly different at $\alpha=0.10$.

tillage	Sweet corn, 2011 cumulative N2O flux (kg N_2O-N/ha/105 days)	Cabbage, 2012 cumulative N2O flux (kg N_2O-N/ha/156 days)
ST same	0.35 a (0.06)	0.10 b (0.01)
ST offset	0.43 a (0.05)	0.11 b (0.01)
FWT	0.43 a (0.03)	0.25 a (0.02)
ANOVA		
Year (Y)	<0.01	
Tillage (T)	<0.01	
Y*T	0.10	

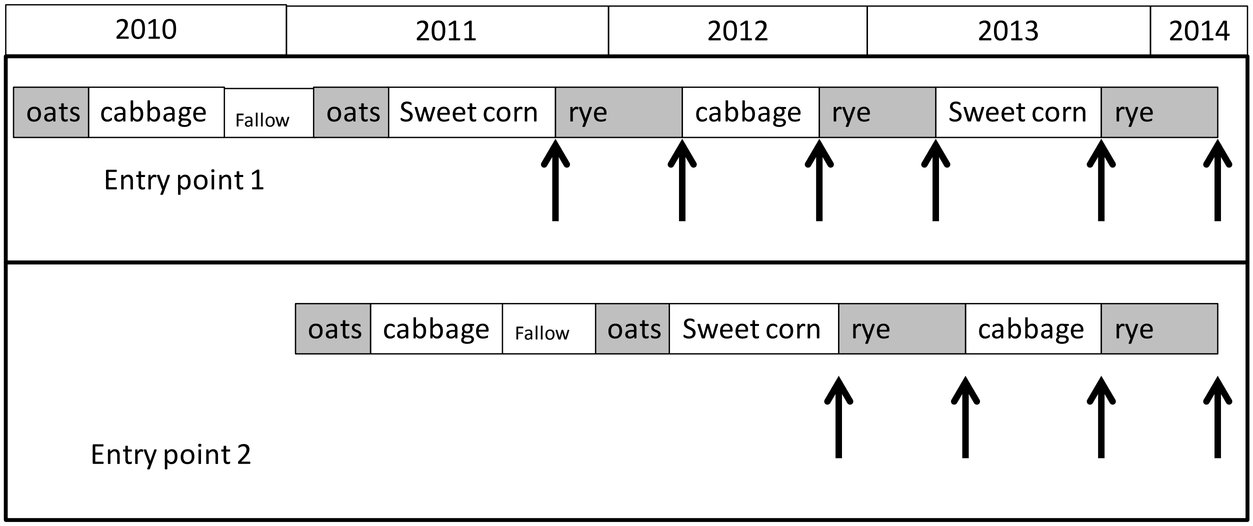


Figure 5.1 Rotation in the two entry points. Solid black arrows represent deep core collection times. Trace gas flux was sampled in Entry point 1 in 2011, 2012, and 2013. Soil nitrate and ammonium were measured biweekly in years 2-4 for entry point 1 and years 2-3 in entry point 2.

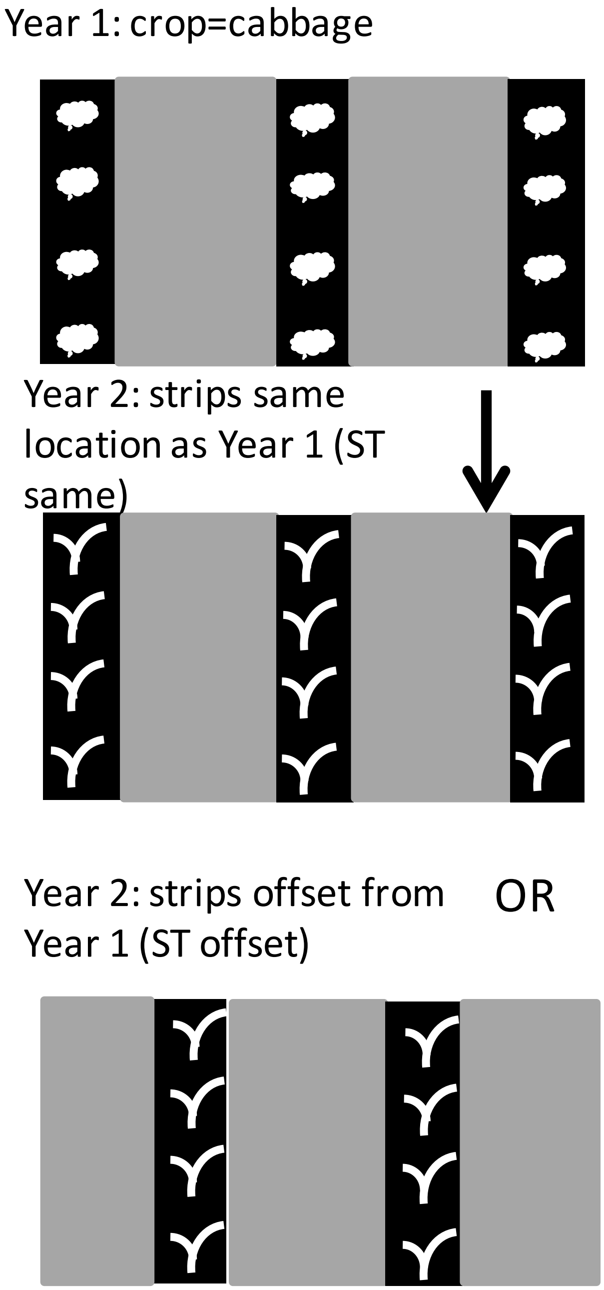


Figure 5.2 Strip position in strip till treatments. Gray boxes represent untilled soil in the BR zone, while black boxes represent tilled soil in the IR zone. Cabbage and sweet corn crops are shown in white. In ST same (middle panel), strips are in the same position from year to year, while strip position shifts from year to year in ST offset (bottom panel). In ST offset, strips are located in the previous year's untilled BR zone.

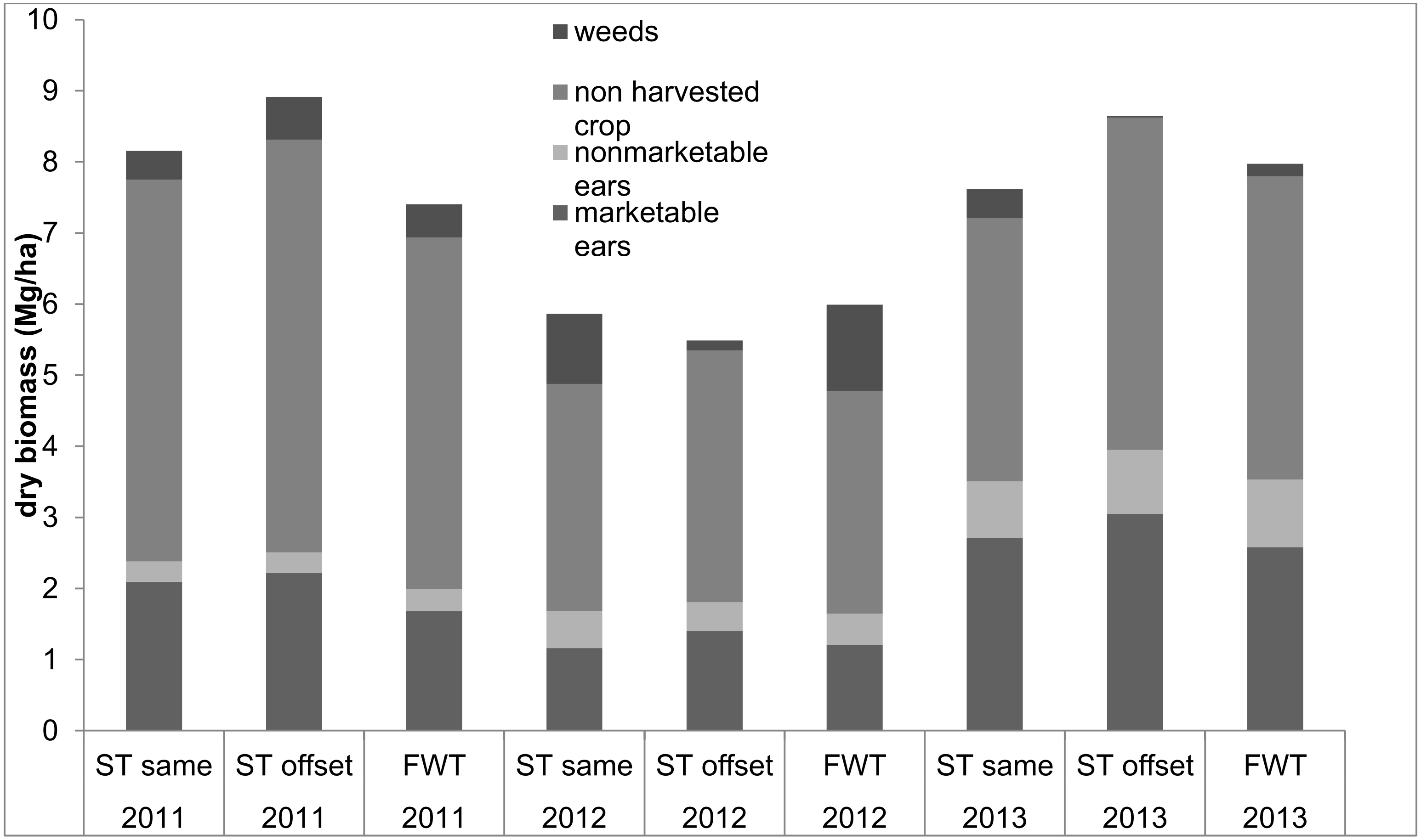


Figure 5.3 Total dry biomass (Mg/ha) produced in sweet corn in 2011, 2012, and 2013, separated into marketable and non-marketable yield, non-harvested portions of the sweet corn plant, and weeds. Two-way ANOVA on total dry biomass indicated significant year effects ($p<0.0001$) but not tillage effects ($p=0.49$) nor year*tillage interactions ($p=0.50$). Two-way ANOVA on weed biomass indicated a significant year*tillage interaction ($p=0.07$), with ST offset having lower weed biomass than ST same and FWT in 2012, and lower weed biomass in 2012 and 2013 compared to 2011.

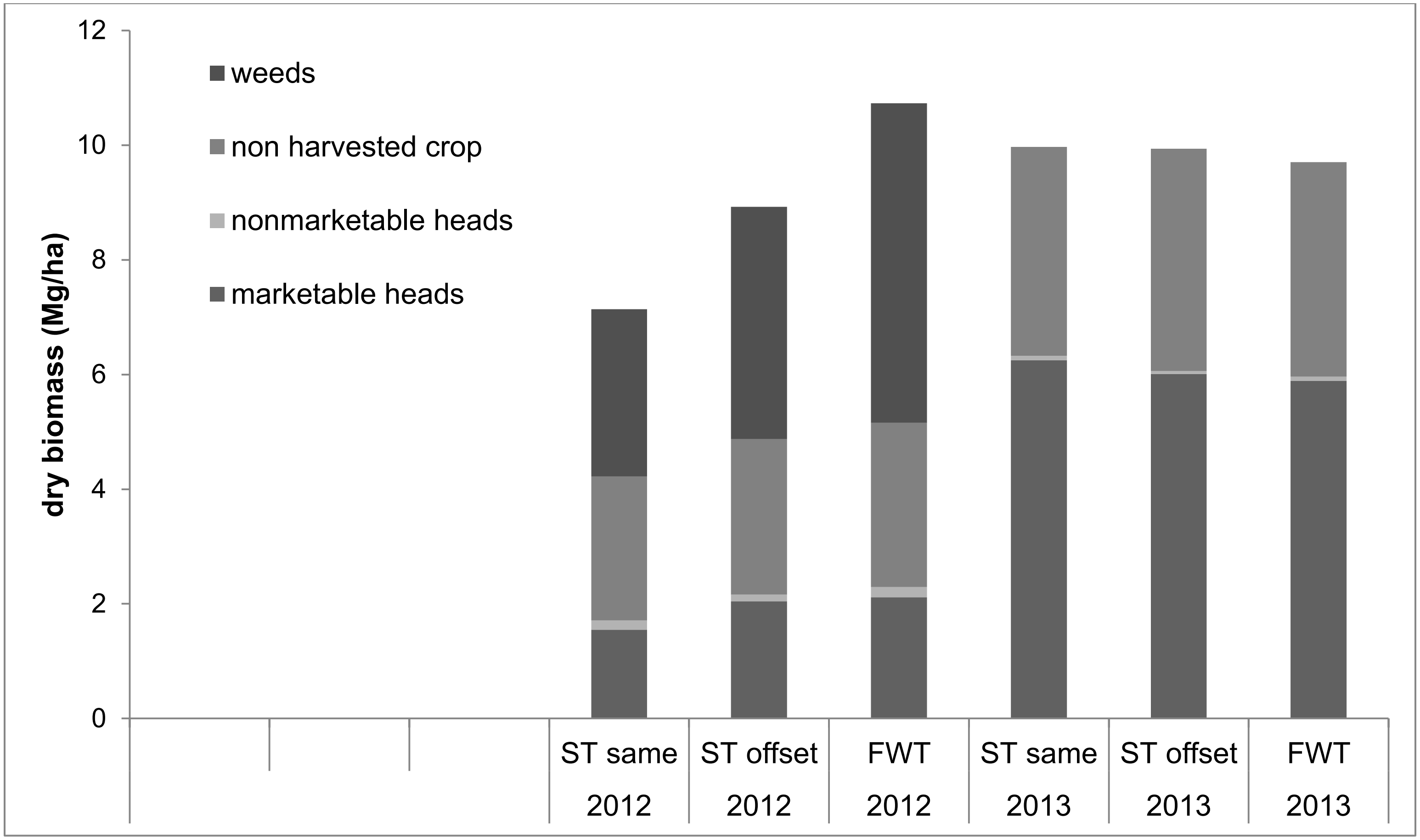


Figure 5.4 Total dry biomass (Mg/ha) produced in cabbage in 2012 and 2013, separated into marketable and non-marketable yield, non-harvested portions of the cabbage plant, and weeds. Two-way ANOVA on total dry biomass did not detect significant year ($p=0.32$), tillage ($p=0.36$), or year*tillage effects ($p=0.26$). Two-way ANOVA on weed biomass and on marketable head yield indicated a significant year effect ($p<0.0001$ for each), but no effects of tillage or year*tillage interactions.

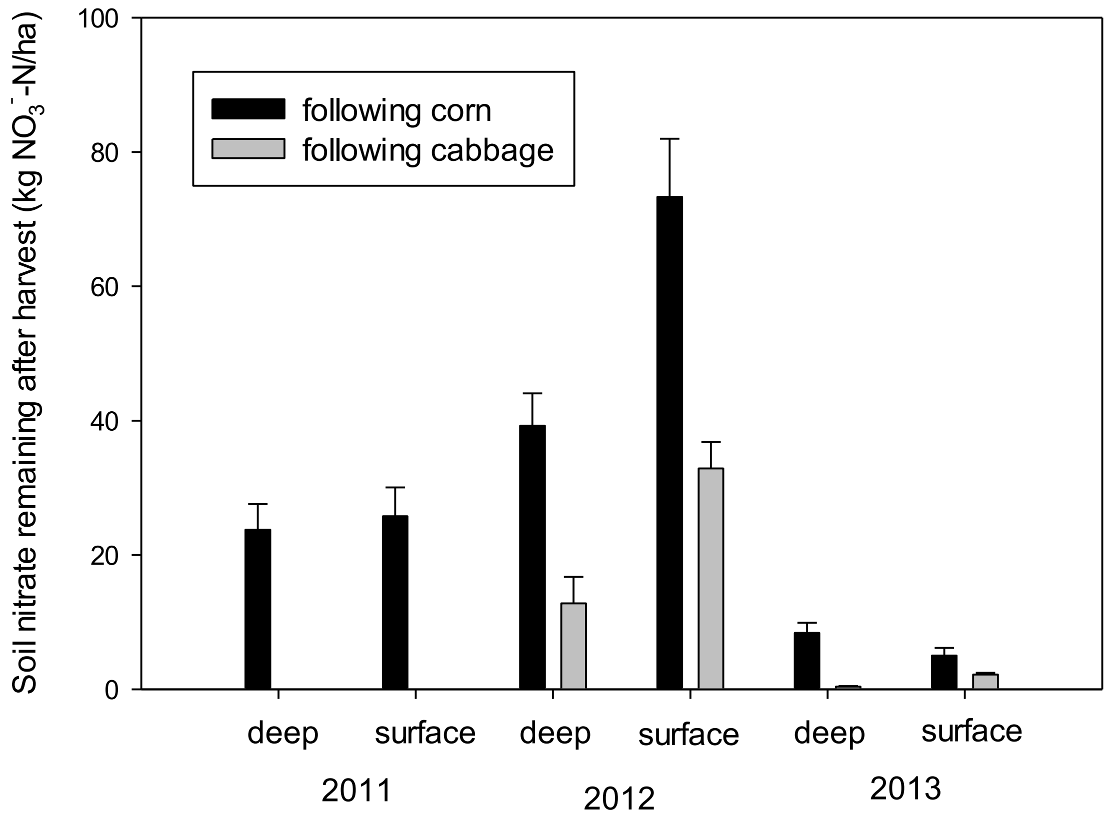


Figure 5.5 Surface (area corrected) and deep soil nitrate following cabbage and sweet corn harvest in 2011, 2012, and 2013. Error bars represent plus one SE. While ANOVA indicated treatment differences within the deep section (see Table 6), averages are reported here to facilitate comparison across years, crops, and with the surface sections.

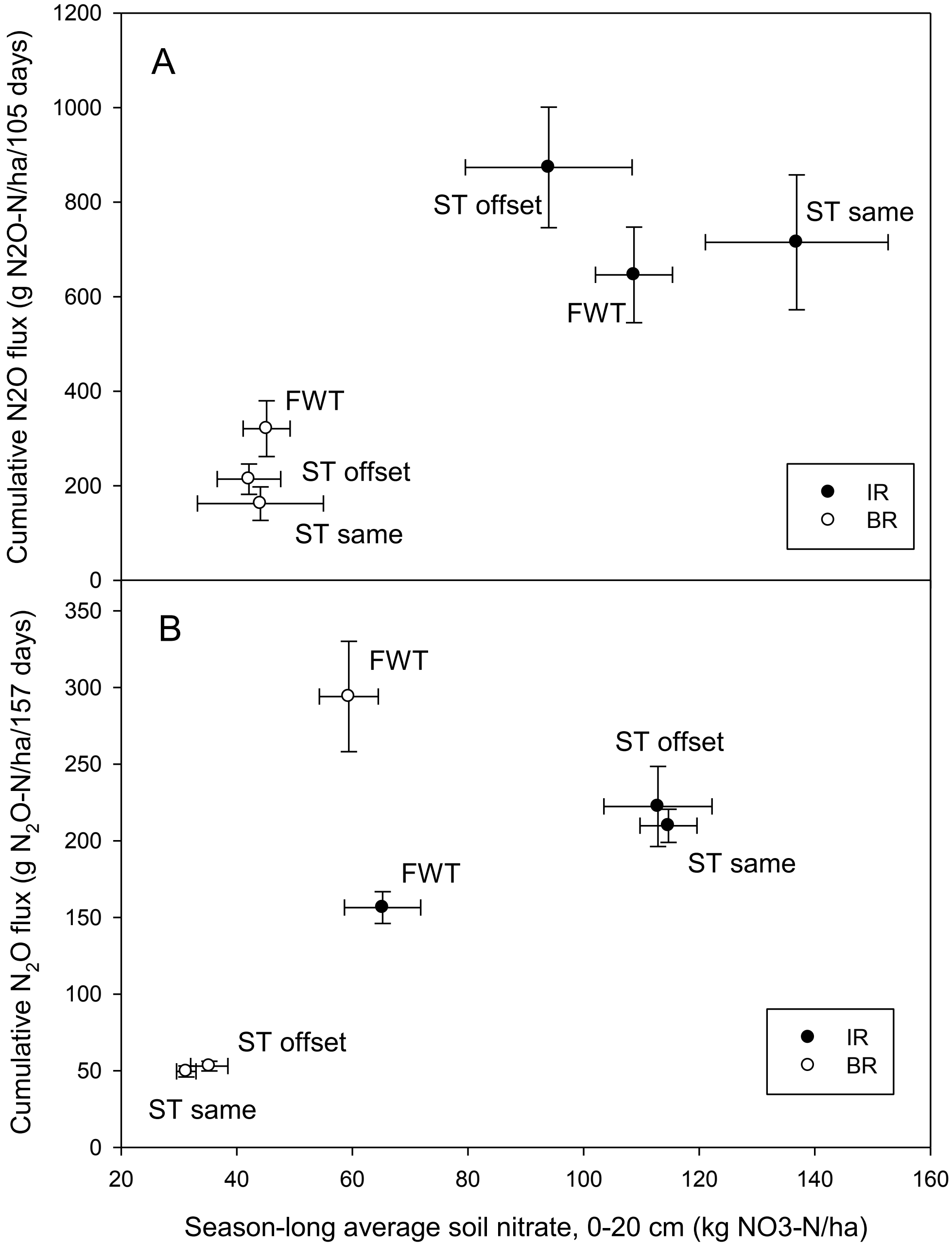


Figure 5.6 Average season-long cumulative N_2O flux vs. average season-long soil nitrate in sweet corn in 2011 (A) and cabbage in 2012 (B). Two-way ANOVA indicated that, within sweet corn, cumulative N_2O flux was greater IR compared to BR, but treatment did not affect flux. In cabbage, two-way ANOVA indicated that BR flux was greater out of FWT than ST and IR flux was greater in ST than in FWT.

APPENDIX

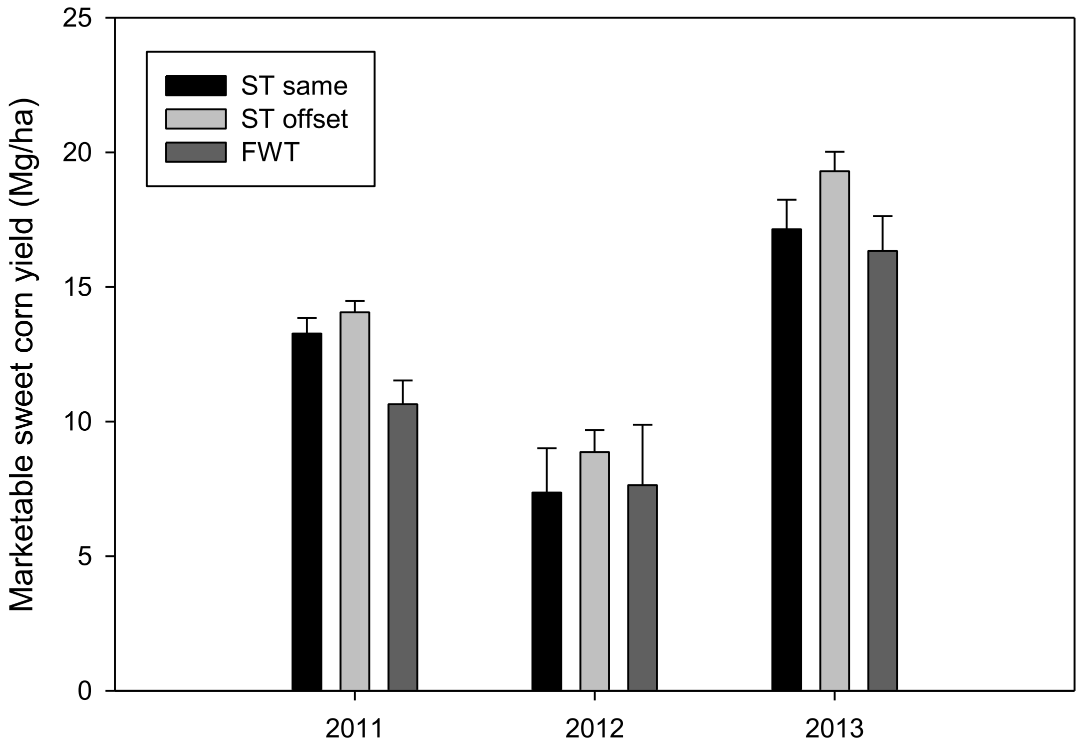


Figure A1 Average marketable sweet corn yield in 2011-2013 for three tillage treatments. Bars represent plus one SE. Two-way ANOVA indicated significant year effect(p<0.0001) and tillage effect (p=0.036), but no interaction (p=0.722). Single df contrasts indicated that ST offset yielded more than FWT (p=0.010), but that ST same was similar to ST offset (p=0.112) and FWT (p=0.258). Single df contrasts also indicated that yield in each year was significantly different than the other years.

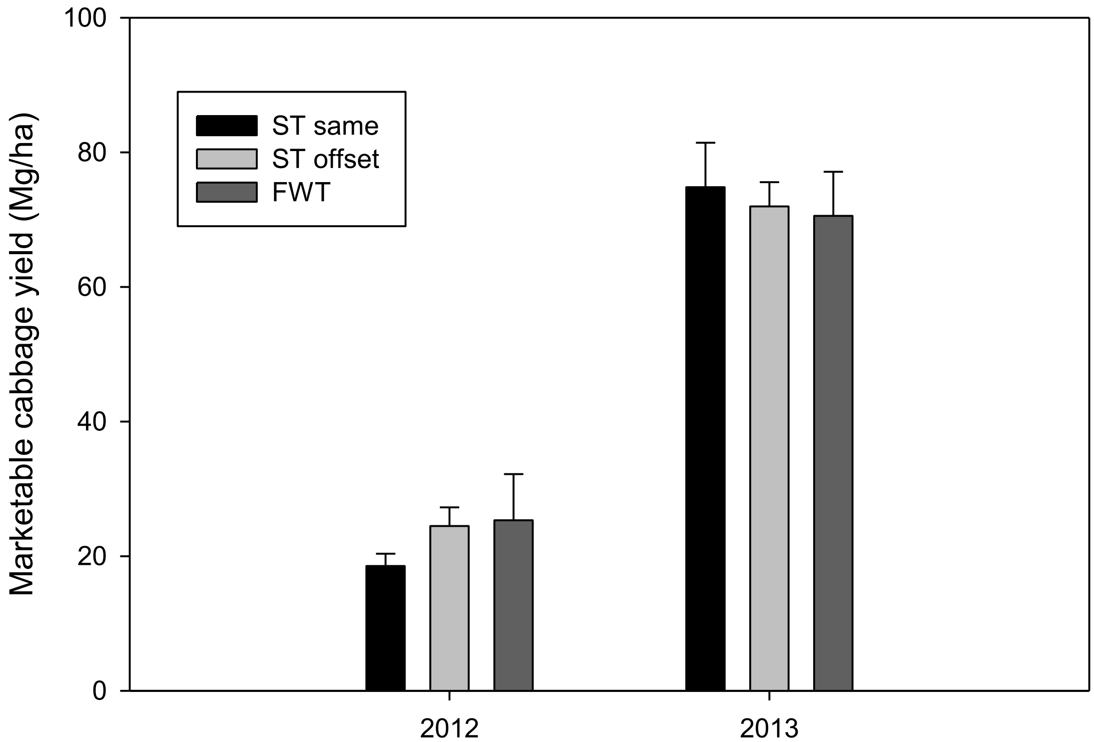


Figure A2 Average marketable cabbage yield in 2012-2013 for three tillage treatments. Bars represent plus one SE. Two-way ANOVA indicated significant year effect($p<0.0001$) but no significant tillage effect ($p=0.923$) or tillage*year interaction ($p=0.387$). Single df contrasts indicated that 2012 yielded more than 2013 ($p<0.0001$).

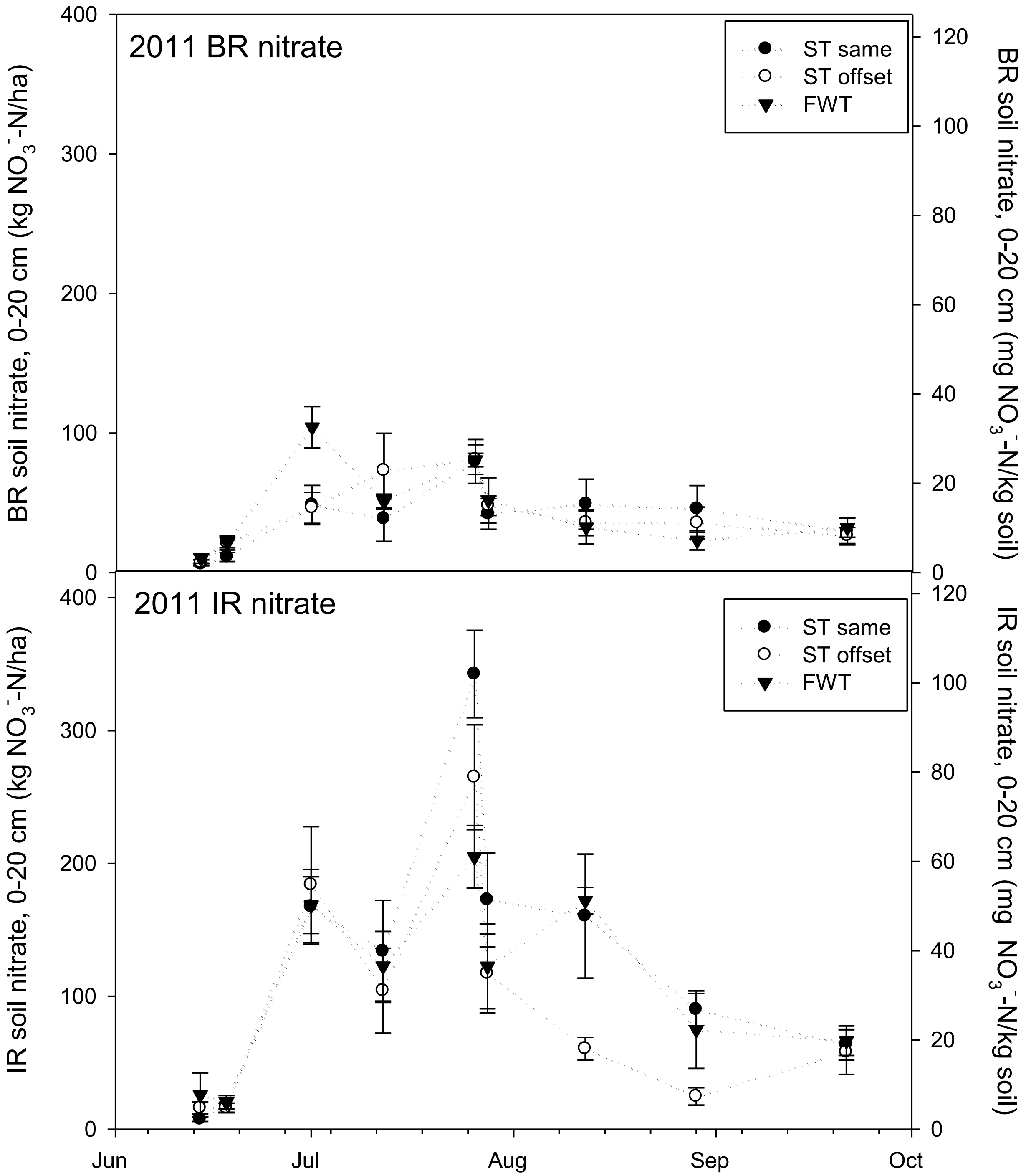


Figure B1 BR and IR soil nitrate in 2011 sweet corn

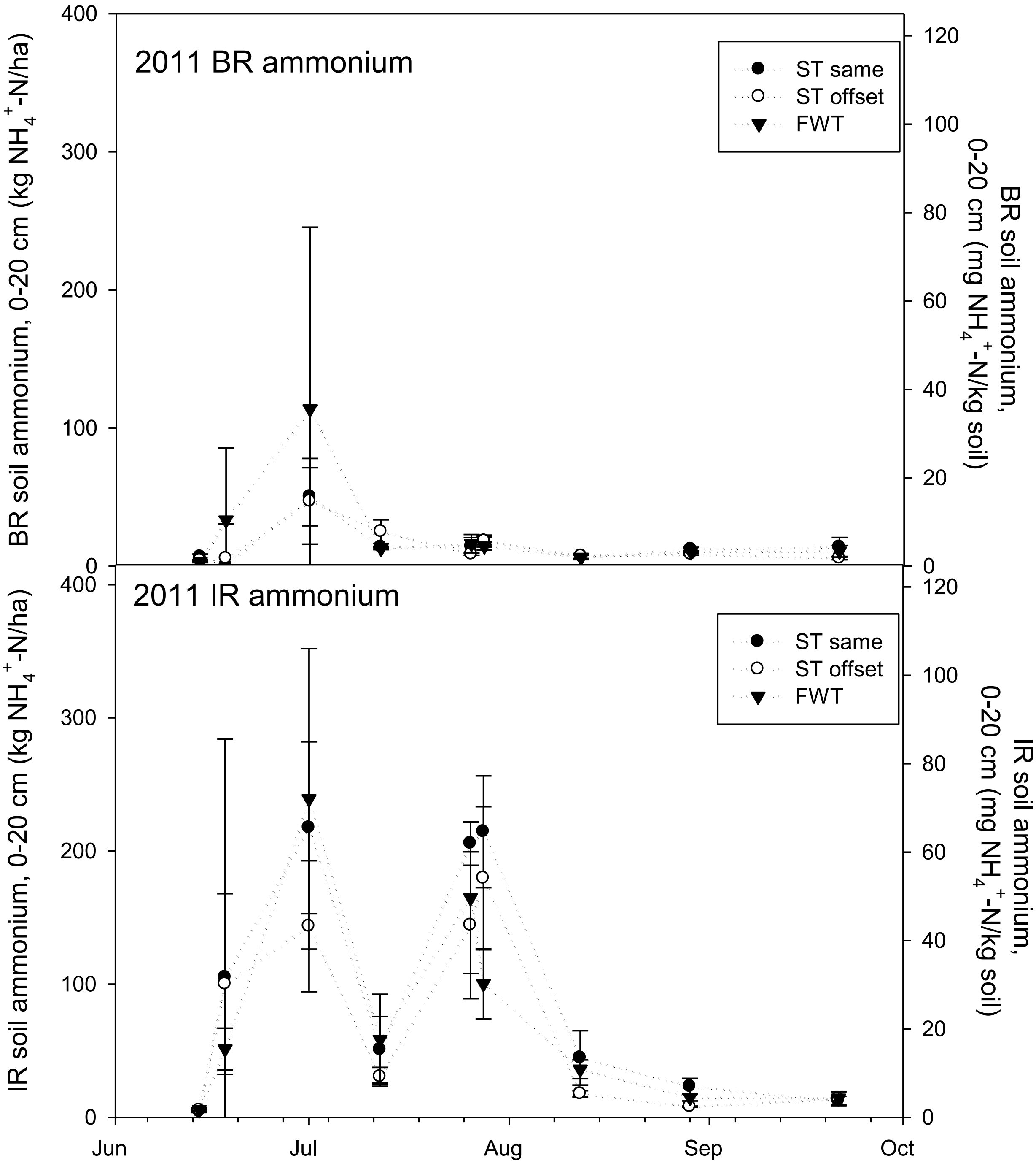


Figure B2 BR and IR soil ammonium in 2011 sweet corn

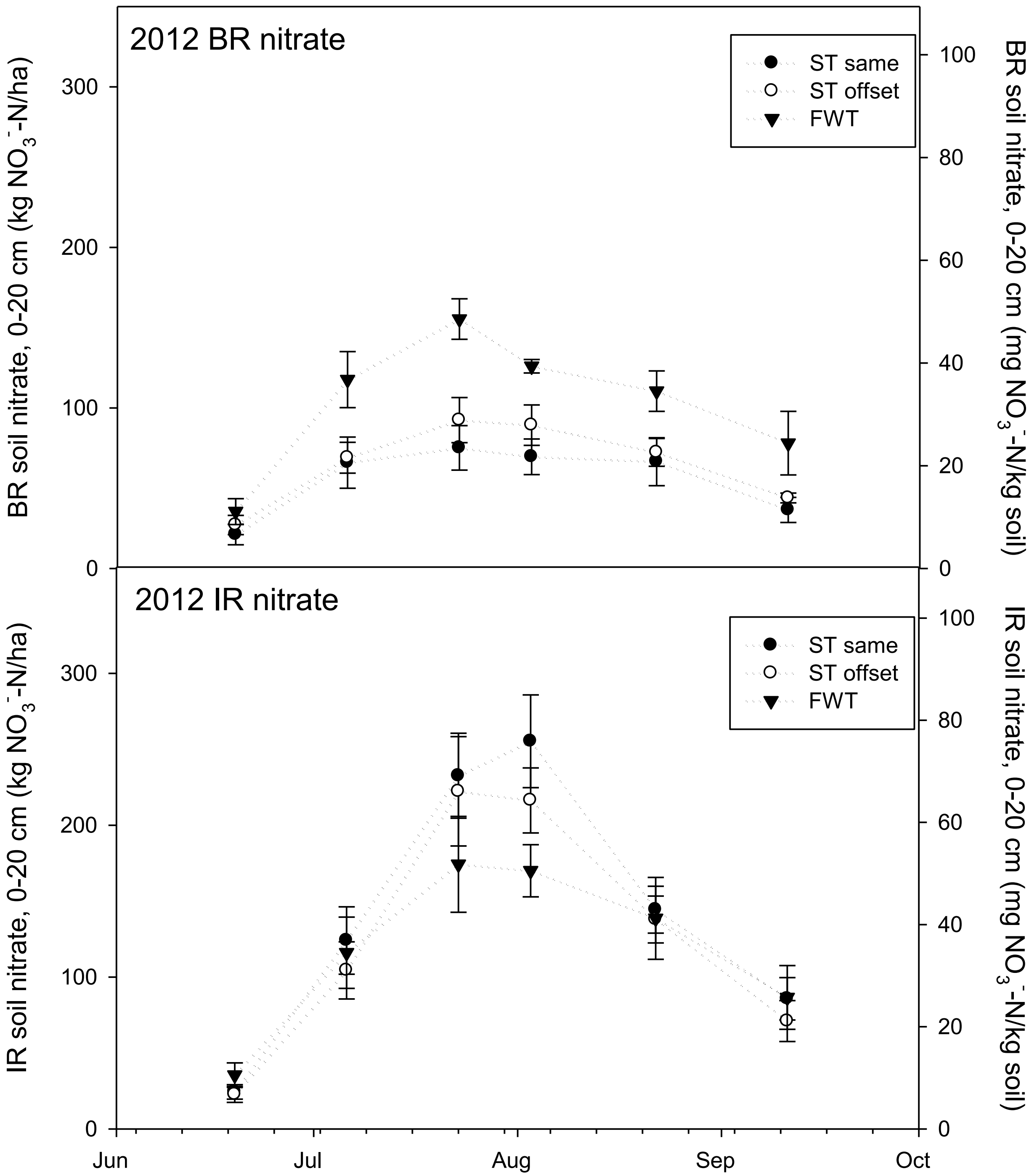


Figure B3 BR and IR soil nitrate in 2012 sweet corn

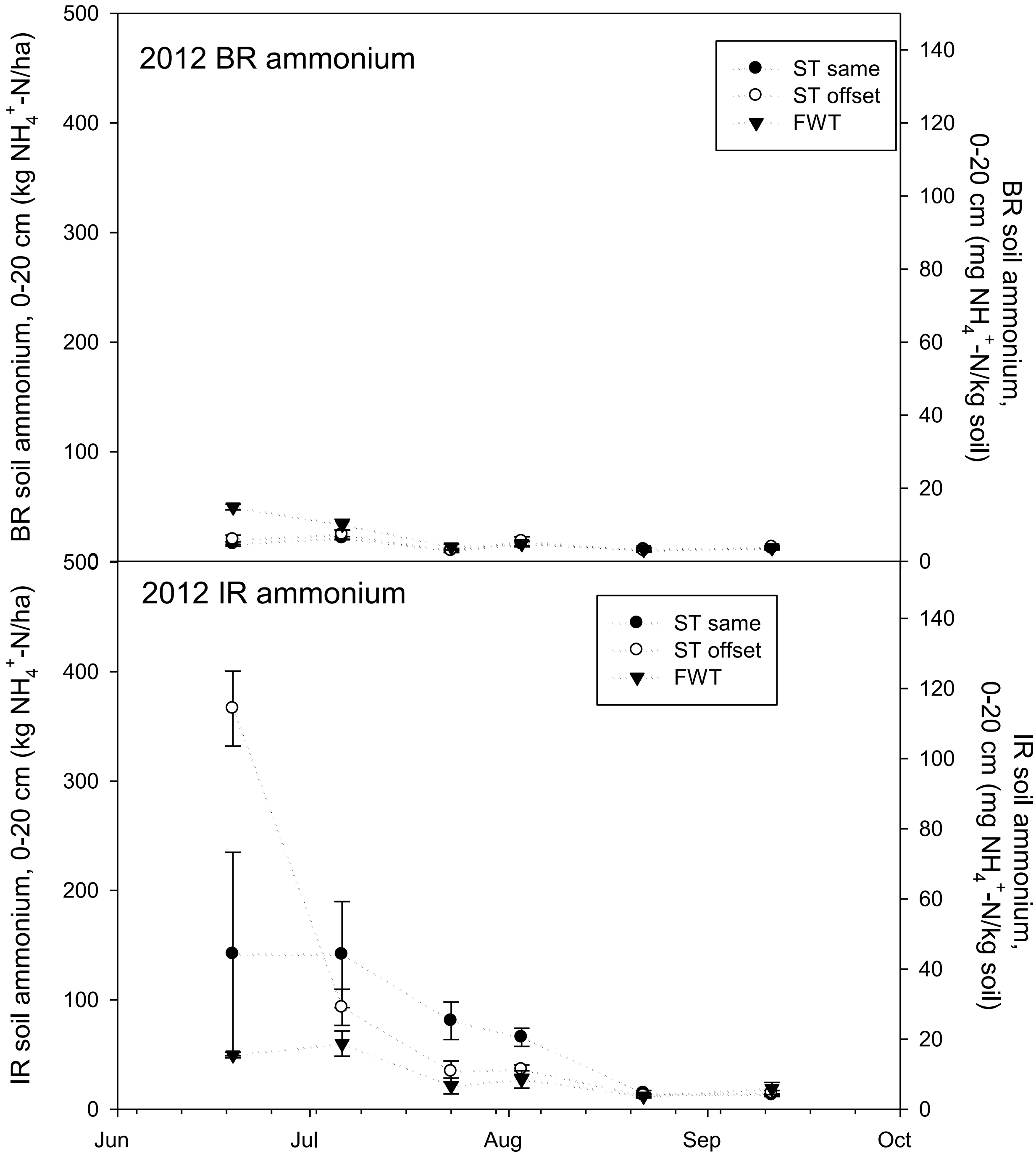


Figure B4 BR and IR soil ammonium in 2012 sweet corn

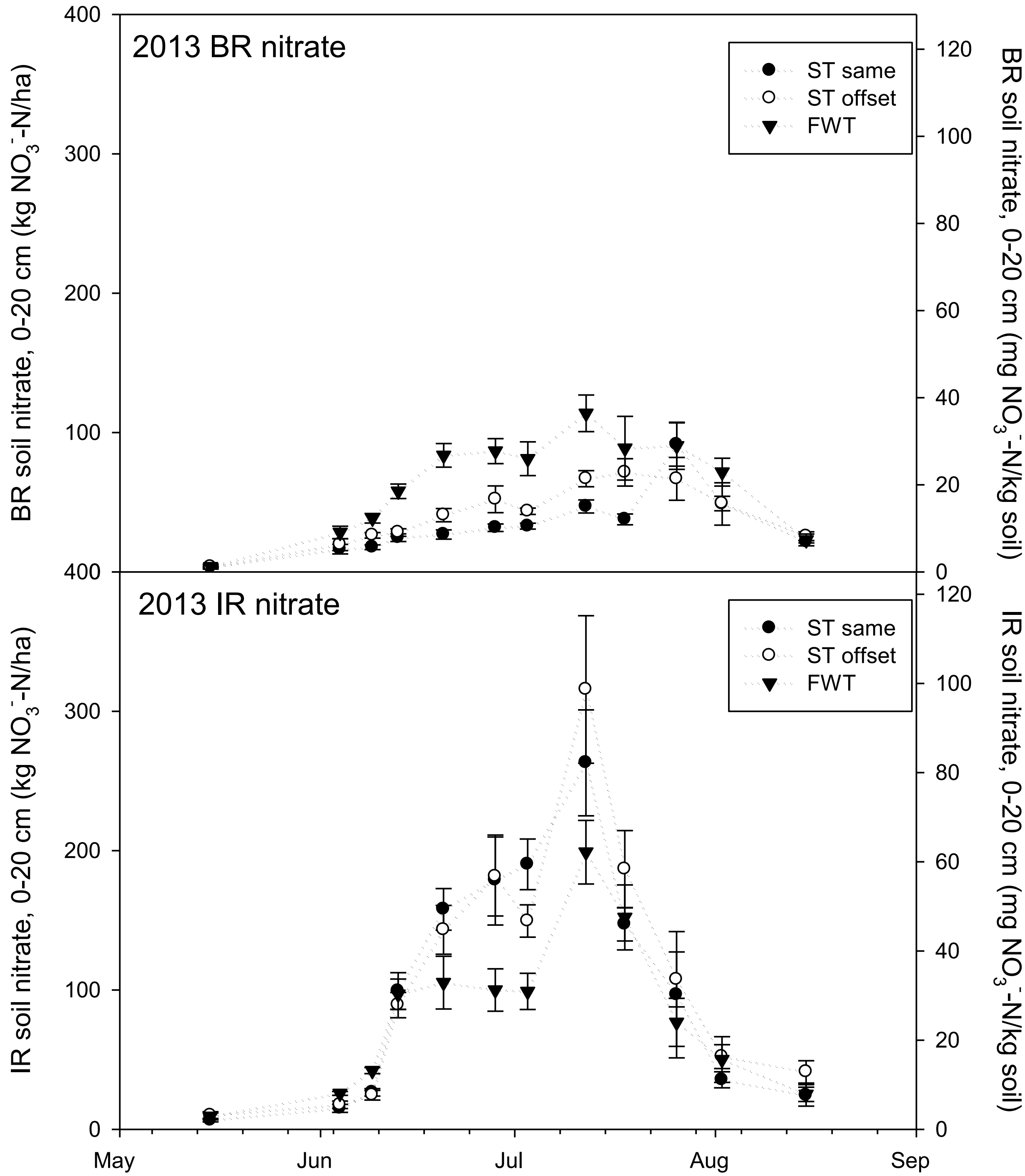


Figure B5 BR and IR soil nitrate in 2013 sweet corn

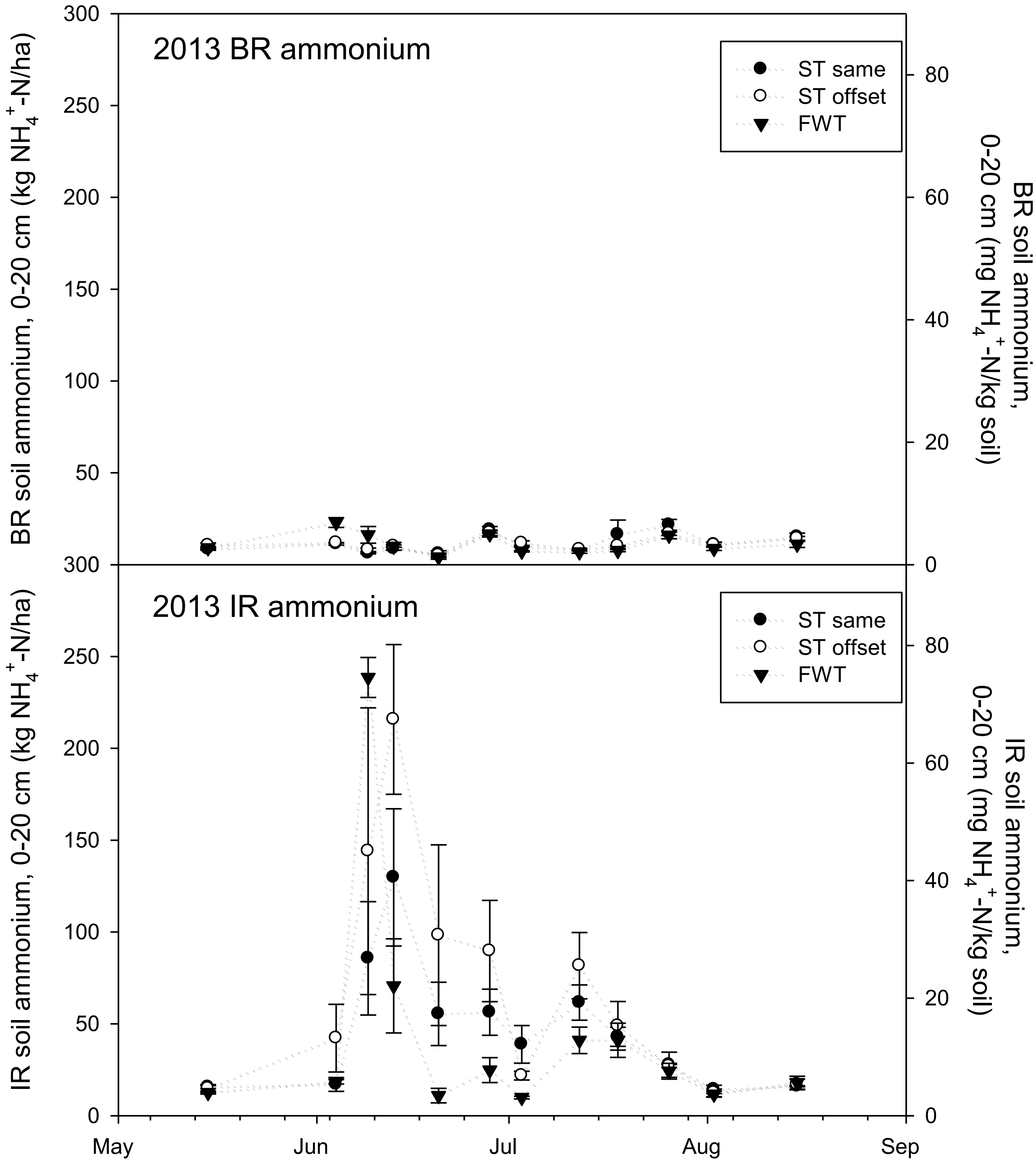


Figure B6 BR and IR soil ammonium in 2013 sweet corn

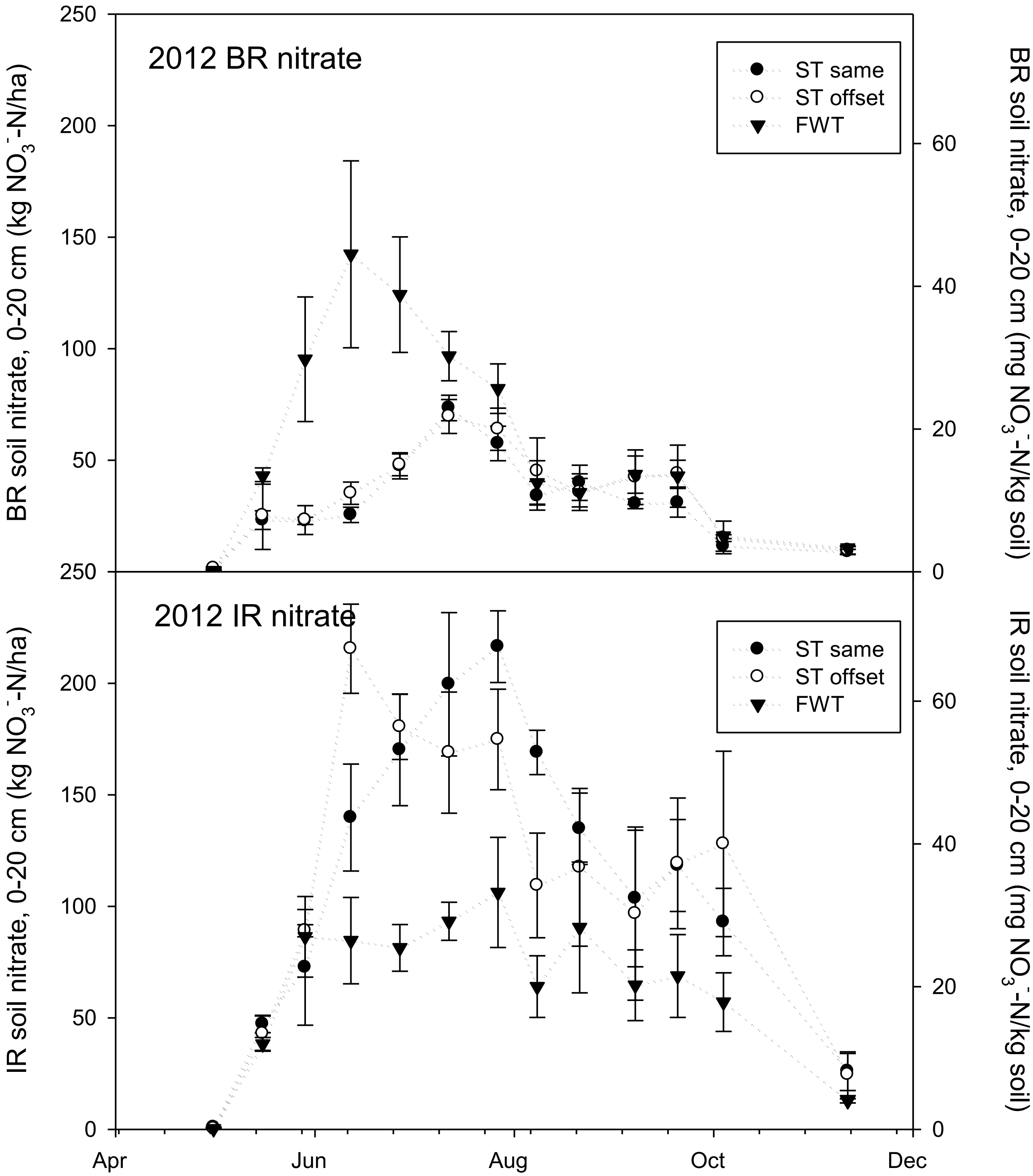


Figure B7 BR and IR soil nitrate in 2012 cabbage

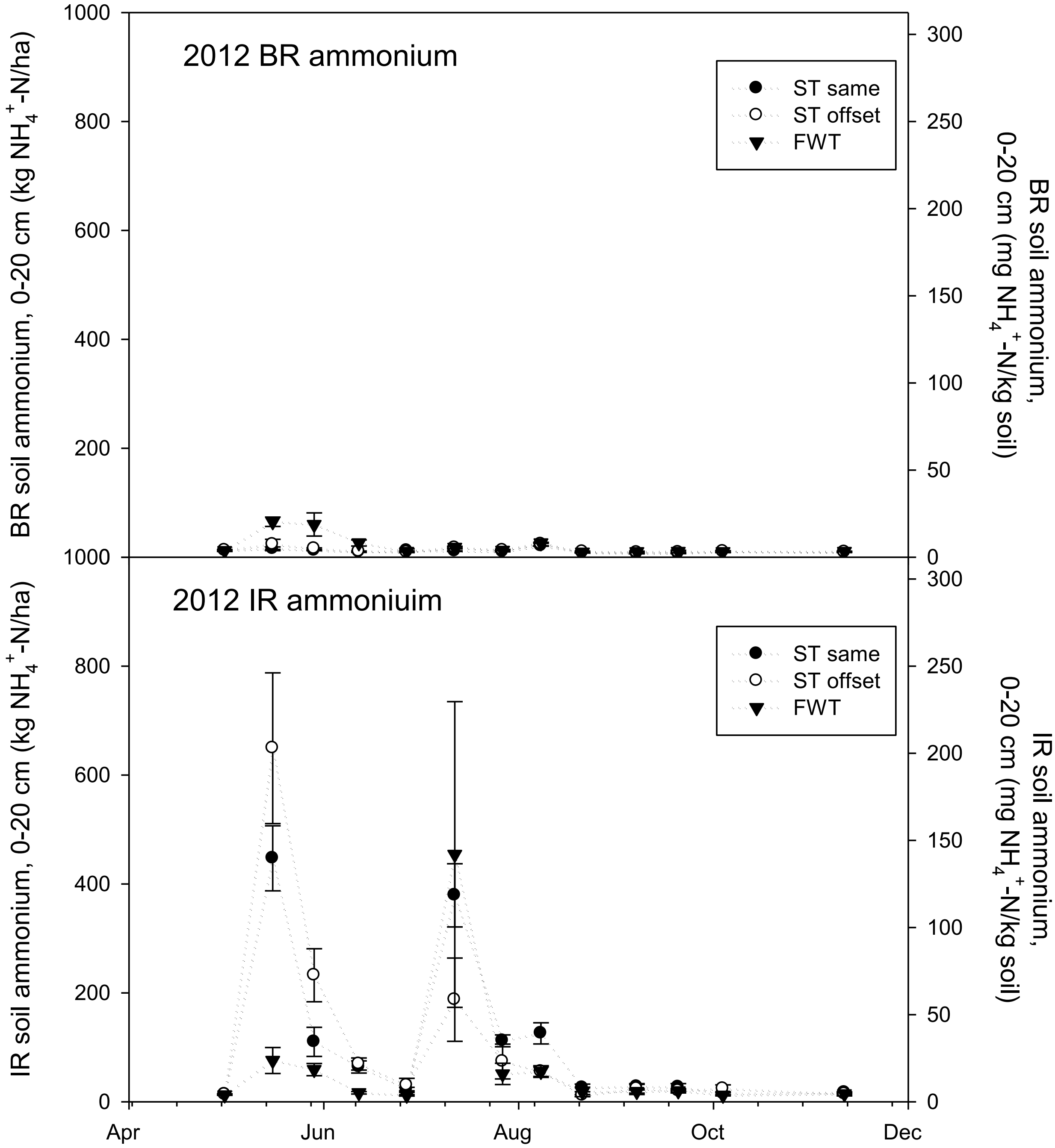


Figure B8 BR and IR soil ammonium in 2012 cabbage

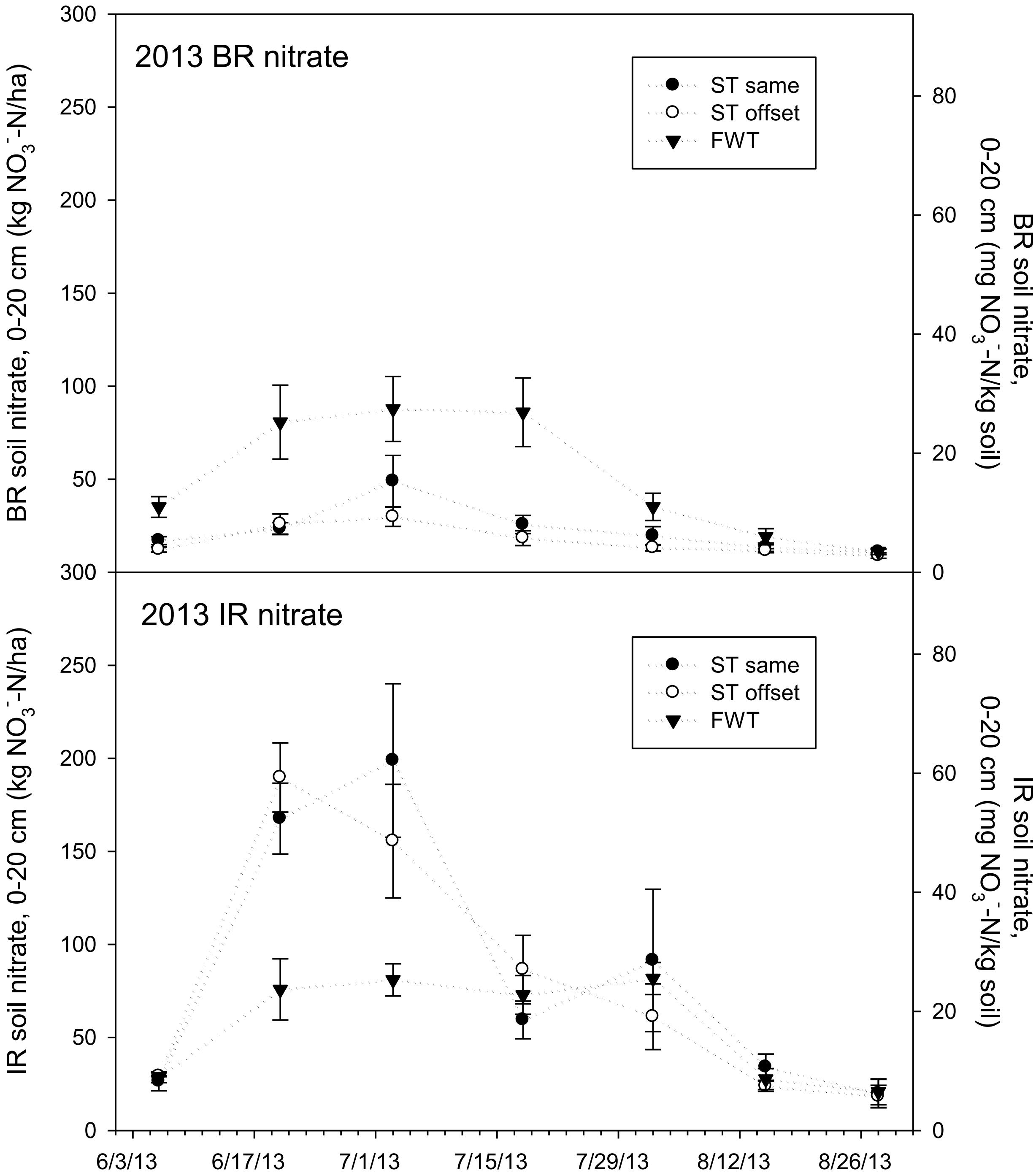


Figure B9 BR and IR soil nitrate in 2013 cabbage

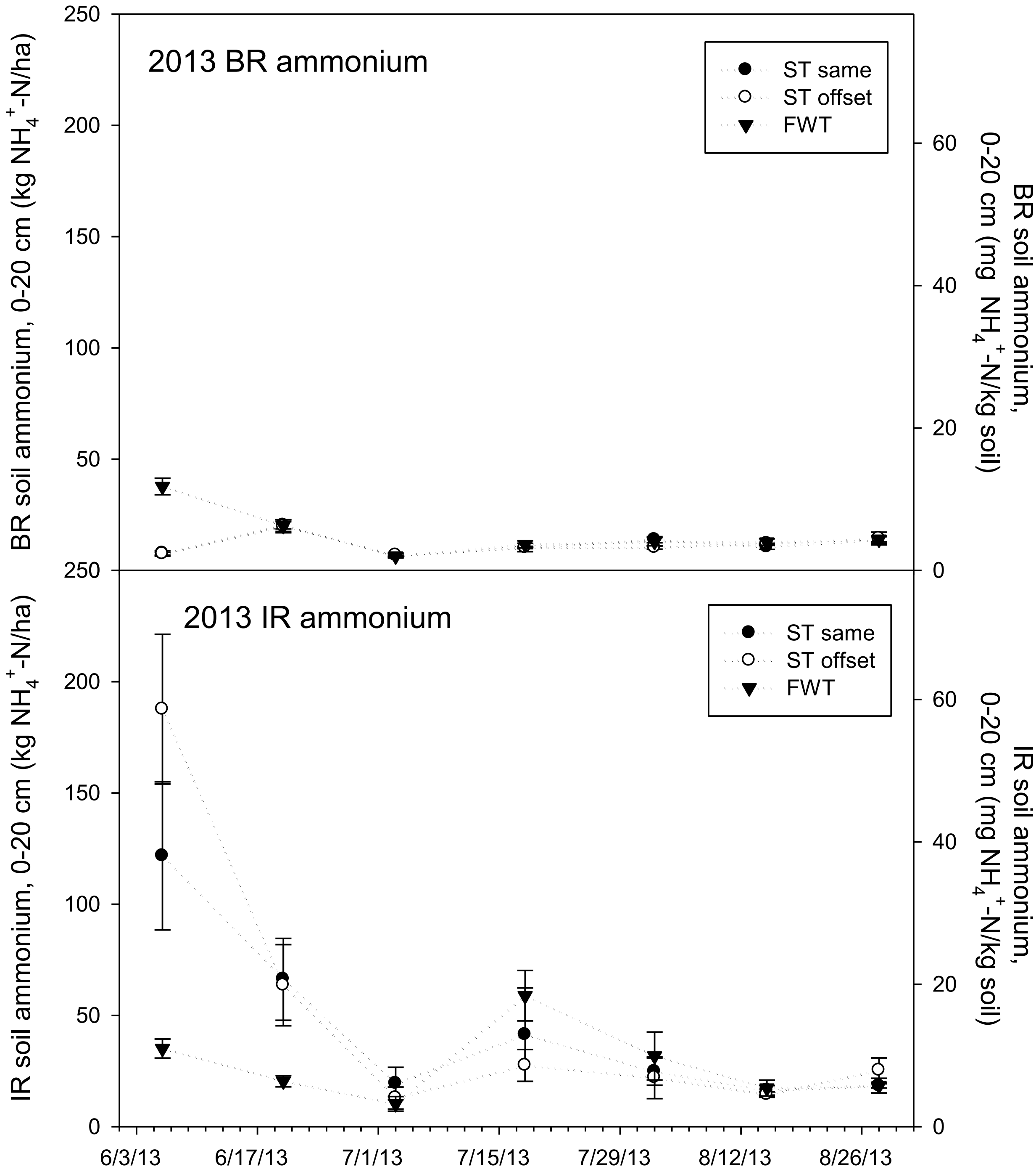


Figure B10 BR and IR soil ammonium in 2013 cabbage

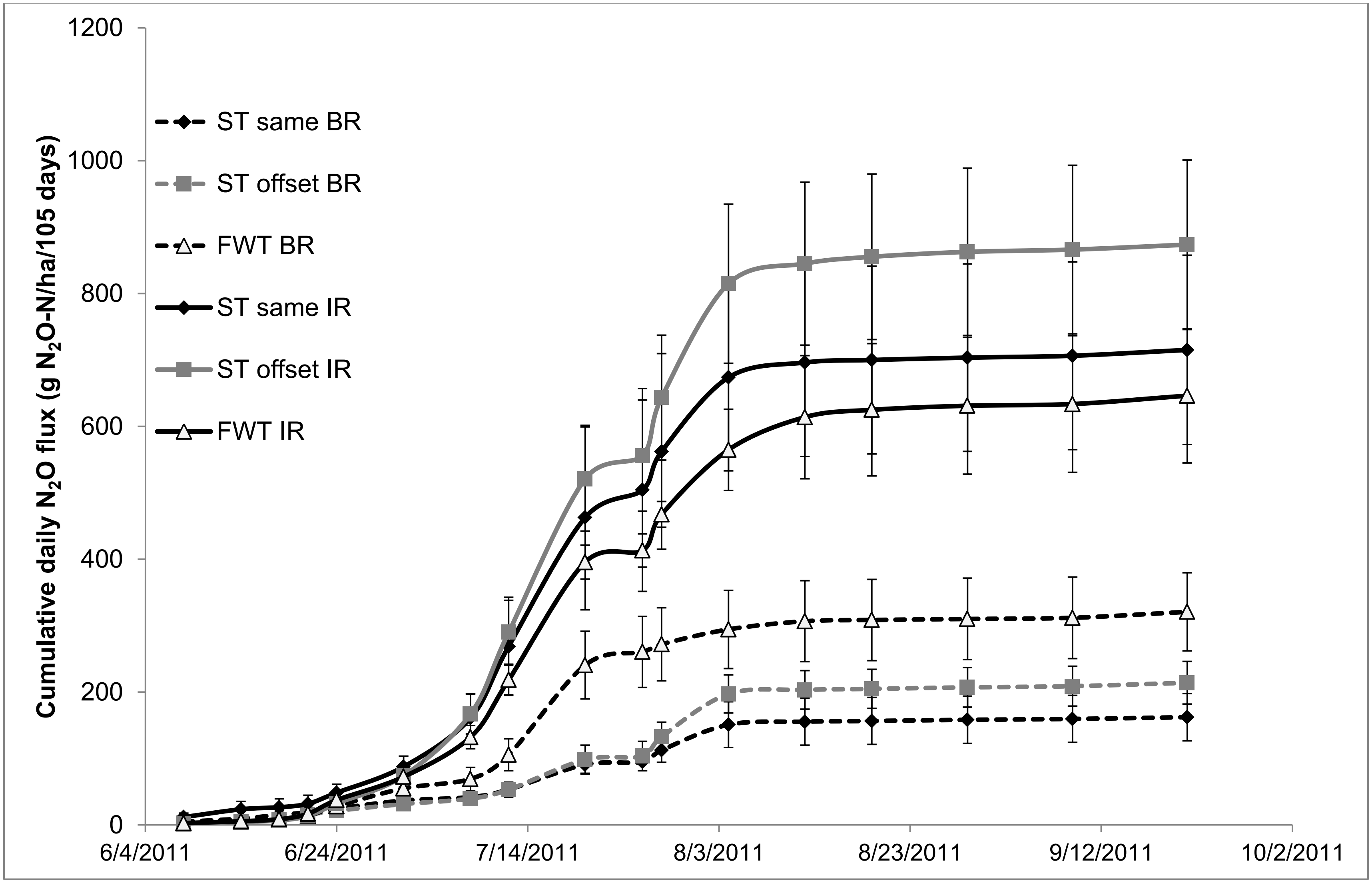


Figure C1 Season-long cumulative nitrous oxide flux in 2011 sweet corn.

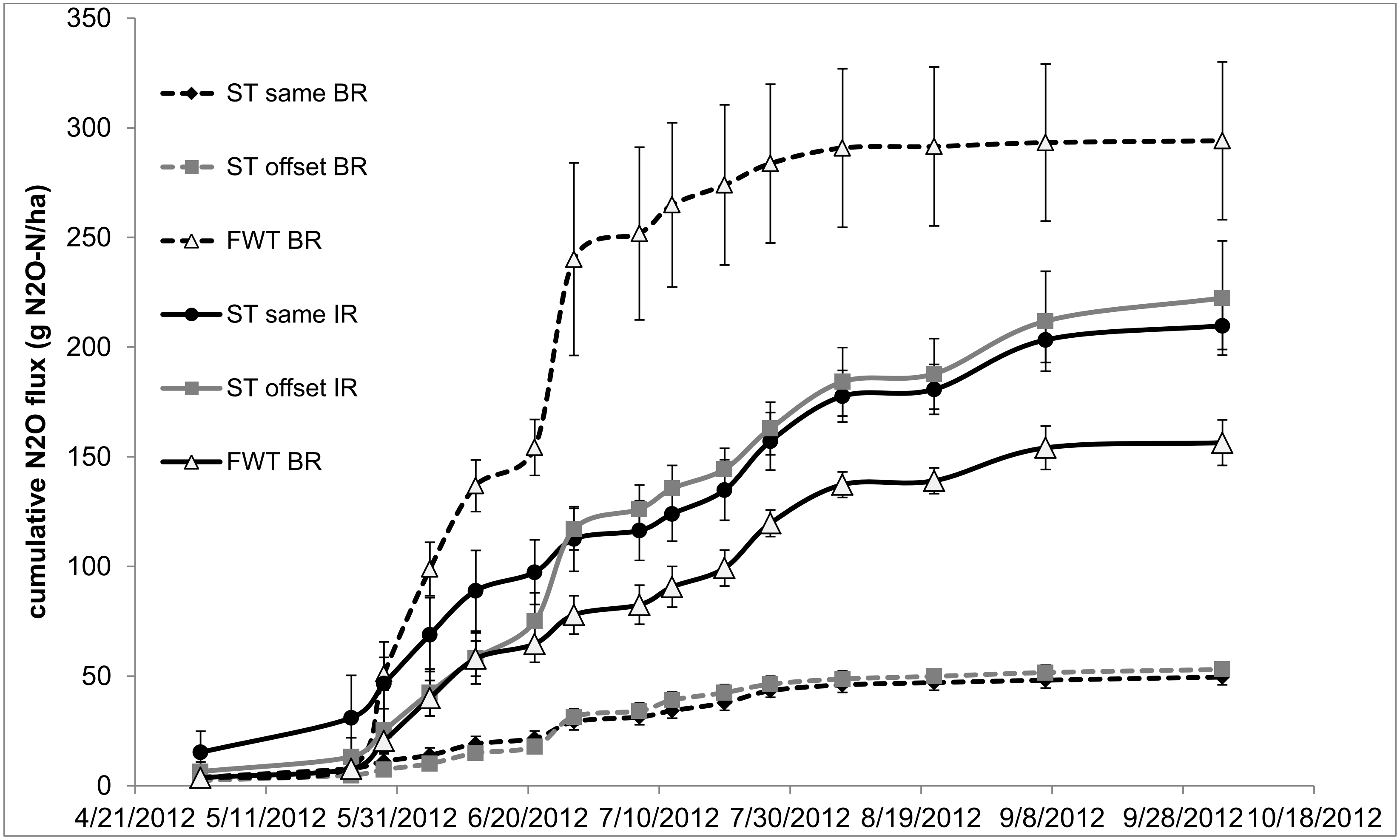


Figure C2 Season-long cumulative nitrous oxide flux in 2012 cabbage

LITERATURE CITED

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

Anonymous. 2012. Recommended chemical soil test procedures for the North Central Region. Missouri Agricultural Experiment Station SB 1001.

Bavin, T.K., T.J. Griffis, J.M. Baker, and R.T. Venterea. 2009. Impact of reduced tillage and cover cropping on the greenhouse gas budget of a maize/soybean rotation ecosystem. Agriculture, Ecosystems and Environment 134:234-242.

Bing, C, F. He, Q. Xu, B. Yin, and G. Cai. 2006. Denitrification Losses and N_2O emissions from nitrogen fertilizer applied to a vegetable field. Pedosphere 16: 390-397.

Blackshaw, R.E., G. Semach, and H.H. Janzen. 2002. Fertilizer application method affects nitrogen uptake in weeds and wheat. Weed Science 50: 643-641.

Cheng, W., Y. Nakajima, S. Sudo, H. Akiyama, and H. Tsuruta. 2002. N_2O and NO emissions from a field of Chinese cabbage as influenced by band application of urea or controlled-release urea fertilizers. Nutrient Cycling in Agroecosystems 63:231–238.

Crum, J.R. and H.P. Collins. 1995. KBS soils. Available at http://lter.kbs.msu.edu/research/site-description-and-maps/soil-description. Kellogg Biological Station Long-Term Ecological Research, Michigan State University, Hickory Corners, MI. Accessed 30 May 2014.

Drury, C.F., W.D. Reynolds, C.S. Tan, T.W. Welacky, W. Calder, and N.B. McLaughlin. 2006. Emissions of nitrous oxide and carbon dioxide: Influence of tillage type and nitrogen placement depth. Soil Science Society of America Journal 70:570–581.

Engel, R., D.L. Liang, R. Wallander, and A. Bembenek. 2010. Influence of urea fertilizer placement on nitrous oxide production from a silt loam soil. Journal of Environmental Quality 39: 115-125.

EPA (Environmental Protection Agency). 2007. Nitrates and Nitrites: TEACH Chemical Summary. Available online at http://www.epa.gov/teach/chem_summ/Nitrates_summary.pdf. Verified 17 June 2014.

Everaarts, A.P. and C.P. De Moel. 1998. The effect of nitrogen and the method of application on yield and quality of white cabbage. European Journal of Agronomy 9: 203-211.

Everaarts, A.P. and R. Booij. 2000. The effect of nitrogen application on nitrogen utilization by white cabbage (*Brassica oleracea* var. *capitata*) and on nitrogen in the soil at harvest. Journal of Horticultural Science and Biotechnology 75: 705-712.

Gruber, S., J. Mohring, and W. Claupein. 2011. On the way towards conservation tillage-soil moisture and mineral nitrogen in a long-term field experiment in Germany. Soil and Tillage Research 115: 80-87.

Haile-Mariam, S., H.P. Collins, and S.S. Higgins. 2008. Greenhouse gas fluxes from an irrigated sweet corn (*Zea mays* L.) – potato (*Solanum tuberosum* L.) rotation. Journal of Environ. Qual. 37:759–771.

Halvorson, A.D. and S.J.Del Grosso. 2013. Nitrogen placement and source effects on nitrous oxide emissions and yields of irrigated corn. Journal of Environmental Quality 42: 312-322.

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: 1-7.

Hoyt, G.D., A.R. Bonanno, and G.C. Parker. 1996. Influence of herbicides and tillage on weed control, yield, and quality of cabbage (*Brassica oleracea* L. var. *capitata*). Weed Technology 10: 50-54.

Hoyt, G.D. and D.W. Monks. 1996. Weed management in strip-tilled Irish potato and sweetpotato systems. HortTechnology 6: 238-240.

Johnson, J.M.F., D.C. Reicosky, R.R. Allmaras, T.J. Sauer, R.T. Venterea, and C.J. Dell. 2005. Greenhouse gas contributions and mitigation potential of agriculture in the central USA. Soil and Tillage Research 83: 79-94.

Johnson, J.M.F., D. Archer, and N. Barbour. 2010. Greenhouse gas emission from contrasting management scenarios in the northern corn belt. Soil Science Society of America Journal 74:396-406.

Kahmark, K. and N. Millar. 2008. KBS LTER Protocols: CH4, N2O, CO2 Fluxes (bucket method). Online at http://lter.kbs.msu.edu/protocols/113. Accessed 6/14/14.

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

Maddux, L.D., P. L. Barnes, C. W. Raczkowski, and D. E. Kisse. 1991. Broadcast and subsurface-banded urea nitrogen in urea ammonium nitrate applied to corn. Soil Science Society of America Journal 55: 264-267.

Malhi, S.S., M. Nyborg, and E.D. Solberg. 1996. Influence of source, method of placement and simulated rainfall on the recovery of N-15-labelled fertilizers under zero tillage. Canadian Journal of Soil Science 76: 93-100.

Malhi, S.S., C.A. Grant, A.M. Johnston, and K.S. Gill. 2001. Nitrogen fertilization management for no-till cereal production in the Canadian Great Plains: a review. Soil and Tillage Research 60: 101-122.

McSwiney, C.P., and G.P. Robertson. 2005. Nonlinear response of N2O flux to incremental fertilizer addition in a continuous maize (*Zea mays* L.) cropping system. Global Change Biology 11: 1712-1719.

Mills, H.A. and W.S. McElhannon. 1982. Nitrogen uptake by sweet corn. HortScience 17:734-744.

Mills, H.A. and W.S. McElhannon. 1983. Effect of broadcast vs. banded applications of nitrapyrin on yield and nitrogen concentration in fieldgrown sweet corn. HortScience 18:740-741.

Mochizuki, M.J., A. Rangarajan, R.R. Bellinder, T. Bjorkman, and H.M. van Es. 2007. Overcoming compaction limitations on cabbage growth and yield in the transition to reduced tillage. HortScience 42: 1690-1694.

Nash, P.R., P.P. Motavelli, and K.A. Nelson. 2012. Nitrous oxide emissions from claypan soils due to nitrogen fertilizer source and tillage/fertilizer placement practices. Soil Science Society of America Journal 76:983-993.

Nash, P.R., K.A. Nelson, and P.P. Motavelli. 2013. Corn yield response to timing of strip-tillage and nitrogen source of application. Agronomy Journal 105: 623-630.

Nolan, B.T., K.J. Hitt and B.C. Ruddy. 2002. Probability of nitrate contamination of recently recharged groundwaters in the conterminous United States. Environ. Sci. Technol. 36:2138–2145

Patterson, D. T. 1995. Effects of environmental stress on weed/crop interactions. Weed Science 43:483–490.

Pfab, H., I. Palmer, F. Buegger, S. Fiedler, T. Muller, and R. Ruser. 2012. Influence of a nitrification inhibitor and of placed N-fertilization on N2O fluxes from a vegetable cropped loamy soil. Agriculture, Ecosystems and Environment 150: 91-101.

Raczkowski, C.W., and D.E. Kissel. 1989. Fate of subsurface-banded and broadcast nitrogen applied to tall fescue. Soil Science Society of America Journal 53: 566-570.

Robertson, G.P. and P.R. Grace. 2004. Greenhouse gas fluxes in tropical and temperate agriculture: the need for a full-cost accounting of global warming potentials. Environment, Development and Sustainability 6: 51- 63.

Rapp, H.S., R.R. Bellinder, H.C. Wien, and F. M. Vermeylen. 2004. Reduced tillage, rye residues, and herbicides influence weed suppression and yield of pumpkins. Weed Technology 18: 953-961.

Rochette, P. 2008. No-till only increases N_2O emissions in poorly-aerated soils. Soil and Tillage Research 101: 97-100.

Sainju, U.M., B.P. Singh, S. Rahman, and V.R. Reddy. 1999. Soil nitrate-nitrogen under tomato following tillage, cover cropping, and nitrogen fertilization. Journal of Environmental Quality 28: 1837-1844.

Sainju, U.M., B.P. Singh, W.F. Whitehead, and S. Wang. 2007. Accumulation and crop uptake of soil mineral nitrogen as influenced by tillage, cover crops, and nitrogen fertilization. Agronomy Journal 99:682–691.

Sainju, U.M., W.F. Whitehead, B.P. Singh, and S. Wang. 2008. Tillage, cover crops, and nitrogen fertilization effects on soil nitrogen and cotton and sorghum yields. European Journal of Agronomy 25: 372-382.

Sainju, U.M. and B.P. Singh. 2008. Nitrogen storage with cover crops and nitrogen fertilization in tilled and nontilled soils. Agronomy Journal 100: 619-627.

Sanderson, K.R. and J.A. Ivany. 1999. Cole crop yield response to reduced nitrogen rates. Canadian Journal of Plant Science 79: 149-151.

Shipitalo, M.J., W.A. Dick, and W.M. Edwards. 2000. Conservation tillage and macropore factors that affect water movement and the fate of chemicals. Soil and Tillage Research 53: 167-183.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, et al. 2008. Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society of London. Series B, Biological sciences 363: 789-813.

Snapp, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep, J. Nyiraneza, and K. O'Neil. 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. Agronomy Journal 97: 322-332.

Stevens, W.B., R.G. Evans, J.D. Jabro, and W.M. Iverson. 2010. Nitrogen availability for sugarbeet affected by tillage system and sprinkler irrigation method. Agronomy Journal 102: 1745-1752.

Syswerda, S.P., B. Basso, S.K. Hamilton, J.B. Tausig, and G.P. Robertson. 2012. Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. Agriculture, Ecosystems and Environment 149: 10-19.

Tremblay, N. and C. Belec. 2006. Adapting nitrogen fertilization to unpredictable seasonal conditions with the least impact on the environment. HortTechnology 16: 408-412.

Turan, M. and F. Sevimli. 2005. Influence of different nitrogen sources and levels on ion content of cabbage (*Brassica oleracea* var. *capitata*). New Zealand Journal of Crop and Horticultural Science 33:241–249.

Tyler, D.D. and G.W. Thomas. 1977. Lysimeter measurements of nitrate and chloride losses from soil under conventional and no-tillage corn. Journal of Environmental Quality 6:63-66.

Van Kessel, C., R. Venterea, J. Six, M. A. Adviento-Borbe, B. Linquist, and K. Van Groenigen. 2013. Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: a meta-analysis. Global Change Biology 19: 33-44.

Wilhoit, J.H., R.D. Morse, and D.H. Vaughan. 1990. Strip-tillage production of summer cabbage using high residue levels. Applied Agricultural Research 5: 338-342