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# Reduced Tillage and Living Mulches for Organic Vegetable Production

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REDUCED TILLAGE AND LIVING MULCHES FOR ORGANIC VEGETABLE  
PRODUCTION

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THESIS

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of  
Science in the College of Agriculture at the University of Kentucky

By

Alex Hessler

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Director: Dr. Krista Jacobsen, Assistant Professor

Lexington, Kentucky

2013

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## ABSTRACT OF THESIS

### REDUCED TILLAGE AND LIVING MULCHES FOR ORGANIC VEGETABLE PRODUCTION

Reduced tillage and living mulches are alternative management strategies that can improve soil quality by minimizing disturbance and building soil organic matter. Weed suppression by these two practices alone is often insufficient to avoid crop yield losses, but their performance in an integrated system is not well understood. This project investigated the production of bell pepper (*Capsicum annuum L.*) and dry bean (*Phaseolus vulgaris L.*) in conventional tillage and strip tillage with a living mulch of teff (*Eragrostis tef Zucc.*) and Korean lespedeza (*Kummerowia stipulacea Maxim.*). Yields of pepper and bean were generally higher under conventional tillage without living mulch. Weed biomass was not influenced by tillage, and was adequately suppressed by teff in a year when conditions for teff growth were favorable. Mowing appeared to suppress weed growth but not living mulch growth. Soil nitrate and ammonium concentration was generally higher under conventional tillage without living mulch. Delaying living mulch seeding by 15 days after crop establishment generally did not affect weed suppression or crop yield. Soil aggregate stability was not consistently affected by tillage or living mulch. Increased mowing frequency, living mulch planting delay, or distance between the crop row and the living mulch may be necessary to achieve acceptable yields with living mulches.

KEY WORDS: Reduced Tillage, Living Mulch, Weed Suppression, Aggregate Stability, Vegetable Production.

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December 11, 2013

REDUCED TILLAGE AND LIVING MULCHES FOR ORGANIC VEGETABLE  
PRODUCTION

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## **Chapter One: Literature review**

### Sustainable agriculture systems

Soil is a physically heterogeneous, chemically dynamic, and biologically active medium that plays a fundamental role in mediating important biogeochemical processes. Many functions, including water storage and release, nutrient cycling, and carbon sequestration are critically important for the production of crops for food, fuel and fiber. Soil quality is a relative measure of a soil's ability to perform these functions. In agroecosystems, the provision of adequate amounts of necessary plant nutrients, water, and oxygen are the primary soil functions related to plant productivity. High quality soils are characterized by conditions that promote root growth and exploration, high water holding capacity, and adequate drainage and aeration (Magdoff and Van Es 2000). This literature review will focus on the elements of sustainable agriculture systems that have significant impact on soil quality, including tillage and cover cropping. Influences of these two practices on soil organic matter, nitrogen fertility, and weed management will be discussed because these issues are major challenges to organic and sustainable production systems. Challenges and opportunities of reduced tillage, for vegetable production in particular, are central to the scope of this project. The second half of the literature review is a thorough survey of living mulches, their management, and challenges to annual crop production.

### Soil organic matter

Soil organic matter (SOM) is comprised of the living and decomposing biomass of organisms within the soil profile. Carbon accounts for approximately half of the mass of soil organic matter (Brady and Weil 1996). Soil particles are bound together into aggregates by fungal hyphae and secondary substances, primarily polysaccharides, exuded by roots,

microorganisms, and microfauna, primarily earthworms (Oades 1993). Aggregation generally reduces soil bulk density, which increases total porosity and improves drainage, aeration, and tilth.

Aggregate formation is influenced by management practices such as tillage and cover cropping that control the accumulation and decomposition of SOM. Variation in aggregate size, structure, and persistence is a foundational component of observable differences in the impact of management systems on long-term soil quality and function. These factors generate a hierarchy of aggregation, with macroaggregates (250-2000 $\mu\text{m}$ ) comprised of microaggregates (53-250 $\mu\text{m}$ ) (Tisdall and Oades 1982). Humic substances, including humic and fulvic acid, formed by the enzymatic repolymerization of lignin and cellulose (Stevenson 1994), promote the flocculation of clay colloids into masses that are the building blocks of soil aggregates (Kretzschmar et al. 1993). Macroaggregate formation is initiated by the binding together and envelopment of soil colloids held by roots and hyphae, and via complexation with microbially derived binding substances (Six et al. 2000). Fragmented organic residue, known as particulate organic matter (POM), is the source of nutrients and energy for microbial growth within and around aggregates. Microaggregate formation occurs within macroaggregates, and is associated with further decomposition of POM and generation of binding substances (Gale et al. 2000). Ultimately, occlusion of POM within aggregates affords a degree of protection from faster rates of decomposition that occur in the more oxygen-rich environment outside of the aggregate (Six et al. 2002).

Nutrient cycling is influenced by the quantity and form of SOM. Sources of organic matter include crop and cover crop residues, compost, and manure. Fresh residues and their recently decomposed cellular constituents are more readily available for microbial oxidation than

their more stable, humified end products. Labile pools of SOM are more sensitive to short term changes in management and have greater influence on nutrient cycling because they are actively involved in biological mineralization and immobilization processes. Organic production systems that include the addition of composts, cover crops, crop residues generate increased SOM, greater bacterial diversity, and a greater capacity to mineralize nitrogen from labile organic matter than conventional systems without these inputs (Berthrong et al. 2013). While long-term organic management may not necessarily increase total soil carbon content, even small increases in the active SOM pool facilitate the production of microbial binding agents that promote soil aggregation (Drinkwater et al. 1995; Steele et al. 2012). Diversity in microbially-mediated patterns of organic matter decomposition also holds promise for synchronizing nutrient availability with crop uptake (Drinkwater and Snapp 2007). Cover crops with a high carbon to nitrogen ratio may promote immobilization of nitrogen immediately following incorporation, then a steady release later in the season (McSwiney et al. 2010).

Inputs of organic matter, endogenous or external, are fundamental drivers of biologically-derived aspects of soil quality. However, long-term studies have demonstrated that SOM levels can decrease because of intensive tillage in spite of the use of organic amendments, cover cropping, or crop rotation (Reeves 1997). Tillage facilitates the oxidation of organic matter by incorporating oxygen into the soil profile, breaking apart soil aggregates, and placing residues into an environment that accelerates decomposition (Magdoff and Van Es 2000). Tillage also creates a soil environment more favorable for bacteria, which are less efficient than fungi at incorporating fresh residues into stable organic matter pools (Six et al. 2006). There is growing awareness that addressing challenges to improving and maintaining soil quality requires

integrating best management practices for crops, fertilizers, irrigation, tillage, and pest management (Karlen et al. 1997).

### Cover crops

It is common practice for farmers to leave soil bare following the harvest of a crop until the following crop is established. A fallow period provides opportunities to manage weeds, and in arid climates, preserve soil moisture by minimizing evapotranspiration. In instances where crop residues may harbor overwintering pathogens, incorporating residues into the soil speeds decomposition and the destruction of pathogenic survival structures (Silva et al. 2012). The most common period in which agricultural fields are left bare is winter and early spring. There are several risks to soil and environmental health posed by bare fallowing during this time. Elevated levels of precipitation may contribute to leaching of inorganic nitrate into ground and surface water (Blesh and Drinkwater 2013). Estimates of losses of nitrogen applied to agricultural fields worldwide are 50% (Smil 1999). Soil erosion driven by water runoff depletes topsoil and is an additional source of sediment and nutrient pollution in surface waters.

Maintaining active plant growth during the off-season is a strategy used to address soil quality concerns during the non-production period of the cropping sequence. A cover crop is a plant not harvested for economic yield, but grown for the purpose of imparting benefits to the soil and the subsequent cash crop. A primary impetus for the early adoption of cover crops by farmers in North America was the reduction in fertilizer inputs via the scavenging of residual nitrogen following crop harvest. Cover crops that reduce nitrogen leaching potential must be capable of exploring the soil volume containing nitrogen while it is still accessible. For most

agricultural systems in temperate climates, that means a cover crop must put on sufficient growth after crop harvest, and prior to the onset of prohibitively cold temperatures and short day-lengths.

Many cereal grains, including winter rye, wheat, oats, and triticale grow well in autumn and spring, and are commonly sown as cover crops (Clark 2008). Winter cover crops can scavenge from 30 to 70 percent of residual nitrate following the removal of a main-season cash crop (Faega et al. 2010; Tonitto et al. 2006; Wyland et al. 1996). Winter cover crops may also reduce erosion by more than 50 percent by intercepting rain, promoting water infiltration, and securing soil around roots (Kaspar et al. 2001).

Summer cover crops can be grown during fallow periods after the harvest of a short-season spring crop or before planting of a fall crop. Warm temperatures and long day length during this period generally facilitate more rapid growth and greater biomass accumulation relative to winter cover crops, however, opportunity costs of growing summer cover crops may be greater than for winter cover crops because they preclude the production of a cash crop during the primary growing season (Snapp and Borden 2005). An evaluation of summer cover crops grown in the Southeastern United States found biomass accumulation ranging from 1420 kg ha<sup>-1</sup> to 4807 kg ha<sup>-1</sup> for legumes, and 3918 kg ha<sup>-1</sup> to 8792 kg ha<sup>-1</sup> for grasses (Creamer and Baldwin 2000).

Cover crops are a primary source of organic matter for promoting soil aggregation and improving soil quality. Decomposing cover crop residue, along with root exudates, promote soil aggregation (Schutter and Dick 2002; Hermawan and Bomke 1997). SOM derived from cover crops behaves differently than from other commonly-used sources of organic matter like animal manure or compost. Cover crops generally generate greater total SOM, with most accumulation

associated with more stable pools, while SOM derived from animal manure is more labile and biologically active (Wander et al. 1994). Differences in SOM formation are attributable to greater bioavailability of carbon and nitrogen in manure relative to plant residues.

#### *Nitrogen contribution of cover crops*

Legume cover crops contribute nitrogen to agroecosystems via symbiosis with nitrogen-fixing bacteria of the genus *Rhizobium*. Nitrogen mobility from leguminous residues differs from that of synthetic nitrogen sources in that its release is mediated by biological decomposition and incorporation into SOM (Crews and Peoples 2005). Total nitrogen content in above ground legume biomass can range from 10 to 217 kg ha<sup>-1</sup>, with 70 to 100% derived from atmospheric fixation (Parr et al. 2011). Blevins et al. (1990) estimated that the fertilizer equivalency value of a vetch (*Vicia spp. L.*) cover crop was 65 to 75 kg ha<sup>-1</sup> preceding corn and 125 to 135 kg ha<sup>-1</sup> preceding grain sorghum. Due to losses from leaching and volatilization, however, not all cover crop-derived N is available for uptake by the following crop (Smith et al. 2007).

The availability of nitrogen captured by non-leguminous cover crops is mediated by factors governing microbial decomposition of organic matter. Typically, nitrogen mineralization by microbial decomposition is favored by organic materials with a C:N ratio of approximately 25:1 (Magdoff and Van Es 2000). The average nitrogen content in summer cover crop biomass amounted to 69.5 kg ha<sup>-1</sup> for legumes and 61.2 kg ha<sup>-1</sup> for grasses, as measured by Creamer and Baldwin (2000). Though the *potential* nitrogen contribution from legume and grass cover crops is high, the C:N ratio of legumes is typically more favorable for mineralization, while for grasses will sometimes favor immobilization (Creamer and Bladwin 2000; Wyland et al. 1995).



Cover crop maturity at termination regulates the C:N ratio and the degree of lignification of plant cells, and influences the degree of immobilization that will occur (Waggoner 1989). Terminating cover crops at an immature stage may mitigate immobilization potential (Clark 2008). Fragmentation of cover crop residues by mowing increases the total amount and rate of nitrogen released by increasing residue surface area and accessibility to microbial attack (Snapp and Borden 2005; Creamer and Dabney 2002). Net mineralization of nitrogen from grass cover crops can be improved by integrating legumes into the mixture. Kuo and Sainju (1998) determined that nitrogen immobilization immediately following cereal rye (*Secale cereal L.*) and vetch incorporation occurred when vetch comprised 40 percent or less of the mixture, while mineralization initiated when vetch content was 60 percent or greater. In addition to improving nitrogen mineralization, cover crop polycultures containing legumes and grasses may accumulate more biomass than either species grown alone (Ranells and Waggoner 1996).

### Reduced tillage

Tillage accomplishes several goals of soil management that benefit crop production. Tillage loosens and homogenizes soil, which improves crop stand establishment and root exploration. Tillage distributes fertilizers, soil amendments, and plant residues into the profile where they are more readily mineralized and available for plant uptake. Tillage also facilitates soil conditions conducive to the effective use of many cultivation tools used for mechanical weed management (Bond and Grundy 2001).

Concerns about the negative impact of conventional tillage (CT) on soil quality have spurred interest in and adoption of reduced tillage (RT) practices. RT includes practices that maintain 30% or of the soil surface area undisturbed. RT encompasses no tillage (NT) as well as

strip tillage (ST) in which only a narrow band for planting the crop is tilled. RT systems typically require the purchase of or modification of tillage, planting, and cultivation equipment that can operate in soils with surface residue. These costs as well as perceived uncertainty of the performance of crops in RT systems are barriers to adoption of RT for some farmers (Rahm and Huffman 1984).

The principal factor responsible for differences in soil quality generated by CT and RT practices is the relative loss or accumulation of SOM. There is great diversity in the depth, intensity, and frequency of tillage in CT systems accomplished by a range of implements. Whereas the majority of organic residues remain on the soil surface in RT systems, especially NT, CT macerates and redistributes residues throughout the soil profile. In three Illinois soils, SOM-carbon and POM-carbon increased by 25-70% in the top five cm of the soil after nine years of NT management, but decreased by 4 to 18% from 5 cm to 17.5 cm deep, relative to CT (Wander et al. 1998).

Long-term evaluations of SOM-carbon changes in agroecosystems have demonstrated that NT generally accumulates more SOM-carbon than CT in the, with a typical difference of approximately  $30 \text{ g m}^{-2} \text{ year}^{-1}$  (Magdoff and Weil 2004). Higher and more consistent moisture content in the soil versus on the soil surface contribute to more rapid decomposition of organic residues in CT systems (Franzluebbers et al. 1996). Slight differences in total SOM-carbon have a disproportionate influence on the physical, chemical, and biological properties of soil quality and function. The lack of soil disturbance and provision of surface litter in NT reduces erosion, and encourages a greater abundance of arthropods and earthworms, which promote cycling of nutrients near the soil surface (Hendrix et al. 1986; Karlen et al. 1994). Lal et al. (1994) found SOM-carbon concentrations decreasing along a gradient of increasing tillage intensity (no tillage

> chisel plow > moldboard plow) and decreasing rotational diversity (corn + oat + meadow > corn + soybean > corn). Production systems that include a diversity of organic inputs, including cover crops and manures, may actually accumulate more soil SOM-carbon and nitrogen than NT systems that do not include organic amendments (Teasdale et al. 2007).

The formation and turnover of aggregates is a more sensitive indicator of soil quality than total carbon. Tillage in CT systems accelerates the decomposition of macroaggregates, thus limiting the formation of microaggregates within macroaggregates. Coarse-sized POM (250-2000  $\mu\text{m}$ ) decreases in size as it decomposes into fine POM (54-250  $\mu\text{m}$ ) and is incorporated into microaggregates (Guggenberger et al. 1994). Carbon constituting fine POM and associated microbially derived binding agents within microaggregates tends to be older and more persistent than that associated with coarse POM, roots, or fungal hyphae (Jastrow et al. 1996). The concentration of fine inter-aggregate POM (iPOM), but not coarse iPOM or free light fraction POM, accounted for the majority of the difference in total SOM-carbon between NT and CT in long term comparison trials in four Midwestern states (Six et al. 1999). While Six et al. (1998) found greater total SOM-carbon in NT than CT converted from natural sod only in the top 5 cm, bulk soil values were not different. The amount of iPOM in NT (337 g C m<sup>-2</sup>), however, was 57% greater than in CT (193 g C m<sup>-2</sup>). The proportion of fine iPOM in NT accounted for the majority of the difference in total POM-carbon between tillage systems, suggesting that the POM within aggregates was older, and hence, more protected from decomposition.

#### *Reduced tillage in vegetable production*

Tillage is a fundamental practice for ensuring yield and quality in most vegetable production systems. The high value of vegetables relative to agronomic crops warrants the

provisioning of optimal conditions for plant growth. Tillage practices that form raised beds are common in vegetable systems for the purposes of promoting soil warming, drainage, and tilling. Tillage is also necessary to facilitate the use of black plastic mulch, which has been shown to generate earlier (one to three weeks) and increased (two to three times) yields relative to bare ground (Lament 1993).

Interest in the environmental and economic benefits of RT has motivated researchers to adapt RT practices to vegetable production systems. Adoption among growers has been facilitated by advancements in RT planting technology, cover crop management, and integrated weed management (Morse 1999). RT environments are typified by a high degree of organic residue retention on the soil surface, which hinders the operation of many standard seeding and transplanting implements. RT planters must be equipped with residue clearing or cutting componentry to enable firm soil contact with seeds or transplants without obstruction by residue (Hoyt et al. 1994). Strip tillage (ST) implements create soil conditions within a narrow tilled strip in which normal, low-residue planting equipment can operate (Wilhoit et al. 1990).

Cover crops grown prior to planting vegetables contribute to surface residue loading in RT systems. Weed suppression is positively correlated with the amount and permanence of cover crop residues on the surface (Price and Norsworthy 2013). Cover crops that are terminated by rolling rather than mowing or herbicide (Leavitt et al. 2011), or have a high carbon to nitrogen ratio (Clark 2008) are more resistant to decomposition and tend to suppress weeds for a longer period. Davis (2010) investigated both factors and found that weed control by rye and vetch cover crops was 26% and 56% greater, respectively, when the cover crops were terminated by roller-crimping rather than herbicides. Weed control, even by a very carbonaceous cover crop

like cereal rye, can be variable, and supplementation with a post-emergence herbicide may improve weed suppression (Mischler et al. 2010).

The desirable level of cover crop biomass production is a compromise among the various management objectives influenced by surface residue. Slower decomposition of residues placed on the surface, primarily due to low moisture content and wet-dry cycles, can reduce mineralization of nitrogen in residues by 30 to 40 percent (Mulvaney et al. 2010). Yields are sometimes depressed in RT systems because the persistence of surface residue prolongs nitrogen immobilization (Jackson et al. 2004).

Cover crop residue intercepts sunlight and can moderate soil surface temperature. Exposed soil absorbs more sunlight than soil covered by residue, and warms more quickly in the spring. Most crops germinate and emerge more quickly in warmer soils, and become better competitors against weeds sooner, resulting in earlier yields. Soil warming is especially important for crops planted earlier in the season, or in climates with unfavorably short or cold summers. Earlier and higher total yields of warm season vegetable crops like pepper, tomato, or squash have been attributed to warmer soil temperatures under black plastic mulch relative to NT systems with or without cover crop residues (Abdul-baki et al. 1999). Yield reductions of vegetable crops planted in RT systems can sometimes be avoided if transplanting is used instead of direct seeding (Mochizuki et al. 2008; Walters and Kindhart 2002).

The presence of surface residue in RT systems can interfere with several key vegetable crop management practices. A rye and vetch cover crop reduced sweet corn yields more than vetch alone (34% versus 19%) because the residue interfered with seed placement, reducing stand establishment and corn ear production (Teasdale et al. 2008). Luna et al. (2012) cited

transplanter obstruction, ineffective weed cultivation, moisture loss and planting delays while waiting for cover crops to mature as principle causes for yield losses of NT pumpkin, cotton, tomato, eggplant, and cowpea. More optimistic yields for broccoli grown with ST suggest that ST may be a more feasible RT strategy.

ST affords the benefits of residue retention between the tilled strips with improved growing conditions in the crop row. Yields of unirrigated cabbage in a ST rye cover crop mulch were equal to that of CT in years with normal precipitation, and 56% higher in an especially dry year (Wilhoit et al. 1990). In some cases, ST can mitigate decreased soil temperature that sometimes reduces yield in NT (Licht and Al-Kaisi 2005). Increasing strip width may generate only marginal increases in soil temperature, while increasing strip depth markedly decreases penetration resistance and increases vegetable crop yield (Mochizuki et al. 2007). Weed management in ST systems is complicated by disparity in weed dynamics and available management techniques presented by the juxtaposed tilled and untilled environment. Novel approaches to managing in-row weeds in ST are necessary, and may involve adapting current techniques for more precise in-row cultivation, or by moving residue into the row (Rostompour 2010). The integration of systems-based management practices like rotation and cultivation that address weed population dynamics in tilled and un-tilled environments is necessary to successfully control weeds in this mixed environment (Brainard et al. 2013).

Net returns from vegetable production systems utilizing RT are a function of the costs of implementing RT and influences on crop yield and quality. Savings in fuel consumption and labor associated with tillage are common with NT and ST. Luna and Staben (2002) calculated that costs of tillage under ST of were reduced by \$36.5 - \$38.5 ha<sup>-1</sup> compared to CT, with an associated reduction in equipment operating time of 0.47 – 0.59 hours ha<sup>-1</sup>. Brainard and Noyes

(2012) calculated equivalent or greater net returns, yield, and weed suppression from ST carrot with a barley crop left standing temporarily as a windbreak until carrot establishment. Where wet soils prohibit tillage for early-planted vegetables in the spring, RT may enable more timely and flexible planting (Carrera et al. 2005). The appropriate equipment, an adaptive approach to cover crop management, and a diverse suite of weed control strategies are fundamental to the success of RT vegetable production.

### Living mulches in sustainable agriculture

Maintaining soil coverage and building soil organic matter are primary motivations for adopting practices like cover cropping and reduced tillage. However, surface residues in conservation tillage may decompose too quickly to provide adequate weed suppression later in the season (Stivers-Young 1998). In the humid Southeast, where weed pressure is high and many soils are degraded, cost-effective soil and weed management strategies that address these interconnected challenges are needed.

Living mulches are cover crops inter-planted within a main crop, and are intended to protect and build soil structure while simultaneously suppressing weed germination and growth. Living mulches can fix nitrogen, harbor beneficial insects, and disrupt pests and diseases (Mohammadi 2012). Living mulches have not been widely adopted, however, because of the difficulty of achieving adequate weed suppression while minimizing competition between the living mulch and crop (Liebman and Staver 2001).

### *Living mulch species*

Plant species grown as living mulches are chosen to suit the objectives of the particular crop management system for which they are used. The ideal living mulch would have the ability

to adequately suppress weed growth without causing reductions in crop yield through competition light, water, and nutrients. Certain plant species exhibit morphological or phenological growth patterns that minimize interference with crop growth in space or time, respectively. Mechanical or chemical suppression of living mulches may be necessary if growth is too vigorous and resources, usually nitrogen or water, are scarce (Liebman and Dyck 1993). Low-growing leguminous species like clover (*Trifolium spp. L.*) and vetch are common candidates for use as living mulch. Subterranean clover (*Trifolium subterraneum*) is a short-statured perennial species that develops a dense groundcover during the autumn and early spring, then senesces in the summer in hot climates. Ilnicki & Enache (1992) found that weed suppression by subterranean clover was generally the same with or without the addition of herbicides or mowing. Subterranean clover's ability to spread via underground stolons contributes to its ability to suppress weeds (Clark 2008), but can also lead to invasion of the crop root zone and competition for nutrients (Lanini et al. 1989). Den Hollander et al. (2007) found that living mulches of subterranean clover, Persian clover (*Trifolium resupinatum*), red clover (*Trifolium pratense*), alsike clover (*Trifolium hybridum*), berseem clover (*Trifolium alexandrinum*), crimson clover (*Trifolium incarnatum*), and white clover (*Trifolium repens*) reduced leek biomass by 60 – 90%, and that the greatest reductions were caused by subterranean clover.

Perennially grown clover species may be especially problematic as living mulches because their well-established root systems may occupy a larger volume of soil than that of annual crops. Differences in yield between wet and dry years (Pederson et al. 2009) or coarse and fine-textured soils (Sawyer et al. 2010), were indicative of competition for water between non-irrigated crops and a kura clover (*Trifolium ambiguum*) living mulch. Ochsner et al. (2010)



measured matric potentials of -4 kPa in the bareground treatments, and from -36 to -41 kPa in kura clover living mulch treatments, at the one meter depth. Perennial white clover forms a denser, more weed suppressive canopy than many other clovers, but still results in yield losses compared to bare ground cultivation if grown too close to the crop (den Hollander et al. 2007; Fischer and Burrill 1993). Annual clovers may suppress weeds without reducing yields when inter-sown between tightly spaced rows of rapidly growing crops like fall broccoli or cabbage (Costello 1994; Infante and Morse 1996) When weed pressure is high, combining a legume with a more aggressively growing cereal grass can suppress weeds more effectively without impacting yields if the living mulch is seeded 2-3 weeks after crop establishment (Vanek et al. 2005).

Buckwheat (*Fagopyrum esculentum Moench*) germinates quickly and forms a dense, weed-suppressive canopy before weeds have time to establish (Clark 2008). Buckwheat has been widely used as a ground cover in vineyard and orchard alleyways to suppress weeds and attract pollinators (Berndt et al. 2002; Nicholls et al. 2000). The wide between-row spacing in vineyards and orchards, which typically includes a clean-cultivated or herbicide-sprayed strip directly beneath the crop, generally precludes competition from the buckwheat. Similar results in vegetable systems were found by Gibson et al. (2011) involving widely spaced, tall-growing crops like tomato. Buckwheat did not respond well to mowing, however, and did not suppress weed growth and seed production later in the season. Members of the Brassicaceae family commonly used as cover crops, including mustard and canola, exhibit similar growing habits as buckwheat. Additionally, the decomposing residue of brassica cover crops release glucosinolates, which have allelopathic properties that suppress seed germination, reduce seedling emergence, and hinder vegetative growth of other plants (Haramato and Gallandt 2004).

Many annual grasses used as cover crops accumulate a tremendous amount of aboveground biomass relative to legumes and broadleaves (Creamer and Baldwin 2000). Cereal rye (*Secale cereal*) is a widely used cover crop that can generate up to 10,000 pounds of biomass per acre (Clark 2008). Extensive tillering and rapid vertical growth, accompanied by a spreading fibrous root system, enable rye to compete aggressively with weeds for light, water, and nutrients. Rye living mulches have been used without negatively impacting yields if initial weed pressure is minimal and actions like delayed seeding or mechanical or chemical suppression are taken to curtail rye vigor (Ateh and Doll, 1996; Brainard and Bellinder 2004). In other cases, rye above-ground biomass (Chase and Mbuya 2008) and allelopathy (Walters and Young 2008, speculation) reduced yields of broccoli and zucchini, respectively, despite repeated mowing and the use of herbicides.

Ryegrass (*Lolium spp. L.*) is a perennial or semi-perennial grass that germinates quickly, does not form spreading stolons or rhizomes, and is extremely traffic-tolerant (UCIPM Online 2011). Italian ryegrass (*Lolium multiflorum*), has been investigated as living mulch for the purpose of reducing nitrate leaching in corn (Kaluli et al. 1999; Liedgens et al. 2004). However, Italian ryegrass and perennial ryegrass (*Lolium perenne*) as living mulches were found to reduce biomass and yield of corn (Faget et al. 2012) and pac choi (*Brassica rapa subsp. Chinensis*) (Wiles et al. 1989). Perennial stands of Kentucky bluegrass (*Poa praetensis L.*), creeping red fescue (*Festuca rubra L.*), and chewing fescue (*Festuca rubra subsp. commutate*) suppressed by herbicides have been used as living mulches for field corn production (Wiggins et al. 2012; Echtenkamp and Moomaw 1989). Competition for water between the living mulch and the crop reduced yields in both studies. Maintaining perennial living mulches may reduce seed and

establishment costs relative to annually planted living mulches, but the well-developed root system that forms over time may not be compatible with the resource demands of annual crops.

### Management to reduce living mulch-crop competition

#### *Establishment*

Living mulches can be established before, after, or concurrently with the planting of the crop. The timing of establishment plays a large role in determining the outcome of living mulch-crop interactions. In so much as the living mulch competes with the crop for resources, its influence on crop growth is analogous to competition from weeds. Leaf area generally increases exponentially in the early stages of vegetative growth (Liebman et al. 2001). Crops compete with living mulches for light most successfully when they are taller and have greater leaf area (Carof et al. 2007). Early emergence and canopy development facilitate the preemptive exploitation of available space and resources to the disadvantage of later emerging individuals. The period of time after emergence until the plant canopy is established and yield is not impacted by weeds is referred to as the critical weed free period (Knezevic et al. 2009). The length of the critical weed free period is a function of crop and weed growth rates and morphology, and will be augmented if transplants are used instead of seeds (Liebman et al. 2001). Weaver (1984) observed critical weed free periods of three weeks for transplanted cabbage, four weeks for direct seeded cucumber, and nine weeks for direct seeded tomato. The critical weed free period for transplanted tomato was five weeks (Weaver and Tan 1983).

Delaying seeding or otherwise limiting the growth of living mulches until the critical weed free period for the crop has partially or entirely passed is a potentially useful strategy for minimizing crop-living mulch competition. Typically, mechanical cultivation or pre- or post-

emergent herbicides are used to maintain weed free conditions prior to establishing the living mulch. Buckwheat seeded between tomato rows 7-9 weeks after transplanting did not influence yield and resulted in a 59% reduction in germinable weed seed production compared to a control where weeds were allowed to emerge 6-7 weeks after transplanting (Gibson et al. 2011). A delay of 10 - 20 days after transplanting was necessary to avoid yield reductions of broccoli by cereal rye (Brainard and Bellinder 2004) and cabbage by vetch and oats (Brainard et al. 2004). In both studies, however, the living mulch did not confer any additional weed suppressive benefit beyond cultivation prior to transplanting due to quick crop canopy closure in the double-row planting system. Kloen and Altieri (1990) found that waiting one week to seed mustard was sufficient to escape broccoli yield reductions. Yields of pumpkin with a vetch-rye living mulch seeded between rows 30 days after transplanting were the same as with the bare ground control, and significantly greater than when vetch-rye was seeded the same day or 20 days prior (Vanek et al. 2005). Weed biomass did not differ among seeding dates, suggesting that preemptive use of resources by pumpkin, rather than living mulch vigor, determined yields. Indeed, the experimenters noted lower soil inorganic nitrogen concentrations in both the pumpkin row and the living mulch row for before- and same-seeded treatments than after-seeded and bare ground treatments.

The living mulch seeding rate should reflect the dual objectives of suppressing weeds quickly and continuously while minimizing adverse interactions with the crop. Therefore, the seeding rate that generates the minimum amount of biomass that adequately suppresses weeds is optimal. 20 kg ha<sup>-1</sup> was a sufficient seeding rate for ryegrass living mulch at a site with low weed pressure (Faget et al. 2010). The seeding rate had to be increased to 50 kg ha<sup>-1</sup> at a site with high weed pressure to prevent weeds from overtopping soybeans and lowering yield.

Seeding rate may influence living mulch biomass when unfavorable conditions hinder living mulch establishment or productivity. Increasing the seeding rate may only improve ground cover in an unfavorably dry year for living mulch germination (Ateh and Doll 1996). Precipitation patterns and the availability of irrigation will determine the relative effectiveness of broadcast seeding living mulch seed versus drilling, which generally yields more consistent stands under dry conditions (Echtenkamp and Moomaw 1989).

### *Suppression*

A vigorous living mulch that effectively suppresses weeds has the potential to cause economically unacceptable crop yield losses due to direct competition for light, water, and nutrients. Management actions that reduce living mulch vegetative growth can limit interference with the crop's ability to capture the maximum amount of solar radiation for photosynthesis. Such actions may be correlated with a decline in living mulch root density and spread, which correlates with increased availability of water and nutrients for crop growth.

Herbicides applied at sub-lethal rates to living mulches can retard plant growth while at the same time reinforcing weed suppression efforts. Herbicides are critical for managing perennial living mulches in no-till production systems. Frequently, a 10-25 cm band of living mulch is killed with herbicide prior to no-till planting, and sub-lethal rates are used to suppress growth between crop rows throughout the season. Using this approach, Pederson et al. (2010) found that soybean yielded 13 – 23 percent less in a clover living mulch than a tilled control in a wet year, but 43 – 56 less during a dryer year. Corn may perform better than soybean in this system because of its rapid growth and height advantage (Oschner et al. 2010; Sawyer et al. 2010). For a short-statured vegetable crop like cabbage, using herbicides can prevent shading by

overtopping weeds even if living mulch biomass is not reduced (Brainard et al. 2004). Cabbage yields when herbicides were used each time rye living mulch height reached 25 cm were greater than treatments involving no herbicides, killing rye at 45 days after planting, or partial rotary hoeing (Brainard et al. 2004).

Mechanical means of suppressing living mulches, like mowing or partial tilling, can be used alone or in concert with herbicides to achieve more thorough control. While mowing may limit height and seed production of living mulches and weeds, total biomass production may be comparable to or greater than without mowing (Chase and Mbuya 2008). If weeds are prostrate or mowing-tolerant, mowing may not be an appropriate tactic (Gibson et al. 2011). Partial rototilling may more thoroughly suppress living mulch vigor than mowing, because the practice disrupts both above and below-ground growth (Brandsaeter et al. 1998). Illnicki and Enache (1992) investigated using herbicides to kill a 20 cm wide planting strip in an established stand of subterranean clover, and then mowing between rows throughout the season for a variety of crops. Mowing improved yields but not weed control for sweet corn, which benefitted from earlier soil warming facilitated by the shortened clover canopy. Mowing also did not improve weed control of summer squash and yields were lower than the control without living mulch. Mowing is rarely effective at reducing yield losses of small, poorly competing crops, even if mowing reduces living mulch biomass production (Wiles et al. 1989). Suppressing living mulch growth earlier in its development is probably critical to minimizing regrowth potential and biomass accumulation. However, controlling living mulch biomass production may not be an effective means of mitigating yield losses if the living mulch has allelopathic properties (Walters and Young 2008).

Other techniques are used to manipulate the availability of resources to the advantage of the crop. Plant and row spacing will determine if and when crop canopy closure occurs and shading minimizes living mulch and weed vigor. A two-row planting system for vegetables encourages quick canopy closure on the bed surface, with most living mulch and weed growth redirected towards the wheel tracks between beds (Infante and Morse 1996). Plant spacing influenced yields of field corn and sweet corn, which yielded as well with a white clover living mulch as without when row spacing was reduced from 0.76 to 0.38 m (Fischer and Burrill 1993). Drip irrigation and supplemental nitrogen applied as a side dress or through the irrigation system is often necessary for heavy-feeding vegetable crops grown with living mulches (R.D. Morse, personal communication). Research suggests that side-dressing does not necessarily reduce yield losses when the living mulch is an aggressive grass species like oats (Brainard et al. 2004).

#### *Influences on soil quality*

Weed management strategies used in annual crop production vary in their impact on soil quality and function. Mechanical cultivation disturbs the soil surface and promotes organic matter decomposition, potentially leading to short-term nitrogen mineralization and loss, and long-term soil structure degradation (Bond and Grundy 2000). The use of living mulches precludes the need for continuous soil disturbance and may contribute additional soil functional properties. The consumption of water and nutrients is the primary mechanism by which living mulches compete with a primary crop. If these nutrients are in excessive, however, their capture by living mulches can have environmental benefits. With lysimeters buried at 1.1 meters, Liedgans et al. (2004) observed 40 percent less deep percolation and 99 percent less leached nitrate beneath corn inter-planted with Italian rygrass compared to corn on bare ground. Using this same crop-living mulch combination, Kaluli et al. (1999) detected a 50 percent reduction in

nitrate in tile drainage water. No differences in deep drainage were observed when evaporation from bare soil was equal to that from corn in a kura clover living mulch (Ochsner et al. 2010). However, soil inorganic nitrate concentrations during corn growth, nitrate leached below the one meter depth, and residual soil nitrate were significantly reduced by the presence of clover, presumably because of immobilization in plant biomass.

Living mulch residues and root exudates contribute to the pool of soil organic matter otherwise derived from crop and cover crop residues, manures, and compost. Earthworms benefit from additions of fresh organic matter and reductions in soil disturbance, with population densities 3.2 to 7.2 times greater under living mulch than with conventional management practices (Pelosi et al. 2008). Increased colonization of corn by arbuscular mycorrhizal fungi in a living mulch system was associated with improved phosphorus uptake by corn (Deguchi et al. 2007; Deguchi et al. 2005). Additions of soil organic matter from living mulch residues may also increase soil water holding capacity. When precipitation is frequent and excessive, however, saturated soil conditions can persist under living mulches to the detriment of crop performance (Wiggans et al. 2012).

### Objectives

Reduced tillage and living mulches offer potential benefits to soil quality and weed management. In organic production systems, the implementation of these strategies is often hindered by the reliance on biological sources of nitrogen and non-chemical approaches to weed management. Quality and yield of vegetables are particularly sensitive to the impact of tillage and weed management on plant growing conditions. The purpose of this research is to investigate the effects of reduced tillage and living mulches on soil nitrogen availability and



plant productivity in organic vegetable cropping systems. Management strategies for reduced tillage and living mulches that are applicable to organic systems were integrated in an attempt to minimize potentially adverse effects on crop growth and yield. Bell pepper (*Capsicum annuum*) was chosen as a transplanted crop, and dry bean (*Phaseolus vulgaris* var. 'Jacob's Cattle Gold') as a direct-seeded crop. The upright growth pattern of pepper is amenable to between-row mowing of the living mulch, and its sensitivity to soil nitrogen availability makes it a good indicator of treatment influences on soil nitrogen. Dry bean is a vigorous crop with quick canopy closure that may compete well against living mulch and weeds. We monitored changes in soil mineral nitrogen concentration, weed community dynamics, and indicators of soil quality to evaluate the agronomic performance of these systems. The applicability of these systems to commercial organic vegetable production was determined by their impact on management objectives related to soil and weed management, and yield. The relative importance of these factors is a function of the capabilities and limitations of organic vegetable production, and is unique to each system and situation.

## Chapter Two: Reduced tillage and living mulches for organic vegetable production

### Materials and methods

#### *Experimental site*

All experiments were carried out in 2012 and 2013 on the Organic Farming Unit at the University of Kentucky Horticulture Research Farm in Fayette County, Kentucky (37° 58' 24" N and 84° 32' 5" W). The site has been certified Organic by the Kentucky Department of Agriculture since 2009. The soil series corresponding to the site is a Maury silt loam (fine, mixed, active, mesic typic paleudalfs). The site has been under intensive vegetable production for the last 35 years. The experiment in 2012 and 2013 occurred in separate but adjacent 15.25 by 90 meter fields, surrounded by sod alleyways.

#### *Experimental design*

The effect of tillage regime, living mulches, and living mulch seeding dates on the yield of two crops (pepper and bean) were studied in a field experiment for two years. Dates on which experimental operations took place are listed in Table 2.1. In 2012, two tillage regimes (conventional till and strip till), two living mulch seeding dates (zero and 15 days after planting the crop), and a no living mulch control were compared for two crops, bell pepper (*Capsicum annuum* var. 'Aristotle') and dry bean (*Phaseolus vulgaris* L. var. 'Jacob's Cattle Gold'). The living mulch consisted of teff (*Eragrostis tef* Zucc. var. 'Tiffany') and Korean lespedeza (*Kummerowia stipulacea* Maxim.). Plots were 4.4 meters wide and 4.1 meters long. In 2012, treatments were arranged in a full factorial, completely randomized design with three replications per treatment combination. In 2013, treatments were blocked by crop. Four 15 cm deep soil cores were taken per plot for baseline data. Cores were homogenized, air dried, and

analyzed by the University of Kentucky Regulatory Services Soil Testing Laboratory in Lexington, KY. Total soil C and N were analyzed by elemental combustion (LECO Corporation, St. Joseph). Soil P, K, Ca, Mg, and Zn were extracted using Mehlich III solution and analyzed by inductively coupled plasma spectroscopy (Varian, Vista Pro CCD, Palo Alto). Soil pH was measured with a glass electrode. Buffer pH was analyzed for a 1:1 ratio of soil and Sikora buffer (triethanolamine, imidazole, MES, acetic acid, and KCL). Particle size was determined via the micropipette method using sodium hexametaphosphate as dispersing agent.

### *Cover crops*

Fields were amended the preceding October of each year with composted horse manure applied at a rate of 22.4 metric tons per hectare. Winter rye (*Secale cereale*) and hairy vetch (*Vicia villosa*) cover crops were seeded in the fall at a rate of 67.4 and 22.5 kg ha<sup>-1</sup>, respectively, overwintered, and terminated by flail mowing on May 4 in 2012 and May 16 in 2013. Cover crop biomass was randomly sampled prior to termination from a 0.25 m<sup>2</sup> area within each plot. Above ground biomass was harvested and sorted into rye, vetch, and weed portions, then dried for 48 hours at 65° C and weighed. Dried samples were processed on a grinding mill to a less than 4mm particle size (Wiley Mill No. 1, Thomas Scientific, Swedesboro, NJ) to homogenize the sample and reduce particle size. Sub-samples were randomly selected from the homogenized samples and ground in a ball grinder (Cianflone Scientific Instrument Corporation, Pittsburgh, PA). Solid carbon and nitrogen content of ground samples was determined by flame combustion (Flash EA 1112 elemental analyzer, CE Elantech Inc., Lakewood, CA).

## *Tillage*

In 2012, soil preparation was accomplished using a two-wheel, walk-behind tractor (BCS model 853, Portland, OR). Conventional tillage (CT) was accomplished with a Berta Franco single rotary plow (Corsalone, Italy), followed by a BCS rear-tine rototiller. In strip tillage (STRIP) plots, the rotary plow was used to till five rows per plot, 20 cm wide and 89 cm apart. The rotary plow was followed by a custom-modified, 25 cm-wide rototiller implement (EarthTools, Owenton, KY). In 2013, a tractor-powered rotary spader (Imants 325 Series, Reusel, Netherlands) was used to prepare CT plots. A commercial strip tiller (Hiniker model 6000, Mankato, MN) was used in STRIP plots to till four 20 cm wide rows per plot spaced 110 cm apart.

## *Planting*

Bell peppers were seeded in 200 cell trays with certified Organic potting mix (McEnroe Organic Farms, Millerton, NY) in March of 2012 and 2013. Four week-old seedlings were transplanted to 72 cell trays. In 2012, transplants were not fertilized prior to planting. In 2013, transplants were fertilized weekly from May 13 to May 31 with liquid fish emulsion (Phytamin 4-5-4) at a rate of 200 ppm-N. Bell pepper transplants and dry bean seed were planted on May 23 in 2012 and May 31 in 2013. Pelletized poultry manure (Harmony 5-4-3, Biosystems LLC, Blacksburg, VA) was surface broadcasted at a rate of 28.06 kg ha<sup>-1</sup>-N on all plots following planting. An additional 39.30 kg ha<sup>-1</sup>-N was applied in bands immediately adjacent to rows of pepper plant. A second banded application of 67.36 kg ha<sup>-1</sup>-N was applied to pepper plots 33 days after planting. All crops were drip irrigated using a single line of drip tape per row for both crops, with irrigation scheduled to maintain soil water potential between -10 and -45 kPa

measured by two tensiometers (Irrometer Model R, Riverside, CA) placed in the field within the row to a depth of 30 cm.

### *Living mulch*

Living mulch seed was broadcast by hand at two seeding dates, at the time of crop planting (0DAP) and 15 days after crop planting (15DAP). Teff was seeded at a rate of 12.6 kg ha<sup>-1</sup>, approximately twice the rate recommended for establishing pure stands of teff for forage production (Miller 2011). Lespedeza was seeded at a rate of 16.5 kg ha<sup>-1</sup>, according to recommended rates for pure stands for forage production (Roberts, 2010). Seed was only spread between crop rows; 10 cm on either side of the row did not receive living mulch seed. After seeding, the soil was cultipacked with the roller bar of the BCS flail mower (disengaged) to improve seed-to-soil contact. Living mulch was mowed with the BCS flail-mower when the vegetation in the living mulch band reached 20 cm in height. Mowing occurred three times in 2012, and twice in 2013. The 20 cm wide, living-mulch free zone was cultivated by hand throughout the cropping sequence to control weeds growing in the crop row. A meter long length of between-row space in all plots was designated as the non-mowed, non-cultivated check. A “no living mulch” treatment was included for both CT and STRIP tillage treatments. The no living mulch treatment in CT was hand cultivated to maintain weed-free conditions in the entire plot throughout the cropping sequence. The no living mulch STRIP treatment was mowed as described above.

### *Living mulch and weed biomass*

Between-row living mulch and weed biomass was sampled prior to mowing. In each plot, one 0.25 m<sup>2</sup> quadrat was randomly placed between two crop rows, and all vegetative

biomass was cut 3-5 cm above the soil. Collected biomass was identified and sorted as teff, lespedeza, or weeds, dried at 65° C for 48 hours, and weighed. The weedy check in each plot was sampled in the same way at the end of the cropping sequence.

#### *Bean and pepper yield*

Yield data were taken from the interior rows of each plot, with 2 border rows on either side of the harvested rows. Beans were harvested when plants had senesced, and pods were full and dry. Peppers were harvested when the majority of fruits had reached marketable size ( $\geq 6.35$  cm long and 6.35 cm wide). Fruit was graded, counted, and weighted as U.S. Fancy, U.S. No. 1, U.S. No. 2, and cull fruit according to United States Standards of Grades for Sweet Peppers (USDA 2005). Peppers were harvested twice in 2012 and once in 2013. In 2012, the second pepper harvest was lost prior to grading, and is therefore not included in total yield for 2012.

#### *Soil mineral nitrogen*

Soil mineral nitrogen was sampled approximately every three weeks, beginning immediately prior to planting and around final harvest. Separate samples were taken for soil within the planting row (in-row) and between the planting rows (between-row). Three 15 cm deep cores were taken from each location within each plot, placed in a plastic bag, and immediately put on ice. A subsample was dried at 65° C for 48 hours to determine soil moisture content. Samples were stored at 45° C and processed within 24 hours. Inorganic ammonium and nitrate was extracted with 1 M KCL using the method outlined by Rice and Smith (1984). 5 grams of wet soil per sample were extracted in 20 ml of 1 M KCL by shaking at 125 rpm for one hour. The extract was then filtered through Whatman Grade 1 filter paper. Ammonium and nitrate concentration was determined from a 2  $\mu$ l aliquot by colorimetric analysis on a microplate

reader (Molecular Devices, VERSAmax, Sunnyvale, CA), after reduction of nitrate using a cadmium reduction microplate device (ParaTechs Co., Lexington, KY) described in Crutchfield and Grove (2011).

### *Aggregate stability*

Soil samples for aggregate stability analysis were taken prior to tillage, and at the end of the cropping sequence. Four 5 cm deep cores were taken and consolidated for each plot, then air-dried at room temperature for a minimum of nine days. Percentage of water-stable aggregates was assessed for aggregates less than 2 mm but greater than 0.25 mm in size following the protocol described in the NRCS Soil Quality Test Kit Guide (USDA 2001). Soil was gently pressed through a 2 mm sieve, and a 10 g subsample placed in a 0.25 mm sieve. Sieves were set on a terry cloth soaked in distilled water for five minutes, until the soil was fully saturated. Sieves with soil were placed in a container filled with distilled water just above the surface of the soil sample. Sieves were lifted up and down over a distance of 1.5 cm for three minutes at a rate of 30 oscillations per minute. Sieves were dried in an oven at 65° C for 48 hours and weighed. The dried soil sample was dispersed by shaking the sieves in a solution containing 59 ml of Calgon bath soap (Ilex Capital, Annapolis, MD) per gallon of tap water until only sand remained. Sieves and sand were dried and weighed. Percent water stable aggregates was calculated as  $(\text{weight of dry aggregates} - \text{sand}) \div (\text{weight of dry soil} - \text{sand}) \times 100$ .

*Dates of experimental operations*

Table 2.1 Dates of experimental operations during 2012 and 2013.

	2012	2013
Pepper transplants started	23 Mar	30 Mar
Cover crop sampled	28 Apr	8 May
Aggregate stability sampled	8 May 20 Sept	13 May 10 Sept
Tillage	21 May	27 May
Peppers and beans planted; ODAP living mulch seeded	23 May	31 May
15DAP living mulch seeded	7 June	15 June
Peppers side-dressed	25 June	3 July
Soil inorganic-N sampled	11 May 31 May 11 July 1 Aug 25 Aug	31 May 24 June 16 July 12 Aug
Living mulch/weed biomass	28 June 17 July 19 Sept	9 July 5 Aug 13 Sept
Living mulch/weeds mowed	29 June 19 July 6 Aug	10 July 5 Aug
Non-mowed check harvested	13 Aug	13 Sept
Peppers harvested	11 Sept 12 Oct	7 Sept
Beans harvested	12 Sept	6 Sept
Aggregate stability sampled	20 Sept	10 Sept



## **Results**

Due to differences in management between crops and years, results for each crop and each year were analyzed separately. Direct comparisons among crops across years were not made.

### **Precipitation and temperature**

2012 was a considerably drier year than average. Total precipitation during the primary crop production sequence period of May to August was 14.7 cm below the average 30-year average for the region (Figure 2.2). In 2012, a total of 34.6 cm of precipitation fell on the experimental site from the date of crop planting (23 May), to the date of the third and final living mulch and weed biomass sample (19 Sept) (Figure 2.1 A). From the date of crop planting, which coincided with the establishment of the zero days after planting (0DAP) living mulch treatment, to the first living mulch and weed biomass sample date (26 June), only 4 cm of precipitation fell. Precipitation from the first to the second biomass sample date (17 July) was 6.8 cm, and 23.9 cm from the second to the final 19 Sept sample date.

2013 was a wetter year than normal, with 27.6 cm more precipitation occurring from May to August than the average for that time period (Figure 2.2). In 2013, a total of 60.1 cm of precipitation fell on the experimental site from the date of crop establishment (31 May) to the date of the third and final living mulch and weed biomass sample date (13 July) (Figure 2.1 B). Precipitation was 30.8 cm from the crop planting date to the first biomass sample (9 July), 10.4 cm from the first to the second biomass sample date (5 Aug), and 19 cm from the second to the final 13 Sept sample date.

Maximum daily temperature is relevant to this experiment primarily due to the impact of high temperatures on pepper flower development and fruit set. Young flower buds, flowers at anthesis, and flowers and fruits up to 14 days after anthesis, are susceptible to abortion when air temperature exceeds 90 °F (Bosland and Votava 2012). In 2012, there were 11 consecutive days on which maximum temperature exceeded 90° F. (28 June to 8 July) (Figure 2.1 A). Maximum temperature on six of those days exceeded 100° F. This period of high temperatures occurred during flower development and early fruit set, and caused visible abortion of a significant number of flowers and small fruit in the bud and button stage. In 2013, maximum temperature exceeded 90 °F on 17 July and no other day (Figure 2.1 B).

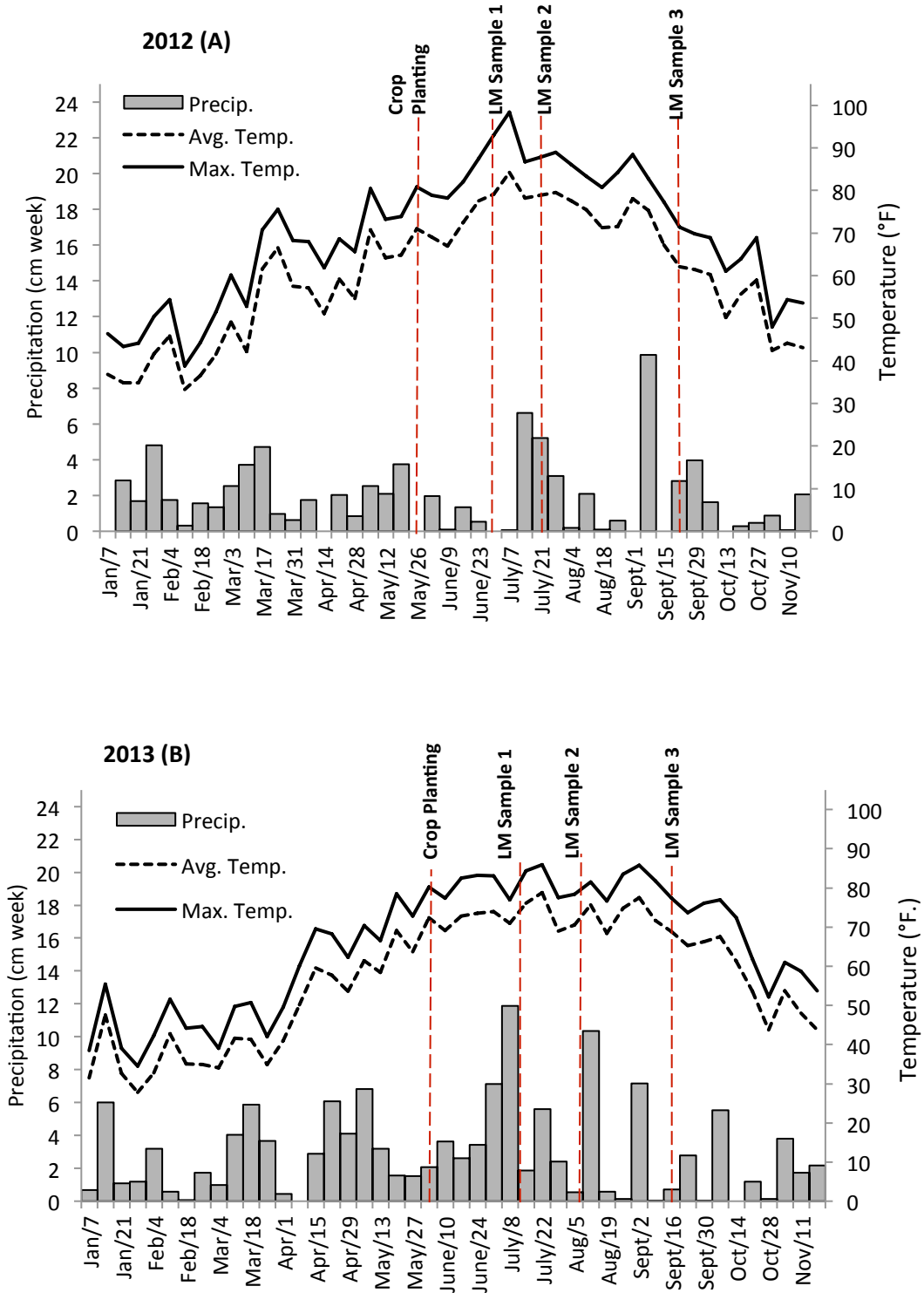


Figure 2.1 Weekly precipitation, average temperature, and maximum temperature at experimental site (U.K. Horticulture Research Farm, Fayette Co. KY) in 2012 (A) and 2013 (B). Dashed red lines indicate date of crop planting, and sample dates for living mulch and weed biomass.

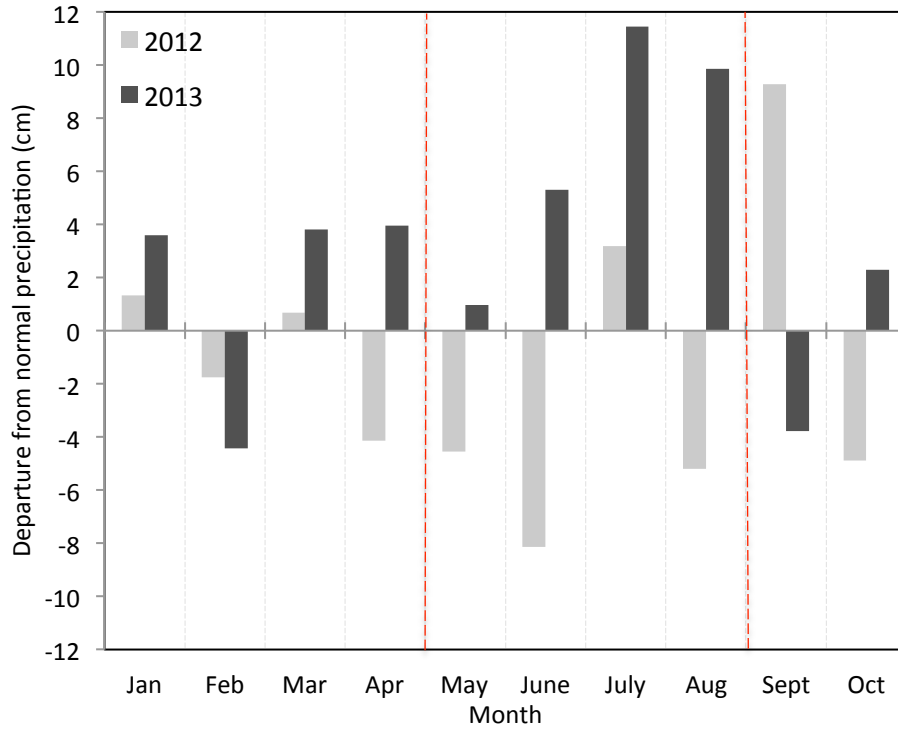


Figure 2.2 Departure from 30-year (1981 – 2010) normal monthly precipitation during 2012 and 2013 at the experimental site, U.K. Horticulture Research Farm, Fayette Co. KY. Dashed red lines indicate beginning and end of cropping sequence (May to Sept) in 2012 and 2013.

Soil and cover crop nutrient content

Table 2.2 Total biomass and carbon and nitrogen content of cover crops.

		Biomass (kg ha <sup>-1</sup> )	% Carbon	% Nitrogen	C:N Ratio
<b>Pepper</b>					
2012	Rye	6773 (±335)	41.78 (±0.05)	0.69 (±0.08)	61.96 (±7.66)
	Vetch	22 (±12)	40.83 (±0.42)	3.06 (±0.38)	14.03 (±1.87)
2013	Rye	8276 (±295)	41.27 (±0.11)	1.51 (±0.08)	27.03 (±1.42)
<b>Bean</b>					
2012	Rye	7282 (±635)	41.33 (±0.4)	0.68 (±0.04)	62.39 (±3.29)
	Vetch	24 (±22)	40.56 (±0.05)	2.95 (±0.13)	13.82 (±0.64)
2013	Rye	9143 (±258)	41.07 (±0.27)	1.25 (±0.05)	32.94 (±1.51)

\* Indicates ± 1 standard error from the mean.

Table 2.3 Initial soil fertility conditions of experimental site, U.K. Horticulture Research Farm.

	pH	Buffer pH	P	K	Ca	Mg	Zn	% OM	% N
-----kg ha <sup>-1</sup> -----									
<b>Pepper</b>									
2012	6.62 (±0.06) *	7.21 (±0.04)	312 (±34) )	683 (±96)	6042 (±60)	427 (±22)	11.2 (±7.6)	2.74 (±0.4)	0.15 (±0.02)
2013	6.25 (±0.02)	7.18 (±0.01)	303 (±7)	430 (±19)	4985 (±56)	353 (±4)	5.28 (±0.21)	0.026 (±0)	0.147 (±0.003)
<b>Bean</b>									
2012	6.61 (±0.07)	7.22 (±0.02)	330 (±41) )	714 (±101)	5929 (±514) )	421 (±27)	11.3 (±5.5)	2.84 (±0.34)	0.15 (±0.01)
2013	6.27 (±0.01)	7.16 (±0.01)	396 (±7)	397 (±9)	5302 (±71)	350 (±6)	5.3 (±0.24)	0.026 (±0.001)	0.145 (±0.004)

\* Indicates ± 1 standard error from the mean.

## Living mulch and weed biomass

### *Pepper*

In 2012, above ground biomass of teff and lespedeza were significantly influenced by tillage and sample date (Figure 2.3A). Biomass of both living mulch species for both tillage treatments was lowest on the first sampling date. Teff biomass in CT reached 504 kg ha<sup>-1</sup> on the second sample date and then leveled off. Teff biomass in STRIP never exceeded 100 kg ha<sup>-1</sup>. Lespedeza biomass continued to increase significantly across sample dates. Biomass was greatest on the third sample date for CT (444.3 kg ha<sup>-1</sup>), relative to STRIP (250 kg ha<sup>-1</sup>). Weed biomass was not influenced by tillage, but increased significantly from the first sample date (512.8 kg ha<sup>-1</sup>) to the second date (855 kg ha<sup>-1</sup>), and declined by the third (295.5 kg ha<sup>-1</sup>) (Figure 2.3 B).

In 2013, teff biomass was almost twice as great for CT than STRIP on the second sample date, when CT teff biomass reached 717.03 kg ha<sup>-1</sup>, before decreasing to 354.67 kg ha<sup>-1</sup> by the third sample date (Figure 2.3 C). Teff biomass was not different among tillage treatments on the first or third sample date. Lespedeza was not influenced by tillage, and never exceeded 70 kg ha<sup>-1</sup>. Weed biomass was greater for CT than STRIP only on the first sampling date (74.2 kg ha<sup>-1</sup> and 2.5 kg ha<sup>-1</sup>, respectively), and never exceeded 74.2 kg ha<sup>-1</sup> that year (Figure 2.3 D). Weed biomass was also influenced by living mulch across sampling dates. Weed biomass on the first sample date (72.82 kg ha<sup>-1</sup>) was nearly 19 times greater for the 15 days after planting living mulch treatment (15DAP) than the zero days after planting treatment (0DAP). Biomass was negligible on the final sampling date.

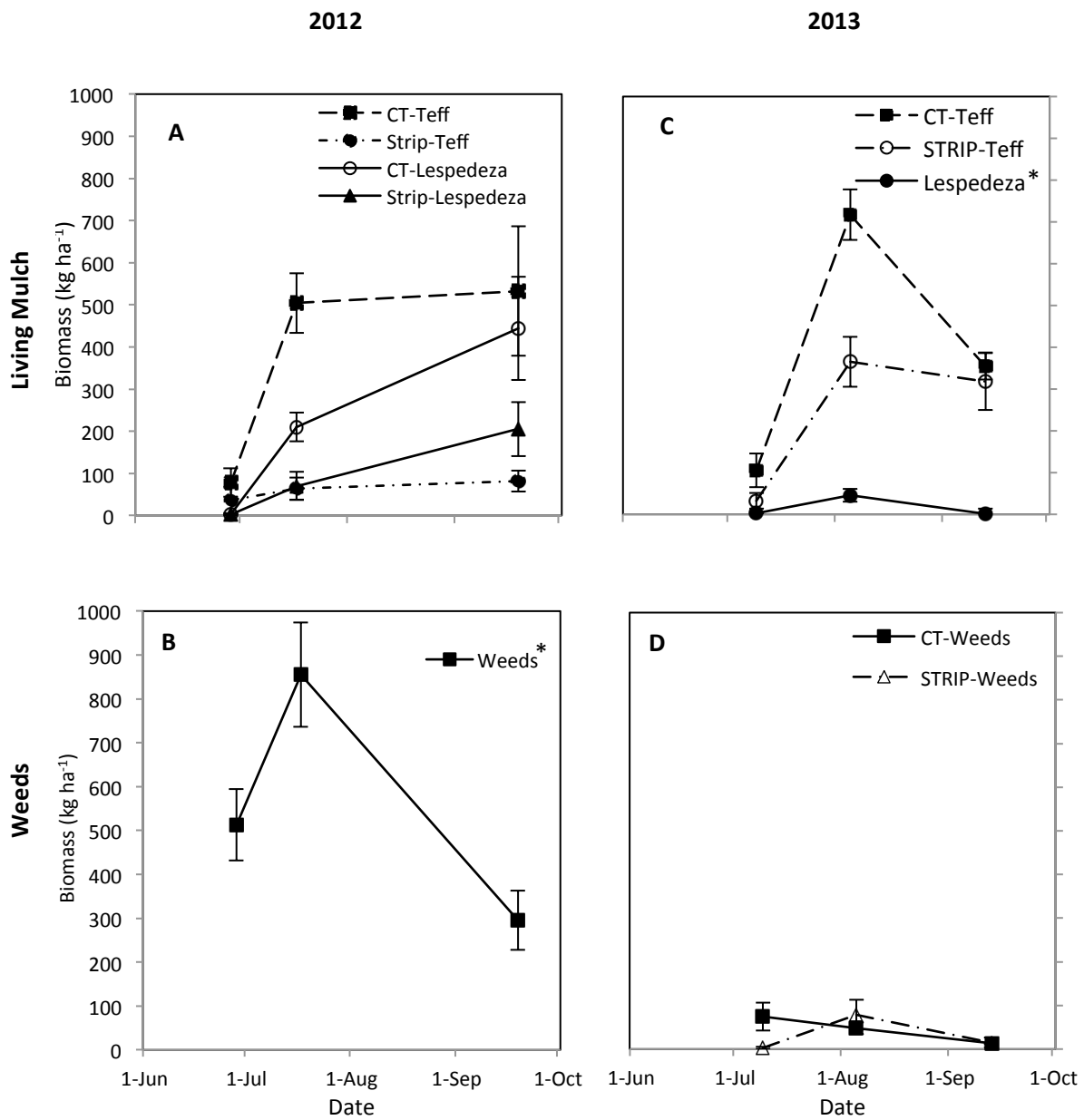


Figure 2.3 Influence of tillage across sample date on living mulch biomass in 2012(A) and 2013 (C), and weed biomass in 2012(B) and 2013(D) in pepper. Bars indicate 1 SE above and below the mean. \* Indicates that tillage by sample date interaction was not significant at  $\alpha = 0.05$ .

### *Bean*

In 2012, teff was not significantly different from the first sampling date (63.8 kg ha<sup>-1</sup>) to the second (98.8 kg ha<sup>-1</sup>), but more than doubled by the final sampling date (213.5 kg ha<sup>-1</sup>) (Figure 2.4 A & Appendix 2). Lespedeza biomass on the first sampling date (3.5 kg ha<sup>-1</sup>) and second sampling date (29.3 kg ha<sup>-1</sup>) was similar, and greatest on the third sampling date (249.4 kg ha<sup>-1</sup>). Weed biomass was similar on the first sampling date (348.3 kg ha<sup>-1</sup>) and second sampling date (349.2 kg ha<sup>-1</sup>), and rose dramatically by the third sampling date (1116.2 kg ha<sup>-1</sup>) (Figure 2.4 B).

In 2013, teff biomass increased substantially from the first sampling date (50.1 kg ha<sup>-1</sup>) to the second (414.1 kg ha<sup>-1</sup>) (Figure 2.4 C). Lespedeza biomass never exceeded 60 kg ha<sup>-1</sup> at any point during the sampling sequence. Weed biomass was greatest on the second sample date (45.5 kg ha<sup>-1</sup>) (Figure 2.4 D).



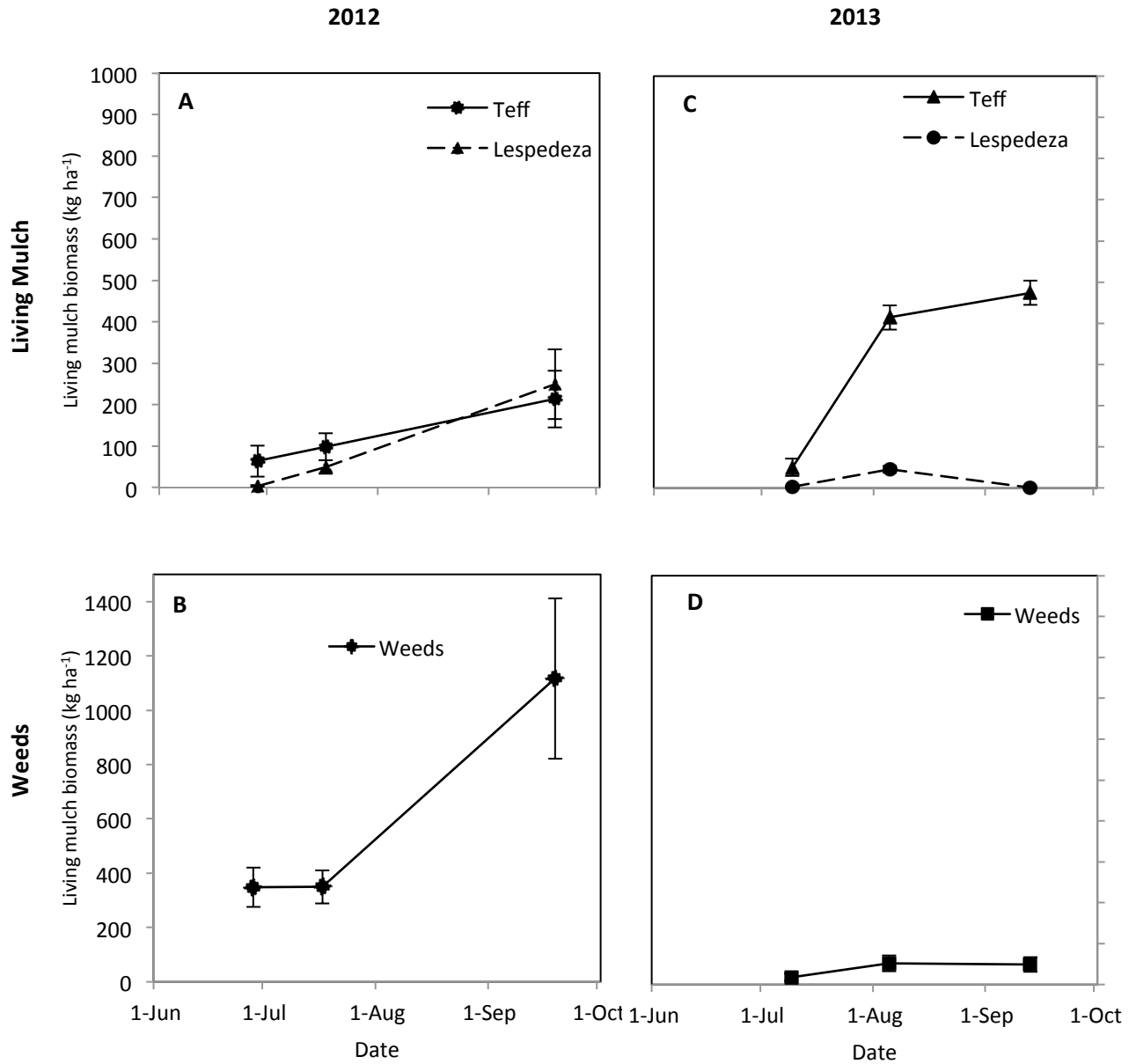


Figure 2.4 Change across sample date of living mulch biomass in 2012 (A) and 2013 (C) and weed biomass in 2012 (B) and 2013 (D) for bean. Bars indicate 1 SE above and below the mean.

### Non-mowed check

The non-mowed check was not mowed or cultivated, and all aboveground biomass in the check was harvested once near the end of the cropping sequence on 13 Aug 2012 and 13 Sept 2013. In Table 2.4, biomass in the non-mowed check is compared to the sum of biomass sampled prior to mowing over the course of the cropping sequence (sample date 1 + sample date 2 + sample date 3). Values are averaged across treatments for a given crop in a given year. Average weed biomass and total biomass for the non-mowed weedy check does not include biomass from the NO living mulch treatments. The sum of biomass sampled on the three sample dates prior to mowing represents cumulative biomass production in the between-row space. Biomass sampled from the non-mowed check represents biomass production in the absence of mowing. The relative difference between the two parameters is considered the impact of mowing on living mulch and weed biomass production over the course of the cropping sequence.

For pepper in 2012, living mulch biomass was not significantly influenced by mowing, but weed biomass and total biomass (weeds + living mulch) were reduced by 71 percent and 55 percent, respectively. In 2013, mowing had no impact on living mulch, weeds, or total biomass for pepper. Weed biomass was reduced by 48 percent, and total biomass 39 percent, due to mowing for bean in 2012. In 2013, only total biomass was significantly influenced by mowing, with a 21 percent decrease compared to the non-mowed check.

Table 2.4 Difference in living mulch (teff + lespedeza), weed, and total (living mulch + weed) biomass between the sum of biomass across three living mulch/weed sample dates and the non-mowed check. Weed biomass from the NO living mulch treatments is not included. Values for biomass measurement for each crop on each year are averaged across treatments.

	Pepper		Bean	
	2012	2013	2012	2013
	-----kg ha <sup>-1</sup> -----			
Living mulch	1115	1059	678	988
Check living mulch	556	1096	534	1099
Percent difference <sup>1</sup>	+101 %	-3 %	+27 %	-1 %
P value*	NS	NS	NS	NS
Weeds	1663	116	1814	118
Check weeds	5621	249	3527	293
Percent difference	-71 %	-54 %	-49 %	-60 %
P value	<.0001	NS	0.0048	NS
Total	2779	1175	2492	1106
Check total	6177	1345	4061	1391
Percent difference	-55 %	-13 %	-39 %	-21 %
P value	<.0001	NS	0.0061	0.0161

<sup>1</sup>Percent difference indicates the percent increase or decrease of the sum of biomass across the three living mulch/weed sample dates relative to biomass in the non-mowed check.

\*P value indicates level of significance for the difference between summed biomass and non-mowed check biomass for each biomass type (living mulch, weeds, or total) for a giving crop in a given year. NS indicates no significance difference at  $\alpha=0.05$

## Soil mineral nitrogen

### *Pepper*

Soil mineral nitrogen concentration (soil N) is presented as the sum of ppm  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N sampled from a depth of 0 to 15 cm. Soil N from within the plant rows (in-row) and between the plant rows (between-row) were analyzed separately.

In 2012, in-row soil N increased significantly from the first to the third sample date, peaking at 29 ppm, then decreased and leveled off by the final two dates (Figure 2.5). Between-row soil N followed a similar trend, peaking at 16 ppm (Figure 2.5 A). Between-row soil N on the third sampling date was 8 ppm higher for CT than STRIP (Figure 2.6 A). Between-row soil N on the third sample date was significantly higher for the NO living mulch treatment (19 ppm), followed by 15DAP (17) ppm, then 0DAP (12 ppm) (Figure 2.6 B). In-row soil N was not significantly affected by tillage across sample dates or living mulch across sample dates.

In 2013, in-row soil N declined gradually from the first sample date (7 ppm) to last sample date (2 ppm) (Figure 2.5 B). Between-row soil N peaked on the second sample date at 8 ppm, then declined steadily to a low of 4 ppm (Figure 2.5 B).

Between-row soil N for STRIP was significantly greater than CT on the third sample date (9 ppm and 4 ppm, respectively), but similar on all other dates (Figure 2.6 C). Though between-row soil N was not significantly influenced by living mulch across sample date, the NO living mulch treatment was 61% greater than the 0DAP living mulch treatment on the third sample (P value < 0.0001).

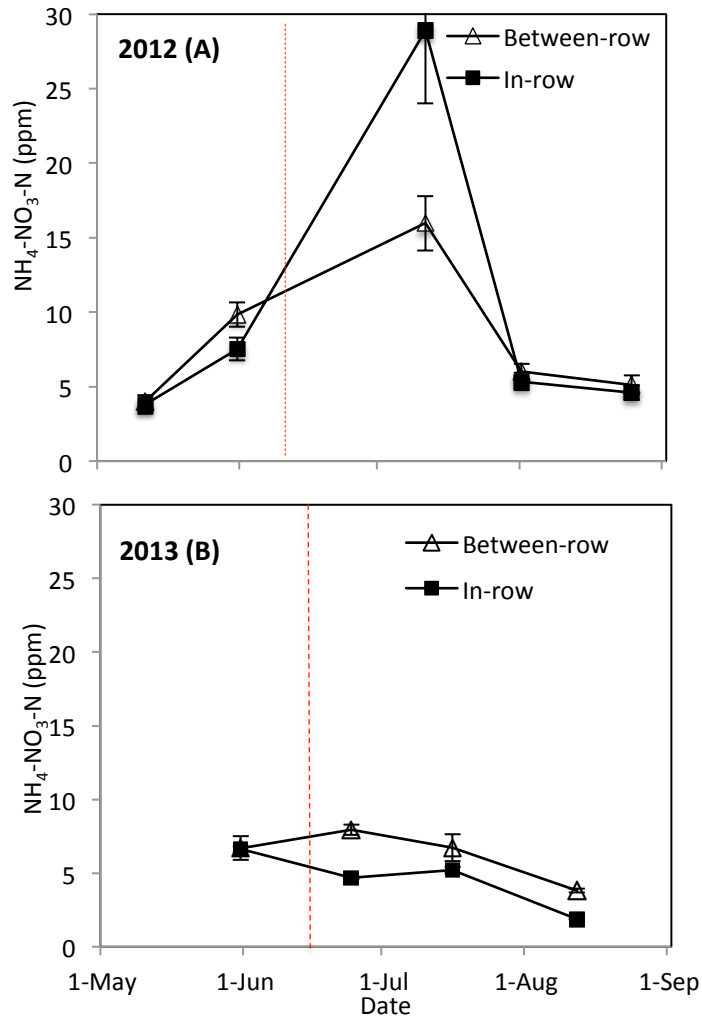


Figure 2.5 Change in between-row and in-row soil mineral nitrogen concentration (ppm  $\text{NH}_4\text{-NO}_3\text{-N}$ ) across sample date in 2012 (A) and 2013 (B) for pepper. Bars indicate 1 SE above and below the mean. Dashed red line indicates date of side-dress fertilizer application.

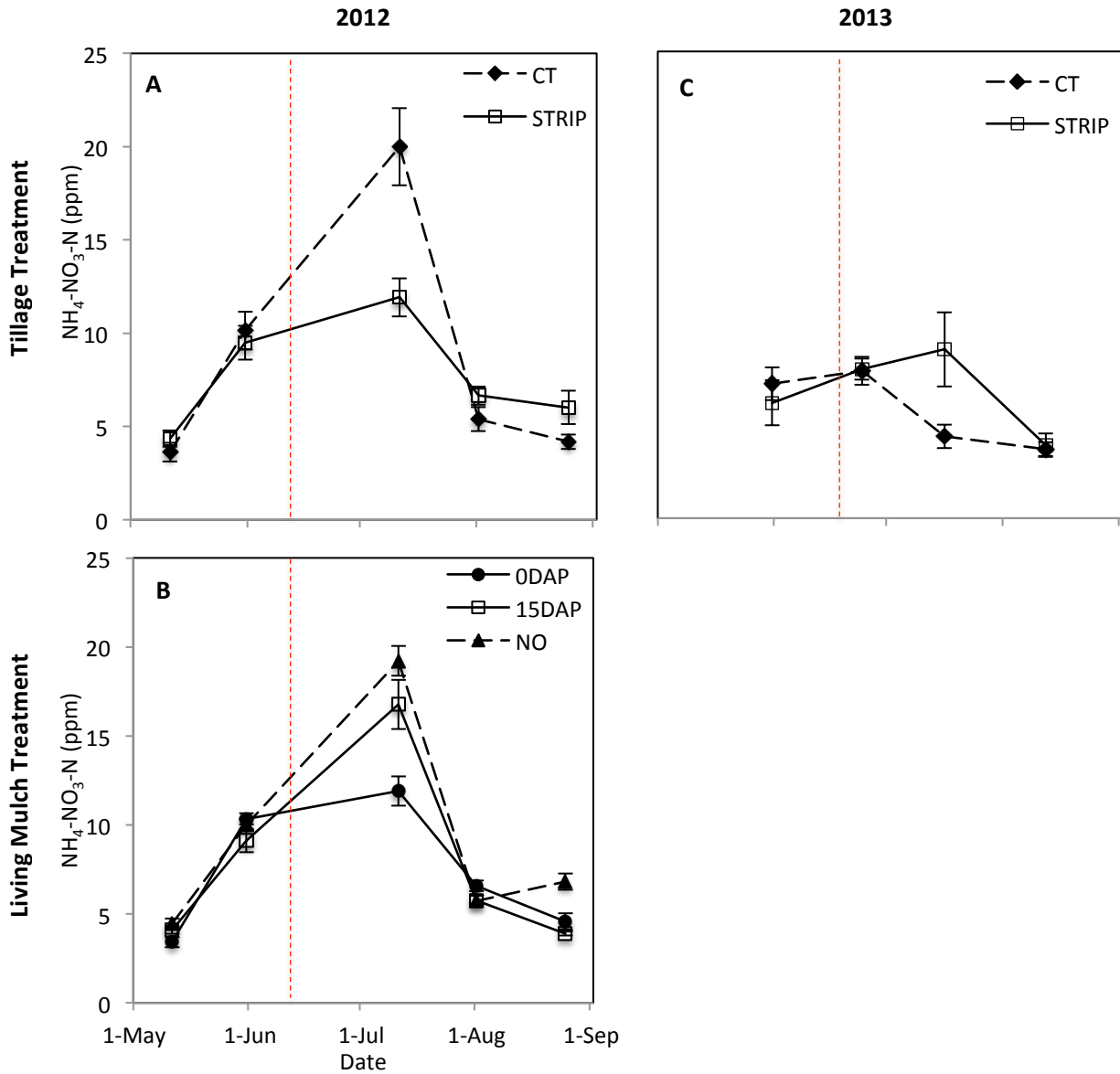


Figure 2.6 Influence of tillage across sample date on between-row soil mineral nitrogen in 2012(A) and 2013 (C), and living mulch across sample date on between-row soil mineral nitrogen in 2012(B) for pepper. Bars indicate 1 SE above and below the mean. \*

## *Bean*

In-row and between-row soil N concentration in 2012 followed a similar trend across sample dates among all treatment combinations, with highest concentrations occurring on the third sample date. Peak N concentration on the third sample date was 14.8 ppm for between-row and 10.3 ppm for in-row (Figure 2.7 A & Appendix 4).

Between-row soil N on the third sample date was 53% greater for CT tillage (17.9 ppm) than STRIP tillage (11.7 ppm) (Figure 2.9 A). On the third sample date, between-row soil N was greatest for the NO living mulch treatment (20 ppm), followed by the 15DAP living mulch (14.2 ppm), then the 0DAP living mulch (10.3 ppm) (Figure 2.8 B). Soil N concentration on the fourth sample date had decreased drastically. Living mulch treatments did not differ significantly, and averaged 6.2 ppm.

In-row N concentration for was significantly influenced by the interaction of tillage, living mulch, and sample date (Appendix 4). The highest concentration occurred on the third sampling date for STRIP-NO (13.1 ppm), and was not significantly different from STRIP-15DAP or any CT-living mulch treatment combinations on that date. The lowest concentration was for STRIP-ODAP (5.65 ppm).

In 2013, in-row and between-row soil N varied significantly across sample dates (Figure 2.7 B). In-row soil N decreased steadily from the first sample date to the second (4 ppm) and third (4.5 ppm), then declined to a low of 2.6 ppm by the final sample date. Between-row N was greatest on the second and third sample date (9.1 ppm and 8.8 ppm, respectively), and lowest on the fourth (4.2 ppm). In-row and between-row soil N were not significantly influenced by tillage or living mulch across sample date in 2013.

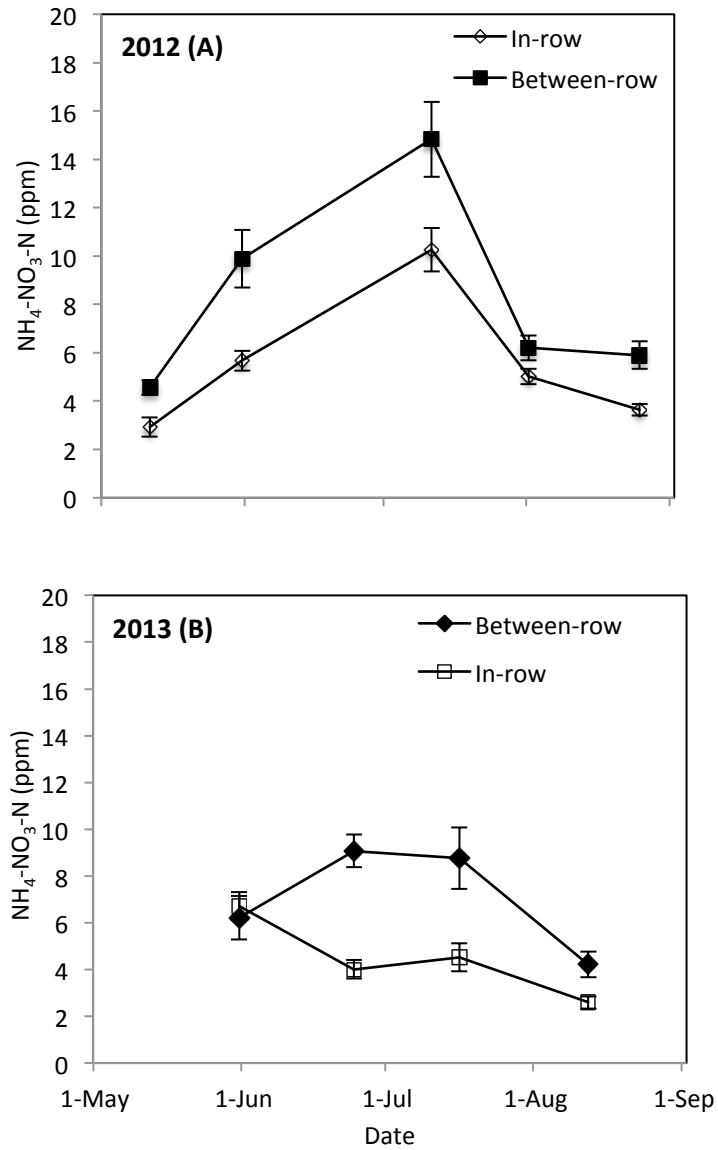


Figure 2.7 Change in between-row and in-row soil mineral nitrogen concentration (ppm NH<sub>4</sub>-NO<sub>3</sub>-N) for bean in 2012(A) and 2013 (B). Bars indicate 1 SE above and below the mean.



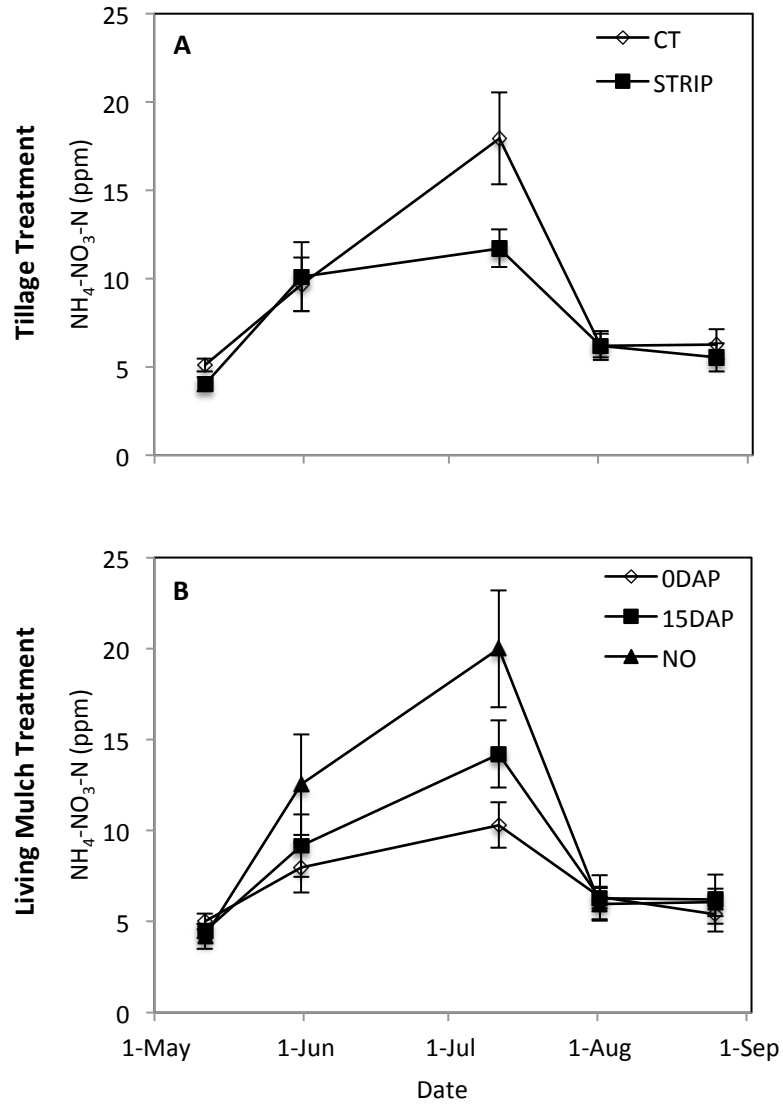


Figure 2.8 Influence of tillage across sample date (A) and living mulch across sample date (B) on between-row soil mineral nitrogen (ppm  $\text{NH}_4\text{-NO}_3\text{-N}$ ) for bean in 2012. Bars indicate 1 SE above and below the mean.

## Pepper yield

Total marketable pepper yield in 2012 was the sum of U.S. Fancy, No. 1, and No. 2 grade fruit, not including cull fruit. Total marketable weight was not significantly different among treatments, and averaged 4,466 kg ha<sup>-1</sup>. Weight of U.S. Fancy peppers was greatest for the NO living mulch treatment (2660 kg ha<sup>-1</sup>). The 0DAP living mulch treatment (1,214 kg ha<sup>-1</sup>) and 15DAP living mulch treatment (1,214 kg ha<sup>-1</sup>) were not significantly different. Weight and number of cull bell peppers was significantly influenced by the interaction of tillage and living mulch. The NO living mulch treatment under conventional tillage had significantly greater cull weight (5,121 kg ha<sup>-1</sup>) than all other treatment combinations. Average cull weight among the other treatments was 1,748 kg ha<sup>-1</sup>.

In 2013, total marketable yield, and yield of U.S. Fancy peppers, were significantly influenced by the interaction of tillage and living mulch. Total marketable fruit weight was greatest for CT combined with NO living mulch (20,227 kg ha<sup>-1</sup>) and lowest for CT combined with 0DAP living mulch (7,344 kg ha<sup>-1</sup>) (Figure 2.9 A). CT-NO also yielded the highest weight of U.S. Fancy fruit (10,555 kg ha<sup>-1</sup>), and CT-0DAP the lowest (1,938 kg ha<sup>-1</sup>) (Figure 2.9 B). U.S. Fancy fruit weight among living mulch treatments were similar under STRIP tillage.

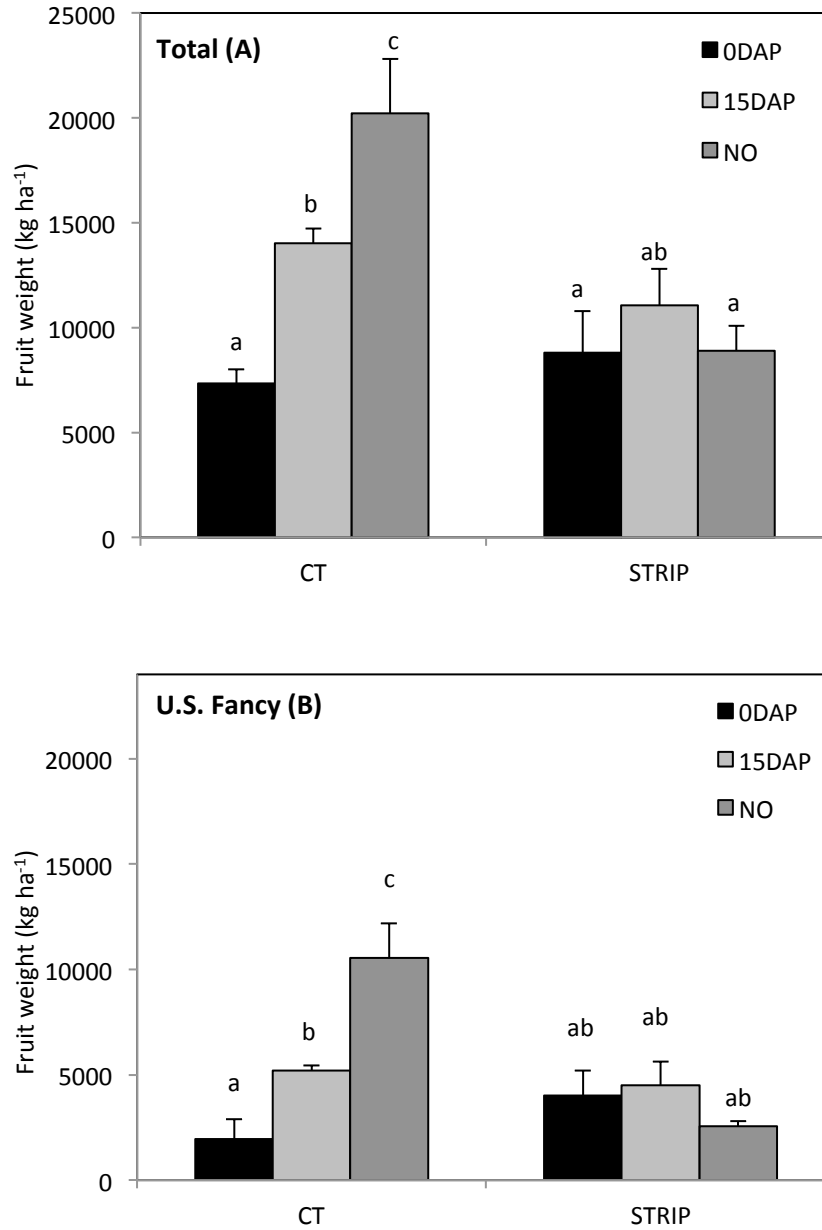


Figure 2.9 Influence tillage and living mulch on total marketable yield (A) and yield of U.S. Fancy peppers (B) 2013. Columns with the same letter are not significantly different at  $P \leq 0.05$ . Bars indicate 1 SE above and below the mean.

### *Bean yield*

In 2012, bean yield was not affected by tillage, living mulch, or the interaction between tillage and living mulch. Average bean yield across all treatments was 798 kg ha<sup>-1</sup>. Though the overall interaction of tillage and living mulch was not significant ( P value = 0.0966), yield for conventional tillage with no living mulch (1105 kg ha<sup>-1</sup>) was significantly greater than all other treatment combinations.

In 2013, bean yield was influenced by the interaction of tillage and living mulch (P = 0.02). STRIP tillage with 15DAP living mulch generated the highest yields (863 kg ha<sup>-1</sup>), and was only significantly greater than STRIP with NO living mulch (432 kg ha<sup>-1</sup>).

### Aggregate stability

#### *Pepper*

There was no significant treatment effect on percent water stable aggregates (% WSA) 2012, with an average of 69%. In 2013, % WSA was greatest for STRIP combined with ODAP living mulch (77%), which was significantly greater than STRIP combined with NO living mulch (64) and CT combined with ODAP living mulch (63%)(P value = 0.03).

#### *Bean*

In 2012, % WSA was significantly affected by tillage (P = 0.047), with 72% for STRIP and 65% for CON. Aggregate stability in 2013 was not influenced by tillage, living mulch, or the interaction of the two. Average % WSA was 64.

## **Discussion**

### Weed and living mulch biomass

Factors that influence the germination, growth, and persistence of living mulch and weed species in cropping systems determine trends in biomass production of these species over time. These include soil moisture and fertility, soil surface tilth, competition for light and nutrients, and tolerance to disturbance. Many of these factors can be actively influenced by management activities like tillage, nutrient management, irrigation, and weed management strategies.

For pepper in 2012, tillage influenced biomass production of teff and lespedeza, but not weeds, over the course of the cropping sequence (Figure 2.3 A & B). Both teff and lespedeza biomass were less than 100 kg ha<sup>-1</sup> for all treatments on the first sample date, 26 June, 80 percent less than weed biomass on that date. By the second sample date, 17 July, teff was nearly 8 times greater and lespedeza 3 times greater in CT than STRIP.

It is highly likely that dry conditions during the living mulch establishment period impacted germination and early growth. The first living mulch and weed biomass sampling date occurred 34 days after establishing the 0DAP living mulch treatment and 19 days after establishing the 15DAP living mulch treatment. The experimental site received only 4 cm of rain from the establishment of the 0DAP living mulch treatment to first biomass sampling date (Figure 2.1 A). These dry conditions severely hindered living mulch germination and growth during this time. Precipitation from the first to the second sample date (21 days) amounted to 6.78 cm. Increased soil moisture likely contributed to the dramatic accumulation of teff and lespedeza biomass after the first sample date.

Teff is known for rapid germination and establishment of a dense canopy, but requires adequate surface soil moisture and fine soil tilth for optimal performance (Miller 2001). Because of its remarkably small seed size (1.3 million seeds per pound), teff seed germinates poorly if the soil surface is too dry or coarse. Lespedeza has comparatively larger seed (236,000 seeds per pound), but can nonetheless be constrained by poor environmental conditions. Infante and Morse (1996) supplied overhead irrigation for two weeks after sowing a living mulch to ensure quick germination and canopy development. Only when favorable growing conditions are present can a rapidly emerging living mulch species like teff possibly out-compete weeds abundantly supplied by the weed seed bank. The primary means of weed suppression by living mulches is direct competition for resources. Living mulch species must be capable of preemptively occupying above- and below-ground space before weeds for suppression to be adequate. Therefore, the rate of living mulch biomass production early in the cropping sequence is critical to minimizing weed germination and emergence.

Teff biomass plateaued and remained constant after the second sample date, while lespedeza biomass continued to increase to the third sampling date, despite being mowed twice more. Averaged across treatments, living mulch biomass (teff + lespedeza) aggregated over the three sample dates was not different from the non-mowed check (Table 2.4). The resilience of teff and lespedeza biomass production in this system is a function of the mowing tolerance of both of these species, which are commonly grazed or cut for hay in forage systems. These observations are consistent with other living mulch studies which found that mowing did not necessarily reduce total biomass production over the course of the cropping sequence (Chase and Mbuya 2008). The consequences of living mulch biomass on yield will be discussed later.

Teff tillers originate from a single, low-to-the-ground crown, and can continue to tiller and regrow as long as the mowing height is not less than 5 cm. Mowing eliminates the apical growing point of lespedeza, but induces extensive lateral branching. The continued increase in lespedeza biomass accumulation may also be attributable to its ability to fix nitrogen in the nitrogen-scarce between-row environment. Furthermore, lespedeza growth is photoperiod sensitive, and is greatest during the months of July and Augusts (Roberts 2000). Persistent living mulch biomass production is important for full-season suppression of weeds in the sub-canopy and later-emerging weeds. Non-mowing tolerant species used as living mulches, e.g. buckwheat, do not provide late-season weed control if mowing is used as a living mulch management strategy (Gibson et al. 2011).

Poor seed-to-soil contact because of thick surface residues is likely responsible for the low biomass observed in the STRIP tillage treatments at the second sampling date. This is especially true for the small-seeded teff, which never produced more than 100 kg ha<sup>-1</sup> biomass in STRIP. Infante and Morse (1996) were the only researchers to over-seed living mulches onto surface residue in reduced tillage systems. They did not observe differences in living mulch biomass in reduced tillage versus conventional tillage systems, possibly due to the supplemental irrigation. Furthermore, living mulch seed sown in their experiment may have been better able to reach the soil through crop residue which was left standing after killing by herbicide, rather mowed and laid flat.

Weed biomass was comparatively large on the first sampling date relative to teff and lespedeza biomass (Figure 2.3 B). Under the dry conditions of May and June in 2012, weed seeds buried deeper in the soil profile may have had more access to a reservoir of moisture unavailable to surface-broadcasted living mulch seeds. Surprisingly, tillage did not influence

weed biomass as expected. Cover crop residues in reduced tillage systems generally reduce weed germination, via reduction in light levels at the soil surface, physical interference, or the production of allelochemicals. With more than 7000 kg ha<sup>-1</sup> of rye residue with a 61:1 C:N ratio generated in the spring of 2012 (Table 2.2), one would expect the contribution of surface residue to weed suppression in STRIP tillage to be significant. However, the amount of rye surface residue necessary to consistently suppress weed emergence by 75% has been estimated to be at least 8,000 kg ha<sup>-1</sup> (Teasdale and Mohler 2000).

There is a suite of site-specific conditions that may have contributed to insignificant weed suppression of cover crop residue in the STRIP tillage treatment. Mechanical cover crop termination techniques differ in the impact on the persistence and spatial distribution of killed residues. Mowing, as opposed to roller-crimping, distributes residue unevenly and increases the rate of microbial decomposition (Creamer and Dabney 2002). It is possible that conservation of soil moisture under killed cover crop residues may actually promote germination of weeds if conditions are dry (Teasdale and Mohler 1993), as was experienced in the summer of 2012. Weed pressure at the experimental site is very high due to past management practices that failed to prevent weed seed production (M.A. Williams, personal communication). Cover crop residue in reduced-tillage systems is less likely to adequately control weeds if the weed seed bank is high (>10,000 seeds m<sup>-2</sup>, Mirsky et al. 2013). The probability that an emerged weed seedling is situated under a thin or bare point in the cover crop residue increases with seed number. We can assume that irregularity in residue distribution due to mowing rather than rolling or killing with herbicide increased the probability of unimpeded weed emergence.

Weed biomass was greatest on the second date, then decreased by 65 percent by the third sample date. Averaged across treatments, mowing reduced net weed biomass production by 71



percent relative to the non-mowed check (Table 2.4). This decline is contrary to several other experiments in which mowing did not improve weed control (Gibson et al. 2011; Illnicki and Enache 1992). Repeated mowing events, combined with increased living mulch biomass, could have contributed to this decline. Weed species-specific phenological and morphological characteristics determine their susceptibility to these potentially suppressive forces. The primary weed species observed at the experimental site were green foxtail (*Setaria faberi* Herrm.), hairy galinsoga (*Galinsoga ciliate* Raf.), redroot pigweed (*Amaranthus retroflexus* L.), and common lambsquarters (*Chenopodium album* L.). Weeds with an apical growing point, like pigweed and lambsquarters, tend to produce lateral shoots when the apex is physically damaged. While this is a form of regrowth, these lateral branches tend to be less vigorous than the dominant shoot, and are more easily shaded by more rapidly recovering species. Hairy galinsoga is a spreading, somewhat prostrate species, and its stature affords a degree of protection from mowing. It is a rapidly growing weed that can produce a tremendous quantity of seed within 35 to 40 days of emergence (Warwick 1983). Mature seed was visible on weed escapes despite the frequency of the first two mowing events. Nonetheless, biomass of the first cohort of galinsoga weeds appeared to decrease after the second mowing.

The ability of giant foxtail, along with most grasses, to emerge from a growing point beneath the mowing height, confers some mowing tolerance. Donald (2007), however, found that one mowing was sufficient to kill broad leaf weeds, and two or more mowings killed grass weeds, specifically giant foxtail. The author recognized that this success was due in part to the thick canopy cover afforded by the main corn crop. Spacing between single pepper rows in this experiment (88.9 cm) was too wide for the crop canopy to have an overwhelming shading effect on weeds in the middle of the between-row space. We can conclude that the cumulative effect of

mowing, living mulch weed competition, and partial shading by the crop is responsible for the ultimate decline in weed biomass. However, because initial weed biomass was high, weed biomass by the third sample date still represented a sizeable portion of total between-row biomass.

The effect of living mulch seeding date on living mulch and weed biomass was not significant for pepper in 2012. Low precipitation during the period between 0DAP and 15DAP living mulch establishment may have prevented 0DAP living mulch from germinating in advance of 15DAP enough to generate differences (Figure 2.1 B). Furthermore, high weed seed density and conditions that favored weed germination over living mulch germination may have muted potential nuances related to living mulch seeding date. Estimates of the number of germinable weed seeds in cropping systems in the top 20 cm of the soil range from 6,000 to 18,000 seeds m<sup>-2</sup> (Sjursen 2012). High weed pressure may have contributed to the lack of a significant influence of tillage on weed biomass during the cropping sequence as well. The cover crop surface residue in STRIP plots was not sufficient to suppress weed growth later in the season. That the residue was mowed, rather than rolled or killed with herbicide, may have increased the rate at which it decomposed and failed to suppress weeds (Creamer and Dabney 2002). Cover crop residue is an effective weed barrier only when it is managed to suite the constraints of a given system. On this site, reducing the initial weed seed bank through other, long-term strategies like bare fallowing may be necessary for cover crop residues to work alone or in concert with living mulches to effectively suppress weeds.

For pepper in 2013, biomass production by teff and lespedeza on the first sample date was minimal (Figure 2.3 C). The first sample date occurred 39 days after pepper planting and establishment of the 0DAP living mulch, and 24 days after establishment of the 15DAP living

mulch. Approximately 30.1 cm of precipitation fell during this period and was evenly distributed such that moisture at the soil surface was sufficient for teff and lespedeza germination. Despite optimal moisture conditions, living mulch biomass production was only 110 kg ha<sup>-1</sup> during this 39 day period. Perhaps neither teff nor lespedeza commenced rapid growth until after an establishment period of several weeks. Living mulch and weeds were mowed the day following the first biomass sampling date because the canopy height had surpassed the predetermined 20 cm threshold. It is apparent that the biomass associated with that height on the first sample date ( $\leq 100$  kg ha<sup>-1</sup>) was not great relative to other sample dates. For teff, a thin-stemmed, erect grass, height may not be well correlated with total biomass during early growth stages. Not until later growth stages does tillering take place and the number of stems per plant increase. Percent canopy cover may be a better early season indicator of living mulch performance for teff and similar species.

More favorable germination conditions on bare soil without surface residue are most likely responsible for differences observed in teff biomass between tillage systems (Figure 2.3 C). Teff biomass in the CT tillage treatment was nearly double that of the STRIP tillage on the second sample date. Teff biomass observed in STRIP was still reasonable (365 kg ha<sup>-1</sup>), considering the amount of rye cover crop residue on the surface (8276 kg ha<sup>-1</sup>). The impact of heavy rains early in the cropping sequence in combination with foot traffic may have helped teff seed sift through the residue layer down to the soil surface. By the third sample date, teff biomass in CT and STRIP tillage treatments were not significantly different. The reasons why teff biomass in CT declined to an amount equivalent to STRIP on the third sample date are unknown. It is unlikely that overall percent teff germination was equal between the two drastically different soil environments.

Lespedeza did not produce substantial amounts of biomass at any point during the season, and was not significantly influenced by tillage across sample dates. This may be because teff biomass production in both tillage systems was sufficient to largely outcompete lespedeza. Rye biomass production in 2013 ( $8276 \text{ kg ha}^{-1}$ ) was great enough to contribute to early and long-term weed suppression. Small differences in lespedeza biomass observed over time between CT and STRIP on the first sample date are inconsequential considering the productivity of teff in the system. Indeed, net living mulch biomass production, consisting primarily of teff, was not reduced by mowing, and averaged more than  $1000 \text{ kg ha}^{-1}$  for the season (Table 2.4).

Weed biomass was minimal in 2013 ( $< 75 \text{ kg ha}^{-1}$  at any point). Living mulch treatment had a small but statistically significant influence on weed biomass across sample dates. That weed biomass measured on the first sample date in the 0DAP living mulch treatment was greater than the 15DAP is not surprising (Figure 2.3 D). Weeds were cultivated in the 15DAP, CT tillage treatment immediately prior to sowing the living mulch. Ensuing weed germination after cultivation may have negated weed biomass differences observed on the first sample date if it were not for optimal moisture conditions that facilitated rapid teff emergence. Weed biomass between the two living mulch treatments were nearly equal by the second and third sample date, probably because teff growth was so aggressive. Net living mulch and weed biomass was not affected by mowing for pepper in 2013. Above average precipitation probably contributed to favorable conditions for regrowth after mowing, especially of teff.

Teff and lespedeza biomass for bean in 2012 remained quite low throughout the duration of the sampling period (Figure 2.4 A). This is especially true for the first two sample dates, when teff and lespedeza biomass remained below  $100 \text{ kg ha}^{-1}$ . The bean variety used, 'Jacob's Cattle Gold' was a bushing variety, but did not stand erect once the canopy began to fill. Based

on visual observation, canopy growth and encroachment into the between-row spaces significantly reduced living mulch growth, despite the 89 cm row spacing. Teasdale and Frank (1983) observed a 50% reduction in light penetration when snap bean canopy closure reached 75 percent. Low weed biomass in bean on the first and second sample date corroborates this hypothesis (Figure 2.4 B)

Both weed biomass and total living mulch biomass (teff + lespedeza) increased substantially from the second to the third sample date (220 percent and 212 percent, respectively). Several factors contributed to this trend. By the final sample date (19 Sept) bean plants were almost entirely defoliated, both by Mexican bean beetle herbivory and by natural senescence. Additionally, weeds and living mulch were not mowed as effectively in bean as in pepper, in an effort to avoid damage to bean plants that had fallen into the row middles. Net living mulch biomass over the course of the three sample dates was not reduced by mowing, relative to the non-mowed check, probably because living mulch biomass was already generally quite low (Table 2.4). Weed biomass production, however was reduced by almost 50 percent, but still totaled over 1800 kg ha<sup>-1</sup> for the season.

In 2013, bean row spacing was 110 cm, 21 cm wider than in 2012. The effect of shading on living mulch growth by the bean canopy is not pronounced as it was in 2012. Teff biomass predominated the between-row vegetation throughout the sampling sequence. Lespedeza and weeds appear to be poor competitors against teff in this system (Figure 2.4 C & D). Defoliation of beans occurred in the same manner as it did in 2012. However, a thick stand of teff thoroughly suppressed weed growth by maintained steady biomass production throughout the season in spite of mowing (Table 2.4).

## Soil mineral nitrogen

Soil mineral nitrogen concentration (soil N) measured in-row and between-row should provide some insight into the interplay of tillage and living mulch effects on plant available nitrogen. In the context of crop production, soil mineral N concentration is typically reported as ppm  $\text{NO}_3\text{-N}$ , because nitrate is the dominant form of nitrogen in the soil taken up by plants. Here, soil mineral nitrogen concentration is presented as ppm  $\text{NH}_4\text{-NO}_3\text{-N}$ , because  $\text{NH}_4\text{-N}$  comprised 62 to 64 percent of total mineral nitrogen measured across sample dates in this experiment (data not shown). Research has demonstrated that for most crops, including pepper, 25 to 30 ppm  $\text{NO}_3\text{-N}$  is considered a sufficient range (Heckman 2002). For pepper, it is most important that soil N concentration falls within this range from the onset of vegetative growth until early fruit set, when crop N demand is greatest.

In this experiment, ppm  $\text{NH}_4\text{-NO}_3\text{-N}$  remained well below the sufficiency range for  $\text{NO}_3\text{-N}$  on most sample dates across all treatments in 2012 and in 2013. Soil mineral N concentrations observed on most sample dates are typical of “background” levels generated by biological mineralization of N from organic matter. The fact that soil N concentrations for the “standard,” conventionally-tilled, no living mulch treatment was also generally well below the sufficiency range suggests that non-treatment related factors are influencing the overall trend in soil N. The fertilizer source used was pelletized poultry manure (5-4-3 N-P-K composition). The majority of N contained in poultry litter is in organic form, immobilized within the manure and litter components. The portion of mineral N ( $\text{NH}_4\text{-NO}_3\text{-N}$ ) in pelletized poultry litter ranges from 0.8 to 0.37 percent (Adeli et al. 2012; Lopez-Mosquera et al. 2007), with an additional 0.2 percent in the form of urea (Lopez-Mosquera et al. 2007).

Management strategies used for this low analysis organic fertilizer source may have contributed to unexpectedly low soil N concentrations. A total of 135 kg ha<sup>-1</sup> N as Harmony 5-4-3 was applied to pepper plots in both years. Of the total application, 21 percent was broadcast over the entire plot to provide some available N for the teff living mulch. In the interest of prolonging nitrogen availability from the fertilizer, a split application was made, with 29 percent applied in a band pre-plant, and the remaining 50 percent banded 33 days after planting. This strategy may have been detrimental to crop nitrogen availability, considering the gradual, microbially-mediated mineralization pattern of this fertilizer source. The mineralization of poultry litter-N ranges from 25 to 40 percent of total N after two months, depending on soil conditions (Tyson and Cabrera 1993). Nitrogen recommendations cannot possibly accommodate the diversity and unpredictability of availability of N from organic fertilizers. Instead, application rates should be modified on a situation-specific basis to account for the behavior of organic fertilizers in the specific soil environment to which they are applied. This slowly mineralizable source of N could probably have been applied completely pre-plant without the risk of significant N losses that can occur from large pre-plant applications of more soluble fertilizers.

Environmental conditions at the soil surface influencing mineralization of the post-plant, banded surface application after planting may have contributed to low observed soil N concentrations. The rate and extent of decomposition of nitrogen-containing organic amendments is greatly increased by incorporation in the soil. Surface applied amendments are subject to poor soil contact and desiccation, which reduces microbial decomposition and mineralization. A 56 percent increase in apparent crop N use efficiency has been observed when pelletized poultry litter was subsurface-banded relative to surface banding (Adeli et al. 2012).

Additionally, loss of N via volatilization of  $N_2O$  and ammonia gases may be higher by 2.5 and 25 percent for surface banded than subsurface-banded pelletized poultry litter, respectively (Cabrera et al. 1994). In-row weed cultivation, if exercised with the intention of incorporating post-plant surface applied poultry litter, could have mitigated these sources of nitrogen use inefficiency to some extent. Ultimately, applying all of the fertilizer N pre-plant and accommodating for anticipated potential N unavailability by applying higher rates may be the most successful strategy.

Both in and between-row soil mineral N for pepper in 2012 peaked on the third soil sample date, 11 July (Figure 2.5 A). It is reasonable to assume that mineralization of N from the side-dress application of poultry litter that occurred 16 days earlier had some influence, despite the limitations on overall N mineralization discussed above.

Between-row soil N for bean in 2012 was generally higher than in-row soil N, contrary to the pattern observed for pepper in this year (2.7 A). Beans did not receive the post-plant side-dress application which boosted in-row soil N concentration in pepper. Furthermore, the bean variety used, Jacob's cattle gold, had a semi-erect, bushing growth habit that ultimately led to shading of and encroachment upon the between-row space. This effectively reduced living mulch and weed biomass while bean foliage was still intact, prior to senescence. The lack of vegetation in the between-row space could have reduced soil N uptake in that area, thereby preserving higher residual soil N levels in the between-row space.

Between-row soil N for pepper, and in- and between-row soil N for bean, also peaked on the third date. This pattern is curious, especially considering that bean did not receive the post-planting side-dress application of poultry litter. This suggests that there is some factor



influencing both row locations. The peak in soil N for both crops in both row locations could be partially attributable to the mineralization of the 28 kg ha<sup>-1</sup> of N that was broadcast pre-plant uniformly across the entire plot. Decomposing cover crop residue may be another source of slowly mineralizable N that was universally present. Organic residues with a C:N ratio of 25:1 to 30:1 are most likely to encourage net nitrogen mineralization. The C:N ratio of rye residue in 2012 was 61:1 (Table 2.2). The characteristics of the cover crop residue do not suggest that a substantial amount of N would be released by their decomposition. However, it is apparent from differences in between-row soil N between CT and STRIP tillage treatments for bean and pepper that residue incorporation influenced N over time (Figure 2.6 A; 2.8 A). Incorporating residues in CT stimulated more rapid decomposition than when left on the surface in STRIP. When incorporated residues have a high C:N ratio, an initial period of rapid N immobilization may occur before net mineralization begins. (Wyland et al. 1995). This lag time was observed in the delay in soil N availability in CT prior to the dramatic jump in N concentration. This delay occurred in STRIP as well, but the effect lasted longer. With high C:N ratio cover crops like mature winter rye, N immobilization, rather than mineralization, may be the dominant process generating disparities in soil N concentration between conventionally tillage and reduced tillage systems (Rice and Smith 1985).

The dramatic decline in between-row soil N in CT after the third sample date for bean and pepper in 2012 is reflected by the continued increase in living mulch (pepper) and weed (bean) biomass observed in CT. It is clear from Figure 2.6 B and Figure 2.8 B that living mulch treatment had an impact on soil N for at least part of the cropping sequence. Differences in between-row soil N among living mulch treatments are greatest on the third sample date, when the NO living mulch treatment had the highest soil N concentration (Figure 2.6 B, pepper, Figure

2.8 B, bean). The NO living mulch treatment includes STRIP tillage with NO living mulch, in which weed biomass was mowed, and CT with NO living mulch, which was cultivated periodically to maintain weed-free conditions. While the living mulch by tillage interaction was not significant across sample dates for either crop, soil N for CT-NO was significantly higher than STRIP-NO on the third sample date (Pepper: 23.2 and 15.2 ppm, respectively,  $P$  value = 0.0004; Bean: 27 and 13 ppm, respectively,  $P$  value = 0.0001). Therefore, CT-NO is largely responsible for the high between-row soil N observed for the NO living mulch treatment on that date. Elevated soil N could be a function of the absence of plant uptake, or the stimulation of mineralization by cultivation. Between-row soil N for the 15DAP living mulch was significantly greater than the 0DAP living mulch on the third date for pepper (Figure 2.6 B) and bean (Figure 2.8 B), even though living mulch and weed biomass measured 6 days later was not different between the two treatments. The additional cultivation prior to establishing the 15DAP living mulch may be the factor responsible for this soil N difference between living mulch treatments. This pattern supports the theory that between-row cultivation promotes N mineralization.

In 2013, in-row and between-row soil N concentration never exceeded 8 ppm for pepper (Figure 2.5 B) and 9 ppm for bean on any sample date (Figure 2.7 B). Biomass production by the rye cover crop in 2013 was substantial, and under certain circumstances could promote soil nitrogen immobilization (Table 2.2). However, characteristics of the cover crop residue and the environmental conditions of this experimental year were more likely to promote net mineralization after a brief period of early immobilization. The C:N ratio of the rye averaged 30:1 for both crops, which is sufficiently low for net mineralization to occur (Table 2.2). Precipitation during the cropping sequence was well above average, and N mineralization would not have been inhibited by dry conditions (Figure 2.1 B). High levels of precipitation may

instead have exacerbated nitrate leaching that often occurs in wet springs following cover crop incorporation (Brennan et al. 2009). In-row soil N for pepper was generally lower than between-row N, even though 106 kg ha<sup>-1</sup>-N was banded in-row (Figure 2.5 B). Leaching of N from the pre-plant application, and leaching and reduced bioavailability of the surface applied post-planting application, could have minimized potential differences. Rapid plant uptake of available mineral N by pepper could have contributed to the steady decline observed in in-row soil N concentration. In-row soil N for bean was also lower than between-row soil N in 2013, possibly due to plant uptake as well (Figure 2.7 B). Despite having the ability fix atmospheric nitrogen, beans (*Phaseolus*) do take up soil mineral N, even when N concentration in the soil is very low (Kage 1995).

Incorporation of cover crop residues occurred in the planting row (in-row) for both tillage treatments. It is possible that more rapid mineralization of N from residues in the in-row space enabled early N losses in 2013 relative to the surface residues left in place in the between-row space under strip tillage. Indeed, between-row soil N was significantly greater in STRIP than CT for pepper on the third soil N sample date (Figure 2.6 C). While tillage across sample date was not significant for bean in 2013, between-row soil N on the third sample date was also significantly higher for STRIP (8) than CT (4) (P value = 0.01). It is possible that slow release of N from unincorporated residues in STRIP bolstered soil N concentration in this highly leaching environment.

Living mulch treatment did not influence between-row soil N across sample dates for pepper or bean in 2013. Living mulch and weed biomass production between 0 day and 15 days after planting living mulch treatments was similar, and thus would not likely influence soil N via uptake or other mechanisms. Nor was the conventionally-tilled, no living mulch treatment

significantly different, despite the absence of vegetation and regular cultivation. This further supports speculation that leaching caused by heavy precipitation minimized potential differences in soil N related to living mulch treatment that could have emerged under different conditions.

Surprisingly there was no treatment influence on in-row soil N for pepper across sample dates. That tillage did not influence in-row soil N could be explained by the fact that soil in the in-row space was equally tilled in CT and STRIP treatments. The absence of living mulch effects suggests that the 10 cm cultivated buffer was sufficient to minimize encroachment by living mulch and weed roots into the crop rooting zone. This is contrary to observations made by Vanek et al. (2005), that lower in-row soil N concentration was caused by living mulches seeded before and at the same time, but not after, transplanting pumpkins. Initial soil N concentrations in that experiment were 25 to 30 ppm, and thus may be more subject to treatment-induced variation. With such low overall soil N concentrations in this experiment so low, potential treatment differences may not be as readily observed.

### Pepper yield

Total marketable pepper fruit averaged 4466 kg ha<sup>-1</sup>. Though total yield was not significantly influenced by treatment, yield of CT with NO living mulch (7747 kg ha<sup>-1</sup>) was significantly higher than all other treatment combinations except STRIP with 0DAP living mulch (4625 kg ha<sup>-1</sup>). Yield of U.S. Fancy grade peppers was highest in the NO living mulch treatment. Though the interaction of tillage and living mulch did not significantly influence yield of U.S. Fancy peppers, yield of U.S. Fancy peppers for CT with NO living mulch was almost double that of STRIP without mulch (P value = 0.04). Conventional tillage without living mulch was also the highest yielding treatment in 2013, with 20227 kg ha<sup>-1</sup> total marketable fruit, more than half of

which were U.S. Fancy. Differences in yield are not supported by observations of in-row soil N concentration, which were not significantly influenced by tillage or living mulch.

### Bean yield

Differences in bean yield in 2012 followed trends observed in pepper yield in 2012 and 2013. Yields were highest in the absence of competing vegetation in the conventional till, no living mulch treatment. In 2013, there was no significant variation in living mulch and weed biomass or soil N concentration that could explain why STRIP with 15DAP living mulch yielded higher than STRIP with NO living mulch, and no other treatments were different.

Yield differences for pepper and bean are more readily explained by observations of between-row N. While in and between-row locations are considered distinct zones for the purposes of sampling, above and belowground barriers do not exist. The absence of treatment effects on in-row soil N suggest that living mulch roots did not encroach into the in-row soil volume. However, that does not imply that pepper roots did not occupy a portion of the between-row space. It is highly unlikely that the 20 cm wide cultivated strip in which plants grew supplied sufficient rooting volume for bean or pepper. Soil N existing in the between-row space may have been exploited via horizontal crop root exploration. Between-row soil N concentration varied significantly among tillage and living mulch treatment across sample dates for pepper and bean in 2012, and pepper in 2013. Between-row soil N may have been an accessible nutrient pool that drove differences in crop yields.

Other influences of living mulch and weed biomass not related to nitrogen uptake may have reduced yields in treatments containing high weed and living mulch biomass. Allelopathic properties of living mulch and weed species have reduced yields in other living mulch systems

(Mochizuki et al. 2008; Walters and Young 2008). Aqueous extracts of giant foxtail, redroot pigweed, and common lambsquarters (predominant weed species observed in the experimental site) are known to reduce germination and growth of some plants (Alam et al. 2002; Martin and Smith 1994; Smith et al. 2001).

Shading by living mulch and weeds did occur early in the cropping sequence when pepper plants were still small. Living mulch and weeds in the between-row space were mowed when vegetation across all treatments reached approximately 20 cm in height. Mowing occurred for the first time 37 days and 40 days after crop establishment in 2012 and 2013, respectively. At this time, living mulch and weed above-ground biomass was as high as or slightly higher than pepper plants before being mowed. The estimated minimum critical weed-free period for pepper is between 6.7 and 15.3 weeks after transplanting to avoid a 5 percent yield loss (Amador-Ramirez 2002) and 3 to 5 weeks after transplanting to avoid a 10 percent yield loss (Motis et al. 2004). Weed competition during the critical weed-free period is especially deleterious to yield because it reduces leaf area before the onset of fruit set. The combined effects of shading and nitrogen stress can result in premature fruit set, which in pepper results in reduced fruit size and poor shape and quality (Fukumoto et al. 2004; Hassan et al. 1987; Schmidt et al. 1983). In 2013, prematurely set fruit was removed to encourage the continuation of vegetative growth. However, fruit removal may have occurred too late to mitigate yield reductions.

None of the above possibilities explain why total marketable and U.S. Fancy yield was significantly greater in CT with 15DAP living mulch than with 0DAP living mulch 2013 (Figure 2.9 A & B). Contrary to expectations, living mulch and weed biomass was not different between the two treatment combinations on any sample date. A 15 day delay in living mulch sowing did not produce significant differences in the timing or total production of living mulch biomass.

The height to which living mulch and weeds are allowed to grow may need to be reduced to bring living mulch-crop competition within an acceptable level. Mowing vegetation frequently during the critical weed-free period is especially important. Maximum living mulch and weed height before mowing in other experiments varied from 7.6 to 25 cm (Brandsaeter et al. 1998; Chase and Mbuya 2008; Gibson et al. 2011; Ilnicki and Enache 1992; Wiles et al. 1989). Mowing was generally conducted two or three times during the season, as it was in this experiment. Of the experiments that used mowing alone as a suppression strategy, only one (Ilnicki and Enache 1992) reported equivalent yields with and without living mulches. Mowing weeds and living mulches to the extent necessary to prevent yield losses may not necessarily be economically feasible. Spacing planting rows closer together could reduce the time until the crop canopy begins to shade the surrounding vegetation. However, like all weed management strategies, the spatial arrangement of crops in the field must accommodate for the size and limitations of the equipment being used, in this case a 60 cm wide flail mower.

The influence that living mulches and weeds have on crop growth depends in part on their proximity in the field. A 5 cm wide buffer on either side of the crop row was not seeded to living mulch and cultivated throughout the cropping sequence to maintain relatively weed-free conditions. Considering that drip irrigation and fertilizer was applied directly in the crop row, it is reasonable to assume that living mulch and weed roots would explore the in-row soil volume for water and nutrients. In other words, crops may require a larger competition-free soil volume than was provided in this experiment. Widening the cultivated buffer might decrease the incidence of below-ground competition for resources, which would decrease the area planted to living mulches unless row spacing was also increased. Living mulches may not be a practical weed management strategy if the area planted to them is insignificant and confers negligible

benefit (weed suppression, organic matter production, erosion control etc.). This is especially true if the cost of living mulch management (e.g. mowing, spraying, partial rototilling) is maintained. Wider row spacing could be used to preserve the area planted to living mulch, but would reduce crop plant population and yield and potentially create more weed problems.

Pepper yields in 2012 and 2013 were considerably lower than yields commonly observed for bell pepper grown in on conventionally tilled bare ground (26295 to 36,000 kg ha<sup>-1</sup>) and strip tillage (14833 to 28130 kg ha<sup>-1</sup>) (Delate et al. 2008; Hartz et al. 1993; Wang and Coolong 2011). The absence of a second harvest certainly contributed to low yield in 2012. In both years, however, visual symptoms of nitrogen stress were apparent, included sparse, chlorotic foliage, short plant stature, premature fruit set, and decreased fruit size at maturity. Harvest was delayed in both years because pepper fruit increased in size very slowly. The high number of culls (34 percent of total yield in 2012; 18 percent of total yield in 2013) resulted primarily from increased physical and biological damage to fruit incurred during this prolonged period of maturation. Higher cull weight for conventional tillage without living mulch in 2012 may be due to increased fruit set but poor fruit enlargement due to a short-lived period of relatively high soil N concentration that occurred 63 days before harvest. While soil N concentration was within the sufficiency range for some treatments on the third soil mineral N sample date in 2012, soil N concentration was well below the critical range for all other sample dates. In living mulch systems, the risk of yield loss due to nitrogen deficiency is high, and warrants precise and adequate fertilizer application to optimize crop competitiveness. High summer temperatures in 2012 also contributed to the loss of early fruit set, though this effect was not quantified.

Yield of bean was also much lower than typical yield for dry bean grown under conventional or strip tillage. Dry bean var. 'Jacobs Cattle Gold' in a six-year variety trial in



Washington State yielded 2141 kg ha<sup>-1</sup> (Miles 2006). This trial was conducted in a region with optimal conditions for dry bean production, and may not be representative of potential yield in the humid Southeast. Expected yield of dry beans (variety not specified) grown in New York range from 2,000 to 2,500 kg ha<sup>-1</sup> (Halseth et al. 2001). Several factors may have contributed to low yields overall and low yields for the conventionally tilled no living mulch treatment. Bean seed was not inoculated prior to planting in either year. It is not known how recently the experimental site was planted to a legume inoculated with the appropriate strain of rhizobium for *Phaseolus vulgaris*. Plant roots were not examined to determine if nodulation had taken place. While indigenous strains of *Rhizobium* capable of forming a symbiosis with *Phaseolus* were likely present, N<sub>2</sub> fixation is generally not as efficient as with the appropriate strain (Sylvia et al. 2005).

In 2012 and 2013, foliar feeding by Mexican bean beetle (*Epilachna varivestis* Mulsant) was extensive. In 2013, OMRI approved organic pesticides were applied to suppress feeding activity of bean beetles. Nonetheless, defoliation of beans by beetles was estimated at 50 % by the time of full pod elongation, but before pod filling. Defoliation of 40 percent of leaf area by Mexican bean beetle can reduce bean leaf photosynthesis by 60 percent (Peterson et al. 1998). Photosynthetic capacity does not recover after defoliation has occurred, and can significantly reduce assimilate production during the critical pod filling stage.

#### Aggregate stability

Soil aggregate formation is influenced by the production and decomposition of soil organic matter (SOM). Macroaggregates (250 – 2000 µm) are more sensitive to short term changes in management practices that influence the cycling of SOM than are microaggregates

(53 – 250  $\mu\text{m}$ ). Inputs of SOM from living mulch roots and residue, as well as differential responses of SOM decomposition to tillage, were expected to influence macroaggregate stability over the course of this experiment. Specifically, we expected to observe greater aggregate stability in STRIP tillage than CT tillage, and in treatments that included living mulch than those that did not.

That was not the case for pepper in 2012, when aggregate stability was similar across all treatments. Though aggregate stability was influenced by tillage and living mulch for pepper in 2013, differences were not as expected. There was no consistent effect of tillage or living mulch on observed values. Differences are also not affected by variation in living mulch and weed biomass production among treatments. Higher aggregate stability was observed for STRIP in bean during 2012, but not in 2013.

It is highly likely that the duration of the cropping sequence (16 weeks in 2012, 15 weeks in 2013) was not long enough for meaningful treatment-induced changes to occur. Research that demonstrates improvements in aggregate stability in reduced tillage systems typically measure changes that occur after 5 years or more (Kaspar et al. 2001; Paul et al. 2013; Six 1999). In fact, conventional tillage may increase aggregate stability temporarily by promoting microbial decomposition of fresh residues into aggregate binding agents (Six et al. 2000). In strip-tilled living mulch treatments, we expected that the dual forces of SOM inputs from living mulches and the absence of soil disturbance from weed cultivation would increase aggregate stability. Total biomass production by weeds and living mulches was substantially less than what would be expected from a cover crop grown for the purpose of biomass production. Additionally, not all of the biomass from mowed living mulch and weed residue was necessarily decomposed within the course of the sampling sequence. Contrary to expectations,

the four to five cultivations that took place in the NO living mulch treatment did not have had a measurable negative impact on aggregate stability that season.

The protocol used to assess aggregate stability was developed by the NRCS for use by NRCS soil specialists, county extension agents, and farmers (USDA 2001). Its purpose is to demonstrate relative differences in aggregate stability in response to management practices in a given site. The materials and methods are intended to be inexpensive, simple, and widely accessible. The protocol is more subject to user error than techniques using more precise instrumentation. The NRCS protocol may lack the precision to measure small changes in aggregate stability over short timeframes, if they occur at all.

## **Conclusions**

Building and preserving soil quality is a central objective of sustainable agricultural management systems. Soil organic matter is a property with substantial influence on soil quality and function, and is highly influenced by management practices. Reduced tillage limits soil disturbance and typically promotes the accumulation of soil organic matter and development of favorable soil physical and chemical properties related to high soil organic matter levels. Unacceptable weed control in reduced tillage systems without the use of herbicides is the primary impediment to the adoption of reduced tillage in organic vegetable production. Living mulches have been employed as an alternative weed management strategy with reportedly similar benefits to soil quality as reduced tillage. However, competition between the crop and living mulch often results in unacceptable yield losses. This project investigated the integration of reduced tillage and living mulch strategies to understand if weed suppression and crop performance could be improved relative to either one of these strategies used alone.

Our results indicate that living mulches can effectively suppress weeds when environmental conditions favor rapid living mulch emergence and growth. Living mulch, particularly teff, was extremely competitive and provided effective weed control in 2013 when soil moisture during germination was adequate and teff was able to accumulate biomass rapidly relative to weeds. Dry conditions in 2012 delayed teff growth, and early weed suppression was poor. Tillage did not impact weed biomass accumulation for either crop in both years. Conventional tillage, however, provided better growing conditions for teff, but not for lespedeza. Seeding the living mulch 15 days after planting the crop as opposed to the same day (0 days after planting) did not result in differences in living mulch or weed biomass. Mowing complimented weed suppression because the living mulch species used were mowing tolerant while the representative weed community generally was not. Early season weed suppression by living mulch was not as critical for quickly growing crops like dry bean due to rapid canopy development.

In-row soil mineral nitrogen concentration was not a significant indicator of differences among tillage or living mulch treatments for pepper or bean in any year. The 20 cm wide clean-cultivated buffer separating the crops from the living mulch was sufficient to minimize belowground interaction in the in-row space. In-row soil mineral N concentration in this experiment was abnormally low across all treatments for both crops, and may have masked the expression of potential treatment differences.

In 2012, between-row soil mineral nitrogen was generally elevated under conventional tillage for both pepper and bean, but only on one mid-season sample date. This is consistent with the pattern of accelerated mineralization of nitrogen from cover crop residues following incorporation by tillage. Living mulch and weed biomass appears to have not decreased

between-row mineral nitrogen concentration, as biomass was generally highest in conventional tillage. Additionally, cultivation for weed control in some treatments appears to have stimulated between-row nitrogen mineralization on one sample day. 2013 was characterized by above average precipitation during the summer months. Soil nitrogen concentration overall was extremely low, probably due to extensive leaching of nitrate beyond the sampling depth. Strip tillage generally exhibited slightly higher soil mineral N concentrations than conventional tillage. Delayed mineralization of surface residues in strip tillage may have prolonged nitrogen availability throughout the cropping sequence.

Pepper yield was consistently highest under conventional tillage in the absence of living mulch and weeds. Yield differences were not reflected by in-row soil nitrogen concentration. Instead, it appears that between-row soil N concentration, and antagonism from living mulch and weeds, are responsible for observed differences. Bean yield followed a similar trend as pepper in 2012, but yield differences in 2013 could not be explained. In the presence of living mulch, pepper yields and bean yields across treatments were similar.

Aggregate stability was expected to increase in association with strip tillage, as well as living mulch treatments that generated the most aboveground biomass. Only for bean in 2012 was aggregate stability greater under strip than conventional tillage. It is highly likely that the duration of the experiment was not sufficient for potential treatment differences to emerge.

This experiment demonstrated the challenges of achieving effective weed management with living mulches without negatively impacting crop yields. Living mulch management strategies, like delayed seeding and mowing, need to be adapted to the behavior of the living mulch species, the weed pressure of the site, and the competitive ability of the crop. Integrating

reduced tillage with living mulch appears to enhance weed suppression as long as conditions for living mulch germination and growth are optimized. This study did not demonstrate that living mulches could effectively suppress weeds without negative consequences for crop performance. Fertilizer timing and placement is critical to shifting the competitive balance toward the crop away from the living mulch and weeds. Long-term studies are needed to evaluate whether components of this system impact indicators of soil quality. Opportunities for modification of the spatial arrangement of crop and living mulch, and tilled and untilled surface, are plentiful, and warrant future investigation.

## Appendix

Appendix 1 ANOVA of living mulch and weed biomass for pepper.

	Teff	Lespedeza	Weeds	Living Mulch Total	Weeds + Living Mulch
<b>2012</b>	P value				
Tillage	0.0124	NS	NS	0.0074	0.0013
Living Mulch	NS	NS	NS	NS	NS
Sample Date	0.0004	<.0001	0.0024	<.0001	0.0021
Living Mulch*Sample Date	NS	NS	NS	NS	NS
Tillage*Living Mulch	NS	NS	0.0203	NS	NS
Tillage*Sample Date	0.0015	0.0366	NS	0.0009	0.037
Tillage*Living Mulch*Sample Date	NS	NS	NS	NS	NS
<b>2013</b>	P value				
Tillage	0.0044	NS	NS	0.001	<.0001
Living Mulch	NS	0.0374	NS	0.0168	<.0001
Sample Date	<.0001	0.0433	0.0241	<.0001	<.0001
Tillage*Living Mulch	NS	NS	0.0043	NS	0.0009
Tillage*Sample Date	0.0038	NS	0.017	0.0196	0.0003
Living Mulch*Sample Date	NS	NS	0.0131	NS	0.0049
Tillage*Living Mulch*Sample Date	NS	NS	NS	NS	0.0315

NS: Differences not significant at  $P \leq 0.05$ .

Appendix 2 ANOVA of living mulch and weed biomass for bean.

	Teff	Lespedeza	Weeds	Living Mulch Total	Weeds + Living Mulch
<b>2012</b>	P value				
Tillage	<.0001	NS	NS	NS	NS
Living Mulch	NS	NS	NS	NS	NS
Sample Date	0.0119	0.0049	0.026	0.0059	0.0007
Living Mulch*Sample Date	NS	NS	NS	NS	NS
Tillage*Living Mulch	NS	NS	NS	NS	NS
Tillage*Sample Date	NS	NS	NS	NS	NS
Tillage*Living Mulch*Sample Date	0.0183	NS	NS	0.0476	NS
<b>2013</b>	P-value				
Tillage	NS	NS	NS	NS	0.0135
Living Mulch	NS	NS	0.0358	NS	0.0135
Sample Date	<.0001	<.0001	NS	<.0001	<.0001
Tillage*Living Mulch	NS	NS	NS	NS	NS
Tillage*Sample Date	NS	NS	NS	NS	NS
Living Mulch*Sample Date	NS	NS	NS	NS	NS
Tillage*Living Mulch*Sample Date	NS	NS	NS	NS	NS

NS: Differences not significant at  $P \leq 0.05$ .



Appendix 3 ANOVA for in-row and between-row soil mineral nitrogen for pepper.

	2012		2013	
	IN	BTW	IN	BTW
	P-value			
Living Mulch	NS	NS	0.0168	0.0512
Tillage	NS	NS	NS	NS
Sample Date	<.0001	<.0001	0.0002	0.0009
Living Mulch*Sample Date	NS	0.0001	NS	NS
Tillage*Living Mulch	NS	0.0255	NS	0.0392
Tillage*Sample Date	NS	<.0001	NS	NS
Tillage*Living Mulch *Sample Date	NS	NS	NS	NS

NS: Differences not significant at  $P \leq 0.05$ .

Appendix 4 ANOVA of in-row and between row soil mineral nitrogen for bean.

	2012		2013	
	IN	BTW	IN	BTW
	P-value			
Tillage	NS	0.0167	NS	<.0001
Living Mulch	NS	NS	NS	NS
Sample Date	<.0001	<.0001	0.0135	<.0001
Tillage*Living Mulch	NS	0.0373	0.0378	0.0172
Tillage*Sample Date	NS	NS	NS	NS
Living Mulch*Sample date	NS	0.0428	NS	NS
Tillage*Living Mulch *Sample Date	0.0277	NS	NS	NS

NS: Differences not significant at  $P \leq 0.05$ .

Appendix 5 ANOVA for pepper yield in 2012.

	U.S Fancy	U.S. No. 1	U.S. No. 2	Total Marketable	Cull
Fruit weight kg ha <sup>-1</sup>					
Tillage	NS	NS	NS	NS	0.0188
Living Mulch	0.0429	NS	NS	NS	NS
Tillage*Living Mulch	NS	NS	NS	NS	0.0146
Fruit number per ha <sup>-1</sup>					
Tillage	NS	NS	NS	NS	0.02
Living Mulch	0.045	NS	NS	0.0536	NS
Tillage*Living Mulch	NS	NS	NS	NS	0.0246

NS: Differences not significant at  $P \leq 0.05$ .

Appendix 6 ANOVA for pepper yield in 2013.

	U.S Fancy	U.S. No. 1	U.S. No. 2	Total Marketable	Cull
Fruit weight kg ha <sup>-1</sup>					
Tillage	0.0225	0.034	0.0184	0.0073	NS
Living Mulch	0.0151	0.0258	NS	0.0054	NS
Tillage*Living Mulch	0.001	NS	0.0107	0.0063	NS
Fruit number ha <sup>-1</sup>					
Tillage	0.0277	NS	0.0107	0.0163	NS
Living Mulch	0.0128	0.051	NS	0.0074	NS
Tillage*Living Mulch	0.0007	NS	0.0066	0.0134	NS

NS: Differences not significant at  $P \leq 0.05$ .

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