A CONSERVATION TILLAGE SYSTEM FOR ORGANIC VEGETABLES

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Science

by

Sara Rostampour

January 2011

ABSTRACT

Organic systems depend on intensive tillage for weed management, yet interest in conservation tillage methods is expanding in response to concerns regarding soil quality and environmental health. Deep zone tillage is one method that minimizes the width of soil disturbance to the planting row while providing sufficient disturbance to increase drainage and aeration and decrease compaction. This research addresses two constraints to an organic reduced tillage vegetable system: in-row weed control and fertility management. Two cover crop mixes, hairy vetch-rye or oats-peas were sown on two different dates at two different rates for the 2009 and 2010 growing seasons. Oat-pea cover crops were winter killed (leaving minimal residue) and hairy vetch-rye plots were flail mowed. Plots were then deep zone tilled, without incorporating cover crop biomass. Peppers were transplanted, and cover crop biomass in half the hairy vetch-rye plots was moved in-row to concentrate it, providing in-row weed control. Time required for cultivation and weeding by hand was recorded for economic analysis. Weed counts and biomass, pepper plant biomass, soil temperature, and soil N were monitored over the season. Planting cover crops earlier increased cover crop biomass significantly in 2009 but increasing seeding rates did not increase biomass either year. In-row mulch effectively decreased mid-season weed biomass. Hairy vetch-rye residue decreased soil temperatures both years, decreasing pepper plant size in these plots. All hairy vetch-rye plots had lower mid-season soil soluble N concentrations than oat-pea plots in 2009, and potentially mineralizable N did not differ either year. Despite the difference in pepper plant sizes throughout the season, total marketable fruit yields did not differ significantly between treatments in 2009 and oat-pea plots produced greater pepper yields than hairy vetch-rye plots in 2010. Partial enterprise budgets were calculated to compare the cost of weed control among

treatments and oat-pea plots were found to be more cost effective both years due to greater pepper yield and reduced cover crop management costs and concentrating hairy vetch-rye residue was more cost effective than leaving it in place.

BIOGRAPHICAL SKETCH

Sara Rostampour was born in Minneapolis and raised in West Saint Paul, Minnesota. She graduated with a Bachelor of Science degree from the University of Minnesota in 2005. In the College of Agriculture, Food and Environmental Sciences as a nutrition science student, she took her first courses focusing on agriculture and its importance. She worked in Minneapolis as a nutrition educator for the USDA's Supplemental Nutrition Program for Women, Infants, and Children (WIC), but maintained her interest in organic and sustainable agriculture and local food systems. She moved to Ithaca, New York in 2008 to study vegetable production at Cornell University.

"The earth was warm under me, and warm as I crumbled it through my fingers...I was something that lay under the sun and felt it, like the pumpkins, and I did not want to be anything more. I was entirely happy." -Willa Cather (My Antonia)

ACKNOWLEDGMENTS

I would like to first thank those that worked with me out in the field or in the lab, doing the tough tasks of data collection: Matt Applegate, Ethan Wilson, Sarah Hulick, and Tracy Mandel. Brian Caldwell shared much useful knowledge with me. Matt Cogger helped me get my bearings when I arrived and Betsy Leonard was indispensible in the lab and field. Additionally, this project was made possible in part due to funding from the Towards Sustainability Foundation and Sustainable Agriculture Research Education. Everything in this thesis was made possible by Anu Rangarajan, with much help from committee members Toni DiTommaso and Chuck Mohler. A number of people provided day-to-day support, including Gonzalo Villarino, Megan Gregory, Allison Jack, Sam Bosco, and Jenn Gardner. Also thanks to “lil’ Mike”, “Big T” and “P-Chub” Rostampour for being themselves and my sweetheart Roman S. Lilligren for his support. I also thank my parents for their encouragement.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1. Management of reduced tillage and cover crops in organic agriculture

Conservation tillage techniques are increasingly used in organic systems. Reduced tillage tends to immobilize nitrogen (N) the first few years but substantially increases soil quality and fertility later. Decreasing tillage also increases perennial weed populations. To both increase soil quality and fertility and decrease weed populations, cover crops have been employed in conservation tillage systems. Residue from a cover crop can enhance soil fertility and decrease weed populations through shading and allelopathy provided sufficient biomass is left on the soil surface. Insufficient biomass can fail to suppress weeds or may even increase weed emergence. Thus, cover crops must be managed carefully, with N fertility and weeds closely monitored, to insure yields are maintained when transitioning to conservation tillage systems.

Tillage effects on soil quality and fertility

Organic farming systems have historically relied upon intensive tillage to a greater extent than systems that use chemical inputs. Benefits of tillage include increased nutrient mineralization from incorporated crop residues and weed control (Trewavas, 2004). However, interest in conservation tillage methods, including in organic systems, is expanding in response to concerns related to soil quality and environmental health (Peigné, 2007).

Tillage is the mechanical manipulation of the soil to enhance crop production. Commonly, primary tillage (e.g. moldboard plowing) is used pre-planting to loosen the soil and bury the previous crop or cover crop residue. Secondary tillage (e.g. disking or harrowing) then follows to create an optimal seedbed and provide early season weed control (ASABE, 2006). In addition, cultivation is a shallow tillage done before or during the growing season for the purpose of weed control, with minimal soil disturbance (Bowman, 2002). Conventional tillage practices consist of soil inversion by primary tillage, followed by one or more secondary tillage operations (Blevins, 1993). However, repeated soil disturbance by intensive tillage practices may decrease soil quality and crop yields by inhibiting the formation of stable aggregates (Kasper, 2009) and increasing the degradation rate of soil organic matter (Dick, 1983). Loss of soil aggregates and organic matter decrease water infiltration and increase soil erosion, which may reduce the soil's ability to maintain yields in future seasons (Blevins, 1993). The repeated passes required by intensive tillage practices also incur significant fuel, machinery, and labor costs.

Methods that reduce tillage intensity have been developed in response to these concerns. By definition, reduced tillage systems retain 15-30% soil cover and conservation tillage systems retain at least 30% of soil cover (ASABE, 2006). Methods include no-till, strip tillage, and ridge tillage. In no-till systems, the soil is not disturbed at all prior to planting, plant residue is maintained year-round and crops are planted in narrow slots with a specialized no-till planter. In strip tillage, disturbance is limited to tilled strips on no more than 30% of the surface, where crops are grown (ASABE, 2006). A method of strip tillage known as deep zone tillage uses a subsoiler in the planting strip to provide sufficient soil disturbance to increase drainage and aeration and decrease compaction (Karunatilake 2002; Raper, 2007). In ridge tillage systems, pre-formed ridges are scraped, crops planted on the bared ridge bases and ridges are rebuilt after planting (ASABE, 2006). Consequently, only strips of soil are disturbed at any given time and residue remains near the soil surface.

In addition to these formally-defined systems that reduce the amount of soil disturbance spatially, tillage may be reduced temporally by rotating more aggressive techniques with less aggressive techniques. For example, seasons where the moldboard plow is used can be rotated with seasons where reduced-tillage implements are used. Alternatively, a permanent bed system may be installed. Over time, total soil disturbance will have been reduced.

Tillage affects soil physical structure, temperature, water content, and soil microbial activity, all of which affect the amount of soil organic matter present. The organic residue left on the surface in no-till systems increases surface soil organic matter (SOM), which increases aggregate stability and decreases soil bulk density, allowing for greater water infiltration and retention in the soil profile (Franzluebbers, 2002). One indicator of SOM, soil organic carbon (SOC), improves soil quality by serving as an energy source for soil microbes and contributing to soil structure (Reeves, 1997). SOC also can increase wet soil aggregate stability, decreasing water erosion (Blanco-Canqui and Lal, 2008), and increasing water content (Blanco-Canqui and Lal, 2007). Increased SOC is associated with decreased maximum bulk density over time. In no-till systems, however, bulk density may decrease in the short-term (Blanco-Canqui et al., 2009).

Tillage incorporates organic C into the soil but also periodically disrupts the soil structure by breaking open macroaggregates. Soil organic matter inside the aggregates is exposed, resulting in net SOM degradation (Balesdent et al., 2000). Reduced and no-till systems generally increase SOM and SOC, relative to conventional tillage (Conant et al., 2007; Thomas et al., 2007; Wander and Bollero, 1999). However, SOC may only be increased in the top 7.5 to 15 cm, with no net increase when the top 60 cm are assessed (Angers et al., 1997; Chatterjee and Lal, 2009; Dick, 1983). Reducing tillage decreases aeration and soil surface temperatures, which decreases microbial degradation of SOM and may be the cause of increased SOC in the top layer of reduced-tillage soils (Blanco-Canqui and Lal, 2008; Blevins and Frye, 1993).

Tillage can also affect available (inorganic) and potentially mineralizable nitrogen (N) in the soil. Available N released from proteins and amino acids per season can be greater with in soils with greater SOM (Grubinger, 1999). Tillage incorporates SOM into the soil and releases N from it by aerating the soil, thereby exposing aggregates to microbial activity. The rate of N mineralization, however, can increase over time with reduced tillage intensity (Doran, 1980; Sharifi et al., 2008), because these systems can accumulate SOM that holds N and also develop higher levels of microbial biomass that perform ammonification and nitrification (Gajda and Pan, 2008). Though the turnover rate of the labile N pool is slower under reduced and no-till, the labile N pool is larger than in conventional tillage systems (Balesdent, 2000). This larger N pool may result in higher N release from SOM in reduced tillage systems (Chatterjee and Lal, 2009).

Although the N mineralization rate may increase after several years of reduced tillage intensity, it can be delayed in conservation tillage systems during the first few years of transition from conventional tillage. This delay limits the amount of plant-available N. Reduced aeration and temperature slow SOM turnover, especially in the short term (D'Haene, 2008). Decreased SOM turnover results in net N immobilization by soil microbes, which can decrease crop yields (Kingery et al., 1996). This decrease in plant-available N is especially problematic for crops with a high N demand in early spring when temperatures are lower and for crops with high N requirements, such as peppers (Berner et al., 2008). Denitrification was found to increase in a Scottish no-till system, particularly in compacted soils after rainfall (Ball et al., 1999). In such soils, a reduced tillage method known to alleviate compaction, such as deep zone till, may alleviate or eliminate the increase in denitrification. Plant available N is decreased more during the transition period when converting from conventional to conservation tillage. However, plant available N can remain limited in long-term conservation tillage systems, as surface residue cools the soil, reducing plant available N in temperate climates relative to conventional tillage systems.

Reduced tillage in organic systems

Studies of reduced and conservation tillage in organic systems have found that equivalent yields are possible, with careful management of N fertility and weeds. More specific information is often lacking. As found in conventional systems, reducing tillage by converting from moldboard to chisel plow, can increase SOC and microbial biomass (Berner et al., 2008); this increase in SOC may increase fertility in the long term. Nitrogen (N) availability is often the most important limiting factor in organic systems (Rosen, 2007). Despite equivalent or higher potentially mineralizable N in organic reduced tillage systems, plant available N can be lower due to net N immobilization in the short-term and increased denitrification in the short- or long-term (Peigné et al., 2007). Organic bell peppers grown in tilled strips had equivalent or greater yield only when sufficient organic fertilizer was provided (Delate, 2008). In long-term studies, decreased N run-off and leaching and increased microbial activity and earthworm numbers increased net available N in organic reduced tilled systems (Peigné et al., 2009).

Several studies had mixed results on the impact of reducing tillage on soil quality of organic systems. Reducing tillage intensity increased earthworm populations in several organic fields, though no effect on soil structure by the earthworms was found in the short-term and long-term studies have not been conducted (Peigné et al., 2009; Peigné et al., 2008). Deep zone tillage decreased soil compaction somewhat but also decreased winter wheat yields in an organic farming experiment in Denmark (Olesen and Munkholm, 2007). Since compaction was not alleviated sufficiently, clover cover crop (*Trifolium repens* L. and *Trifolium pratense* L.) growth was decreased and the insufficient N was fixed for winter wheat (Olesen and Munkholm, 2007).

Organic systems typically have greater weed species diversity, and more annual weeds that emerge over longer period of times compared with conventional systems (Ryan et al., 2010). The composition of this weed community shifts when tillage is reduced in organic systems. Increased crop residue in conservation tillage systems may interfere with the emergence of small-seeded weeds, and germination of buried seeds of some weed species is reduced without the light exposure from soil inversion (Bond and Grundy, 2001). However, perennial and biennial species (especially with rhizomes or creeping roots) are favored over time, because they are not well-controlled with reduced tillage and survive to the next growing season (Torreson et al., 2003). Both perennial and annual monocots may also be favored over annual dicots (Moonen and Barberi, 2004).

Adequate weed control has been found in some studies of organic grains during the transition to reduced tillage. Shallow plowing that only disturbed the top 5 cm of soil was used to reduce tillage in an organic system with a pasture/grain crop rotation. After shallow plowing, soil moisture, retention, weed control and yields were improved (Krauss et al., 2010). Reduced tillage may control annual weeds as well as conventional tillage (Gruber and Claupein, 2009), though intensive tillage is likely to be needed to control a perennial weed infestation (Gruber and Claupein, 2009). Longer term studies focused on a wider range of crops would help determine optimal management strategies for weeds in organic reduced tillage systems.

Cover crop effects on weed populations, soil quality, and soil fertility

While cover crops are primarily recognized for their benefit to soil quality and fertility, with careful management, they can also be used for effective non-chemical weed suppression. In temperate climates, cover crops are often planted in late summer or fall after vegetable harvest. Some cover crops are killed by cold temperatures over the winter, leaving only a dead residue in the spring. Winter-hardy cover crops grow in the spring and need to be killed prior to crop planting (Teasdale, 1996). These winter-hardy cover crops suppress weeds early in the spring prior to planting the cash crop, and after the cover crop is killed, the residue left on the soil surface in conservation tillage systems may also be managed to suppress weeds. Cover crops may be grown simultaneously between the rows of a cash crop (intercropped), but must be managed carefully to avoid competition with the cash crop. Cover crops can reduce weed emergence and growth through allelopathy and competition for nutrients, water, and light. They can also reduce the weed seedbank indirectly, by providing habitat for weed seed predators. Systems using intercropping will be discussed first, followed by systems using cover crops grown over the winter, with a more detailed discussion of weed suppression mechanisms.

Weed suppression during cover crop growth

Because of the risk of competition with the cash crop, growing the cover crop in the off-season and killing it before crop planting is preferred. This requires having a planting window at the end of a crop harvest, to allow seeding and establishment of a cover crop prior to winter. Overwintering cover crops can reduce the weed seedbank compared to crop residue or bare soils (Moonen and Barberi, 2004). Cover crop seeding rates, dates and arrangements are aspects of cover crop planting that can be manipulated to affect biomass production and weed suppression.

Increasing cover crop seeding rates increases weed suppression if cover crop biomass is increased compared to lower seeding rates (Liebman et al., 2001). A study of legume-oat cover crops for organic vegetable systems evaluated the effect of seeding rate in the central coast of California (Brennan et al., 2009). Doubling and tripling the cover crop seeding rate increased initial but not final cover crop biomass production and decreased weed biomass, compared to the regular seeding rate. Because costs of tripling the seeding rate were minimal, the investigators recommended the increased cover crop seeding rate for reduction of the weed sandbank (Brennan et al., 2009). Increasing rye seeding rate also increased early season rye biomass and decreased early season weed biomass (Boyd et al., 2009).

Seeding date of cover crops can also contribute to weed suppressiveness. Seeding as early as possible increases fall growth and biomass and subsequent competition with weeds (Noffsinger, et al., 1998; Tawaha et al., 2001). Increasing the seeding rate at later plantings has been found to increase weed suppression relative to later plantings at standard rates (Turk and Tawaha, 2003).

When cover crop seeding is not possible due to possible late-season harvests, interseeding cover crops between rows of a cash crop can ensure a cover crop will be in place as a winter cover to reduce soil erosion and scavenge soluble N.Interseeding cover crops with cash crops for weed suppression has, however, had mixed success, since these cover crops must be at a population high enough to suppress weeds but not compete with the crop. Shading by the cover crops decreases weed populations or growth by decreasing both the quantity and quality of light available to stimulate germination and growth (Libeman et al., 2001). Methods to decrease cover crop competition with the cash crop include choosing less competitive cover crop species, mowing the cover crop, decreasing seeding rate or delaying cover crop planting. Interseeding with competitive cover crops such as cereal rye (*Secale cereale* L.), black oat (*Avena strigosa* Schreb.), and annual ryegrass (*Lolium multiflorum* L.), suppressed weeds effectively but also decreased organic broccoli (*Brassica oleracea* L. *var. Italica*) yields (Chase and Mbuya, 2008). Legumes were less competitive with broccoli but also less weed-suppressive. Mowing the more competitive cover crops at three and seven weeks did not suppress them sufficiently to prevent broccoli yield losses. Similarly, interseeding rye at lower densities was ineffective at weed suppression in broccoli and other weed management methods were needed (Brainard and Bellinder, 2004). However, Brainard et al. (2008) found that red clover integrated into a conventional vegetable system had little weed suppression effect, whether undersown or monocropped during the growing season.

By delaying cereal rye interseeding to 10 or 20 days after broccoli transplanting, yield was not decreased, but weeds were not suppressed either. Cabbage yields were also maintained by delaying cover crop interseeding to 20 or 30 days after transplanting, but weeds were not suppressed (Brainard et al., 2004). Similar results were found when Lana vetch (*Vicia villosa ssp. dasycarpa* Ten.) and cereal rye were interseeded with pumpkins (*Cucubita pepo* L.) (Vanek et al., 2005). Cover crops had to be interseeded after the pumpkins to avoid yield reductions. Regardless of the effects on weeds, interseeding cover crops provide soil benefits and may be grown for that reason alone.

Certain grasses exhibit allelopathy, the suppression of plant growth through release of toxic secondary metabolites. Cereal rye in particular is known to have strong allelopathic effects, which contributes to its effectiveness for weed suppression relative to other cover crops and mulches (Batish et al., 2001). Allelopathic chemicals found in rye consist mainly of hydroxamic acids and may be present in both the living crop and the residue (Tabaglio et al., 2008). Precise amounts of hydroxamic acids found in rye vary based on cultivar and growth, but sufficient amounts to decrease weed densities has been found in both greenhouse and field conditions (Gavazzi et al., 2010).

Other cover crops may have allelopathic effects, but the magnitude of weed suppression is less than with rye. The extracts of cereal rye, brown mustard (*Brassica juncea* L.) and hairy vetch all had concentration-dependent inhibition on weed germination, shoot elongation, and seedling root growth (Ercoli et al., 2007). Methanol and ethyl acetate extracts from hairy vetch and cowpea residues reduced germination and radical elongation of common chickweed (*Stellaria media* L.), redroot pigweed (*Amaranthus retroflexus* L.), and wild carrot (*Daucus carota* L.) (Hill et al., 2007) and the water extracts of both cover crops have been found to decrease radical growth of several other weed species (Hill et al., 2006). However, controls in these studies were inadequate, and the results may not apply in a field setting. Creamer et al. (1996) found that rye and crimson clover (*Trifolium incarnatum* L.) exhibited allelopathy in a field study that controlled for allelopathy relative to physical suppression. Weed suppression from hairy vetch and barley (*Hordeum vulgare* L.) was only from physical suppression. Thus, only allelopathic grasses reliably suppress weeds through allelopathy. This explains why legumes are so much more effective for weed suppression when mixed with allelopathic grasses. For example, interseeded lana vetch was significantly more effective when seeded with rye (Vanek et al., 2005). Such grasses are recommended alone or in mixture with legumes for effective weed suppression.

In addition to allelopathy and direct competition, cover crops may also contributed to weed seed predation. They can increase insect species diversity during their growth, which can increase weed seed predation and decrease the weed seedbank. Oat-pea and rye-vetch cover crops have been found to be beneficial for weed seed predator *H. rufipes* (Shearin, 2008). Presence of *Harpalus rufipes* De Geer, a predator, was positively correlated with mean seed predation (Gallandt et al., 2005). Cover crop residue increased predation of weed seed and predatory insect pupae by fire ants (*Solenopsis invicta* Buren) (Pullaro et al., 2006). Vertebrates such as mice have also been found to be important aboveground weed seed predators in organic cereal fields, and possibly more reliable than invertebrate predators (Westerman et al., 2003). While the amount of weed suppression during cover crop growth is not always consistent, both weed populations and the weed seedbank can be decreased with careful planning.

Weed suppression by cover crop residue

In temperate climates, winter-hardy cover crops are often planted in late summer or fall after vegetables to suppress fall weeds and provide a winter soil cover.

The cover crops produce biomass in the early spring that can enhance N fertility and suppress weeds (Teasdale, 1996). Many species can be killed mechanically, at mid to late flowering (Creamer, et al., 1995). Instead of incorporating cover crop residue, as in conventional tillage systems, the residue can be left on the soil surface as a mulch for weed control in conservation or no-till systems (Kruidof et al., 2009). This residue can suppress weeds during the growing season through temperature modification, allelopathy, and shading. Mulch decreases diurnal temperature fluxuations, which is often a signal for weed seeds to break dormancy (Teasdale and Mohler, 1993). Thus, weed germination is decreased. Lastly, similar to allelochemical release during growth, allelopathic grass residue will release allelochemicals it degrades (Grubinger, 2007). Weed growth is typically more suppressed by allelopathy than the crop (Bhowmik and Inderjit, 2003). To ensure crops are not stunted, planting should be delayed several weeks after the cover crop is killed. All of these mechanisms contributed to cover crop residue providing weed control.

Several studies have examined the effect of incorporating different cover crop species into the soil for weed suppression. Isik et al. (2009) planted winter cover crops such as ryegrass, oat (*Avena sativa* L.), rye, wheat (*Triticum aestivum* L.), geleman clover (*Trifolium meneghinianum* Clem.), Egyptian clover (*Trifolium alexsandrinum* L.), common vetch (*Vicia sativa* L.), and hairy vetch (*Vicia villosa* Roth). The cover crop residue was later incorporated with shallow cultivation to examine the effect on weed suppression. Hairy vetch reduced weeds by 70% in the early season, leading to the highest pepper yield. Similar results were found by Ngouajio et al. (2003) and Ngouajio and Mennan (2005). Cereal rye, ryegrass, common vetch and hairy vetch decreased weed biomass in a organic tomato (*Solanum* *lycopersicum* L.) crop when grown before and incorporated into the soil (Mennan et al., 2009).

The ability of cover crop residue to suppress weeds depends upon sufficient cover crop biomass production (Turk and Tawaha, 2003). If insufficient residue is present, weed growth may not be suppressed and weed emergence can even be stimulated by trapped moisture (Teasdale and Mohler, 1993). Frequently, the amount of residue that can be grown in place is insufficient to control weeds effectively (Teasdale and Mohler, 2000). As mentioned before, allelopathic grasses may be grown alone or in mixture with legumes to suppress weeds. Cereal rye in particular has been found to suppress weeds effectively when three times the amount that can be grown in a specific area is applied (Teasdale and Mohler, 2000). However, rye alone provides less ground cover than when grown in biculture with hairy vetch, because of the lower biomass produced (Ruffo and Bollero, 2003). Because hairy vetch degrades more quickly than grasses, it is also more suppressive in biculture. Thus, grass-legume bicultures are often preferred to grass monocultures to maximize biomass production (Sainju et al., 2005). The residue can then serve as weed-suppressing mulch for the following crop, with allelopathic benefits if a grass such as rye is used.

A comparison of rye-pea (*Pisum sativum* L.) cover crop mixes that were mowed and undercut found that residue of mixtures with at least 50% rye or more suppressed weeds best. Effective suppression from rye mixes was thought to be due in part to allelopathic activity (Akemo et al., 2000). A residue from a hairy vetch-rye-crimson clover (*Trifolium incarnatum* L.)-barley (*Hordeum vulgare* L.) mix decreased weeds effectively in four tomato (*Solanum lycopersicum* L.) systems (Creamer et al., 1996). In a study of organic pickling cucumber (*Cucumis sativus* L.), rye and oat cover crops were observed in four tillage systems: conventional no-till, strip till, conventional till with cover crops and conventional till without cover crops. The no-till system decreased weed biomass and density and decreased herbicide was needed, but cereal rye decreased pickling cucumber fruit number and weight, for unknown reasons **(**Wang et al., 2006).

Weed control efficacy of killed triticale (*X Triticosecale* Wittm.)-lana vetch and cereal rye-lana vetch cover crop mixtures was compared to an herbicide-treated, conventionally tilled fallow (Herrero et al., 2001). Weed pressure was low, and early-season weed suppression from the residue was similar in all treatments. As expected, late-season weeds were not suppressed by the residue. Cow pea (*Vigna unguiculata* L. Walp.) cover crop residue used in arid climate pepper production provided season-long weed control without herbicides and increased pepper growth by cooling soil temperature, which could become too high in this environment (Hutchinson and McGiffen, 2000). While the weed suppression would be useful to any pepper system, soil cooling can be a disadvantage for warm,-weather crops in more temperate climates.

Cover crops have successfully suppressed weeds in no-till sweet corn (*Zea mays* var. 'Silver Queen') (Carrera et al., 2004). Hairy vetch, rye, and hairy vetch-rye cover crops were killed by mowing, rolling, or contact herbicide and the residue was left on the soil surface. No treatment effect of kill method was found. The cover crops suppressed weeds as effectively as black polyethylene mulch and increased sweet corn yield, relative to a bare ground treatment without herbicide. Weed biomass was also decreased. Various cover crops partially improved weed suppression for conventionally-grown celery (*Apium graveolens* L. ‘Dutchess’) in muck soil (Charles et al., 2006). However, the additional N provided by legumes can increase weed growth; hairy vetch increased yellow foxtail (*Setaria glauca* L.) growth in one study. In contrast, allelopathic grasses were more suppressive (Creamer et al., 1996).

Killed hairy vetch-rye residue in a reduced-tillage organic system was insufficient for weed suppression and increased monocot weed density relative to conventionally tilled organic and non-organic plots, decreasing sweet potato [*Ipomoea batatas* (L.) Lam.] yield by 45% (Treadwell et al., 2007). While cover crops can decrease weeds, sufficient cover crop residue and additional midseason weed control are essential for maintaining cash crop yields.

A study on organic sweet potato (*Ipomoea batatas* L.) compared treatments of conventional tillage with no cover crop, conventional tillage with incorporate hairy vetch-rye, reduced-tillage hairy vetch-rye in strips with the crops in tilled beds, and non-organic, conventionally tilled plots (Treadwell et al., 2007). Monocot weeds in reduced-tillage hairy vetch-rye plots decreased crop yield by 45% one year. In another study, hairy vetch residue alone without herbicides did not decrease weed biomass well in a no-till tomato system and was not recommended for use in a monoculture (Kieling et al., 2009). However, hairy vetch residue alone was effective at suppressing weeds for no-till tomatoes when mowed and concentrated into strips around the tomatoes with a mower-rake machine (Campilglia et al, 2010). No study has looked at concentrated cover crop residue in a reduced-tillage vegetable system. However, it is clear that sufficient cover crop residue is needed for effective weed control.

Cover effects on soil quality and fertility

Whether cover crops are incorporated into soil with conventional tillage or left on the surface, as in conservation or no-till systems, growing cover crops can provide benefits to subsequent crops by increasing soil fertility. The previously mentioned grass-legume mixtures are also able to fix N, while minimizing leaching (Grubinger, 2007). This is especially important in conservation or no-till systems, where N can be limiting. Additionally in these systems, cover crop roots also can create biopores for movement of air and water and for easier vegetable root penetration in a compacted soil (Stirzaker and White, 1995). This reduction in bulk density from biopores may help combat the increased bulk density that occurs when transitioning to reduce tillage.

Cover crop residue tends to decrease soil temperatures and N mineralization rate, especially when present in amounts needed for weed suppression. Due to the complexity of these factors, results for crop yields in systems with cover crop residue are mixed. Cover crops can increase plant available N by fixing or sequestering it, or temporarily decrease it due to immobilization during microbial decomposition of residue. A temporary decrease in available N was found with a rye residue in both strip tilled and untilled plots. Crop foliar N was decreased as N was immobilized during rye decomposition (Bottenberg et al., 1999). A cover crop trial in the Northeast found that oilseed radish (*Raphanus sativus* L.), white mustard (*Brassica hirta* Moench), and yellow mustard (*Brassica hirta* Moench) are well-suited as fall cover crops, accumulating biomass and potentially leachable nitrogen quickly and suppressing weeds in the fall. The following spring, higher soil inorganic N was found in cover crop plots than bare plots (Stivers-Young, 1998).

A benefit of grass-legume bicultures is that the N is released more slowly than it is from a legume monoculture (Ranells and Wagger, 1996). A comparison of N dynamics in a hairy vetch–rye biculture with hairy vetch and rye monocultures found the highest N-mineralization rates in hairy vetch monocultures, intermediate net N-mineralization rates in the bicultures, and net N-immobilization in rye monocultures

(Rosecrance et al., 2000). Bicultures reduced N losses through leaching and denitrification. In another study of grass and legume cover crops (including hairy vetch and rye), grass-legume mixtures increased N fertility, but monoculture rye immobilized N (Teasdale and Abdul-Baki, 1998). In hairy vetch-rye mixtures, the vetch fixes N and rye scavenges N (Clark et al., 1994). Grass-legume mixes are optimal for both fixing scavenging and fixing N.

In warmer climates, hairy vetch residue alone can maintain or increase vegetable yields in conventional reduced tillage systems, compared to black polyethylene mulch and bareground treatments, due to increased available N released from the vetch (Abdul-Baki et al., 1996; Abdul-Baki et al., 2002). The need for N inputs was reduced in both processing and fresh market tomatoes. However, fruit maturity of processing tomatoes was delayed, most likely from the cooling effect of the residue (especially relative to the black mulch). Mowed and concentrated hairy vetch residue alone also provided significant amounts of N for no-till tomatoes (Campilglia et al, 2010). Organic yields of sweet potatoes were only equivalent to conventional yields when compost was added, regardless of cover crop (with or without hairy vetch-rye) or tillage treatment (conventional or reduced tilled) (Treadwell et al., 2007). In a non-organic system, various cover crop residues reduced the need for fertilizer for conventionally-grown celery (Charles et al., 2006). Thus, although cover crops can enhance N fertility, the benefit will vary depending on species, amount of time grown, planting density, weather conditions, and the microbial population. Extra N fertilization is clearly needed when transitioning to conservation tillage.

Integration of cover crops in organic, conservation tillage systems has numerous potential benefits. More research, however, is needed to help farmers maximize soil fertility, quality and weed suppressive benefits, without decreasing crop yields. Manipulation of species choice, planting dates and rates, killing method, and physical movement or concentration of cover crop residue into the crop row present several strategies for growers to optimize these benefits. The combination of appropriate strategies remains highly dependent upon the local climate and subsequent cash crop to be grown.

WORKS CITED

Abdul–Baki, A.A., J.R. Teasdale, R.W. Goth, and K.G. Haynes. 2002. Marketable yields of fresh–market tomatoes grown in plastic and hairy vetch mulches. HortScience. 37(6):878–881.

Abdul–Baki, A.A., A.E. Watada, J.R. Teasdale, and R.D. Morse. 1996. Hairy vetch mulch favorably impacts yield of processing tomatoes. HortScience. 31(3):338–340.

Abouziena, H.F., O.M. Hafez, I.M. El–Metwally, S.D. Sharma, and M. Singh. 2008. Comparison of weed suppression and mandarin fruit yield and quality obtained with organic mulches, synthetic mulches, cultivation, and glyphosate. HortScience. 43(3):795–799.

Agele, S.O., G.O. Iremiren, and S.O. Ojeniyi. 2000. Effects of tillage and mulching on the growth, development and yield of late–season tomato (*Lycopersicon esculentum* L.) in the humid south of Nigeria. J. Agricultural Sci. 134(1):55–59.

Akemo, M.C., E.E. Regnier, and M.A. Bennett. 2000. Weed suppression in spring–sown rye–pea cover crop mixes, Weed Technol., 14(3):545–549.

Angers, D.A., M.A. Bolinder, M.R. Carter, E.G. Gregorich, C.F. Drury, B.C. Liang, R.P Voroney, R.R. Simard, R.G. Donald, R.P. Beyaert, and J. Matel. 1997. Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada, Soil and Tillage Res. 41(3–4):191–201.

ASABE, 2006. Terminology and definitions for soil tillage and soil–tool relationships, Amer. Soc. of Agricultural and Biological Engineers, St. Joseph MI.

Balesdent, J., C. Chenu, and M. Balabane. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil and Tillage Res. 53(3–4):215–230.

Ball, B.C., A. Scott, and J.P. Parker. 1999. N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil and Tillage Res. 53(1):29–39.

Bàrberi, P.; Bigongiali, F., Antichi, D., Carlesi, S., Fontanelli, M., Frasconi, C. and Lulli, L., 2008. Innovative crop and weed management strategies for organic spinach crop yield and weed suppression. Proc. of the Second Scientific Conf. of the Intl. Soc. of Organic Agr. Res. 1:252-255.

Batish, D.R., H.P. Singh, R.K. Kohli, and S. Kaur. 2001. Crop allelopathy and its role in ecology. Agr., Allelopathy in Agroecosystems. 4(2):121–161.

Berner, A., I. Hildermann, A. Fliessbach, L. Pfiffner, U. Niggli, and P. Mäder. 2008. Crop yield and soil fertility response to reduced tillage under organic management. Soil and Tillage Res. 101(1–2):89–96.

Bhowmik P.C. and Inderjit. 2003. Challenges and opportunities in implementing allelopathy for natural weed management. Crop Protection. 22(4):661–671.

Blackshaw, R.E., J.R. Moyer, R.C. Doram, and A.L. Boswell. 2001. Yellow sweetclover, green manure, and its residues effectively suppress weeds during fallow. Weed Sci. 49 (3):406–413.

Blanco–Canqui, H. and R. Lal. 2007. Soil structure and organic carbon relationships following 10 years of wheat straw management in no–till. Soil and Tillage Res. 95(1–2):240–254.

Blanco–Canqui, H. and R. Lal. 2008. No–tillage and soil–profile carbon sequestration: An on–farm assessment. Soil Sci. Soc. Amer. J. 72(3):693–701.

Blanco–Canqui, H., M.M. Mikha, J.G. Benjamin, L.R. Stone, A.J. Schlegel, D.J. Lyon, M.F. Vigil, and W. Stahlman. 2009. Regional Study of No–Till Impacts on Near–Surface Aggregate Properties that Influence Soil Erodibility. Soil Sci. Soc. Amer. J. 73(4):1361–1368.

Blevins, R.L. and W.W. Frye. 1993. Conservation tillage – an ecological approach to soil–management. Advances in Agron. 51:33–78.

Bottenberg, H. J. Masiunas, and C. Eastman. 1999. Strip tillage reduces yield loss of snapbean planted in rye mulch. HortTechnology. 9(2):235–240.

Bond, W. and A.C. Grundy. 2001. Non–chemical weed management in organic farming systems. Weed Res. 41(5):383–405.

Bowman, Greg (ed.). 2002. Steel in the field: A farmer's guide to weed management tools. 2nd ed. Sustainable Agr. Publications. Beltsville, MD.

Boyd, N.S., E.B. Brennan, R.F. Smith, and R. Yokota. 2009. Effect of seeding rate and planting arrangement on rye cover crop and weed growth. Agron. J. 101(1):47–51.

Brainard, D.C. and R.R. Bellinder. 2004. Weed suppression in a broccoli–winter rye intercropping system. Weed Sci. 52(2):281–290.

Brainard, D.C., R.R. Bellinder, A.J. Miller. 2004. Cultivation and interseeding for weed control in transplanted cabbage. Weed Tech. 18(3):704-710.

Brainard, D.C., R.R. Bellinder, R.R. Hahn, and D.A. Shah. 2008. Crop rotation, cover crop, and weed management effects on weed seedbanks and yields in snap bean, sweet corn, and cabbage. Weed Sci. 56(3):434-441.

Brennan, E.B., N.S. Boyd, R.F. Smith, and P. Foster. 2009. Seeding rate and planting arrangement effects on growth and weed suppression of a legume–oat cover crop for organic vegetable systems. Agron. J. 101(4):979–988.

Burkhard, N., Lynch, D. Percival, and M. Sharifi. 2009. Organic mulch impact on vegetation dynamics and productivity of highbush blueberry under organic production. HortScience. 44(3):688–696.

Campiglia, E., F. Caporali, E. Radicetti, and R. Mancinelli. 2010. Hairy vetch (*Vicia villosa* Roth.) cover crop residue management for improving weed control and yield in no–tillage tomato (*Lycopersicon esculentum* Mill.) production. European Journal of Agron.. 33(2):94–102.

Campiglia, E., R. Paolini, G. Colla, and R. Mancinelli. 2009. The effects of cover cropping on yield and weed control of potato in a transitional system. Field Crops Res. 112(1):16–23.

Carrera, L.M., A.A. Abdul–Baki, and J.R. Teasdale. 2004. Cover crop management and weed suppression in no–tillage sweet corn production. HortScience. 39(6):1262–1266.

Charles, K.S., M. Ngouajio, D.D. Warncke, K.L. Poff, and M.K. Hausbeck. 2006. Integration of cover crops and fertilizer rates for weed management in celery. Weed Sci. 54(2):326–334.

Chase, C.A. and O.S. Mbuya. 2008. Greater interference from living mulches than weeds in organic broccoli production. Weed Technol. 22(2):280–285.

Chatterjee, A. and R. Lal. 2009. On farm assessment of tillage impact on soil carbon and associated soil quality parameters. Soil and Tillage Res. 104(2):270–277.

Clark, A.J., A.M. Decker, and J.J. Meisinger. 1994. Seeding rate and kill date effects on hairy vetch–cereal rye cover crop mixtures for corn production. Agron. J. 86(6):1065–1070.

Conant, R.T., M. Easter, K. Paustian, A. Swan, and S. Williams. 2007. Impacts of periodic tillage on soil C stocks: A synthesis. Soil and Tillage Res. 95(1–2):1–10.

Copaja, S.V., E. Villarroel, H.R. Bravo, L. Pizarro, and V.H. Argandoña. 2006. Hydroxamic acids in *Secale cereale* L. and the relationship with their antifeedant and allelopathic properties. Zeitschrift fur Naturforschung C–A J. of BioSci.s. 61(9–10):670–676.

Creamer, N.G., M.A. Bennett, B.R. Stinner. 1997. Evaluation of cover crop mixtures for use in vegetable production systems. HortScience. 32(5):866–870.

Creamer, N.G., M.A. Bennett, B.R. Stinner, and J. Cardina. 1996. A comparison of four processing tomato production systems differing in cover crop and chemical inputs. J. Amer. Soc. For Hort. Sci. 121(3):559-568.

Creamer, N.G., M.A. Bennett, B.R. Stinner, J. Cardina and E.E. Regnier. 1996. Mechanisms of weed suppression in cover crop–based production systems. HortScience. 31(3):410–413.

Creamer, N. G., B. Plassman, M.A. Bennett, R.K. Wood, B.R. Stinner, and J. Cardina. 1995. A method for mechanically killing cover crops to optimize weed suppression. Am. J. of Alternative Agr. 10(4):157-162.

Cromar, H.E., S.D. Murphy, and C.J. Swanton. 1999. Influence of tillage and crop residue on postdispersal predation of weed seeds. Weed Sci. 47(2):184–194.

Delate, K., C. Cambardella, and A. McKern. 2008. Effects of organic fertilization and cover crops on an organic pepper system. HortTechnology. 18(2):215–226.

D'Haene, K., J. Vermang, W.M. Cornelis, B.L.M. Leroy, W. Schiettecatte, S. De Neve, D. Gabriels, and G. Hofman. 2008. Reduced tillage effects on physical properties of silt loam soils growing root crops . Soil and Tillage Res. 45(2):213–217.

Dick, W.A. 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci. Soc. Amer. J. 47(1):102–107.

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. of Amer. J. 44(4):765–771.

Einhellig, F.A. 1996. Interactions involving allelopathy in cropping systems. Agron. J. 88(6):886–893.

Ercoli, L., A. Masoni, S. Pampana, and I. Arduini. 2007. Allelopathic effects of rye, brown mustard and hairy vetch on redroot pigweed, common lambsquarter and knotweed. Allelopathy J. 19(1):249–256.

Fontanelli, M., Frasconi, C., Lulli, L., Antichi, D., Bigongiali, F., Carlesi, S., Bàrberi:and Peruzzi, A. 2008. Innovative crop and weed management strategies in organic spinach: machine performances and cultivation costs. Proc. of the Second Scientific Conf. of the Intl. Soc. of Organic Agr. Res. 1:256–259.

Franzluebbers, A.J. 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. Soil and Tillage Res. 66(2):197–205.

Gajda, A.M. 2008. Effect of different tillage systems on some microbiological properties of soils under winter wheat. Intl. Agrophysics. 22(3):201–208.

Gallandt, E.R., Molloy, T., Lynch, R.P. and Drummond, F.A. 2005. Effect of cover–cropping systems on invertebrate seed predation. Weed Sci. 53(1):69–76.

Gavazzi, C., M. Schulz, A. Marocco, and V. Tabaglio. 2010. Sustainable weed control by allelochemicals from rye cover crops:from the greenhouse to field evidence. Allelopathy J. 25(1):259–273.

Gruber, S. and W. Claupein. 2008. Effects of conservation tillage on Canada thistle (*Cirsium arvense*) in organic farming. Proc. of the Second Scientific Conf. of the Intl. Soc. of Organic Agr. Res. 1:430–433.

Gruber, S. and W. Claupein. 2009. Effect of tillage intensity on weed infestation in organic farming, Soil and Tillage Res. 105(1):104–111.

Grubinger, V. 1999. Sustainable Vegetable Production From Start–Up to Market. 1st ed. Natural Resource, Agr. and Engineering Service. Ithaca, NY.

Guertal, E.A., E.J. Sikora, A.K. Hagan, and R. Rodríguez–Kábana. 1998. Effect of winter cover crops on populations of southern root–knot and reniform nematodes. Agr. Ecosystems and Environ. 70(1):1–6.

Hamido, S.A. and K. Kpomblekou–A. 2009. Cover crop and tillage effects on soil enzyme activities following tomato, Soil and Tillage Res. 105(2):269–274.

Heckman, J.R. 2002. In–season soil nitrate testing as a guide to nitrogen management for annual crops. HortTechnology. 12(4):706–710.

Herrero, EV, J.P. Mitchell, W.T. Lanini, S.R. Temple, E.M. Miyao, R.D. Morse, E. Campiglia. 2001. Use of cover crop mulches in a no–till furrow–irrigated processing tomato production system. HortTechnology. 11(1):43–48.

Hill, E. C., M. Ngouajio, and M. G. Nair. 2006. Differential response of weeds and vegetable crops to aqueous extracts of hairy vetch and cowpea. HortScience. 41(3):695–700.

Hill, E.C., M. Ngouajio, and M.G. Nair. 2007. Allelopathic potential of hairy vetch (*Vicia villosa)* and cowpea (*Vigna unguiculata*) methanol and ethyl acetate extracts on weeds and vegetables. Weed Technol. 21(2):437–444.

Hoyt, G.D. 1999. Tillage and cover residue effects on vegetable yields. HortTechnology. 9(3):351–358.

Hutchinson, C.M. and M.E. McGiffen. 2000. Cowpea cover crop mulch for weed control in desert pepper production. HortScience. 35(2):196–198.

Ilnicki, R.D. and A.J. Enache. 1992. Subterranean clover living mulch:an alternative method of weed control. Agr. Ecosystems and Environ. 40(1–4):249–264.

Isik, D., E. Kaya, M. Ngouajio, and H. Mennan. 2009. Weed suppression in organic pepper (*Capsicum annuum* L.) with winter cover crops. Crop Protection. 28(4):356–363.

Jackson, L.E., I. Ramirez, R. Yokota, S.A. Fennimore, S.T. Koike, D.M. Henderson, W.E. Chaney, F.J. Calderón, and K. Klonsky. 2004. On–farm assessment of organic matter and tillage management on vegetable yield, soil, weeds, pests, and economics in California. Agr., Ecosystems and Environ. 103(3):443–463.

Juroszek, P. and H.H. Tsai. 2009. Yields of organically grown sweet pepper cultivars and lines during the hot–wet and cool–dry season in the tropics. HortTechnology. 19(2):418–422.

Karunatilake, U.P. and H.M. van Es. 2002. Rainfall and tillage effects on soil structure after alfalfa conversion to maize on a clay loam soil in New York. Soil and Tillage Res. 67(2):135–146.

Kasper, M., G.D. Buchan, A. Mentler, W.E.H. Blum. 2009. Influence of soil tillage systems on aggregate stability and the distribution of C and N in different aggregate fractions. Soil and Tillage Res. 105:192–199.

Kieling, A. dos S., J.J. Comin, J.A. Fayad, M.A. Lana, E. Lovato. 2009. Winter cover crops in no–tillage system without herbicides: Effects on weed biomass and tomato yield. Ciencia Rural. 39 (7):2207–2209.

Kingery, W.L., C.W. Wood, and J.C. Williams. 1996. Tillage and amendment effects on soil carbon and nitrogen mineralization and phosphorus release. Soil and Tillage Res. 37(4):239–250.

Krauss, M., A., D. Berner, A. Burger, A. Wiemken, U. Niggli, and P. Mäder. 2010. Reduced tillage in temperate organic farming:implications for crop management and forage production. Soil Use and Management. 26(1):12–20.

Kristiansen, P., B.M. Sindel, and R.S. Jessop. 2008. Weed management in organic echinacea (*Echinacea purpurea*) and lettuce (*Lactuca sativa*) production. Renewable Agr. and Food Systems. 23(2):120–135.

Kruidhof, H. M., L. Bastiaans, and M.J. Kropff. 2009. Cover crop residue management for optimizing weed control. Plant and Soil. 318(1/2):169–184.

Mennan, H. M., M. Ngouajio, D. Isik, E. Kaya. 2009. Effects of alternative winter cover cropping systems on weed suppression in organically grown tomato (*Solanum lycopersicum*). Phytoparasitica. 37(4):385–396.

Moonen, A.C. and P. Barberi. 2004. Size and composition of the weed seedbank after 7 years of different cover–crop maize management systems. Weed Res. 44:163–177.

Ngouajio, M., M.E. McGiffen,Jr., and C.M. Hutchinson. 2003. Effect of cover crop and management system on weed populations in lettuce. Crop Prot. 22(1): 57–64.

Ngouajio, M. and H. Mennan. 2005. Weed populations and pickling cucumber (*Cucumis sativus*) yield under summer and winter cover crop systems. Crop Prot. 24(6):521–526.

Niemeyer, H.M. 2009. Hydroxamic Acids Derived from 2–Hydroxy–2H–1.4–Benzoxazin–3(4H)–one: Key defense chemicals of cereals. J. of agricultural and food chem. 57(5):1677–1696.

Noffsinger S.L., D.E. Stamer, and E. van Santen. 1998. Planting date and seeding rate effects on white lupin yield in Alabama and Virginia. J. Prod. Agr. 11(1):100-107.

Norsworthy, J.K., M.S. Malik, P. Jha, and M.B. Riley. 2007. Suppression of *Digitaria sanguinalis* and *Amaranthus palmeri* using autumn–sown glucosinolate–producing cover crops in organically grown bell pepper. Weed Res. 47(5):425–432.

Olesen, J.E. and L.J. Munkholm. 2007. Subsoil loosening in a crop rotation for organic farming eliminated plough pan with mixed effects on crop yield. Soil and Tillage Res. 94(2):376–385.

Olsen, J., L. Kristensen, J. Weiner, and H.W. Griepentrog. 2005. Increased density and spatial uniformity increase weed suppression by spring wheat. Weed Res. 45(4):316–321.

Peigné, J., A. Aveline, M. Cannavaciuolo, J.L. Giteau, and Y. Gautronneau. 2008. Soil tillage in organic farming: Impacts of conservation tillage on soil fertility, weeds and crops. Proc. of the Second Scientific Conf. of the Intl. Soc. of Organic Agr. Res. 1:422–425.

Peigné, J., B.C. Ball, J. Roger–Estrade, and C. David. 2007. Is conservation tillage suitable for organic farming? A review. Soil Use and Management. 23(2):129–144.

Peigné, J., M. Cannavaciuolo, Y. Gautronneau, A. Aveline, J.L. Giteau, and D. Cluzeau. 2009. Earthworm populations under different tillage systems in organic farming. Soil and Tillage Res. 104(2):207–214.

Pullaro, T.C., C. Marino, D.M. Jackson, H.F. Harrison, and A.P. Keinath. 2006. Effects of killed cover crop mulch on weeds, weed seeds, and herbivores. Agr., Ecosystems and Environ. 115(1–4):97–104.

Ranells, N.N. and M.G. Wagger. 1996. Nitrogen release from grass and legume cover crop monocultures and bicultures. Agron. J. 88(5):777–782.

Raper, R.L. 2007. In–row subsoilers that reduce soil compaction and residue disturbance. Appl. Eng. in Agr. 23(3):253–258.

Reeves, D.W. 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil and Tillage Res. 43(1–2):131–167.

Rosecrance, R.C., G.W. McCarty, D.R. Shelton, and J.R. Teasdale. 2000. Denitrification and N mineralization from hairy vetch and rye cover crop monocultures and bicultures. Plant Soil. 227(1–2):283–290.

Rosen, C.J. and D.L. Allan. 2007. Exploring the benefits of organic nutrient sources for crop production and soil quality. HortTechnology. 17(4):422–430.

Ruffo M.L. and G.A. Bollero. 2003. Modeling rye and hairy vetch residue decomposition as a function of degree–days and decomposition days. Agron. J. 95(4):900–907.

Ryan, MR, R.G. Smith, S.B. Mirsky, D.A. Mortensen, and R. Seidel. 2010. Management filters and species traits:weed community assembly in long–term organic and conventional systems. Weed Sci. 58(3):265–277.

Sainju, U. M., W.F. Whitehead, B.P. Singh. Biculture legume–cereal cover crops for enhanced biomass yield and carbon and nitrogen. 2005. Agron. J. 97(5):1403–1412.

Sharifi, M., B.J. Zebarth, D.L. Burton, C.A. Grant, S. Bittman, C.F. Drury, B.G. McConkey, and N. Ziadi. 2008. Response of potentially mineralizable soil nitrogen and indices of nitrogen availability to tillage system. Soil Sci. Soc. of Amer. J. 72(4):1124–1131.

Silva Hirata, A.C., E.K. Hirata, P.A. Monquero, A.R. Golla, and N. Narita. 2009. Plantas de cobertura no controle de plantas daninhas na cultura do tomate em plantio direto. Planta daninha. 27(3):465–472.

Stirzaker, R.J. and White, I., 1995. Amelioration of soil compaction by a cover–crop for no–tillage lettuce production, Australian J. of Agricultural Res., 46(3):553–68.

Stivers–Young, L. 1998. Growth, nitrogen accumulation, and weed suppression by fall cover crops following early harvest of vegetables. HortScience. 33(1):60–63.

Szafirowska, A. and K. Elkner. 2009. The comparison of yielding and nutritive value of organic and conventional pepper fruits. Vegetable Crops Res. Bul. 71:111–121.

Tabaglio, V., C. Gavazzi, M. Schulz, and A. Marocco. 2008. Alternative weed control using the allelopathic effect of natural benzoxazinoids from rye mulch. Agron. for Sustainable Dev. 28(3):397–401.

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(3):673-680.

Teasdale, J.R. 1996. Contribution of cover crops to weed management in sustainable agricultural systems. J. Production Agr. 9(4):475–479.

Teasdale, J.R. and A.A. Abdul–Baki. 1998. Comparison of mixtures vs. monocultures of cover crops for fresh–market tomato production with and without herbicide. HortScience. 33(7):1163–1166.

Teasdale, J.R. and C.L. Mohler. 2000. The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci. 48(3):385–392.

Thomas, G.A., R.C. Dalal, and J. Standley. 2007. No–till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi–arid subtropics. Soil and Tillage Res. 94(2):295–304.

Thomas, R., J. O' Sullivan, A. Hamill, and C.J. Swanton. 2001. Conservation tillage systems for processing tomato production. HortScience. 36(7):1264–1268.

Tonitto, C., M.B. David, and L.E. Drinkwater. 2006. Replacing bare fallows with cover crops in fertilizer–intensive cropping systems:A meta–analysis of crop yield and N dynamics. Agr., Ecosystems and Environ. 112(1):58–72.

Torbert, H.A., K.N. Potter, and J.E. Morrison. 1998. Tillage intensity and crop residue effects on nitrogen and carbon cycling in a Vertisol. Communications in soil sci. and plant analysis. 29(5–6):717–727.

Torresen, K.S., R. Skuterud, H.J. Tandsaether, and M. Bredesen Hagemo. 2003. Long–term experiments with reduced tillage in spring cereals. I. Effects on weed flora, weed seedbank and grain yield. Crop Protection. 22(1):185–200.

Treadwell, D.D., N.G. Creamer, J.R. Schultheis, and G.D. Hoyt. 2007. Cover crop management affects weeds and yield in organically managed sweetpotato systems. Weed Technol. 21(4):1039–1048.

Trewavas, A. 2004. A critical assessment of organic farming–and–food assertions with particular respect to the UK and the potential environmental benefits of no–till agriculture. Crop Protection. 23(9):757–781.

Turk, M.A. and A.M. Tawaha. 2003. Weed control in cereals in Jordan. Crop Protection. 22(2):239–246.

Tawaha, A.M., Turk, M.A. and Machaireh, G.A., 2001. Morphological and yield traits of Awnless barley as affected by date and rate of sowing under Mediterranean condition. Crop Res. 22(3):311–313.

Valenzuela–Solano, C. and D.M. Crohn. 2006. Are decomposition and N release from organic mulches determined mainly by their chemical composition? Soil Biol. and Biochem. 38(2):377–384.

Vanek, S., H.C. Wien, and A. Rangarajan. 2005. Time of interseeding of lana vetch and winter rye cover strips determines competitive impact on pumpkins grown using organic practices. HortScience. 40(6):1716–1722.

Vian, J.F., J. Peigne, R. Chaussod, J. Roger-Estrade. 2009. Effects of four tillage systems on soil structure and soil microbial biomass in organic farming. Soil Use and Management. 25(5):1-10.

Wander, M.M. and G.A. Bollero. 1999. Soil quality assessment of tillage impacts in Illinois. Soil Sci. Soc. of Amer. J. 63(4):961–971.

Wang, G.Y. and M. Ngouajio. 2008. Integration of cover crop, conservation tillage, and low herbicide rate for machine–harvested pickling cucumbers. HortScience. 43(6):1770–1774.

Westerman, P.R., A. Hofman, L.E.M. Vet, and W. van der Werf. 2003. Relative importance of vertebrates and invertebrates in epigeaic weed seed predation in organic cereal fields. Agr., Ecosystems and Environ. 95(2–3):417–425.

Zotarelli, L., L. Avila, J.M.S. Scholberg, and B.J.R. Alves. 2009. Benefits of vetch and rye cover crops to sweet corn under no–tillage. Agron. J. 101(2):252–260.

Chapter 2. A conservation tillage system for organic vegetables

Introduction

Conservation tillage would be useful in organic vegetable production to improve soil quality and reduce labor and fuel costs. However, conservation tillage can reduce N fertility and increase weed competition, decreasing vegetable yields. Challenges can be compounded because organic farmers cannot rely on inorganic fertilizers or herbicides. Organic vegetable systems with reduced tillage have sometimes been found to yield as well as those with conventional tillage, but not consistently.

Cover crops may be introduced into the system to alleviate both fertility and weed problems (Lu et al., 2000). Legume cover crops can fix substantial amounts of N when planted the fall before a given season (Clark, 2007) and can produce greater amounts of biomass when grown as part of a grass-legume biculture. Cover crop residue will suppress weeds when present in sufficient amounts (Sainju et al., 2005; Mohler and Teasdale, 1993). Furthermore, grass-legume bicultures are able to both fix and scavenge significant amounts of N. Hairy vetch (*Vicia villosa* Roth) -cereal rye (*Secale cereale* L.) bicultures have been well-studied (Carrera et al., 2004; Rosecrance et al., 2000; Treadwell et al., 2007; Sainju et al., 2005) because they are both able to overwinter well in temperate climates. Rye also has allelopathic effects that can reduce weed seed germination (Tabaglio et al., 2008).

Before a cash crop is planted, cover crops are often mowed and then incorporated, or left on the soil surface as a mulch. The residue can then be managed to provide optimal benefits for the following crop. The amount of hairy vetch-rye residue that is needed to effectively suppress weeds is approximately three times the amount that can be grown *in situ* in the northeastern U.S.A. (Teasdale and Mohler, 2000). Because vegetables are most vulnerable to competition from neighboring weeds, concentrating hairy vetch-rye biomass in the row may provide enough residue to suppress weeds in the early season. The residue may also provide a significant amount of N as it decomposes, contributing to vegetable plant growth. However, cover crop residue can also cool the soil, reducing N mineralization and potentially reducing yield. The environmental, economic, and management benefits of integrating cover crops into a reduced tillage system must be balanced against potential losses of yield or quality of the crop.

This research addresses two constraints to an organic vegetable reduced tillage system: in-row weed control and fertility management. A temperature-sensitive crop, bell peppers (*Capsicum annuum* L. 'Ace'), was chosen to determine if a cover crop can be managed to decrease weed competition, enhance fertility, and improve total marketable yield. This experiment tested the hypothesis that moving cover crop residue into the crop row effectively suppresses weeds and increases N availability to peppers, leading to increased yields in an organic, conservation tillage system. Additional hypotheses were that seeding the cover crop earlier would increase cover crop biomass relative to a later seeding date, and that a higher seeding rate would compensate for the later seeding date. Weed control costs were also calculated and compared to yields to determine which cover crop management system would be most profitable.

Materials and methods

Treatments were established in 2008 and 2009 at the Cornell Organic Research Farm in Freeville, NY. This farm is certified by the Northeast Organic Farming Association of New York LLC. The soil types present at the experimental site were a Howard gravelly loam with 3.5% organic matter (OM) and pH 7.3 in 2009 and a Howard gravelly loam and silt loam with 6.7% OM and pH 7.3. Both soils are loamy-skeletal, mixed, mesic Glossoboric Hapludalfs. The cropping history of the field used in 2008-2009 was various legume and grass cover crops in 2006, rye cover crop in fall 2007, summer fallow followed by buckwheat in late summer which was mowed and plowed under before these experimental plots were established in 2008. The field used in 2009-2010 was bare fallow in summer 2007 followed by (*Avena sativa* L.) -pea (*Pisum sativum* L.) cover crop in July 2007. Peppers were planted followed by cereal rye in 2008. This rye was harvested for seed in late summer 2009 and the stubble plowed under before seeding these experimental plots.

Air temperatures and precipitation were measured at a weather station approximately 0.5 km from the each field site (Table 1).

Table 1. Mean monthly air temperature and total precipitation in 2009 and 2010 at Freeville, NY.

	Mean air temperature (^{o}C)				Total precipitation (mm)			
	2008^{z}	2009	2010	8-y average^{y}	2008	2009	2010	8-y average
January		-8.5	-4.9	-5.9		10.2	40.9	54.3
February		-2.8	-3.8	-5.2		28.7	10.9	47.8
March		1.8	3.5	-0.9		68.1	54.1	75.3
April		8.9	10.4	4.0		68.8	51.1	71.7
May		14.1	16.1	11.1		78.5	60.2	88.1
June		17.7	19.6	18.3		103.1	94.7	119.9
July		19.3	22.7	20.1		90.7	91.9	125.3
August		20.6	21.1	20.1		117.1	100.1	110.8
September	16.7	15.2	16.6	15.9	52.8	57.7	136.7	104.2
October	8.2	8.9		8.8	77.7	63.8		98.2
November	3.3	6.1		4.3	56.6	38.1		75.5
December	-1.7	-2.3		-2.5	35.8	25.4		62.5

^{z}Freeville, NY weather station, 2010.
^{y}Freeville, NY weather station, 2001-2009.

Treatments were arranged in a randomized block split-split plot design with four replicates. Main plot treatments were cover crop management, split plots were cover crop seeding dates and split-split plots were seeding rates. Cover crop management treatments consisted of an oat-pea (OP) cover crop that was winter killed leaving minimal residue, hairy vetch-rye mowed and not concentrated into the row (HVR), and hairy vetch-rye mowed and later concentrated into the row (HVR-InRow). All field practices and dates of activities are summarized in Table 2.

Table 2. Timeline of production and cultural practices followed for peppers grown in an organic reduced tillage system.

Activity	*2009 crop*	*2010 crop*
Seed cover crop ('early')	5 Sept. 2008	30 Aug. 2009
Seed cover crop ('late')	26 Sept. 2008	21 Sept. 2009
Spread composted dairy manure at 45 N kg·ha^{-1}	–	28 Aug. 2009
Seed peppers in greenhouse	15 Apr. 2009	16 Apr. 2010
Rototill OP plots	–	15 Apr. 2010
Flail mow HVR plots	28 May 2009	27 May 2010
Compost spread at 161.4 kg N·ha^{-1}	–	28 May 2010
Rototill OP plots	9 June 2009	6 June 2010
Zone build		6 June 2010
Transplant peppers	10 June 2009	10 June 2010
Move mulch in-row		14 June 2010
Sidedress at 45 N kg·ha^{-1} with composted poultry manure	25 June 2009	23 June 2010
Cultivate all plots	22 June 2009	2 July 2010
Fertilize with fish emulsion at 149.8 mg N/L with 1.0 L solution six plants^{-1}	2 July 2009	–
Pull rye by hand	–	6 July 2010
Sidedress at 45 N kg·ha^{-1} with composted poultry manure	9 July 2009	9 July 2010
Cultivate OP plots	10 July 2009	–
Weed HVR plots by hand	30 July 2009	15 July 2010
Weed OP plots by hand	11 Aug. 2009	15 July 2010
Cultivate all plots	6 Aug. 2009	28 July 2010
Weed all plots by hand		11 Aug. 2010
Spray copper preventatively		19 Aug. to 15 Sept. 2010
Harvest peppers	25 Aug. to 1 Oct. 2009	2 Sept. to 4 Oct. 2010

Early and late cover crop seeding dates were approximately three weeks apart in each year (Table 2). Seeding was done using a Great Plains no-till drill (Great Plains Manufacturing, Inc, Salinas, KS). Cover crop seeding rate ('standard' or 'high') was nested within a subplot for cover crop seeding date ('early' or 'late'). Rates were based upon current recommendations for cover crop mixes in vegetable systems; the standard rate was 112 kg oats and 556 kg peas per hectare or 112 kg rye and 28 kg hairy vetch per hectare. These rates were doubled for the 'high' treatments. All cover crop seed was certified organic. Rhizobia inoculum was not used in 2008 due to unavailability of an organic product, but inoculum was likely abundant due to the legume cover crop planted in 2006. N-Dure inoculum for peas and hairy vetch was applied to the cover crop seed before planting in 2009 (INTX Microbials, Kentland, IN). Because of the previous rye harvest from the field used for the 2009-2010 experiment, a composted dairy manure was spread in fall 2009 at rate of 45 N $kg \cdot ha^{-1}$ (Fessenden Dairy, King Ferry, NY) prior to seeding cover crops.

Peppers (var. 'Ace') were seeded for transplanting in a certified organic greenhouse (Table 2). Potting media was made with one part each peatmoss, perlite, and vermiculite by volume. In 2009, 91 g bloodmeal, 91 g rock phosphate, 91 g greensand and 2.2 L of vermicompost (Worm Power, Avon, NY) were mixed with 19.8 L of the peat-perlite-vermiculite mix. In 2010, 45.5 g bloodmeal, 45.5 g rock phosphate 45.5 g greensand and1.1 L of vermicompost were mixed with 20.9 L of the peat-perlite-vermiculite mix. Greenhouse air temperatures were maintained at 24°C day and 18.5°C night and flats were watered daily. Peppers were moved to cold frames designated for organic crops on 29 May 2009 and 28 May 2010 for hardening before transplanting. Transplants were fertilized with 2-4-1 Neptune's Organic Fish Emulsion (Neptune's Harvest, Gloucester, MA) at a rate of 149.8 mg N/L with 0.95 L solution per 128-cell flat on 15 May, 22 May, 5 Jun, 13 May, 8 June 2009 and 13 May and 8 June 2010.

In the spring, just before flail mowing the overwintered HVR cover crops, the total aboveground biomass (method below) was recorded to evaluate the influence of planting date and seeding rate on biomass production. Oat-pea biomass was also sampled in the fall, before winter kill. All HVR plots were flail mowed three times the first year with a 370 Flail Mower (John Deere Agriculture, Moline, IL) and once the second year with a Model 38 Crop Chopper Flail Harvester (New Holland Agriculture, New Holland, PA) (Table 2). Mowing was timed to hairy vetch anthesis to avoid cover crop re-growth.

All main plots were then deep zone tilled with the centers of the tilled zone 76 cm apart using a two-row Zone Builder (Unverferth Manufacturing Co. Inc, Kalida, OH) (Table 2). The shank on the unit was set at 30.5 cm depth, just below a measured soil compaction zone. Behind each shank were two coulters and a rolling basket. This finishing unit prepared a 25 cm wide tilled soil strip. Front-mounted row cleaners pushed residue out of the rows during tillage of all plots to preserve biomass.

Organic peppers were transplanted 38 cm apart in the row with a no-till transplanter (Table 2). After transplanting, peppers were fertilized with 2-4-1 Fish Emulsion (Neptune's Harvest, Gloucester, MA) at a rate of 149.8 mg $N{\cdot}L^{-1}$ with 1.0 L solution per six plants 2 July 2009. Due to heavy rain the second year, peppers were hand-transplanted in 2010. Each field plot had four planted rows and was approximately 6.1 m in length and 4.6 m wide. Cover crop biomass in the HVR-InRow plots was raked into the pepper row (consisting of the 15 cm on both sides of the peppers) by hand (Table 2). All plots were sidedressed at a rate of 45 N $kg{\cdot}ha^{-1}$

with Kreher's composted poultry manure (Kreher's Poultry Farms, Clarence, NY) (Table 2). Peppers were harvested six times in 2009 and three times in 2010.

Weed control

Before spring deep zone tillage and planting, oat-pea plots were cultivated to a 6 cm depth to control extensive weed growth that had occurred from lack of ground cover (Table 2). Additionally, OP plots were cultivated to 10 cm depth with a Perfecta II field cultivator (Unverferth Manufacturing Co., Inc., Kalida, OH) 15 Apr. 2010 due to volunteer rye from previous field use.

After peppers were established, all plots were cultivated two times in each year with a belly-mounted S-tine cultivator (Saukville Tractor Corp., Newburg, WI) (Table 2). An additional cultivation with a custom-made 4-row high residue cultivator (Brillion Farm Equipment, Brillion, WI) was done in 2010. In 2009, OP plots required an extra midseason cultivation with the S-tine cultivating tractor. Due to extensive in-row weed growth, in-row weeds were weeded by hand on 30 July 2009 in HVR-InRow and HVR plots, on 11 Aug. 2009 in OP plots and 15 July and 11 Aug. 2010 in all plots. All hand weeding in data collection areas was timed to determine labor hours per hectare needed for each treatment.

Insects and plant pathogens

Peppers were scouted weekly after transplanting to assess insect and disease incidence. Insect levels in pepper plants were low and did not require pesticide applications. In 2010, copper hydroxide (Nu Cop 50;Albaugh Inc., Ankeny, IA) was sprayed for bacterial spot (*Xanthomonas campestris pv. Vesicatoria*) after the disease was found in a nearby organic pepper planting (Table 2).

Measurements

Cover crop biomasses

Aboveground plant biomass was sampled to quantify the effect of cover crop planting date and rate on cover crop biomass. For OP biomass, two 0.25 m^2 quadrats were randomly placed within each plot and above-ground plant material cut 2.54 cm above the soil on 22 Oct. 2008 and 23 Oct. 2009. In the spring, two 0.25 m^2 quadrats were randomly placed in each plot and plant material cut as above on 28 May 2009 and 27 May 2010.

After transplanting peppers, cover crop residue in hairy vetch-rye plots was assessed on 16 June 2010. Residue was cut at ground level and removed from two 0.25 m^2 quadrats per plot, separating in-row (the inner 30.5 cm) and between-row (the 15 cm on either side of the inner row). For all cover crop biomass measurements, weeds were separated from the cover crop biomass, dried at 71ºC for three days, and weighed.

Soil measurements

Temperature

Button temperature sensors (WatchDog 100 series, Spectrum Technologies, Plainfield, IL) were placed approximately 0.15 m below ground in seven treatments (late/standard/OP, late/high and early/late and early/standard HVR and early/standard and early/late HVR-InRow), representing varying levels of cover crop residue, in three experimental blocks on 19 June 2009 and 15 June 2010. Placement was in row to avoid damage from machinery. The temperature was recorded every two hours until the end of the season (30 Sept. 2009 and 2010).

Nitrogen

Soil soluble nitrogen (N) was monitored over the season to assess the impact of cover crop rates on soil and crop fertility. Samples were taken approximately every two weeks, starting before cover crop mowing and ending at the start of pepper harvest (18 May, 23 June, 8 July, 21 July, 3 Aug., 18 Aug., 8 Sept. 2009 and 25 May, 15 June, 30 June, 19 July, 3 Aug., 17 Aug., and 30 Aug. 2010). All sampling was from three randomly selected locations 15 cm deep in the two pepper data collection rows. Sub-samples were mixed, passed through a 2 mm sieve and air-dried. Approximately 8 g of dried soil from each plot were added to 50 mL plastic centrifuge tubes with 40 ml of 2.0M KCl, with two tubes per plot. Tubes were weighed before and after adding soil and placed on a shaker for 1 hr. Tubes were left upright for at least fifteen minutes to allow soil to settle. The supernatant was filtered through Whatman 42 filter paper and the extract was collected and frozen until analysis for nitrate and ammonium.

Potentially mineralizable nitrogen was assessed on 23 June and 8 Sept. 2009 and 25 May, 15 June, and 30 Aug. 2010. The same collection method was used, with fresh soil sieved and refrigerated before processing the same or next day. Ten mL of deionized water was added to 50 mL centrifuge tubes and approximately 8 g fresh soil was added (actual weight was recorded). Tubes were then purged of oxygen with nitrogen gas, sealed, and left in an incubator at 30° C for one week. After the incubation period, tubes were removed from the incubator and 30 mL 2.67M KCl was added to each tube. Tubes were placed on a shaker for 1 hr, removed, filtered as above, and analyzed for soluble N (Drinkwater et al., 1996; Keeney and Bremner, 1966). Both soluble N and potentially mineralization N extractions were sent to a Michigan State University nutrient analysis lab for determination of NH^{4+} and NO^{3-} concentrations. Initial NH^{4+} values found from the soluble soil N measurement were subtracted from NH^{4+} values found post-incubation to determine N mineralization potential.

Weed measurements

To quantify in- and between-row weeds, two 0.25 m^2 quadrats per plot were randomly placed on one of the two inner rows, centered on the row on 8 July 2009 and 20 July 2009. Weeds were also counted at the end of the season on 3 Sept. 2009 and 27 Aug. 2010. Weeds were categorized as cool-season dicotyledons, warm-season dicotyledons, perennial graminoids, perennial dicotyledons, or annual graminoids.

The midseason in-row weeds were pulled by hand from the 15 cm at either side of the center of the row. Roots were then clipped off so only aboveground biomass would be measured. Weeds were sorted and categorized (as listed above), dried for three days at 71º C and weighed. In- and between-row weed biomass was also assessed on 3 Sept. 2009 and 27 Aug. 2010. Dominant species were noted.

To determine the cost of midseason in-row weed control, the number of people pulling in-row weeds and time required to weed data areas was recorded.

Pepper biomass and yield

Aboveground pepper biomass

Five times throughout the season, three pepper plants per plot were cut at ground level, dried for three days at 71º C, and weighed. Fruits and vegetative parts were weighed separately. Due to small plot sizes, pepper plants were taken from the outside two rows the first year. The second year, three pepper plants were taken randomly from the area 0.76-1.52 m in from the top and bottom edges of the inner two rows on 3 Aug. 2010 to avoid taking bordering plants and not to interfere with harvest collection from data areas.

Yield and fruit quality assessment

Peppers from the data collection areas were picked when the lobes were well-formed and felt firm when lightly squeezed, and when pepper length at least 0.06 m (Gast, 1994). Marketable peppers were weighed and categorized into small (less than 150.1 g), medium (150.1-170.0 g), large (170.1-200.0 g), and extra large (above 200.0 g), and fresh weights were recorded by category. Damaged peppers were also weighed and the cause of damage was noted (rot, sunscald, or European corn borer damage). Mature green peppers were harvested by hand from all plots on 25 Aug., 1 Sept., 10 Sept., 17 Sept., 24 Sept. and 1 Oct. 2009 and 2 Sept., 14 Sept., 23 Sept. and 4 Oct. 2010.Early yield was analyzed using the sum of the first two harvests in 2009 and the first harvest in 2010. Total yield was analyzed using all six harvests in 2009 and all three harvests in 2010.

Statistical analysis

All data were analyzed using the proc mixed procedure in SAS version 9.2 (SAS Institute, 2009). The Tukey-Kramer test was used to determine significant differences for pairwise comparisons.

Economic analysis

Partial budgets were made to compare the cost of the different cover crop management strategies, as weed control techniques. Actual cost of cover crop seed was used. The costs of mechanical weed control and cover crop management for each treatment were determined using custom rates from Pennsylvania (Pike, 2010). Labor costs for hand weeding were calculated at \$15 hour^{-1} (Glasmeier, 2010) and multiplied by the time required for each operation. The various costs of weed control for each plot were totaled and the totals compared using SAS Proc mixed.

Results

Cover crop aboveground biomass

Fall oat-pea (OP) biomass averaged 936 kg·ha^{-1} in 2008 and was not affected by planting date or seeding rate (Table 3). In 2009, a significant interaction between CCD and CCR indicated that the early cover crop planting date (CCD) increased OP biomass to a greater extent than seeding rate (CCR) (Table 4). Earlier CCD resulted in a ten-fold greater biomass than the later CCD of OP. Increasing the seeding rate for the late planting significantly increased biomass but did not compensate for the later planting in 2009.

Table 3. Mean biomass (kg·ha^{-1}) of oat-pea cover crop, sampled on 23 Oct. 2008 and 2009 and seeded at different dates (CCD) and rates (CCR).

	Biomass (kg·ha^{-1})		
Treatment	2008	2009	
CCD[z]			
Early	909	1700	
Late	964	185	
CCR[y]			
Standard	887	710	
High	985	1170	
*CCD*CCR*			
Early standard	–	640	b
Early high	–	1500	a
Late standard	–	70	c
Late high	–	120	c
Statistical significance			
CCD	ns	0.003	
CCR	ns	<0.001	
CCD*CCR	ns	<0.001	

[z]Early seeding date was 5 Sept. 2008 and 30 Aug. 2009 and late seeding date was 26 Sept. 2008 and 21 Sept. 2009.
[y]Standard seeding rate was 112 kg·ha^{-1} oats and 56 kg·ha^{-1} peas or 112 kg·ha^{-1} rye and 28 kg·ha^{-1} hairy vetch and high seeding rate was 224 kg·ha^{-1} oats and 112 kg·ha^{-1} peas or 224 kg·ha^{-1} rye and 56 kg·ha^{-1} hairy vetch.

Some OP residue was still present on the soil surface in May 2009 but not in 2010 (Table 4). In both years, the amount of OP residue was significantly lower than the hairy vetch and rye (HVR). The biomass in the HVR plots to be concentrated (HVRInRow) and not concentrated (HVR) were similar. Planting hairy vetch-rye earlier in the fall significantly increased the amount of biomass the following spring in 2009 but not 2010. Increasing the CCR did not increase biomass significantly overall, but did increase biomass for HVR and HVR-InRow in 2009.

Table 4. Mean cover crop biomass on 23 May 2009 and 27 May 2010 before mowing.

	Biomass ($kg \cdot ha^{-1}$)	
Treatment	2009	2010
CCD[z]		
Early	6000 b[y]	5500
Late	3580 a	4560
CCR[x]		
Standard	4600	4720
High	5000	5320
CCM		
HVR early	7,600 a	–
HVR late	4,800 b	–
Statistical significance		
CCD	0.0004	ns
CCR	ns	ns
CCM	<0.0001	<0.0001
CCD*CCR	ns	ns
CCD*CCM	0.047	ns
CCR*CCM	ns	ns
CCD*CCR*CCM	ns	ns

[z]Early seeding date was 5 Sept. 2008 and 30 Aug. 2009 and late seeding date was 26 Sept. 2008 and 21 Sept. 2009.

[y] Standard seeding rate was 112 $kg \cdot ha^{-1}$ oats with 56 $kg \cdot ha^{-1}$ peas or 112 $kg \cdot ha^{-1}$ rye with 28 $kg \cdot ha^{-1}$ hairy vetch and high seeding rate was double these amounts.

[x] Means followed by different letters are significantly different at $P<0.05$.

After concentrating the cover crop residue in the row, biomass measurement confirmed high levels in HVR-InRow plots (Table 5). Between-row residue was higher in HVR plots than HVR-InRow plots, but this difference was not significant due to high variability.

Table 5. Mean cover crop residue biomass after concentrating mulch in-row in HVR-InRow plots in 2010.

Treatment	In-row ($kg \cdot ha^{-1}$)		Between-row ($kg \cdot ha^{-1}$)		Total ($kg \cdot ha^{-1}$)	
CCD[z]						
Early	2,000		2,200		4,200	
Late	1,800		2,100		3,900	
CCR[y]						
Standard	1,900		2,500		4,400	
High	1,900		1,800		3,700	
CCM						
HVR	1,400	b[x]	3,000		4,400	
HVR-InRow	2,400	a	1,300		4,400	
*CCD*CCM*						
HVR early	–		3,500	a	5,100	a
HVR late	–		2,500	a	3,500	ab
HVR-InRow early	–		880	b	3,200	b
HVR-InRow late	–		1,700	a	4,200	ab
Statistical significance						
CCD	ns		ns		ns	
CCR	ns		ns		ns	
CCM	0.046		ns		ns	
CCD*CCR	ns		ns		ns	
CCD*CCM	ns		0.019		0.043	
CCR*CCM	ns		ns		ns	
CCD*CCR*CCM	ns		ns		ns	

[z] Early seeding date was 30 Aug. 2009 and late seeding date was 21 Sept. 2009.
[y] Standard seeding rate was 112 $kg \cdot ha^{-1}$ oats with 56 $kg \cdot ha^{-1}$ peas or 112 $kg \cdot ha^{-1}$ rye with 28 $kg \cdot ha^{-1}$ hairy vetch and high seeding rate was double these amounts.
[x]Means followed by different letters are significantly different at $P<0.05$.

Soil measurements

Temperature

Average daily soil temperature was significantly higher in OP plots (*P*=0.041, *P* =0.037) compared with HVR plots in early July 2009 and 2010 (Figure 1, 2). OP plots were also significantly warmer than HVR plots (*P* =0.019) in late June 2010.

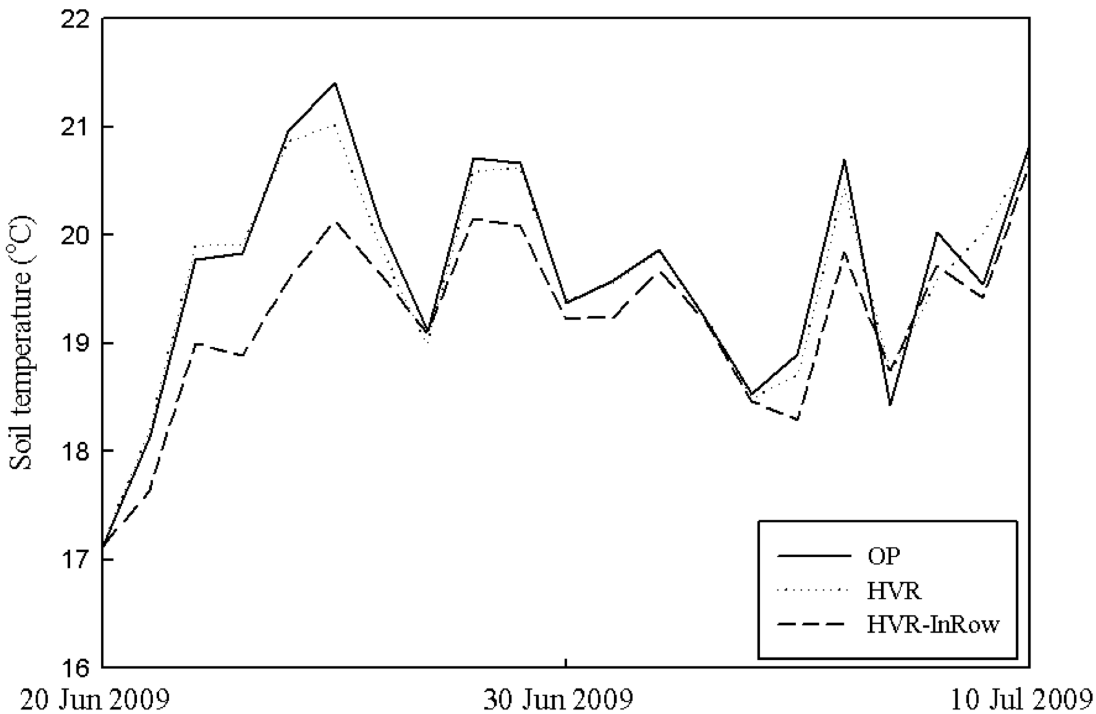

Figure 1. Average daily soil temperature by CCM (cover crop management) treatment, 20 June to 10 July 2009.

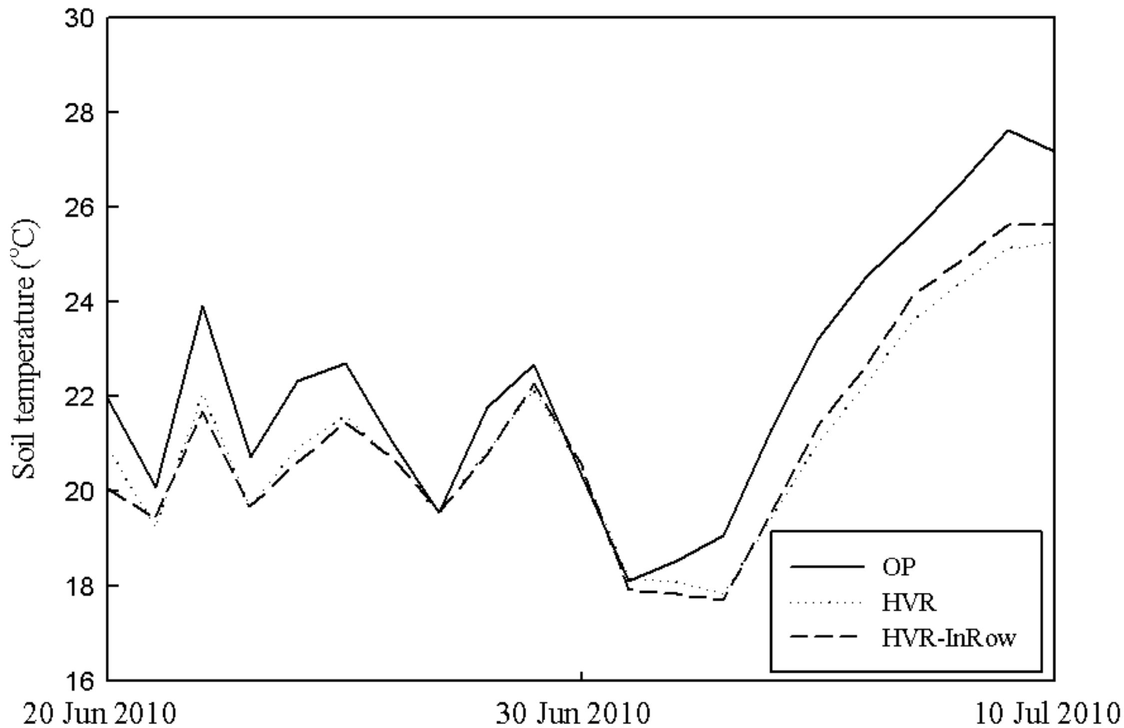

Figure 2. Average daily soil temperature by CCM (cover crop management) treatment, 20 June to 10 July 2010.

Nitrogen

Estimated N contributions from cover crops were based on cover crop biomass. Cover crop residue in HVR and HVR-InRow plots contributed 72 kg $N{\cdot}ha^{-1}$ for the early CCD and 43 kg $N{\cdot}ha^{-1}$ for the late CCD in 2009; residue in OP plots contributed 6.5 kg $N{\cdot}ha^{-1}$. Residue contributed 60 kg $N{\cdot}ha^{-1}$ in HVR and HVR-InRow plots and 0 kg $N{\cdot}ha^{-1}$ in OP plots in 2010. Soil organic matter (SOM) was calculated conservatively as contributing 11.2 kg $N{\cdot}ha^{-1}$ for each percent SOM. Estimated N contributions from cover crop, SOM, and organic amendments were totaled and estimated for each treatment. See Table 6 and 7 for estimated N contributions.

Table 6. Estimated N contributions (N·ha^{-1}) by treatment for 2009 pepper crops.

Treatment		OM	Cover crop	Amendment	Total
OP					
Early	Standard	39	7	90	136
Early	High	39	7	90	136
Late	Standard	39	7	90	136
Late	High	39	7	90	136
HVR					
Early	Standard	39	72	90	201
Early	High	39	72	90	201
Late	Standard	39	43	90	172
Late	High	39	43	90	172
HVR-InRow					
Early	Standard	39	72	90	201
Early	High	39	72	90	201
Late	Standard	39	43	90	172
Late	High	39	43	90	172

Table 7. Estimated N contributions (N·ha^{-1}) by treatment for 2010 pepper crops.

Treatment		OM	Cover crop	Amendment	Total
OP					
Early	Standard	75	0	296	326
Early	High	75	0	296	326
Late	Standard	75	0	296	326
Late	High	75	0	296	326
HVR					
Early	Standard	75	60	296	386
Early	High	75	60	296	386
Late	Standard	75	60	296	386
Late	High	75	60	296	386
HVR-InRow					
Early	Standard	75	60	296	386
Early	High	75	60	296	386
Late	Standard	75	60	296	386
Late	High	75	60	296	386

N mineralization potential sampled from within the row did not differ significantly among seeding dates, seeding rates (CCR) or management treatments except that it was higher for early seeding than for late seeding on 25 May 2010 (Appendix A).

Soil soluble N peaked in late July or early August in all treatments in both years (Table 8, 9). At this peak in 2009, OP plots had significantly higher soil soluble N concentrations, though rates did not differ among treatments at the beginning or end of the seasons (Table 8). In 2010, OP plots only had higher soil soluble N at the beginning of the season, and afterward all CCM were similar (Table 9). Pre-season testing for N mineralization potential found no significant differences, indicating that rototilling the OP plots caused the OP peaks. In 2010, the OP plots were rototilled an additional time in April, and a peak was seen in late May.

Plots that had the earlier CCD had slightly higher total soil soluble N during midseason in 2009 and 2010. This difference was only significant for HVR and HVR-InRow plots on the 15 June and 30 June 2010 and only for the HVR and HVR-InRow plots on 19 July 2010. In OP plots on those dates, the CCD did not significantly affect soil soluble N. The higher CCR increased soil soluble N slightly but significantly midseason in both years.

Table 8. Mean total soluble N (NO^{3-}-N and NH^{4+}-N) sampled seven times during the season in 2009.

	Total soluble N ($mg \cdot kg^{-1}$)						
Treatment	18 May	23 Jun	8 July	21 July	3 Aug.	18 Aug.	8 Sept.
CCD							
Early[z]	4.3	6.3	16	17	18	8.1	7.7
Late	3.8	5.8	13	13	15	7.8	7.3
CCR							
Standard[y]	3.9	5.9	15	16	16	8.3	7.5
High	4.2	6.2	14	14	17	7.6	7.5
CCM							
OP	4.4	6.4	20 a[x]	20 a	23 a	8.7 a	7.2
HVR	3.7	5.7	9.3 b	9.7 b	9.9 b	7.2 b	7.8
*CCD*CCR*							
Early standard	–	–	–	–	16 b	–	–
Early high	–	–	–	–	20 a	–	–
Late standard	–	–	–	–	15 b	–	–
Late high	–	–	–	–	14 b	–	–
Statistical significance							
CCD	ns	ns	ns	ns	ns	ns	ns
CCR	ns	ns	ns	ns	ns	ns	ns
CCM	ns	ns	0.048	0.044	0.010	0.044	ns
CCD*CCR	ns	ns	ns	ns	0.013	ns	ns
CCD*CCM	ns	ns	ns	ns	ns	ns	ns
CCR*CCM	ns	ns	ns	ns	ns	ns	ns
CCD*CCR*CCM	ns	ns	ns	ns	ns	ns	ns

[z] Early seeding date was 5 Sept. 2008 and 30 Aug. 2009 and late seeding date was 26 Sept. 2008 and 21 Sept. 2009.
[y] Standard seeding rate was 112 $kg \cdot ha^{-1}$ oats with 56 $kg \cdot ha^{-1}$ peas or 112 $kg \cdot ha^{-1}$ rye with 28 $kg \cdot ha^{-1}$ hairy vetch and high seeding rate was double these amounts.
[x] Means followed by different letters are significantly different at $P<0.05$.

Table 9. Mean total soluble N (NO^{3-}-N and NH^{4+}-N) sampled seven times during the season in 2010.

Treatment	Total soluble N ($mg \cdot kg^{-1}$) 25 May	15 Jun	30 Jun	19 July	3 Aug.	17 Aug.	30 Aug.
CCD[z]							
Early	13	22	33	29	19 a[y]	13	7.2
Late	16	23	27	25	12 b	11	5.9
CCR[x]							
Standard	15	23	33	26	15	12	6.3
High	14	22	26	28	15	12	6.8
CCM							
OP	27	24	29	25	14	10	5.5
HVR	2.6	21	30	29	17	14	7.6
*CCD*CCM*							
OP early	–	21 ab	29 ab	–	–	–	–
OP late	–	28 a	30 ab	–	–	–	–
HVR early	–	24 ab	37 a	–	–	–	–
HVR late	–	18 b	23 b	–	–	–	–
*CCR*CCM*							
OP standard	–	28 a	–	26 b	–	–	–
OP high	–	22 b	–	23 b	–	–	–
HVR standard	–	19 b	–	25 b	–	–	–
HVR high	–	23 b	–	32 a	–	–	–
Statistical significance							
CCD	ns	ns	0.047	ns	0.015	ns	ns
CCR	ns	ns	0.047	ns	ns	ns	ns
CCM	ns	ns	ns	ns	ns	ns	ns
CCD*CCR	ns	ns	ns	ns	ns	ns	ns
CCD*CCM	ns	0.008	0.026	ns	ns	ns	ns
CCR*CCM	ns	0.003	ns	0.049	ns	ns	ns
CCD*CCR*CCM	ns	ns	ns	ns	ns	ns	ns

Early seeding date was 5 Sept. 2008 and 30 Aug. 2009 and late seeding date was 26 Sept. 2008 and 21 Sept. 2009.

[y] Standard seeding rate was 112 $kg \cdot ha^{-1}$ oats with 56 $kg \cdot ha^{-1}$ peas or 112 $kg \cdot ha^{-1}$ rye with 28 $kg \cdot ha^{-1}$ hairy vetch and high seeding rate was double these amounts.

[x] Means followed by different letters are significantly different at $P<0.05$.

Treatment effects on weeds

Warm-season broadleaf weeds such as *Amaranthus retroflexus* L. (redroot pigweed), *Amaranthus powellii* S. Wats. (Powell's amaranth), *Chenopodium album* L. (lambsquarters), and *Galinsoga quadriradiata* Cav. (hairy galinsoga) dominated midseason samples both years. Cool-season broadleaf weeds such as *Veronica persica* Poiret (Persian speedwell), *Stellaria media* (L.) Vill. (common chickweed), *Cerastium fontanum* ssp. *vulgare* L. (mouse-eared chickweed) dominated the final weed assessments both years. Cool-season weeds were also present midseason. A few biennial and perennial broadleaf and graminoid species were found throughout the season, including *Taraxacum officinale* F.H. Wigg (common dandelion), *Rumex crispus* L. (curly dock), and *R. obtusifolius* L. (broadleaf dock) in 2009 and 2010, and *Cyperus esculentus* L. (yellow nutsedge) in 2010. The annual grass *Setaria viridis* (L.) P.Beauv. (green foxtail) was also found both years. No significant differences were found for biennial and perennial weed counts or biomass among treatments.

Weed counts

When weeds were counted in and between the planting row, OP plots had significantly more weeds than HVR/HVR-InRow plots in 2009 but not 2010 (Table 10). In-row residue in HVR-InRow plots decreased in-row weeds significantly midseason and at harvest in 2009 but the difference was not significant in 2010. Cover crop seeding rates and dates did not affect early season weed counts, but late CCD increased between-row weeds in HVR plots on 20 July 2009 (Table 10).

Aboveground dry weight

OP plots had significantly higher spring weed biomass than HVR and HVR-InRow plots both years. Weed biomass was significantly higher in plots with the later seeding CCD and standard CCR in 2009 (Table 8). The increase associated with the later CCD was more pronounced in HVR and HVR-InRow plots than OP plots; weeds in OP plots more than doubled with the later CCD but increased more in HVR and HVR-InRow plots. Residue was low in both OP plots, so the early CCD decreased weeds somewhat but not as much as the early CCD for HVR plots.

In-row residue (HVR InRow) decreased in-row weed biomass compared to HVR at midseason in both years and at harvest in 2009 (Table 9).

Pepper biomass and yield

Pepper aboveground biomass

Pepper plants in OP plots were significantly larger than plants in HVR-InRow plots by midseason in both years, and were larger than plants in HVR plots by early August in both years. Cover crop seeding date and rate had no effect on plant size except that higher CCR produced larger plants than the standard CCR on 3 Aug. 2009 (Table 10).

Table 10. Mean number of weeds m^{-2}, following cover crops seeded at different dates (CCD), rates (CCR) and in-season management strategies (CCM), 2009 and 2010.

	Weed count (m^{-2})							
	8 July 2009		20 July 2009		3 Sep 2009		26 Aug. 2010	
Treatment	In-row	Between-row	In-row	Between-row	In-row	Between-row	In-row	Between-row
CCD[z]								
Early	240	440	64	96	150	280	69	170
Late	200	420	72	92	170	280	53	210
CCR[y]								
Standard	270	460	64	92	170	300	48	190
High	196	400	72	100	150	260	48	190
CCM								
OP	520 a[x]	1000 a	110 a	110	300 a	500 a	51	200
HVR	84 b	110 b	60 b	72	110 b	180 b	52	210
HVR-InRow	28 b	120 b	32 c	96	62 b	160 b	41	170
*CCR*CCM*								
OP standard	–	–	–	–	–	–	74 ab	160 b
OP high	–	–	–	–	–	–	11 c	250 a
HVR standard	–	–	–	–	–	–	98 a	250 a
HVR high	–	–	–	–	–	–	65 ab	160 b
HVR-InRow standard	–	–	–	–	–	–	45 bc	160 b
HVR-InRow high	–	–	–	–	–	–	57 abc	170 b
Statistical significance								
CCD	ns	ns	ns	ns	ns	ns	ns	0.026
CCR	ns	ns	ns	ns	ns	ns	ns	ns
CCM	<0.0001	<0.0001	<0.0001	ns	0.0009	<0.0001	ns	ns
CCD*CCR	ns	ns	ns	ns	ns	ns	ns	ns
CCD*CCM	ns	ns	ns	ns	ns	ns	ns	ns
CCR*CCM	ns	ns	ns	ns	ns	ns	0.004	0.0007
CCD*CCR*CCM	ns	ns	ns	ns	ns	ns	ns	ns

[z]Early seeding date was 5 Sept. 2008 and 30 Aug. 2009 and late seeding date was 26 Sept. 2008 and 21 Sept. 2009.
[y] Standard seeding rate was 112 kg·ha^{-1} oats with 56 kg·ha^{-1} peas or 112 kg·ha^{-1} rye with 28 kg·ha^{-1} hairy vetch and high seeding rate was double these amounts.
[x]Means followed by different letters are significantly different at $P < 0.05$ by LSD.

Table 11. Mean weed biomasses in cover crops on 23 May 2009 and 27 May 2010 before mowing.

	Biomass ($g \cdot m^{-2}$)[z]		
Treatment	2009		2010
CCD[y]			
Early	44	a[x]	8.4
Late	140	b	11
CCR[w]			
Standard	58	a	10
High	68	b	8.3
CCM			
OP	220		5.0
HVR	26		1.5
*CCR*CCD*			
Early standard	38	bc	–
Early high	25	c	–
Late standard	120	a	–
Late high	68	b	–
*CCD*CCM*			
OP early	60	b	–
OP late	160	a	–
HVR early	3.1	c	–
HVR late	23	bc	–
*CCR*CCM*			
OP standard	140	a	–
OP high	85	b	–
HVR standard	18	c	–
HVR high	8.0	c	–
Statistical significance			
CCD	0.018		ns
CCR	0.0002		ns
CCM	0.012		ns
CCD*CCR	0.016		ns
CCD*CCM	ns		ns
CCR*CCM	0.006		ns
CCD*CCR*CCM	ns		ns

[z] Data were log transformed for analysis; back-transformed least squared means of the log-transformed values are presented.

[y] Early seeding date was 5 Sept. 2008 and 30 Aug. 2009 and late seeding date was 26 Sept. 2008 and 21 Sept. 2009.

[x] Means followed by different letters are significantly different at $P<0.05$.

[w] Standard seeding rate was 112 $kg \cdot ha^{-1}$ oats with 56 $kg \cdot ha^{-1}$ peas or 112 $kg \cdot ha^{-1}$ rye with 28 $kg \cdot ha^{-1}$ hairy vetch and high seeding rate was double these amounts.

Table 12. In-row weed biomass sampled two and three times during the season, following cover crops seeded at different dates (CCD) and rates (CCR) and with three in-season management strategies (CCM).

	Weed biomass (g·m^{-2})				
	2009[z]		2010[y]		
Treatment	Midseason[x]	Final[w]	Midseason[v]	Midseason	Final
CCD[v]					
Early	52 a[u]	17	10	14	86
Late	40 b	27	11	11	106
CCR[t]					
Standard	48	27	9	13	96
High	43	16	11	12	96
CCM					
OP	0.21 c	18	14 a	13	102
HVR	160 a	48	11 a	17	104
HVR-InRow	51 b	11	5 b	8	82
Statistical significance					
CCD	0.0123	ns	ns	ns	ns
CCR	ns	ns	ns	ns	ns
CCM	<0.0001	ns	0.036	ns	ns
CCD*CCR	ns	ns	ns	ns	ns
CCD*CCM	ns	ns	ns	ns	ns
CCR*CCM	ns	ns	ns	ns	ns
CCD*CCR*CCM	ns	ns	ns	ns	ns

[z]Midseason biomass was taken 30 July 2009 for HVR and HVR-InRow plots and 11 Aug. 2009 for OP plots, when weeds were removed by hand. Final biomass was taken 3 Sept. 2009 for all plots.
[y]Midseason biomass was taken 15 July and 11 Aug. 2010, when weeds were removed by hand. Final biomass was taken 27 Aug. 2010.
[x]Data square root transformed, non-transformed least squared means are presented.
[w]Data log transformed, non-transformed least squared means are presented.
[v]Early seeding date was 5 Sept. 2008 and 30 Aug. 2009 and late seeding date was 26 Sept. 2008 and 21 Sept. 2009.
[u] Means followed by different letters are significantly different at $P<0.05$.
[t] Standard seeding rate was 112 kg·ha^{-1} oats with 56 kg·ha^{-1} peas or 112 kg·ha^{-1} rye with 28 kg·ha^{-1} hairy vetch and high seeding rate was double these amounts.

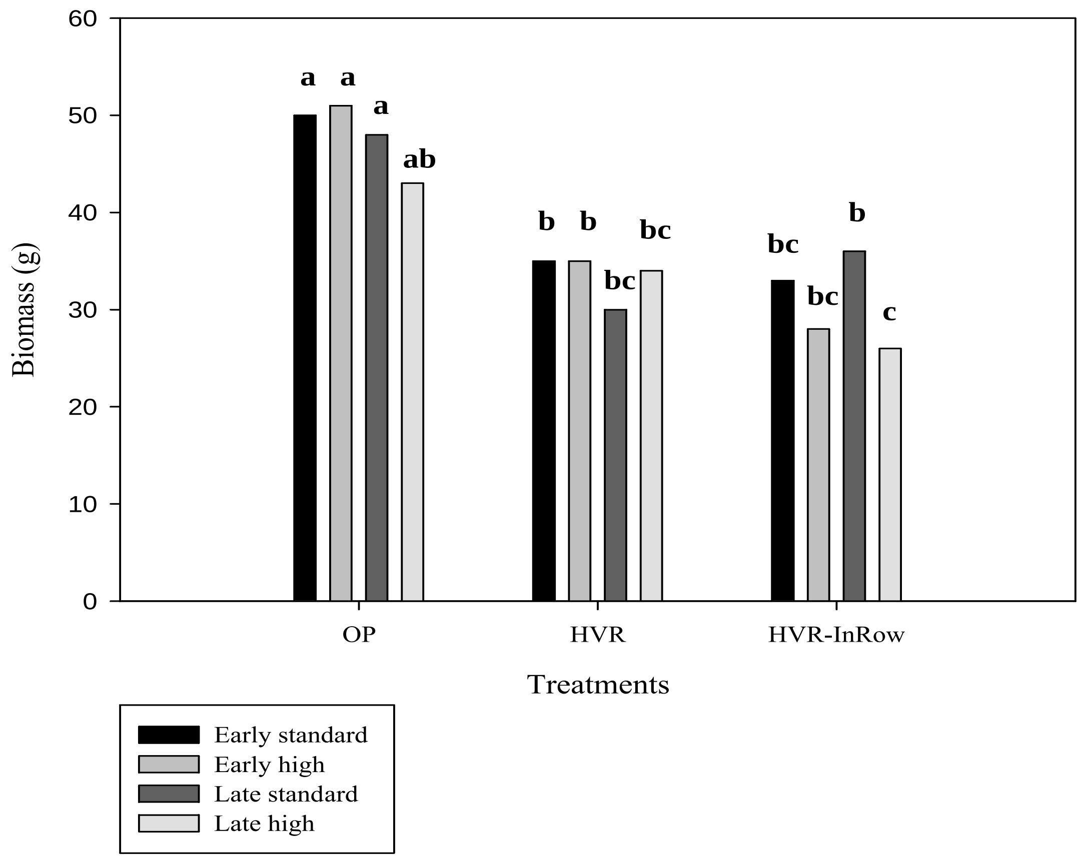

Figure 3. Mean pepper plant biomass (g) for a CCD*CCR*CCM interaction on 9 Sept. 2009.

Table 13. Mean pepper plant biomass at five dates in 2009 and at mid-harvest in 2010. Plants were grown following cover crops seeded at different dates (CCD) and rates (CCR) and managed in-season with various strategies (CCM).

	Biomass per plant (g)					
	2009					2010
Treatment	7 July	21 July	3 Aug.	18 Aug.	9 Sep.	3 Aug.
CCD[z]						
Early	1.1	3.4	12	39	92	30
Late	1.1	3.4	11	36	93	27
CCR[y]						
Standard	1.1	3.6	11 b	39	94	28
High	1.1	3.2	12 a	36	91	28
CCM						
OP	1.5 a[x]	4.6 a	14 a	48 a	105	35 a
HVR	1.0 b	3.2 ab	11 b	33 b	95	25 b
HVR-InRow	0.8 b	2.5 b	9.5 b	31 b	78	26 b
Statistical significance						
CCD	ns	ns	ns	ns	ns	ns
CCR	ns	ns	0.024	ns	ns	ns
CCM	<.0001	0.032	0.001	0.0006	0.020	0.010
CCD*CCR	ns	ns	ns	ns	ns	ns
CCD*CCM	ns	ns	ns	ns	ns	ns
CCR*CCM	ns	ns	ns	ns	ns	ns
CCD*CCR*CCM	ns	ns	ns	ns	0.010	ns

[z] Early seeding date was 5 Sept. 2008 and 30 Aug. 2009 and late seeding date was 26 Sept. 2008 and 21 Sept. 2009.

[y] Standard seeding rate was 112 $kg \cdot ha^{-1}$ oats with 56 $kg \cdot ha^{-1}$ peas or 112 $kg \cdot ha^{-1}$ rye with 28 $kg \cdot ha^{-1}$ hairy vetch and high seeding rate was double these amounts.

[x] Means followed by different letters are significantly different at $P<0.05$.

Table 14. Mean marketable fruit number per hectare by weight of bell peppers cv. 'Ace' grown following cover crops seeded at different dates (CCD) and rates (CCR) and in-season management strategies. Plots were managed organically in Freeville, NY, in 2009 and 2010.

	Number fruit ha^{-1} [z]			
Treatment	2009		2010	
CCD[x]				
Early	44,000		55,000	
Late	45,000		53,000	
CCR[w]				
Standard	45,000		56,000	
High	44,000		52,000	
CCM				
OP	48,000		64,000	
HVR	43,000		50,000	
HVR-InRow	43,000		49,000	
Size				
Small[y]	13,000	a	162,000	a
Medium	4,700	b	37,500	b
Large	1,400	b	15,600	c
Extra large	–		1,550	d
Statistical significance				
CCD	ns		ns	
CCR	ns		0.027	
CCM	ns		<0.0001	
CCD*CCR	ns		ns	
CCD*CCM	ns		ns	
CCR*CCM	ns		ns	
CCD*CCR*CCM	ns		ns	
Size	<0.0001		<0.0001	
CCD*size	ns		ns	
CCR*size	ns		ns	
CCM*size	0.006		<0.0001	
CCD*CCR*size	ns		ns	
CCD*CCM*size	ns		ns	
CCR*CCM*size	ns		ns	
CCD*CCR*CCM*size	ns		ns	

[z]Peppers were sorted by weight into small (less than 150.1 g), medium (150.1-170.0 g), large (170.1-200.0 g), and extra large (above 200.0 g).

[y] Early seeding date was 5 Sept. 2008 and 30 Aug. 2009 and late seeding date was 26 Sept. 2008 and 21 Sept. 2009.

[x] Standard seeding rate was 112 $kg \cdot ha^{-1}$ oats with 56 $kg \cdot ha^{-1}$ peas or 112 $kg \cdot ha^{-1}$ rye with 28 $kg \cdot ha^{-1}$ hairy vetch and high seeding rate was double these amounts.

[w] Means followed by different letters are significantly different at $P<0.05$.

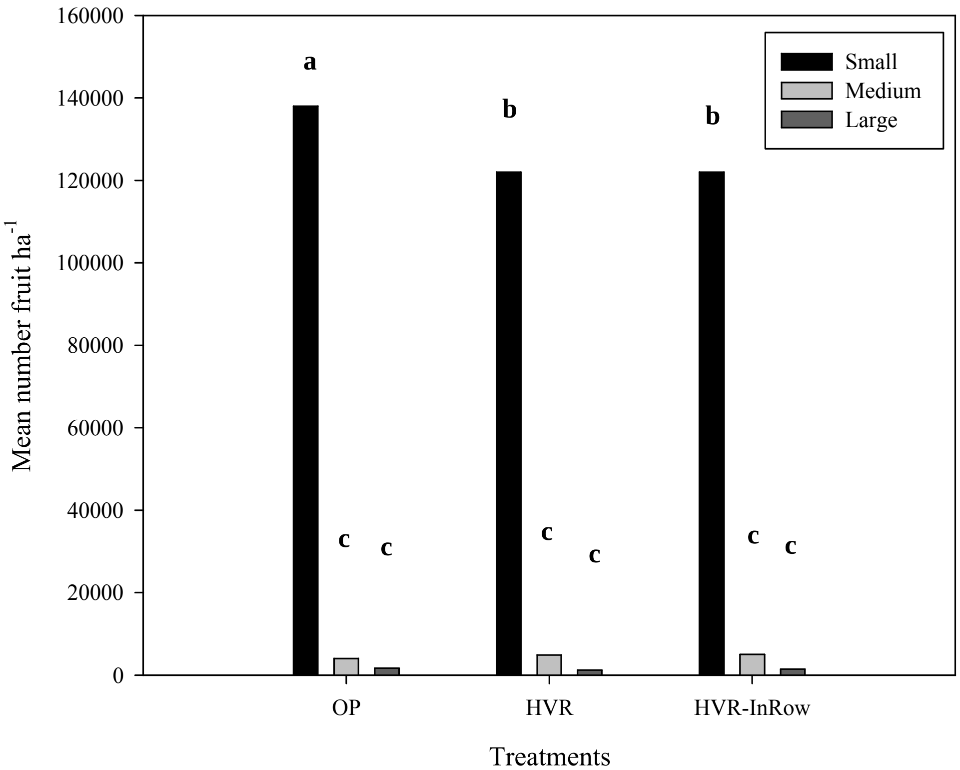

Figure 4. Mean marketable fruit number of bell peppers per hectare by CCM*size interaction in 2009.

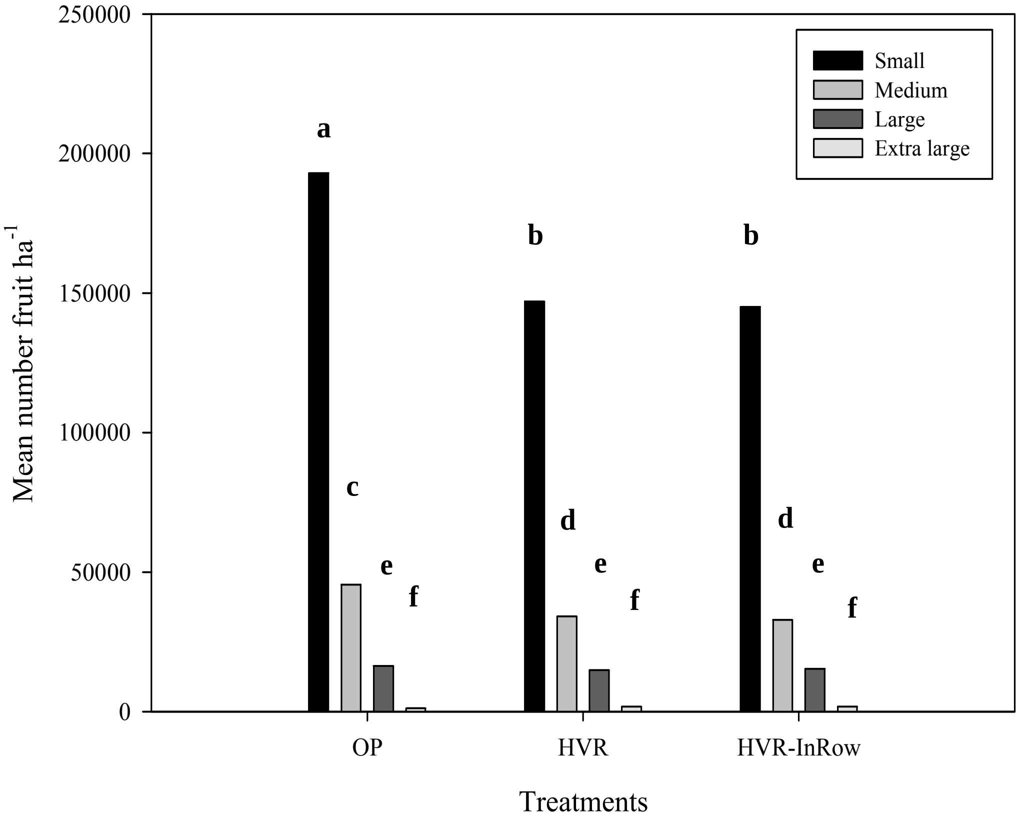

Figure 5. Mean marketable fruit number of bell peppers per hectare by CCM*size interaction in 2010.

Economic analysis

The higher cover crop seeding rate (CCR) increased weed control costs both years and cost per unit peppers produced in 2010 (Table 13). In 2009, the higher CCR significantly increased weed control costs for HVR and HVR-InRow plots with the earlier seeding date (CCD) but not OP plots or the HVR and HVR-InRow plots with the later CCD. Weed control costs per ha and cost per ton of peppers produced were significantly highest in HVR plots both years, mostly due to the increased cost of hand weeding. Weed control costs per ha were significantly lower in OP plots than HVR-InRow plots in 2009 but were equivalent in 2010. Weed control cost per ton peppers produced was equivalent for OP and HVR-InRow plots in 2009 but was lower for OP plots in 2010.

Table 15. Cost of weed management per hectare or per marketable ton of bell peppers cv. 'Ace', including the cost of growing and managing the cover crops.

	2009		2010	
Treatment	$ per ha	per ton	$ per ha	$ per ton
CCD[z]				
Early	$1880	$130	$1470	$50
Late	$1740	$130	$1370	$50
CCR[y]				
Standard	$1680	$120	$1300 a[x]	$50 a
High	$1950	$140	$1530 b	$60 b
CCM				
OP	$1260	$80 a	$1110 a	$30 a
HVR	$2540	$190 b	$1790 b	$70 c
HVR-InRow	$1640	$120 a	$1350 a	$50 b
Statistical significance				
CCD	ns	ns	ns	ns
CCR	0.029	ns	0.002	0.0002
CCM	0.036	0.046	<0.0001	<0.0001
CCD*CCR	0.043	ns	ns	ns
CCD*CCM	ns	ns	ns	ns
CCR*CCM	0.022	ns	ns	ns
CCD*CCR*CCM	0.034	ns	ns	ns

[z] Early seeding date was 5 Sept. 2008 and 30 Aug. 2009 and late seeding date was 26 Sept. 2008 and 21 Sept. 2009.

[y] Standard seeding rate was 112 $kg \cdot ha^{-1}$ oats with 56 $kg \cdot ha^{-1}$ peas or 112 $kg \cdot ha^{-1}$ rye with 28 $kg \cdot ha^{-1}$ hairy vetch and high seeding rate was double these amounts.

[x] Means followed by different letters are significantly different at $P<0.05$.

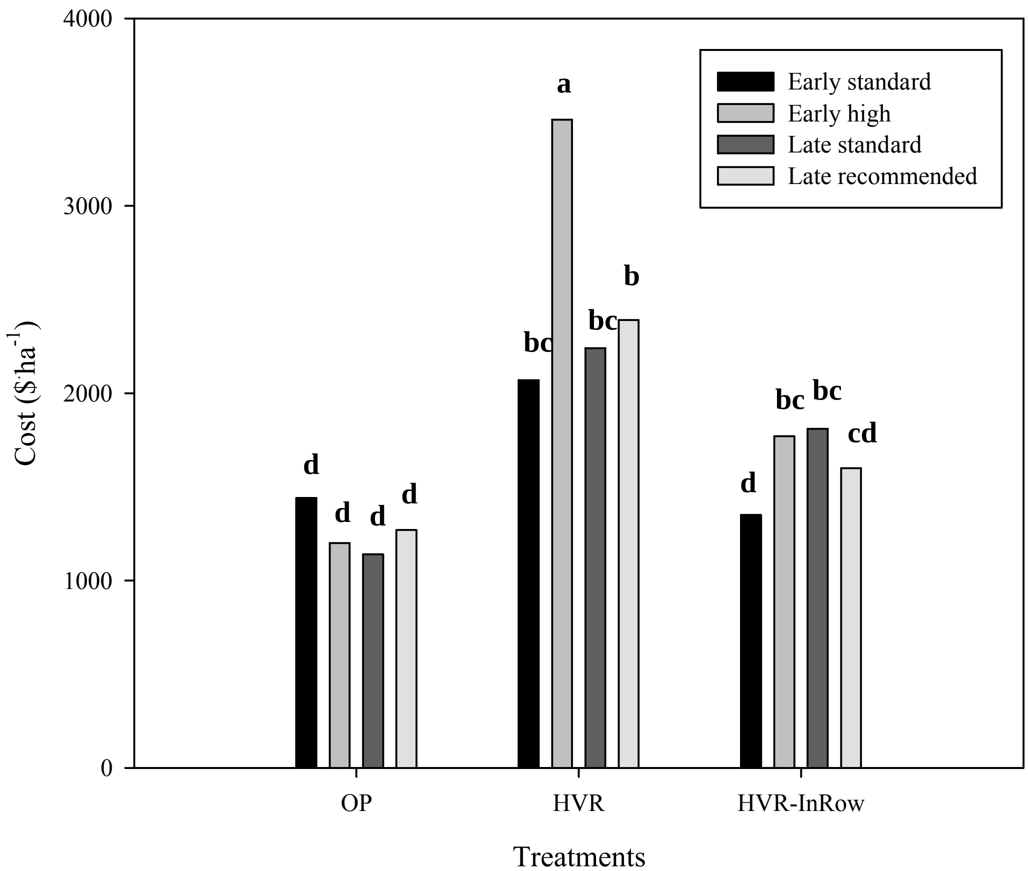

Figure 6. Cost of weed management ($) in 2009 for CCD*CCR*CCM interaction.

Discussion

As expected, OP cover crop was killed both winters (Clark, 2007), but biomass only remained in spring 2009. Active soil organic matter decomposition rates are mediated by soil microbial enzymatic activity, which is increased significantly with increased temperatures when no other limiting factors like pH, nutrient availability, oxygen, or moisture are active (von Lützow and Kögel-Knabner, 2009). Although precipitation was greater in spring 2009, the comparatively higher temperature in winter and spring 2010 (Table 1) likely stimulated microbial activity enough to fully degrade the OP biomass by spring. The early CCD increased biomass both years, but this difference was only significant in 2009 (Table 3). Standard cover crop seeding rates should be followed to minimize costs (Table 13) unless reducing weed growth or producing seed are management objectives (Table 8). Plantings should be made as early as practically possible, however, to maximize biomass production (Table 3).

However, hairy vetch-rye residue, especially in HVR-InRow plots, decreased soil temperatures in early July both years (Figure 1 and 2). This decrease in temperature occurred during a rapid growth phase for peppers (Gaskell and Smith, 2007). The higher temperature in OP plots likely increased soil N mineralization, because OP plots had higher soil soluble N, despite lower N inputs from cover crop residue. Soil soluble N may also have been increased in OP plots compared with HVR and HVR-InRow plots by pre-season rototilling which aerated the soil and would have promoted N mineralization (D'Haene, 2008); the greater soluble N in OP relative to HVR and HVR-InRow was higher in 2010, after rototilling twice. A control for a similar study in the future should include a treatment with hairy vetch-rye mowed and incorporated, to compare relative effects on plant-available N.

Although increased N fertility in OP plots (Table 3) may have increased the biomass of nitrophilic weeds such as *Amaranthus* spp. midseason, non-nitrophilic weeds such as *Stellaria media* were also abundant, and greater weed counts and biomass did not always coincide with greater N fertility (Table 4 and 6). The OP treatment had high numbers of weeds at the end of the season in 2009 (Table 7), when soil soluble N was equivalent to the other treatments (Table 6). Moreover, HVR plots had greater midseason weed biomass than HVR-InRow plots in 2009 (Table 8), although soil soluble N was equivalent (Table 6). The increase in-row residue in HVR-InRow (Table 4) decreased weeds (Table 7 and 8), which is consistent with previous findings on concentrated residue amounts (Teasdale and Mohler, 2000). Greater in-row residue in HVR-InRow may have mitigated the effect of lower soil soluble N by decreasing weed competition; marketable pepper yield in HVR-InRow was equivalent to the other treatments in 2009 (Table 10).

Total marketable yield was greater in 2010 than 2009 (Table 10), likely from higher summer air temperatures and lower summer precipitation (indicating increased sunlight) (Table 1) and greater N inputs from compost and manure. In 2010, larger plant size of OP plots led to higher early and total yields, outweighing the benefits of decreased weeds from residue suppression in HVR-InRow plots Although concentrated residue in HVR-InRow plots decreased weeds relative to HVR plots, yields in HVR and HVR-InRow plots were equivalent both years. Economically, weed control in OP plots was cheapest, and weed control in HVR-InRow was cheaper than in HVR plots, mainly due to residue decreasing costs of weeding by hand (Table 12). Cultivating plots was likely more effective in OP plots, with no residue, and HVR-InRow plots, with residue concentrated in-row.

Although concentrating cover crop residue in this reduced-tillage, organic vegetable system did not successfully maintain yields relative to the same system without cover crop residue, it did reduce weed pressure and weed control costs relative to the same zone-tillage system with the cover crop handled in a more conventional manner. Although yield is always of great importance to the farmer, yield in any given year needs to be weighed against the proven advantages of systems that include high biomass cover crops in the rotation.

Also, this system could be successfully applied in other ways. Warm-season crops such as peppers yield better with higher soil temperatures in temperate climates, regardless of fertility (Wein, 1997). Because the concentrated residue did decrease the number and biomass of in-row weeds significantly, moving mulch in-row could be used with less temperature-sensitive crops such as *Brassicas*. Nitrogen fertility should still be carefully managed to insure optimal yields, especially when tillage is reduced. In both years, the field was plowed before planting cover crops and this research was thus done during the first year of transition to a conservation tillage system. Additionally, because N fertility can build up in the soil after several years of reduced tillage (Doran, 1980), concentrating cover crop residue in-row may be more effective after transition.

After several years of reduced tillage, perennial weeds typically increase. The majority of weeds in this system were warm- and cool-season annuals and the density of perennial weeds was too low to assess their response to the treatments, but anecdotal observations indicate that many perennial species emerge readily through even very thick layers of mulch (C. Mohler, pers. comm.). One way growers could use the zone-tillage/residue movement system explored here and still control perennial weeds would be to rotate weed management and tillage intensity to match field conditions and crops. Cover crop residue could be used to reduce in-row weeds in fields with low perennial weed populations, sufficient soil fertility, and cool-season crops. Tillage intensity could be increased when needed to manage perennial weed infestations. These practices should increase soil quality in the long-term to ensure future crop production.

WORKS CITED

Carrera, L.M., A.A. Abdul–Baki, and J.R. Teasdale. 2004. Cover crop management and weed suppression in no–tillage sweet corn production. HortScience. 39(6):1262–1266.

Clark, A (ed.). 2007. Managing Cover Crops Profitably, 3rd edition. USDA Sustainable Agriculture and Research Education. Sustainable Agr. Publications. Beltsville, MD.

Clark, A.J., A.M. Decker, and J.J. Meisinger. 1994. Seeding rate and kill date effects on hairy vetch–cereal rye cover crop mixtures for corn production. Agron. J. 86(6):1065–1070.

Cline, G. R., and A.F. Silvernail. 2001. Residual nitrogen and kill date effects on winter cover crop growth and nitrogen content in a vegetable production system. HortTech. 11(2):219–225.

Delgado, J. A. 1998. Sequential NLEAP simulations to examine effect of early and late planted winter cover crops on nitrogen dynamics. J. of Soil and Water Conservation. 53(3):241–244.

Delgado, J. A., M.J. Shaffer, and M.K. Brodahl. 1998. New NLEAP for shallow and deep rooted crop rotations. J. Soil Water Cons. 53(4):338–340.

Dendooven, L., R. Merckx, and K. Vlassak. 1995. Limitations of a calculated N mineralization potential in studies of the N mineralization process. Plant and Soil. 177(2):175–181.

D’Haene, K., J. Vermang, W.M. Cornelis, B.L.M. Leroy, W. Schiettecatte, S. De Neve, D. Gabriels, and G. Hofman. 2008. The effect of reduced tillage on nitrogen dynamics in silt loam soils. Soil and Tillage Res. 45(2):213–217.

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. of Amer. J. 44(4):765–771.

Drinkwater, L.E., C.A. Cambardella, J.D. Reeder, and C.W. Rice. 1996. Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. In: Doran, J.D. and Jones, A., Editors, 1996. Methods for Assessing Soil Quality, Soil Science Society of Amer., Madison, WI:217–229.

Gaskell M. and R. Smith. 2007. Nitrogen sources for organic vegetable crops. HortTechnology. 17(4):431–441.

Gast, K.L.B. 1994. Harvest Maturity Indicators for Fruits and Vegetables. Kansas State University. 25 October 2010. <http://www.ksre.ksu.edu/library/hort2/mf1175.pdf>.

Glasmeier, A.K. Living Wage Calculator. Poverty in America, Pennsylvania State University. 20 August 2010. <http://www.livingwage.geog.psu.edu/>.

Keeney, D.R. and J.M. Bremner. 1966. Comparison and evaluation of laboratory methods of obtaining an index of soil nitrogen availability. Agron. J. 58(5):498–503.

Lu, Y.C., K.B.Watkins, J.R.Teasdale, A.A. Abdul–Baki. 2000. Cover crops in sustainable food production. Food Rev. Intl. 16(2):121–157.

Mohler, C.L. and J.R. Teasdale. 1993. Response of weed emergence to rate of *Vicia-villosa* Roth and *Secale cereale* L. residue. Weed Res. 33(6):487-499.

NEWA. 2010. Network for Environ. and Weather Awareness. New York State Integrated Pest Management Program, Cornell University. 24 October 2010. <http://newa.nysaes.cornell.edu/>.

NRCC. 2010. Northeast Regional Climate Center, Cornell University. 24 October 2010. <http://www.nrcc.cornell.edu/climate/ithaca/>.Pike, A. W. 2010. Pennsylvania's 2010 Machinery Custom Rates. U.S. Dept. Agr., Natl. Agricultural Stat. Serv., Harrisburg, PA.

Rosecrance, R.C., G.W. McCarty, D.R. Shelton, and J.R. Teasdale. 2000. Denitrification and N mineralization from hairy vetch and rye cover crop monocultures and bicultures. Plant Soil. 227(1–2):283–290.

Ruffo M.L. and G.A. Bollero, 2003. Modeling rye and hairy vetch residue decomposition as a function of degree–days and decomposition days. Agron. J. 95(4):900–907.

Sainju, U. M., W.F. Whitehead, B.P. Singh. 2005. Biculture legume–cereal cover crops for enhanced biomass yield and carbon and nitrogen. Agron. J. 97(5):1403–1412.

Tabaglio, V., C. Gavazzi, M. Schulz, and A. Marocco. 2008. Alternative weed control using the allelopathic effect of natural benzoxazinoids from rye mulch. Agron. for Sustainable Dev. 28(3):397–401.

Teasdale, J.R. and A.A. Abdul–Baki. 1998. Comparison of mixtures vs. monocultures of cover crops for fresh–market tomato production with and without herbicide. HortScience. 33(7):1163–1166.

Teasdale, J.R. and C.L. Mohler. 2000. The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci. 48(3):385–392.

Treadwell, D.D., N.G. Creamer, J.R. Schultheis, and G.D. Hoyt. 2007. Cover crop management affects weeds and yield in organically managed sweetpotato systems. Weed Technol. 21(4):1039–1048.

Varco, J. J., W.W. Frye, M.S. Smith, and C.T. MacKown. 1989. Tillage effects on nitrogen recovery by corn from a nitrogen–15 labeled legume cover crop. Soil Sci. Soc. Am. J. 53(3):822–827.

von Lützow, M. and I. Kögel–Knabner. 2009. Temperature sensitivity of soil organic matter decomposition—what do we know? Biology and Fertility of Soils. 46(1):1–15.

Wein, H.C. (ed.) 1997. The Physiology of Vegetable Crops. 1st ed. CAB Intl. Wallingford, U.K.

Wilson, D. O. and W.L. Hargrove. 1986. Release of nitrogen from crimson clover residue under two tillage systems. Soil Sci. Soc. Am. J. 50(5):1251–1254.

APPENDIX

Table A1. Soil N mineralization potential (NH4+-N) sampled two and three times during the 2009 and 2010 season, following cover crops seeded at different dates (CCD) and rates (CCR) and in-season management strategies (CCM). Plots were managed organically in Freeville, NY.

Treatment	Soil N mineralization potential ($mg \cdot kg^{-1} \cdot wk^{-1}$)				
	2009		2010		
	23 Jun	8 Sept	25 May	15 Jun	30 Sept
CCD					
Early[z]	8.2	5.7	9.5 b	14.9	6.8
Late	8.5	5.8	6.8 a	12.0	7.2
CCR					
Standard[x]	8.4	5.8	8.4	12.0	7.3
High	8.3	5.7	7.8	14.8	6.7
CCM					
OP	8.1	5.6	3.8	11.2	5.8
HVR	9.6	6.4	9.9	14.6	7.0
HVR-InRow	7.4	5.2	10.7	14.6	8.2
Statistical significance					
CCD	ns	ns	0.044	ns	ns
CCR	ns	ns	ns	ns	ns
CCM	ns	ns	ns	ns	ns
CCD*CCR	ns	ns	ns	ns	ns
CCD*CCM	ns	ns	ns	ns	ns
CCR*CCM	ns	ns	ns	ns	ns
CCD*CCR*CCM	ns	ns	ns	ns	ns

[z]Early seeding date was 5 Sept. 2008 and 30 Aug. 2009 and late seeding date was 26 Sept. 2008 and 21 Sept. 2009.

[y]Means followed by different letters are significantly different at LSD=0.05.

[x]Standard and high seeding rates were 112 and 224 $kg \cdot ha^{-1}$ oats and 56 and 112 $kg \cdot ha^{-1}$ peas, or 112 and 224 $kg \cdot ha^{-1}$ rye and 28 and 56 $kg \cdot ha^{-1}$ hairy vetch, respectively.

Table A2. Petiole sap NO^{3-}-N concentrations taken 6 Aug. 2009 of bell peppers cv. 'Ace' grown following cover crops seeded at different dates and rates and in-season management strategies. Plots were managed organically in Freeville, NY, 2009.

Plot number	Reflectoquant ($mg \cdot L^{-1}$)	Cardymeter ($mg \cdot L^{-1}$)
304	1155	1065
305	1490	1625
207	1535	1100
Outside of treatment plots, unfertilized	10	1577.5