To the Graduate Council:

I am submitting herewith a thesis written by Sarah Elizabeth Broughton entitled "The Effects of Living Mulches on Organic, Reduced-Till Broccoli Growth and Management." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant Sciences.

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The Effects of Living Mulches on Organic, Reduced-Till Broccoli Growth and Management

A Thesis Presented for
the Master of Science
Degree
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Sarah Elizabeth Broughton
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Abstract

Conservation tillage programs have been successfully implemented for many agronomic cropping systems, but adoption of reduced tillage for vegetable crops has been slow. As many conventionally managed conservation tillage programs rely on synthetic herbicides for clean cultivation, alternative methods must be devised to suppress weed pressure and reduce reliance on mechanical cultivation to aid in the development of reduced tillage programs for organic cropping system. Strip tillage is a reduced tillage method that is well suited to vegetable crop production, and the utilization of cover crops and living mulches between rows provides a viable weed management option for organic systems.

The adoption of reduced tillage and the inclusion of cover crops and living mulches have the potential to alter the agroecosystem in ways that impact plant development and crop yield, and augment weed, insect and disease pressure. The current study focuses on the use of strip tillage and the interplanting of spring-seeded living mulches and overwintered cover crops for early-season organic broccoli production. Data were collected on ground cover provided by cover crops and living mulches, crop physiological status (petiole sap nitrate, photosynthetic rate, plant growth and crop biomass) and pest pressure (weed relative abundance, insect density and disease incidence and severity).

Living mulches provided the greatest ground coverage when cover crop establishment was poor; however, when cover crops produced a large amount of biomass, living mulch establishment was suppressed. Decreases in herbivorous pests and suppression of grassy and cool-season weed species were also observed, indicating that strip tillage and the use of spring-seeded living mulches and overwintered cover crops may provide beneficial pest management strategies. Decreases in crop growth and biomass, and decreases in petiole sap nitrate were observed, however, indicating reductions in crop vigor and yield may be expected with the implementation of strip tillage and living mulch crops. It is suggested that the utilization of strip tillage and living mulch crops may provide benefits to pest management which may outweigh declines in yield.

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Chapter One: Introduction and literature review

The Natural Resource Conservation Service defines conservation tillage as any tillage system that leaves greater than 30% residue remaining on the soil surface after planting (Horowitz et al., 2010). Integrating reduced tillage practices into organic systems can enhance soil environmental conditions, creating an environment that is better able to support plant growth. Cover crops and living mulches make reduced tillage more feasible by aiding in insect, weed and disease management. The use of reduced tillage and living mulches can promote productivity and increase efficiency, further enhancing sustainability, making them valuable assets to organic crop production.

Conservation tillage programs maintain soils by minimizing soil erosion and improving physical, chemical and biological conditions. Introduced in the 1950's, conservation tillage has become an acceptable cultural practice due to improved herbicide development, equipment modifications and increased concerns for erosion (Hoyt, 1999). While reduced tillage systems have been implemented successfully for row crops, conservation tillage practices evaluated in vegetable cropping systems have produced variable results due to factors, such as poor plant establishment and impeded root growth. Previous research conducted at the East Tennessee Research and Education Center Organic Crops Unit has demonstrated constraints of no-tillage due to compaction of clayey soils, limiting root growth and impeding plant development. Strip tillage provides an alternative reduced tillage practice that is well suited to the production of transplanted vegetables; planting into a tilled strip maximizes root growth, allowing for improved plant setting (Wilhoit et al., 1990). While the planting area is tilled, cover crop residues remain between rows, providing protection from soil erosion and weed control.

The implementation of an organic, reduced tillage system has been hampered by the lack of effective herbicides certified for organic use. Many conventional, no-till fields are maintained using herbicides. New methods of weed control must be devised for use in organic systems. Traditionally, tillage and mechanical cultivation have offered successful results in controlling weeds, further limiting the application of reduced tillage.

Utilizing living mulches in conservation tillage systems has strong potential to increase sustainability, allowing for maximum plant growth and pest control with minimal soil disturbance. Living mulches can provide an alternative means of weed management in reduced tillage systems for early season vegetable production when cool-season cover crops have not yet matured or accumulated adequate biomass to provide killed residue mulches. Intercropping an economically important crop with an undersown plant species that has no direct market value is a cultural control method that helps to diversify the agroecosystem and may provide further benefits, including erosion reduction, enhanced fertility, improved soil quality and beneficial pest management. Research has demonstrated that living mulches, when undersown with a vegetable crop, have the ability to decrease injury imposed by insect pests and reduce weed pressure, two of the primary challenges faced in organic vegetable production systems.

Results have been variable, and research has also demonstrated that living mulches may compete with the main crop or may inadequately suppress weeds, limiting the successful implementation of living mulches into production systems. Research on living mulch crops must be directed at determining key factors that limit crop yield, affecting success in these systems, and devising effective methods for enhancing crop production and aiding with pest management. With consistently positive results, methods utilizing reduced tillage and living mulch crops can be implemented within cropping systems, increasing the sustainability of organic vegetable production.

Reduced Tillage

Bare soil left exposed by tillage increases the potential for erosion by wind and water, nutrient leaching, reduced biological diversity and loss of organic matter. However, with perpetual cover from living or decaying vegetation, most of the environmental damage caused by tillage can be decreased or even reversed. Conservation tillage is being used to boost the image of modern farming. However, along with this technology has come requisite pesticide usage to manage cover crops, control weeds and prevent insect damage (Kuepper, 2001).

A high percentage of land in East Tennessee is subject to erosion due to slope and slow water penetration into the soil. When cropped continuously using conventional tillage methods, high value crops cannot remain productive over an extended period of time (Rutledge, 1999). In Tennessee, the successful implementation of conservation tillage programs in row crop production has caused some interest among vegetable growers, but adoption of these practices has been slow (Rutledge, 1999). However, production of both direct seeded and transplanted vegetable crops has increased. This increase has been attributed to the development and commercialization of reduced tillage planters and seeders, advancements in producing and managing high-residue cover crop mulches and improvements and acceptance of integrated weed management technologies (Morse, 1999a).

As a hybrid system between no-till and conventional tillage, strip tillage can offer improvements to soil quality while also encouraging plant growth. The benefits of strip tillage include reduction of soil compaction from heavy farm equipment, preservation of soil micro and macro biota and reduced soil erosion and runoff from fields (Luna and Staben, 2003). For successful establishment of transplanted crops, several key production objectives must be achieved. First, a dense, uniformly distributed cover crop must be produced. Second, cover crops must be properly managed to leave a heavy, uniformly distributed, killed mulch over the soil surface. Third, transplants must be established into cover crops with minimal disturbance of surface residues and surface soil. Lastly, year-round weed control strategies must be adopted (Morse, 1999a). Strip tillage also facilitates successful plant establishment because planting into a tilled strip maximizes root growth, allowing for improved plant setting (Wilhoit et al., 1990).

Organic farming is assumed to be dependent upon clean tillage and cultivation; this assumption has been used disparagingly to characterize organic crop production as both erosive and environmentally destructive (Kuepper, 2001). The development of reduced tillage systems that are effective in managing weed and insect pests while enhancing efficiency and maintaining or boosting yields in organic systems is a timely, and cutting edge topic. As organic growers seek improvements in soil fertility, biological activity, and soil physical properties, typically through management systems that emphasize the integration of individual farm processes into a whole farm system, the integration of reduced tillage should prove beneficial in boosting the overall sustainability of organic crop production (Baldwin, 2006).

Soil Organic Fraction

Soil quality refers to the sustained capability of a soil to accept, store and recycle water, nutrients and energy; it is the soil's capacity to support crop growth without resulting in soil degradation or otherwise harming the environment. Soil quality is comprised of intrinsic and dynamic portions. The intrinsic soil component is a function of the geologic materials of which a soil is comprised, such as mineralogy and particle size distribution. Factors such as climate, topography and hydrology are important intrinsic determinants of soil quality. Dynamic soil quality encompasses soil properties that change over relatively short time periods in response to human use, and are strongly influenced by agronomic practices. Decreases in soil structural stability, porosity and soil organic matter are characteristics of declining soil quality (Carter, 2002).

Soil texture is the relative percentage of sand, silt and clay found in soil (Sullivan, 2004). Soil structure refers to the way sand silt and clay are aggregated together into larger secondary clusters (Sullivan, 2004). Soil texture and structure determine the amount of available pore space (Sullivan, 2004). While soil texture is related to soil mineralogy and cannot be changed, soil structure can be improved or destroyed by soil management practices (Sullivan, 2004). Improvements to soil structure facilitate easier tillage, increased water storage capacity, reduced erosion, and deeper, more prolific plant root systems. Soil that tills easily, has good seedbed quality, seedling emergence and deep root penetration is said to have good tilth. Good tilth is dependent upon soil aggregation.

Soil organic matter is linked to desirable soil physical, chemical and biological properties, and is closely associated with soil productivity. Biologically active soil organic matter is believed to be the key to soil productivity when fertility is biologically mediated, such as with the use of composts and green manures. Active soil organic matter refers to a heterogeneous mix of living and dead organic materials that are readily circulated through biological pools (Wander et al., 1994). It is a major soil nutrient reservoir. The balance between decay and renewal processes in this pool controls nutrient availability and soil organic matter status, determining whether organic matter is aggrading or degrading overall. Two types of organic matter change can be associated with organic farm systems: accumulation of biologically active soil organic matter and accumulation of more stable, yet still labile, soil organic matter (Wander et al., 1994). In agricultural soils, the microbial biomass acts as a source-sink for labile nutrients, and practices that alter the size of the biomass or its rate of turnover can affect crop growth (Granatstein et al., 1987).

Soil Physical Properties and Nutrient Cycling

Tillage regimes differing in crop residue placement and soil disturbance have the potential to modify soil physical properties, such as bulk density and soil moisture, which can in turn alter soil pH and fertility. Such changes may affect the availability and cycling of nutrients.

Reduced tillage systems, through the placement of crop residues on the soil surface, tend to accumulate increased amounts of organic matter relative to plowed soil. Edwards et al. (1992) observed organic matter increases of 56% in the top 10 cm of the soil after 10 years of reduced tillage, while organic matter levels in conventionally tilled plots remained constant. Doran (1980) observed a similar trend with increased organic matter at the soil surface in reduced tillage soils. Increased organic matter in surface soils, caused by the accumulation of crop residues and killed mulches, may affect bulk density. Edwards et al. (1992) found that reduced tillage soils had significantly lower bulk density than those under conventional tillage.

The concentration of plant residues on the soil surface also impacts soil moisture in reduced tillage systems by decreasing rates of evaporation. Fields maintained using reduced tillage typically have higher surface soil water content than plowed soil, enabling plants to tolerate drought and continue growing during periods of dryness (Johnson and Hoyt, 1999).

Increased soil moisture affects soil temperature. Cover residues create an insulation effect causing fields to remain cooler earlier in the season. As more energy is required to heat wet soil, fields warm more slowly. Cooler temperatures can delay early crop growth, potentially affecting yield. Once warmed, this same insulation effect keeps fields warmer through the downward convection of heat (Johnson and Hoyt, 1999).

Soil nutrients tend to be stratified under reduced tillage systems, with the highest nutrient concentrations found in the 0-5 cm soil depth. Nutrients derived from crop residues, applied fertilizers and manures, especially those nutrients that are relatively immobile, tend to accumulate at or near the soil surface in long-term reduced tillage systems due to limited soil mixing (Johnson and Hoyt, 1999). The wetter, cooler soil environment found under reduced tillage, along with impacts on microbial populations, may also impact the cycling of nutrients and availability to plants.

Cover Crops and Living Mulches

Cover crops provide a vegetative cover during periods when a cash crop is not present. These crops can then be tilled into the soil, or mechanically killed and left as residue on the soil surface acting as a mulch. Green manures are grown as cover crops and incorporated into the soil to increase soil fertility, organic matter and tilth. Alterations to the soil resulting from the utilization of cover crops and incorporation of green manures include reduced rates of erosion, decreased soil temperatures, increased soil organic matter, improved water infiltration rates, increased microbial activity, improved soil structure, enhanced weed control and increased crop yield.

Living mulches are cover crops that are grown during cash crop production; transplants may be sown directly into a living mulch crop, or the mulch may be seeded at the time of planting. Living mulches are intended to provide living ground cover throughout the growing season, and are established between rows of the main crop to suppress weeds. In addition to weed suppression, living mulches can provide diversity within a cropping system, reduce erosion, enhance fertility, improve soil quality, and assist with pest management and encourage beneficial organisms.

Soil Erosion and Water Management

Historically, cover crops were used to fix nitrogen (N) and as a source of forage in integrated agricultural systems (Ritter et al., 1998). With the advent of synthetic fertilizer, focus shifted away from cover crops as a means of enhancing soil fertility. Today, renewed interest in the reduction of water runoff and soil erosion has facilitated research on the incorporation of cover crops into crop rotation schedules. In addition to protecting the soil from erosion, cover crops also improve soil structure, tilth and water-holding capacity, and can decrease reliance on synthetic fertilizer inputs by fixing N and reducing nitrate leaching, reducing the chance of environmental pollution (Hartwig and Ammon, 2002).

Cover crops provide vegetative cover during periods when a crop is not present to cushion the force of falling raindrops, slowing the rate of runoff and improving moisture infiltration in the soil (Hartwig and Ammon, 2002). Bare ground is highly susceptible to rain drop splashes that can detach soil particles, increasing soil erosion rates (Hartwig and Ammon, 2002). Crop residues and living mulches also increase soil porosity as a result of increases in organic matter (Browning, 1937). Increased porosity results in increased soil permeability, enhancing water infiltration rates (Browning, 1937). The presence of a mulch, living or dead, can decrease the water runoff velocity, allowing heavier particles to settle as opposed to being lost (Browning, 1937). Hall et al. (1984) reported reductions in soil loss of 86-99% in no-till corn with a living mulch of birdsfoot trefoil or crownvetch as compared to conventionally tilled corn.

Cover crops and green manures provide a two-fold service in relation to water management. In addition to slowing the rate of water runoff, cover crops also aid in managing soil water during the growing season. In early spring, when wet soils may cause delays in crop production, cover crop growth and transpiration rates are at their highest (Ebelhar et al., 1984). In the summer months, when crop transpiration rates are greatest and rainfall is low, mulches slow evaporation and provide more available moisture for cash crops, preventing damage due to drought stress. Whereas killed mulches aid in retaining water, living mulches require an adequate supply of moisture for growth and development. Similar to cover crop growth in spring, living mulch crops may remove water from the soil. When utilized during summer crop production, living mulches may compete with a cash crop for available soil moisture, especially during years with little rainfall.

Cover Crop and Living Mulch Effects on Soil Quality

Organic matter refers to the fraction of the soil that is composed of both living organisms and once-living residues in various stages of decomposition (Sullivan, 2004). Humus is the end product of decomposition; it is relatively stable and requires long periods of time to further degrade. Benefits of topsoil rich in organic matter and humus are rapid decomposition of crop residues, granulation of soil into water-stable aggregates, decreased crusting and clodding, improved internal drainage, better water infiltration, increased water and nutrient holding capacity (Sullivan, 2004).

Soil organic matter is considered to be a key attribute of soil and environmental quality. Increases in organic matter have profound effects on soil physical and chemical properties. Soils maintained under reduced tillage, utilizing a cover crop in their rotation, show increasing levels of the soil organic fraction over time (Danso et al., 1991). Organic additions increase the number of larger size aggregates in the soil. Cover crop residue benefits aggregation chiefly by furnishing a carbon (C) source to the microorganisms directly playing a role in aggregation (Hoyt and Hargrove, 1986). Stimulation of these organisms produces a glue that binds soil particles together into aggregates (Hartwig and Ammon, 2002). As organic matter additions accumulate on the soil surface, soil tilth and productivity greatly increase.

Organic inputs, which regulate soil organic matter, influence soil particles and the relation between soil organic matter and soil aggregates. The leading management strategy for increasing soil organic matter quantity is increasing the proportion of crop residues returned to the soil. Wani et al. (1994) found that adopting green manures and organic amendments in crop rotations provided a measurable increase in soil organic matter quality and other soil quality attributes as compared to systems of continuous cereal production.

Cover Crops Utilized in the Investigated Cropping System

Austrian winter pea, a field pea, is a viney winter annual with stems up to 1.2 m (4 ft.) long (Ball et al., 2002). It is primarily adapted to temperature zones A through C (Fig. A.1) and is mainly used as silage and green manure. Optimum seeding time is Sept. through Oct. at 22.5-33.5 kg/ha (20-30 lbs./A.), when sown with a small grain (Ball et al., 2002). Field peas can withstand temperatures as low as 12 °C (10 °F) but are sensitive to heat (Clark, 2007). Under long, cool, moist seasons, a crop can produce more than 2.26 metric tons (5,000 lbs.) of dry matter/A., yielding 101-168 kg N/ha (90-150 lbs. N/A.) (Clark, 2007). The inclusion of grain legume crops, such as field peas, improves sustainability by providing disease suppression and enhancing soil tilth. Austrian winter peas are moisture efficient and provide rapid spring growth, outcompeting weeds while contributing N. They are easily killed by discing or mowing after full bloom, the maturity stage at which optimum N is provided (Clark, 2007).

Triticale, a cereal grain, is an annual bunch grass that grows up to 1.2 m (4 ft.) tall (Ball et al., 2002). It is primarily adapted to zones A through D (Fig. A.1), and in the South East is seeded Sept. through Oct. at 67-101 kg/ha (60-90 lbs./A.) in mixtures (Ball et al., 2002). Cereal grains are good at scavenging excess nutrients and holding them until decomposition (Ball et al., 2002).

Winter oats provide quick, weed-suppressing biomass, take up excess soil nutrients and can improve the quality of legumes when planted in mixtures. They are an upright annual grass able to produce 1-1.8 metric tons (2,000-4,000 lbs.) of dry matter/A (Clark, 2007). Winter oats can also be used as a N catch crop. Quick Fall germination makes winter oats suitable as a smother crop, and allelopathic effects can further hinder weed growth. When temperatures are cold enough that the crop is winterkilled, in zone B (Fig. A.1) and colder, further management is not necessary; otherwise, oats can be killed by rolling-crimping or mowing at the soft dough stage (Clark, 2007).

Crimson clover is a winter annual legume that grows up to 1 m (3 ft.) tall (Ball et al., 2002). It is primarily adapted to zones A and B with limited use in zone C (Fig. A.1) (Ball et al., 2002). Crimson clover suppresses weeds by forming a thick mulch. It supports high densities of beneficial insects by providing food and habitat, but may also support and increase soil-borne plant pathogens. A stand of crimson clover can produce 1.4-2.3 metric tons (3,000-5,000 lbs.) of dry matter/A., contributing 78-168 kg/ha (70-150 lbs.) N/A. (Clark, 2007). It grows well in mixtures with small grains; oats are frequently used as a nurse crop or as a high-biomass, nutrient scavenging partner. In addition to N fixation, crimson clover adds to the soil organic N pool by scavenging for mineralized N (Clark, 2007).

Annual ryegrass is an annual bunch grass that grows up to 1 m (3 ft.) tall (Ball et al., 2002). It is primarily adapted to zones A and B, and can grow in some areas of zone C (Fig. A.1). Fall seeding in Sept. through Oct. generally produces the best stands (Ball et al., 2002). Ryegrass is quick growing and non-spreading. It has an extensive soil-holding root system, making it good for preventing erosion. Dense shallow roots also improve water infiltration and soil tilth. Rapid growth above ground helps supply organic matter, producing 1.8-3.6 metric tons (4,000-8,000 lbs.) dry matter/A. (Clark, 2007). It attracts few insect pests and can generally help lower pest levels in legume stands and vegetable crops. Ryegrass has a high moisture requirement and is also a high N user, capturing leftover N and reducing leaching; it is capable of taking up to 18 kg (40 lbs.) N/A. Annual ryegrass has a biennial tendency and may reseed in areas with mild winters, which may create a weed problem. It can be killed mechanically by discing or plowing, but mowing may not kill it completely (Clark, 2007).

Red clover is a short-lived perennial, growing for approximately 2 years in the South. It is leafy and erect-growing, reaching up to 1m (3 ft.) tall (Ball et al., 2002). It is primarily adapted to zones C and D, acting as a winter annual in zone A (Fig. A.1) (Ball et al., 2002). Red clover helps to suppress weeds and breaks up soil. When allowed to grow a full season, it can produce 1.8-3.6 metric tons (4,000-8,000 lbs.) of dry matter/A., fixing 84-168 kg/ha (75-150 lbs.) N/A. (Clark, 2007). It is widely adapted to different soil types and climate niches but may establish slower, produce less biomass and fix less N than other legumes. Red clover is a great soil conditioner; its extensive root system permeates topsoil while the taproot may penetrate several feet. In addition, it attracts beneficial insects. Medium red clover can be cut multiple times and grows back quickly; however, actively growing red clover can be difficult to kill mechanically (Clark, 2007).

To avoid competition, seed size, aggressiveness, and time of planting should be assessed. Desirable grass and legume species for use as living mulches are those that rapidly establish a closed canopy or impede weed establishment through allelopathy (Chase and Mbuya, 2008). Small seeded species, such as clovers, typically have minimal impact on weeds, whereas more aggressive species, such as ryegrass, have been shown to cause reductions in crop yield (Brainard and Bellinder, 2004). To avoid competition from aggressive species, planting of living mulches can be delayed until after the cash crop has been established; however, delayed seeding may inhibit establishment of a sufficient cover beyond the critical weed-free period. A second alternative is mechanical suppression. Taller growing and highly competitive species will require management, such as mowing, to reduce damage to the main crop. Lower growing mulches may preclude the need for weed management, but may not be as effective as taller-growing species (Chase and Mbuya, 2008).

Weed Management

Inadequate weed control has been a severe problem in reduced tillage vegetable systems; cultivation and plastic mulches typically used in vegetable production are not frequently utilized under reduced tillage. Cultural weed control methods, when used in conjunction with reduced tillage, can decrease weed germination. Cultural weed control exploits plant competition. The first plants to occupy an area have a competitive advantage over those that follow; promoting the growth of the planted crop may therefore help decrease germination and growth of an interfering weed species. Suppressing weed seed germination can be accomplished by enhancing rapid growth and canopy closure by close planting spaces, or by inhibiting or delaying germination, emergence and growth of weeds (Morse, 1999b). Research on reduced tillage systems for fall broccoli using tight plant spacing and high residues has demonstrated that a closed crop canopy can exclude weed growth between plants resulting in no yield reductions when compared to herbicide-treated controls (Morse, 1999b).

Though many factors impact weed seedling emergence, soil disturbance can profoundly affect weed germination. Tillage can promote the germination of seeds in the soil seedbank because of exposure to light, improved soil aeration, increased loss of volatile inhibitors from the soil and movement of seeds to more favorable germination sites (Myers et al., 2005). Tillage also alters surface residues, changing the effects of shading, temperature and pH, which may also affect weed seed germination (Myers et al., 2005). In addition, species composition and density tend to vary between disturbed and undisturbed soils (Myers et al., 2005).

The presence of cover crop mulches, dead or living, can help to control escaped weeds or slow down the invasion of new weeds. DeGreggorio and Ashley (1985, 1986) found that a white clover living mulch provided weed control comparable to commercial herbicide programs in sweet corn and snap beans. With minimal competition for below ground resources, mulch crops can reduce sunlight availability to weeds without directly impacting the main crop. The main crop comprises the uppermost canopy, which, if full, can decrease weed pressure; the living mulch provides a middle canopy between the main crop and weeds directly impacting the light reaching the weedy understory.

Research on the use of reduced tillage with sweet potatoes has demonstrated that the incorporation of organic matter via cover crops may have a direct positive effect on weed management due to a delay in N availability to weeds (Treadwell et al., 2007). As a result, weeds were effectively managed by surface residues in the first six weeks after planting. However, hand removal in reduced tillage treatments disturbed surface residues, providing opportunities for weed germination. Organically managed, reduced tillage treatments were significantly weedier at harvest.

Interseeded crops, or living mulches, provide an alternative for early-season reduced tillage systems when cover crops have not reached a sufficient stage of maturity to be killed. Interseeded living mulch crops can be chosen to compliment a cash crop in resource use while interfering with weed growth and suppressing weed emergence through competition between the mulch and weeds for resources (Brainard and Bellinder, 2004). However, in practice, interseeded crops may suppress neither crop nor weeds, or may suppress both. Research results have demonstrated that the use of living mulches for weed suppression is variable; while some systems have produced comparable yields to a conventional control, others have shown significant differences in yield between the two due to competition (Brainard and Bellinder, 2004).

In a study to determine the ability of living mulches to suppress weeds when sown at various days after planting broccoli, Brainard and Bellinder (2004) found the greatest weed suppression when mulches were sown when the crop was transplanted. Weed emergence was significantly reduced; unfortunately, so was crop yield. Mulches sown 10 days after transplanting (DAT) did not reduce yield but provided only modest weed suppression. There was a significant effect on in-row weeds in two of three years, however, suggesting that later sowings may provide some weed suppression. At 20 DAT there were no significant effects on weed suppression.

Contrary to the results above, where living mulches were unsuccessful at suppressing weeds, Ilnicki and Enache (1992) found that the use of subterranean clover as a living mulch in a no-till, vegetable production system provided excellent weed control. All living mulch treatments greatly reduced weed biomass. The subclover was suppressed by mowing to reduce interference with the cash crop at critical growth periods. The experiment was trialed on corn, soybean, summer squash, spring cabbage, tomatoes and snap beans. Yields for corn, soybean, and tomatoes were comparable to or greater than herbicide controls. Weed biomass in all living mulch treatments was significantly lower than treatments without the subterranean clover.

Insect Management

Studies have indicated that living mulches, when undersown with a vegetable crop, have the ability to decrease injury imposed by insect pests. However, results have been mixed; in some instances, living mulches may interfere with the successes of predation and parasitism. Several hypotheses allow us to predict insect interactions in more complex cropping systems. The Resource Concentration Hypothesis postulates that herbivores are less likely to find and remain on their host plant in florally diverse habitats. A second hypothesis, the Natural Enemies Hypothesis, states that populations of insect natural enemies will increase in vegetatively diverse cropping systems due to the variety of microhabitats and food sources (Hooks et al., 1998). In field situations utilizing living mulches, herbivorous insects spend less time on cash crops, while greater populations of natural enemies lower pest populations. Thus, a lower risk of damage to cash crops is expected, giving strong indications toward the benefits of incorporating living mulches into organic vegetable production systems.

Observed interactions have not been this straight forward. "Certain insect pests associated with *Brassica* crops (e.g.; flea beetles, aphids, and cabbage root flies) are consistently found at lower densities on *Brassica* plants in the presence of non-host vegetation (Hooks and Johnson, 2006)." This decrease in aphid populations associated with interplanting of living mulches can be attributed to the decrease in the number of winged forms, which are known to be affected by crop background (Costello and Altieri, 1995). Despite these remarks, results from a California study focusing on aphid populations within broccoli plots planted alongside a living mulch demonstrated that living mulches may not completely suppress aphid populations (Costello and Altieri, 1995). Findings indicated that early season aphid populations were consistently lower on broccoli in all living mulch plots, compared to clean cultivation, due to reduced alate aphid colonization. However, by the end of the season, no differences in aphid abundance were measured. These findings indicate that aphid growth rates in crops with living mulches were higher than bare ground plots. Further, findings also suggest that aphid parasitism was significantly higher in clean cultivated plots as compared with all living mulch plots (Costello and Altieri, 1995).

The variability of insect pest management, caused by increasing vegetative diversity, could be in part attributed to differences in natural enemy feeding ranges (generalist vs. specialist) and methods of host finding (visual, olfactory, random) as well as differences in herbivore response to changes in host plant quality in diverse plantings (Costello and Altieri, 1995). Vegetative diversity may interfere with specialist parasitoid searching abilities due to the masking of chemical cues used to find hosts or the inability to recognize field boundaries (Costello and Altieri, 1995). Increased plant structural complexity, the way in which plant surface area is connected, may also cause disorientation in parasitoids causing them to search randomly (Costello and Altieri, 1995). As a result, parasitoid species may spend more time on vegetation that does not harbor hosts and less on the cash crop where pest species are located (Costello and Altieri, 1995).

In a 2006 study focusing on population densities of two herbivorous lepidopteran pests, *Artogeia rapae* (small white) and *Trichoplusia ni* (cabbage looper), in diverse cruciferous cropping habitats, Hooks and Johnson (2006) found that *A. rapae* offspring may be significantly reduced by the actions of natural enemies in florally diverse broccoli plantings as compared to monoculture stands. Results also indicated that population densities of *T. ni* were frequently lower on broccoli plants in yellow sweet clover habitats than monoculture or a system of broccoli intercropped with peppers. In both studies, fewer eggs were found in living mulch plots. Contrary to the findings of Costello, results indicated that biological control agents appear to be the most significant factor influencing pest abundance (Hooks and Johnson, 2006).

In a follow-up study of the same nature by Hooks et al. (2007), using clovers as living mulches to suppress pests and augment spider populations, findings showed that lepidopteran eggs and caterpillar densities were significantly greater in bare ground plots as compared to those intercropped with a living mulch. Further, spider densities were higher on bare ground plots during the early season; later in the growing season, densities were significantly higher in intercropped broccoli. The increase in spider density later in the season is most likely the result of living mulch expansion throughout the season, allowing spiders access to the crop canopy as the mulches approached the broccoli plants. Finally, yield data for bare ground and living mulch plots were similar; however, significantly fewer insect contaminants were counted in broccoli harvested from living mulch plots than bare ground plots.

A study by Frank and Liburd (2005) on the incidence of aphids and whiteflies on synthetic and living mulches showed successful reduction in population densities, as well as delays in the onset and spread of associated insect-borne diseases. Plants in buckwheat and clover living mulches had significantly less whiteflies and aphids than plants in white and reflective plastic mulches, which showed similar effects to bare ground. Additionally, though no differences in diversity of natural enemies were observed between mulch treatments, both clover and buckwheat living mulch treatments had significantly greater population densities of natural enemies than either plastic mulch or bare ground.

Research results have been variable in determining the effect of intercropped living mulches on insect populations. Type of pest, natural enemy and cover crop are important in determining insect interactions, providing benefits in some instances and negative effects in others.

Disease Incidence and Severity

Conservation tillage practices can variably increase, decrease or have no effect on plant diseases (Bockus and Schroyer, 1998; Sturtz et al., 1997; Watkins and Boosalis, 1994). With dramatically different environmental conditions, the microbial community is altered under conservation tillage (Conway, 1996). Changes in cropping practice alters the physical and chemical properties of the soil environment, impacting plant growth. Tillage shifts populations of microbiota associated with crop residue, indirectly affecting the survival of plant pathogens (Watkins and Boosalis, 1994).

Several key environmental parameters are changed as farmers adopt conservation tillage systems. Crop residues reduce soil temperature and increase water infiltration and the amount of moisture at deeper levels in the soil profile (Bockus and Schroyer, 1998). In addition, due to the application of nutrients to the surface with little mixing, less mobile nutrients may become concentrated at surface layers and diminish with depth (Bockus and Schroyer, 1998).

Practices that provide a suitable habitat for pathogen survival and concentrate inoculum in close proximity to a host plant increase the threat of serious disease outbreak. Spring plowing and discing moves the energy source or pathogen away from crowns and roots (Watkins and Boosalis, 1994). Additionally, wet, cool spring weather is likely to stimulate multiplication, and infection by soil-borne pathogens may occur earlier than infection by airborne inoculum (Watkins and Boosalis, 1994). Earlier infection by soil-borne pathogens may be due to higher concentrations of pathogen inoculum, increasing the risk of infection for Spring crops grown under reduced-tillage (Watkins and Boosalis, 1994).

High crop residues, continuously moist soil conditions and soil compaction are potential constraints to conservation tillage systems. For these reasons, plant diseases are considered to be a major impediment to the successful adaptation of conservation tillage in humid climates (Sturtz et al., 1997).

Conservation tillage tends to concentrate plant debris and consequently microbial biomass in the top 5-15 cm of soil, promoting the survival of pathogens (Sturtz et al., 1997). In conventional tillage systems, residue is buried and exposed to rapid microbial degradation, killing pathogens. Leaving crop residues at the surface lengthens the time pathogens occupy residues before they are destroyed by native microflora (Bockus and Schroyer, 1998). This concentration of plant debris in the top 10-15 cm of soil can promote the survival of pathogens until a following crop is planted by providing an energy source prior to host infection. Most leaf-, stem-, head-, and grain- infecting pathogens depend on host residues for survival between crops and production of inoculum (Watkins and Boosalis, 1994). The presence of large numbers of infective propagules in the upper soil layers, combined with favorable environmental conditions, has prompted concerns that increased root disease and depressed yields may arise under reduced-tillage systems (Bockus and Schroyer, 1998).

Survival and distribution of pathogen inoculum is also influenced by compaction. Soil compaction is associated with primary and secondary tillage but can occur under no-till systems. Under conservation tillage, the formation of plow pans can alter both fitness and depth distribution of fungal propagules (Peters et al., 2003; Sturtz et al., 1997). Increased hydrophilic pathogen inoculum concentrations may be found above the hard pan, as well as greater activity of pathogens over resident soil microflora at low osmotic water potentials in dry conditions below the hard pan. Additionally, soil compaction can cause abiotic induced root diseases from the accumulation of toxic concentrations of salt, pesticides or phytotoxins. Compaction can lead to reduced soil microbial biomass and soil enzyme activity, having adverse implications for long-term soil health. Periodic tillage may alleviate such compaction in no-till systems (Peters et al., 2003; Sturtz et al., 1997).

Crop retention and soil compaction also affect plant health. The concentration of pathogen inoculum in reduced tillage systems can be several orders of magnitude greater than those in conventionally plowed systems (Watkins and Boosalis, 1994). Roots confined to or growing near the surface may therefore be subject to infection due to their close proximity to pathogens (Watkins and Boosalis, 1994). However, by altering soil density, temperature, macroporosity, nutrient availability, water retention and distribution, crop residues influence patterns of root growth in the uppermost soil layers (Sturtz et al., 1997). Horizontal root development, associated with adventitious root elongation, may be favored in reduced-tillage systems. A more vigorous root system may offset damage from disease and associated yield reductions (Sturtz et al., 1997).

Additionally, crop residues stimulate populations of antagonistic organisms. These antagonisms in the root zone can lead to the formation of disease-suppressive soils. Increases in the relative populations of both beneficial and deleterious microflora often occur in the surface layers of soils under reduced tillage systems. This high soil microbial activity can lead to competition that may ameliorate pathogen activity and survival (Sturtz et al., 1997).

These effects are influenced by soil and crop management practices, primarily the addition of organic and fertilizer amendments. Such practices may increase competition for C and N, limit oxygen (O_2), produce antimicrobial compounds or stimulate propagules to germinate then lyse (Conway, 1996). Additionally, fungi may enter fungistasis, a resting period, on contact with natural soils as a result of aggressive competition. Reduced tillage systems utilizing organic amendments and mulches may have an increased propensity towards pathogen suppression as a result of increased soil microbial activity (Sturtz et al., 1997).

Vesicular arbuscular mychorrizae may be stimulated under conditions with high organic matter, like those found in reduced tillage systems. These fungi have been implicated in the direct suppression of fungal pathogens and provide plant growth benefits such as improved drought resistance and improved nutrient uptake (Sturtz et al., 1997).

While crop residues may foster an increase in total microbial biomass, causing competition for resources and potentially limiting disease outbreaks, other control measures may be implemented within reduced tillage systems to further decrease disease prevalence. Control of pathogens in conservation systems can be accomplished by a variety of means without significantly increasing production costs: use of disease resistant or adapted cultivars and high quality certified seed, control of insects and weeds to reduce the primary inoculum source of viruses, use of fungicidal seed treatments or foliar sprays, crop rotation to allow for the natural biological destruction of soil pathogens, and tillage rotation to enhance weathering of crop residues (Watkins and Boosalis, 1994).

Soil agroecosystems can be modified through conservation tillage practices to improve disease suppression. It is now widely acknowledged that root zone microflora can stimulate plant growth, improve stress tolerance, induce disease resistance in plants and/or suppress disease development. Though reduced tillage systems have the potential to concentrate and increase the occurrence of plant pathogens in the uppermost soil layers, competition between microbial populations for space and energy substrate in the root zone may largely prevent root diseases from developing. A balanced, competitive soil microbial environment colonized by a community of pathogen antagonists appears to be the key factor.

Competition, Physiological Status and Crop Yield

Prior experiments with reduced tillage for vegetable production have resulted in various degrees of success depending on crop, location, moisture and temperature. Competition from living mulches may result in nutrient deficiency, osmotic stress and reduced interception of sunlight; reductions in plant functioning may lead to slowed growth, decreased crop biomass, delayed maturity and reduced yields (Chapin, 1991; Theriault et al., 2009; Wiles et al., 1989).

Broccoli is a nitrogen demanding crop, and N supply is a determining factor in crop productivity (Tremblay, 1989; Vagen et al., 2004); however, N requirements for broccoli have been inconsistent with varying rates impacting yield in different ways (Abdul-Baki et al., 1997). Maximum yields are often obtained at high N rates, though research results have varied. Tremblay (1989) obtained maximum broccoli yield at a rate of 150 kg N/ha (134 lbs. N/A.) while Zebarth et al. (1995) observed maximum yields at rates of 400 kg N/ha (357 lbs. N/A.). Vagen et al. (2004) observed increased leaf area and total crop biomass at higher N rates as a result of higher amounts of intercepted radiation.

The use of a handheld Cardy nitrate meter has been demonstrated to provide an accurate method of measuring crop fertility status (Kubota et al., 1997). Typically, N concentration decreases as biomass increases (Vagen et al., 2004). Expected rates of NO_3^-–N in broccoli leaves are: 800-1,000 ppm at the six leaf stage, 500-800 ppm one week prior to the first harvest and 300-500 ppm at first harvest (Hochmuth, 1994). Concentrations lower than these indicate the need for N fertilizer (Gardner and Roth, 1989).

The use of cover crops alone as a source of N has proven insufficient at providing adequate fertility (Abdul-Baki et al., 1997). The observation that more N is accumulated in crops when organic residues are tilled under as compared to surface residues is explained by greater decomposition and faster mineralization under plowed soil (Abdul-Baki et al., 1997). Additionally, interseeded living mulch crops may compete with the main crop for available N. Surplus amounts of fertilizer, intended to counteract competition with a ryegrass living mulch crop, were found to only slightly increase N uptake by a leek crop, indicating biological storage of N by the living mulch and reduced allocation to the main crop (Muller-Scharer, 1996). Theriault et al. (2009) were also unable to prevent competition from living mulch crops despite taking measures to supply adequate nutrients, light and water.

Nutrient deficiency has been demonstrated to result in smaller plants and declines in photosynthesis, transpiration and stomatal conductance due to the influence on biochemical reactions necessary for optimal photosynthesis and respiration (Bottrill et al., 1970; Chapin, 1991). Close correlations have been demonstrated between leaf N content and photosynthetic rates. Low N supply results in lower concentrations of photosynthetic enzymes, causing a low rate of photosynthesis per gram of leaf (Chapin, 1991).

The low photosynthetic potential observed in N limited plants does not directly cause slowed growth and delayed maturity. Declines in growth rate and resource acquisition are basic responses made by all plants experiencing environmental stressors. In the case of N deficiency, changes in plant-water relations have been suggested as the mechanism by which N limitation causes reductions in growth. Water and osmotic stress cause reductions in growth through changes in hormonal balance, altering the flexibility of the cell wall and limiting growth (Chapin, 1991). Stirzaker et al. (1993) suggested that uneven wetting of roots in reduced tillage situations may result in slow growth. Fluctuations in soil penetrability can cause isolated inhospitable soil conditions. Leaf expansion may be reduced when roots encounter hard soil, and growth may be slowed when part of the root system experiences dry soil while other parts of the roots experience favorable conditions.

Declines in physiological status caused by inhospitable soil conditions and competition from living mulches can lead to reduced yields. A study by Hoyt (1999) revealed that greater success may be had with full season crops than short season. Greater vegetable yields were observed from short season crops in treatments with a high degree of tillage due to lack of earliness in crops planted under reduced tillage. The greatest early yield of snap beans was in plowed and disced treatments, with the lowest in no-till; however, by the final harvests, snap bean yields in strip and no-till equaled plowed and disced treatments. Cabbage yield was greatest in plowed and disced bare ground treatments, though yield in strip tillage treatments under bare ground were only slightly lower. Compared to these cool season crops, greater total marketable yield from tomato resulted from reduced tillage treatments compared with surface tillage. No differences among tillage treatments were observed in winter squash.

Research by Wilhoit et al. (1990) demonstrated that reduced tillage can offer significant benefits in years of little rainfall due to conservation of soil moisture from surface residue and cover crop mulches. With limited rainfall, cabbage yield and head size were significantly higher in reduced tillage plots with heavy surface mulches. When rainfall was not a limiting factor, there was a trend toward lower yield under no-till though no significant differences in yield or head size were observed between tillage treatments. This work indicated that similar yields can be obtained with strip and conventional tillage when soil moisture conditions are optimal. Under irregular rainfall patterns, resulting in periods of decreased soil moisture, cabbage yields in strip tillage plots were equal to those under conventional tillage and higher than no-till. Strip tillage appears to offer greater yield stability than either conventional or no-till. Strip tillage is therefore a feasible compromise between conventional and no-till, offering reduced rates of soil erosion compared to conventional tillage and increased yields compared to no-tillage.

Reduced tillage systems utilizing residue mulches typically show yields correlated with the amount of weed suppression offered by the mulch (Masiunas, 1998); however, integrating living mulches into a production system has the potential to cause competition between the mulch and main crop for resources (Brainard and Bellinder, 2004). Research results have demonstrated that, while some systems utilizing living mulches have produced comparable yields to a conventional control, others have shown significant differences in yield due to competition (Brainard and Bellinder, 2004).

Living mulches showed no effects, beneficial or detrimental, when overseeded alongside broccoli transplants. Significant impacts due to competition were observed only in plots with prolific weed biomass, where living mulches were unable to suppress weed populations (Infante and Morse, 1996). However, Biazzo and Masiunas (2000) found the greatest yields of hot pepper and okra under conventional tillage. Perennial ryegrass and canola were found to suppress yields the greatest. Yields in plots with clover living mulches were 50% less than yields in conventionally tilled plots, but were still close to reported average yields. Decreases in tomato fruit yield were observed by Swenson et al. (2004) under different living mulches. Treatments under conventional tillage with black plastic produced greatest total and marketable fruit yield under drought situations. Compared to herbicide-treated plots, plots with living mulches produced greater marketable fruit yield.

In a 2007 study comparing broccoli grown on bare ground, or intercropped with strawberry clover, white clover or yellow sweet clover, the largest crowns by diameter were harvested from broccoli undersown with strawberry or white clover (Hooks et al., 2007). Broccoli harvested from yellow sweet clover plots contained the smallest crowns by weight, indicating that, compared to bare ground, the use of a clover living mulch may either increase or decrease head size depending upon the species of clover. A similar study utilizing buckwheat and yellow mustard living mulches in zucchini production demonstrated significantly greater cash crop biomass in buckwheat plots compared with bare ground (Hooks et al., 1998). Marketable zucchini yields were also significantly greater in both buckwheat and yellow mustard treatments compared with bare ground. Chase and Mbuya (2008) found rye, black oat and annual ryegrass used as living mulches, which were most effective at suppressing weeds, the most likely to suppress the cash crop. No adverse effects on broccoli yield were reported with leguminous living mulches. A study by Brainard and Bellinder (2004) demonstrated that competition can be reduced by delaying planting. Rye planted at the time of transplanting resulted in yield losses; however, at 10 and 20 DAT, there were no reductions in broccoli yield.

Conclusion

Reduced tillage systems provide many benefits to crop production including reductions in erosion and water runoff, as well as enhanced soil environmental conditions. Strip-tillage in particular is well suited to vegetable production, providing the benefits of reduced tillage while allowing improved plant setting and root growth.

Though research results have been variable, depending upon crop and living mulch species, the use of living mulches have been demonstrated to increase yields with the correct match of production system, crop and living mulch. Though decreases in yield may be observed, the inclusion of a living mulch offers many great benefits to organic crop production such as increases in beneficial insect population, decreases in insect pest populations and weed control, which may outweigh the decline in yield.

The use of living mulches provides a method of weed management that makes reduced tillage a more feasible operation in organic systems. The incorporation of living mulches can increase farm diversity, establishing a system that naturally balances insects, weeds and diseases, and may be more resilient at suppressing pest populations if they increase. Thus, reducing tillage and the inclusion of a living ground cover can promote productivity, increase efficiency and further enhance sustainability, making it a valuable asset to organic production.

To evaluate the validity of these conclusions, this research project aims to 1) determine the feasibility of overseeding living mulches into an existing, fall-sown cover crop; 2) assess the effects of reduced tillage and living mulches on the growth and physiological status of organic spring broccoli and; 4) assess the effects of reduced tillage and living mulches on weed emergence, beneficial and pest insect density and disease incidence and severity.

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Appendix A

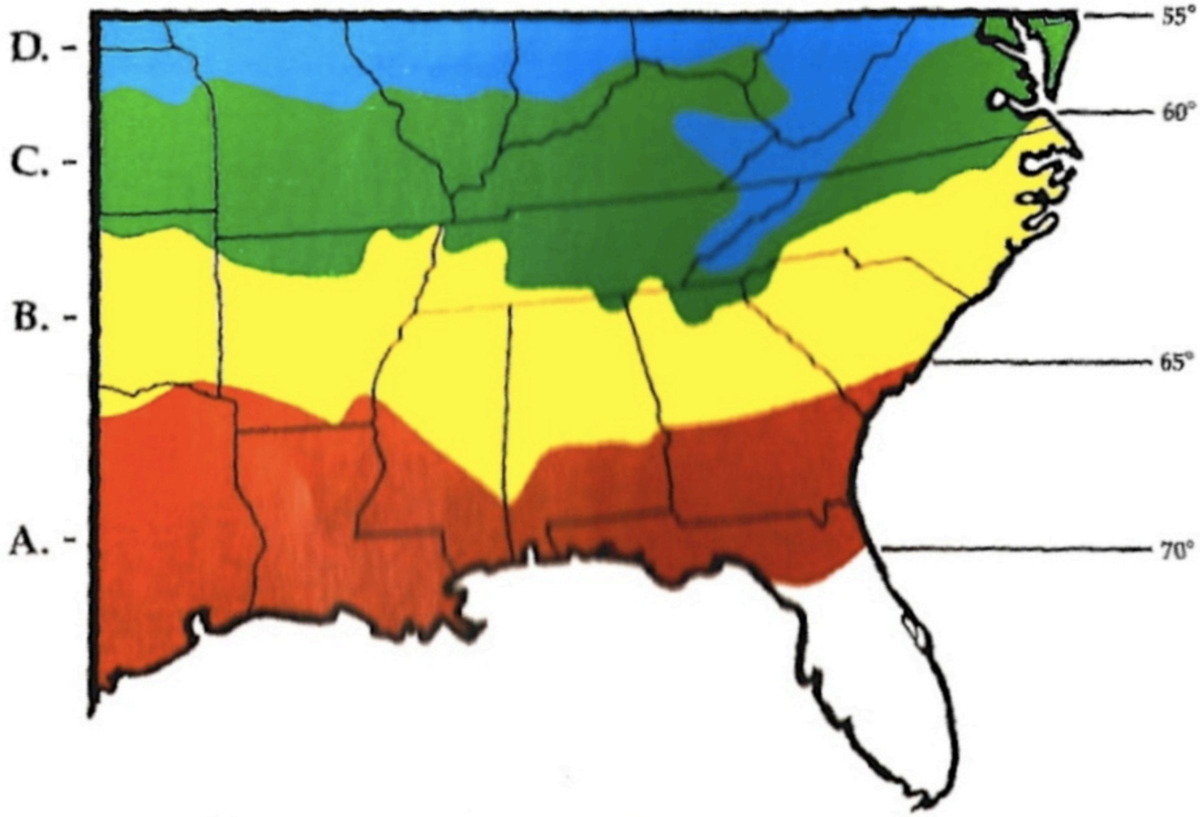

Figure A.1 Adaptation zones and mean annual air temperature (°F) for cover crop species utilized in the Southern US (Ball et al., 2002).

Chapter Two: Ground coverage and living mulch establishment in an organic, strip tillage system

Abstract

Changes in the soil environment due to reduced tillage are associated with the amount and types of mulch crops and crop residues on the soil surface. The inclusion of a living mulch crop has the potential to maintain the integrity of a reduced tillage system by providing ground coverage later in the growing season as cover crops decay. Additionally, living mulches provide an alternative weed management strategy for organic, reduced-tillage systems. In the current study, spring-seeded living mulches of annual ryegrass and red clover were oversown into an established, overwintered cover crop in a strip tillage system for early-season organic broccoli, compared to a tilled system utilizing cover crops as green manures. Ground coverage by cover crops and living mulches, and total coverage by non-marketable crops was assessed. Samples were taken throughout the broccoli production period to measure cover crop decay and establishment of the living mulches. In both years, a living mulch of annual ryegrass established more quickly, and provided greater ground coverage than red clover. In 2009, the inclusion of annual ryegrass in tilled plots provided ground coverage comparable to strip tilled systems. The incorporation of a living mulch proved most beneficial when ground coverage by cover crops was sparse, as in 2009; when ground coverage by cover crops was more dense, in 2010, ground coverage by living mulches was decreased.

Introduction

Research on conservation tillage systems for vegetable crop production has demonstrated that reduced tillage programs may either enhance or suppress crop growth and yield due to alterations to the soil environment. Strip tillage is a conservation tillage practice that is well suited to the production of transplanted vegetables. Planting into a tilled strip maximizes root growth, allowing for improved plant setting, while cover crop residues remain between rows providing protection from soil erosion and weed competition.

Living mulches are cover crops that are interplanted and grown alongside a cash crop to provide ground cover and prevent erosion. They may also suppress insect pests and weed populations. However, living mulches may compete with the vegetable crop for available resources; using strip tillage to separate the vegetable crop from the immediate growing area of the living mulch may limit such competition (Biazzo and Masiunas, 2000; Wilhoit et al., 1990). When integrated in a reduced tillage system, living mulches may help to maintain the integrity of the system by replacing decaying plant residues (Infante and Morse, 1996).

Modifications to management practices can alter physical conditions within the cropping system, affecting crop growth. Soils under reduced tillage often have greater soil moisture with decreased temperature fluctuations (Teasdale and Mohler, 1993) due to the presence of crop residues and killed mulches. Soil moisture is generally greater under reduced tillage due to decreases in water evaporation from the soil surface resulting from the accumulation of crop residues (Johnson and Hoyt, 1999). An organic mulch on the soil surface intercepts solar radiation, reducing maximum soil temperatures (Teasdale and Mohler, 1993).

Alterations in soil temperature and moisture conditions within the seedbed and plant rooting zone impact seed germination and plant establishment (Licht and Al-Kaisi, 2005). Higher surface water content in reduced tillage soils during the growing season enables plants to continue growing during periods of water shortage (Johnson and Hoyt, 1999). In addition to the higher level of plant-available water, infiltration is improved in reduced tillage systems compared to those that are conventionally tilled. Due to the presence of surface residues, water runoff and erosion is often less (Infante and Morse, 1996). Higher soil moisture has also been demonstrated to benefit crop production by contributing to higher vegetable yields (Biazzo and Masiunas, 2000; Johnson and Hoyt, 1999; Wilhoit et al., 1990). However, while crop residues and dead mulches may increase water infiltration and soil water holding capacity, living cover crops and mulches require water to grow, and interspecific competition can potentially reduce yields of cash crops (Dabney et al., 2001). Biazzo and Masiunas (2000) observed drier conditions under living mulches of perennial ryegrass, red clover and canola, which limited the availability of water to okra and pepper, reducing crop growth.

In addition to affecting crop growth by altering the soil environment, the presence of mulches, dead or living, may help control escaped weeds or slow the invasion of new weeds. Ilnicki and Enache (1992) found that the use of subterranean clover as a living mulch in a no-till, vegetable production system provided excellent weed control. All living mulch treatments greatly reduced weed biomass. The integration of a living mulch into a production system creates competition between the mulch and weeds for below-ground resources. Living mulches also reduce sunlight availability by creating a middle canopy between the main crop and weeds, directly impacting the amount of light that reaches the weed canopy (Brainard and Bellinder, 2004).

Annual ryegrass and red clover have been utilized as living mulches based upon their ability to establish within the cool season and persist through the warmer months. Annual ryegrass is an annual bunch grass that grows up to 1 m tall (3 ft.). It is quick growing and non-spreading, with an extensive root system (Clark, 2007). Rapid growth above ground helps supply organic matter and smother weeds. Ryegrass has a high moisture requirement and is also a high N user; this allows it to capture leftover N and reduce leaching, but also increases the potential for interspecific competition with the cash crop (Clark, 2007). It can be killed by disking or plowing, but may not be completely killed by mowing; this allows it to be managed mechanically throughout the growing season (Clark, 2007).

Red clover is a short-lived perennial, growing for approximately 2 years in the South. It is leafy with an erect growth habit, reaching up to 1 m (3 ft.) tall. Red clover helps suppress weeds, breaks up soil and fixes atmospheric nitrogen (N) (Clark, 2007). It is widely adapted to different soil types and climate niches but may establish slower, produce less biomass and fix less N than other legumes (Clark, 2007). Red clover is a great soil conditioner; its extensive root system spreads throughout the topsoil while the taproot may penetrate several feet. In addition, it attracts beneficial insects. Medium red clover can be cut multiple times and grows back quickly. Actively growing red clover can be difficult to kill mechanically, allowing it to be managed mechanically throughout the growing season (Clark,2007).

Since cover crop residues and living mulches, in addition to reduced tillage, can have significant impacts on crop growth and management, it is important to determine the level of ground coverage provided by cover and living mulch crops within management systems utilizing these techniques. The objective of this study was to assess the impact of tillage system and living mulch species on ground coverage.

Materials and Methods

The experiment was conducted on a Dewey Silt Loam at the East Tennessee Research and Education Center Organic Crops Unit, in Knoxville, TN, on 0.07 ha (0.18

A.) of land. Two treatments were assessed within the experiment. The tillage treatment was comprised of tilled and strip tilled plots; tillage occurred only once prior to transplanting broccoli as a method of establishing the research plot. Additionally, two living mulches, red clover and annual ryegrass, were assessed relative to a no-mulch control. A bi-culture of triticale (*x. Triticosecale* spp.), sown at 90 kg/ha (80 lbs./A.), and Austrian winter pea (*Pisum sativum)*, sown at 90 kg/ha (80 lbs./A.), was seeded on 5 Nov. 2008 for the 2009 growing season. A bi-culture of crimson clover (*Trifolium incarnatum*), sown at 28 kg/ha (25 lbs./A.), and winter oats (*Avena sativa)*, sown at 123 kg/ha (110 lbs./A.), was seeded on 20 Sept. 2009 for the 2010 growing season. Cover crops were drilled both years.

In 2009, the research plot was established on a tract of land previously planted to an assortment of vegetable crops. The plot was rotated to a different tract of land for the 2010 season, previously in cucurbits (summer squash, watermelon and pumpkin). In the spring prior to tillage, the field was flail mowed to a height of 5 cm (2 in.). Tilled plots were established to a depth of 15 cm (6 in.) using a rototiller. Strip tilled plots were established using a Maschio Multivator (Maschio Group, Eldridge, Iowa) leaving a 15 cm (6 in.) strip tilled to a depth of 15 cm. In 2009, broccoli (*Brassica oleracea* cv. Belstar F1) was transplanted on 13 Apr.; in 2010, broccoli was transplanted on 7 Apr. Plants were set 45 cm (18 in.) apart within rows and 91 cm (36 in.) between rows, with four rows per experimental treatment. Each treatment plot was 3.6 m x 3.6 m (12 ft. x 12 ft.). In 2009, four replicates were sampled. In 2010, three replicates were sampled; pressure from *Rhizoctonia spp*. greatly reduced the number of transplants within the fourth replicate, which was discarded from the study.

In 2009, living mulches of annual ryegrass (*Lolium multiflorum* cv. Marshall) and red clover (*Trifolium pratense* cv. Cinnamon Plus) were broadcast two days after transplanting (DAT) broccoli, on 15 Apr. In 2010, living mulches in tilled plots were broadcast 5 DAT, on 12 Apr. Strip tilled plots had two living mulch planting dates: 1) one month prior to broccoli transplanting on 8 Mar. 2010 and; 2) 5 DAT on 12 Apr. 2010. In both years, annual ryegrass was sown at a rate of 33 kg/ha (30 lbs./A.) and red clover was sown at a rate of 11 kg/ha (10 lbs./A.). Mulch crops were mowed to a height of 7 cm (3 in.) as they reached the broccoli canopy. In 2009, living mulch plots were mowed once (9 June); in 2010, the plots were mowed three times (19 Apr., 6 May and 2 June). In both years, all plots were spot-hoed weekly to manage weeds. In tilled and strip tilled plots, all observed weeds in the planting row and between rows were removed. Hoeing events were timed for each plot to determine whether different levels of management were necessary among treatment combinations.

A drip irrigation system was established to provide supplemental water when soil moisture readings, measured with Watermark soil moisture sensors (Irrometer 200SS; Riverside, CA, US), rose above 30 cb indicating limited availability of plant-accessible water. In both years, all treatment combinations received equivalent amounts of supplemental water on all irrigation events. Monthly rainfall and temperature averages are reported in Table B.1.

Ground coverage was assessed using a linear transect. The transect was laid diagonally across each plot at a length of 5 m (17 ft.); samples were taken every 45 cm (1.5 ft.), providing 10 samples per transect. Two transects were measured; samples were collected across each diagonal for a total of 20 samples per plot. At each sampling location, the crop observed directly under the marker was noted; possible observations included bare ground, broccoli, weed, cover crop species (triticale, Austrian winter pea, crimson clover or winter oats) and living mulch species (annual ryegrass and red clover). Cover crop species were summed to provide a total value for cover crops. Total ground coverage by non-marketable crops was also calculated and is reported as the sum of cover crops plus living mulch species. If any portion of a plant was observed under the marker, the crop was counted. Both living and desiccated crop residues were counted. In 2009, samples were collected on two dates, corresponding with the vegetative and buttoning growth stages of the broccoli crop; 28 May and 29 June, respectively. In 2010, samples were collected on four dates, corresponding with the transplanting, vegetative, buttoning and pre-harvest growth stages of the broccoli crop; 12 Apr., 4 May, 19 May and 13 June, respectively.

The experimental design was a randomized complete block with a split-plot arrangement of treatments. Tillage treatments (tilled and strip tilled) comprised the main plot. In 2009, the living mulch sub-plot had three levels: red clover, annual ryegrass and no-mulch. In 2010, main and sub-plots remained the same with the addition of an early planting date (one month prior to transplant) for the living mulch treatment added to the strip-tilled treatments only. All data were analyzed by mixed model ANOVA using SAS (SAS 9.1, SAS Institute Inc., Cary, NC). Tillage and living mulch treatments were analyzed as fixed effects; replicate and sampling date were analyzed as random effects. A probability level of $P < 0.10$ or below was accepted. In 2010, comparisons were made between living mulch species within the strip tilled treatment only. Heavy infestation of crabgrass (*Digitaria sanguinalis*) within tilled plots prior to living mulch establishment required mechanical management. All tilled plots were hoed, significantly reducing living mulch germination and establishment. No analyses were made between tilled and strip tilled plots in 2010, and no analyses were made for levels of the living mulch treatment within tilled plots.

Results

In 2009, living mulches provided significantly greater ($P < 0.10$) ground coverage in tilled (17.08%) compared to strip tilled (10.83%) plots on the first sampling date (Fig B.1), 28 May, corresponding to the vegetative period of broccoli growth. Though not significantly different, similar trends were observed for the later sampling date.

In 2009 and 2010, greater ground coverage by cover crops was observed in strip tilled plots compared to tilled plots, as expected. No difference was observed for ground coverage by cover crops among living mulch treatments in either year. In 2009, ground coverage by cover crops (Austrian winter pea and triticale) was sparse; however, in 2010, cover crops (crimson clover and winter oat) were more dense, providing greater ground coverage. Results between years were not statistically comparable, due to differences in cover crop species and environmental conditions.

On both sampling dates in 2009, a living mulch of annual ryegrass provided significantly greater ($P < 0.01$) ground coverage than red clover (Fig B.2). On 28 May, ground coverage by annual ryegrass was 35%, and 6.87% by red clover; on 29 June, ground coverage by annual ryegrass was 42.5% and 19.37% by red clover.

In 2009, a significant interaction occurred between tillage and living mulch treatments on both sampling dates. On 28 May, a living mulch of annual ryegrass provided the greatest ground coverage ($P < 0.01$) in each tillage treatment; however, ryegrass in tilled plots (45%) provided greater ground coverage than strip tilled plots (25%) (Fig. B.3). No differences were observed between red clover and the no mulch control between tillage treatments. At the later sampling date, 29 June, ground coverage in strip tilled and tilled/red clover plots (20% and 19% respectively) did not significantly differ from strip tilled/ryegrass plots (31.25%) (Fig. B.4). No difference in ground coverage by red clover was observed between tillage treatments. Ryegrass, however, provided greater ($P < 0.10$) ground coverage in tilled (53.75%) compared to strip tilled (31.25%) plots (Fig. B.4).

Total ground coverage by non-marketable crops was measured as the sum of coverage by cover crops and living mulches. In 2009, significantly greater ($P < 0.01$) total ground coverage occurred in annual ryegrass plots (Fig. B.5) on both sampling dates (28 May=53.12%, 29 June=61.25%). On the May sampling date, no-mulch plots (21.87%) showed similar levels of ground coverage to red clover plots (28.12%); however, on the June sampling date, no-mulch plots (9.37%) had significantly less ground coverage than red clover plots (29.37%).

In 2010, comparisons were made among living mulch plots within the strip tilled treatment only. Two planting dates, one month prior to transplanting broccoli and 5 DAT, were assessed for each living mulch species. Ground coverage by cover crops, living mulch crops and total ground coverage by non-marketable crops were assessed on four sampling dates corresponding to four stages of broccoli growth: transplant, vegetative, buttoning and pre-harvest. Significant differences were observed only for the 19 May sampling date, corresponding with the buttoning growth stage of the broccoli crop.

In 2010, on the 19 May sampling date, a living mulch of annual ryegrass provided significantly greater ($P < 0.10$) ground coverage than red clover, with no difference observed between living mulch sowing dates (Fig. B.6). Total ground coverage by non-marketable crops was greatest ($P < 0.05$) in the early-sown ryegrass plots (83%); however, clover plots sown 5 DAT provided an equivalent level of ground coverage (Fig. B.7). Plots of ryegrass sown 5 DAT and early-sown clover showed no differences from the no-mulch control.

In both 2009 and 2010, no difference in ground coverage by cover crops was observed among living mulch plots. Though results between years were not statistically comparable, due to differences in cover crop species and environmental conditions, greater ground coverage by cover crops was observed in 2010 while greater ground coverage by living mulches occurred in 2009 (Table B.2). In 2009, when ground coverage by cover crops was sparse, the inclusion of living mulch crops, specifically annual ryegrass, greatly increased total ground coverage by non-marketable crops. However, in 2010, when ground coverage by cover crops was more dense, the inclusion of living mulches had a less noticeable impact on total ground coverage by non-marketable crops (Table B.2).

All plots were hoed weekly to manage weeds. In order to determine whether tillage or living mulch treatments required different levels of maintenance, hoeing events were timed for each treatment combination. At the end of the growing season, hoeing times were totaled for each treatment combination. No difference in hoeing time was found between tillage treatments, or among living mulch plots in 2009 or 2010 (data not shown).

Discussion

Ground coverage was sampled multiple times throughout the broccoli production period to assess changes in coverage from cover crops and living mulches over time. Measurements were taken at each broccoli growth stage as physiological parameters of broccoli are expected to change as the crop matures. Measurements of petiole sap nitrate and photosynthesis (data not shown) at each broccoli growth stage indicate that competition from established cover crops and living mulches may have impeded broccoli growth and maturity, resulting in smaller, less-mature plants within strip tilled plots. Thus, it is possible that broccoli plants were at different states of maturity between tillage treatments on the dates that ground coverage was sampled.

Differences in ground coverage by living mulches between tillage treatments were observed on the first sampling date in 2009; a similar trend was observed on the second sampling date. Greater ground coverage by living mulch crops was observed in tilled compared to strip tilled plots. This difference in ground coverage may indicate that tilled soil provides a more hospitable environment for the establishment of a living mulch crop. Tilled soil has been demonstrated to provide a better seed bed for crop establishment than non-tilled (Wilhoit et al., 1990). Soil disturbance enhances seed emergence by providing aeration, and moving crop residues that shade the soil surface and reduce temperatures (Myers et al., 2005). Compaction in reduced tillage systems can also result in reductions of crop growth and yield. Subsoil compaction has been demonstrated to impact productivity for up to 11 years. Tillage alleviates soil compaction; without tillage, the threat of surface and subsoil compaction can be significant (Sidhu and Duiker, 2006). Additionally, competition from established cover crops in strip tilled plots may have negatively impacted living mulch establishment. Established cover crops compete with newly emerging plants for below-ground resources, and create a higher crop canopy that reduces the amount of light reaching the soil surface (Brainard and Bellinder, 2004). Even if sufficient crop establishment is achieved, competition may result in slowed growth (Kankanen et al., 2001).

Analysis of ground coverage between living mulch species demonstrated that annual ryegrass provided greater coverage than red clover in both 2009 and 2010. Slow establishment and limited ground cover from small-seeded species, such as red clover, have been documented (Brainard and Bellinder, 2004). Ryegrass is considered to be an aggressive species that establishes quickly (Clark, 2007; Ball et al. 2002). Though ground coverage was significantly less from red clover than ryegrass at both sampling dates, coverage from red clover increased by three times between sampling dates.

In 2009, a significant interaction occurred between tillage and living mulch treatments on both sampling dates. On the first sampling date, ryegrass provided the greatest ground coverage, with the highest percentages occurring in tilled plots. No differences were observed between red clover and no-mulch plots between tillage treatments. At the second sampling date, tilled/ryegrass plots provided the greatest ground coverage overall, but no significant difference was observed between red clover and annual ryegrass in strip tilled plots. Data suggest that annual ryegrass establishes more quickly, providing greater levels of ground coverage earlier in the growing season. However, by later sampling dates, red clover provided statistically similar amounts of ground coverage within strip tilled plots. Desirable grass and legume species for use as living mulches are those that rapidly establish a closed canopy (Chase and Mbuya, 2008). This may indicate that annual ryegrass is more suitable for selection as a living mulch than red clover.

In 2010, living mulch crops were sown on two dates; one month prior to transplanting broccoli and 5 DAT. A significant difference between living mulch crops and planting dates was observed only for the May 19 sampling date. No difference in ground coverage was observed between sowing dates for annual ryegrass. Though lower than the level of ground coverage provided by the annual ryegrass living mulch, the earlier planting date resulted in greater ground coverage by red clover. Abdin et al. (1997) observed greater biomass and ground coverage at earlier (10 DAT) compared to later (20 DAT) seeding dates when establishing interseeded grass and legume species in a corn crop. However, greater ground coverage by ryegrass was observed from plots with the later seeding date. The optimal spring seeding range for annual ryegrass and red clover is Feb. through Mar. (Ball et al., 2002). In the 2009 growing season, living mulches were sown 2 DAT, which occurred at the end of the optimal range for spring seeding. It was hypothesized that seeding living mulches earlier within the suggested range would result in better establishment and greater ground coverage. Data suggest that sowing date has no significant impact on ground coverage; no significant differences were observed between sowing dates for either living mulch species. Seeding living mulches at the time of transplanting may be more beneficial than seeding early, as established mulch crops may compete with crop establishment (Brainard and Bellinder, 2004).

In 2009, the greatest total ground coverage by a non-marketable crop was observed in ryegrass plots at both sampling dates. In 2010, a significant difference in total ground coverage by non-marketable crops was observed only on the May 19 sampling date. The greatest total ground coverage was observed in early-sown ryegrass and red clover sown 5 DAT. Ryegrass sown 5 DAT had significantly lower total ground coverage than early-sown ryegrass; however, no differences in ground coverage were observed between living mulch sowing dates, suggesting that the observed difference in total ground coverage may be the result of ground coverage by cover crops.

Cover crops of winter oats and crimson clover afforded greater ground coverage in 2010 than cover crops of triticale and Austrian winter pea in 2009. In 2009, when ground coverage by cover crops was sparse, living mulch crops provided the majority of total ground coverage. The Natural Resource Conservation Service (NRCS) has defined conservation tillage as any tillage system that leaves greater than 30 percent residue remaining on the soil surface after planting (Hortowitz et al., 2010). Though cover crops were unable to meet this requirement in 2009, demonstrated by the May 28 sampling date, the addition of living mulches greatly increased the percentage of the soil surface covered by a living crop or decaying crop residue, meeting or, in the case of annual ryegrass, exceeding the level suggested by the NRCS.

In 2010, cover crops provided the majority of total ground coverage; however, this high level of ground coverage resulted in decreased ground coverage by living mulches. As cited above, cover crops may reduce living mulch stand by competing for above- and below-ground resources, reducing establishment and delaying growth of interplanted crops. Total ground coverage by non-marketable crops was greatest in 2010; however, the addition of an annual ryegrass living mulch in 2009 resulted in total ground coverage similar to levels observed in 2010.

Cover crop and living mulch establishment may have been negatively impacted by the method of crop establishment and the method of weed management. In both years, cover crop seed was planted in the fall using a grain drill; living mulch crops were broadcast in the spring. Kankanen et al. (2001) observed that broadcasting resulted in lower biomass than drilling in an undersown bi-culture of red clover and meadow fescue (*Festuca pratensis* Hudson). However, the highest marketable crop yields were observed when undersown species were broadcast compared to drilled, suggesting that broadcasting may be a more economically productive method of intercrop establishment. Additionally, Boyd and Brennan (2006) observed that mechanical weed management using a rotary hoe did not adversely affect total cover crop biomass and density; crop density generally declines by 10% with rotary hoeing. In both years of the current study, all plots were hand hoed weekly; it is possible that frequent hand hoeing could lead to greater reductions in crop density and ground coverage. This may be one explanation for the lack of differences observed for three of four sampling dates in 2010.

In order to determine whether tillage and living mulch treatments required different levels of weed maintenance, weekly hoeing events were timed. No differences were observed between tillage treatments or among living mulch treatments in 2009 or 2010 indicating that strip tillage and the incoporation of living mulches does not require more time managing weeds than clean cultivation. This may be due to reductions in weed pressure within these systems (DeGregorio and Ashley, 1985, 1986; Ilnicki and Enache, 1992).

Conclusions

In this study, the implementation of strip tillage limited the growth and establishment of living mulch crops. In 2009, poor cover crop establishment provided insufficient ground coverage at the beginning of the broccoli production period. Spring-seeded living mulches, sown 2 DAT, significantly increased total ground coverage by non-marketable crops. However, greater than thirty percent total ground coverage was achieved in annual ryegrass plots only. In 2010, cover crop biomass was greatly increased, providing high levels of ground coverage. However, ground coverage by living mulches was low, suggesting that a dense cover crop may hinder living mulch establishment. In 2010, cover crops provided the greatest percentage of total ground coverage by non-marketable crops. It appears that the greatest application of living mulch crops is in boosting total ground coverage when cover crop establishment is poor; however, when a dense cover crop provides a high level of ground coverage, living mulch crops may be of little benefit.

Additionally, annual ryegrass established the quickest and provided the greatest ground coverage within strip tilled plots in both years, indicating it would make a better selection than red clover for use as a living mulch in reduced tillage organic broccoli production systems for East Tennessee. In 2010, no differences in sowing date were observed for either living mulch species, indicating that seeding living mulches before broccoli transplanting may not increase ground coverage.

Several questions have been raised by the current study. Ground coverage of thirty percent has been suggested as the necessary amount to reduce erosion; further research should be conducted to determine the level of ground coverage necessary for optimal weed management. In order to determine an optimal beneficial level of ground coverage, it is important to understand the impact of varying levels of interseeded living mulch crops on cash crop establishment and yield. With an understanding of the recommended species and level of ground coverage necessary to reduce erosion and manage weed populations, growers would be better able to make decisions regarding the usage of cover crops and living mulches and more likely benefit from the integration of interseeded crops. Additionally, thresholds will vary among living mulch species; to provide suggestions for successful production systems using interseeded crops, different cover crop and living mulch combinations should be trialed in multiple climate regimes. Lastly, in order to properly manage weeds within these systems, different weed management techniques and frequencies should be assessed to determine the effects on cover crop and living mulch biomass and ground coverage.

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Appendix B

Table B.1 Mean monthly rainfall and temperature for 2009 and 2010

Year	*Month*	*Mean Temperature (°C)*	*Mean Temperature (°F)*	*Mean Rainfall (cm)*	*Mean Rainfall (in)*
2009	*Mar.*	8.16	46.7	7.39	2.91
	Apr.	16.22	61.2	6.04	2.38
	May	20.61	69.1	10.97	4.32
	June	25.38	77.7	4.64	1.83
2010	*Mar.*	10.50	50.9	8.53	3.36
	Apr.	14.38	57.9	7.64	3.01
	May	19.27	66.7	17.19	6.77
	June	23.55	74.4	10.51	4.14
	July	22.83	73.1	19.58	7.71

Mean monthly rainfall and temperature during the early-season broccoli production period in 2009 and 2010 at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN.

Table B.2 Ground coverage by cover crops, living mulches and total non-marketable crop coverage sampled at the buttoning growth stage of broccoli in 2009 and 2010

Year	*Treatment*	*Cover Crop Coverage*	*Living Mulch Coverage*	*Total Non-Marketable Crop Coverage*
2009	*No-mulch*	9.4	0.0 c *	9.4 c *
	Red Clover	10.0	19.4 b	29.4 b
	Ryegrass	18.7	42.5 a	61.3 a
2010	*No-mulch*	60.0 ab***	0.0 b ***	60.0 b **
	Red Clover (1)	60.0 ab	1.6 b	61.6 b
	Red Clover (2)	68.3 a	5.0 ab	73.3 ab
	Ryegrass (1)	63.3 a	20.0 a	83.3 a
	Ryegrass (2)	45.0 b	18.3 a	65.0 b

Ground coverage from cover crops (Austrian winter pea and triticale in 2009, and winter oat and crimson clover in 2010), living mulches (annual ryegrass and red clover) and total non-marketable crop coverage (the sum of cover crops and living mulches) among living mulch treatments in an organic broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. In 2009, living mulches were seeded 2 DAT; in 2010, living mulches were seeded on one month prior to transplanting broccoli (1) and 5 DAT (2). In 2009, data were analyzed using a factorial design. In 2010, data were analyzed using a nested design due to the addition of a second living mulch planting date. Asterisks represent a significant difference by LSD mean separation; * $P < 0.01$, ** $P < 0.05$, *** $P < 0.10$. In 2009, cover crop coverage F=1.10, LSD mean=11.62 N=20; living mulch coverage, F=38.62, LSD mean=10.54, N=20; total non-marketable crop coverage, F=69.92, LSD mean=9.63, N=20. In 2010, cover crop coverage F=2.73, LSD mean=17.18, N=20; living mulch coverage F=3.67, LSD mean=16.12, N=20; total non-marketable crop coverage F=3.90, LSD mean=15.98, N=20.

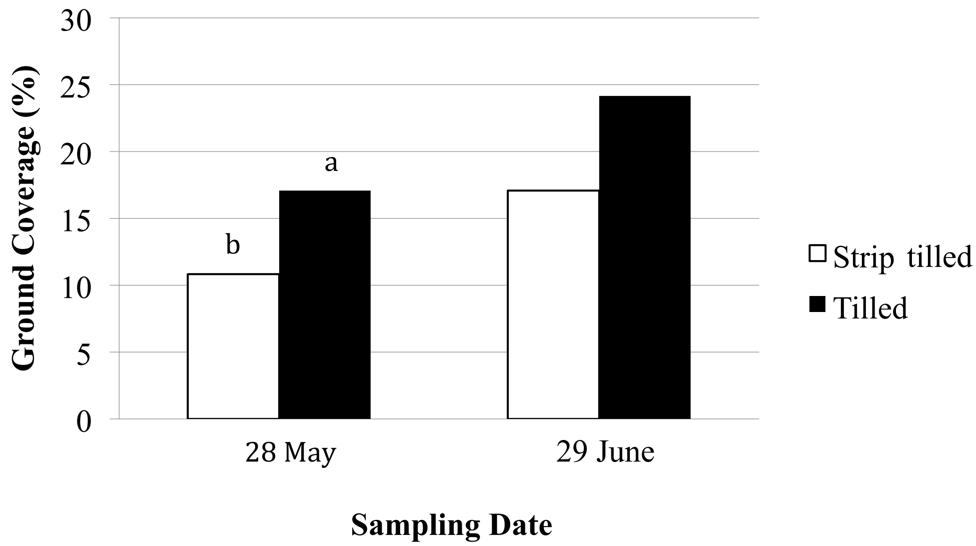

Figure B.1 Ground coverage from living mulches between tillage treatments in 2009

Ground coverage from living mulches (annual ryegrass and red clover) between tillage treatments in an organic broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Ground coverage was measured on 28 May and 29 June, corresponding with the vegetative and buttoning broccoli growth stages, respectively. Letters represent a significant difference by LSD mean separation within each growth stage. For 28 May, $P < 0.10$, F=4.72, LSD mean=7.04, N=20.

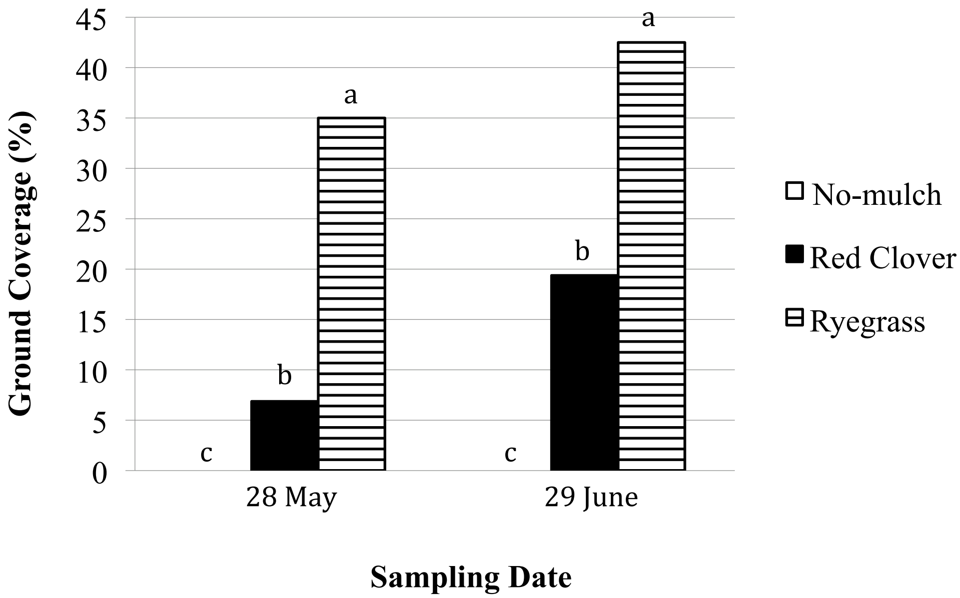

Figure B.2 Ground coverage among living mulch treatments in 2009

Ground coverage among living mulch treatments (no-mulch, red clover and annual ryegrass) in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Ground coverage was measured on 28 May and 29 June, corresponding with the vegetative and buttoning broccoli growth stages, respectively. Living mulches were seeded 2 DAT. Letters represent a significant difference by LSD mean separation within each growth stage. For 28 May, $P < 0.01$, F=74.08, LSD mean=6.63, N=20; for 29 June, $P < 0.01$, F=38.62, LSD mean=10.54, N=20.

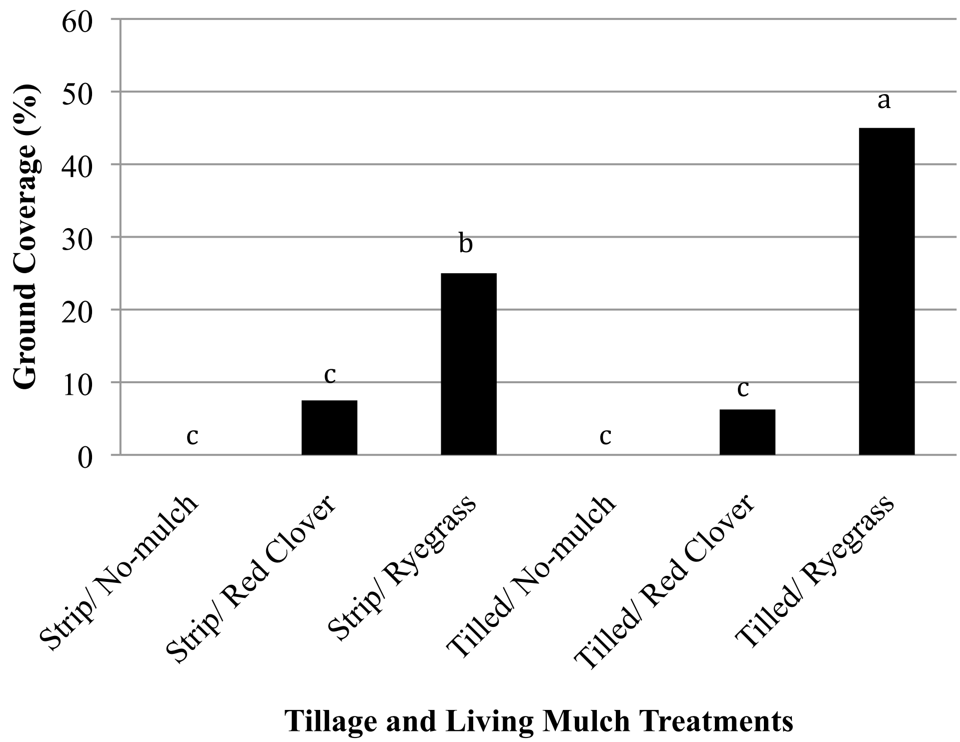

Figure B.3 Tillage by living mulch interaction at the vegetative growth stage of broccoli in 2009

Ground coverage from living mulches (annual ryegrass and red clover) within tillage treatment at the vegetative growth stage in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Ground coverage was measured on 28 May, corresponding with the vegetative growth stage of broccoli. Letters represent a significant difference by LSD mean separation; $P < 0.01$, F=7.66, LSD mean=9.49, N=20.

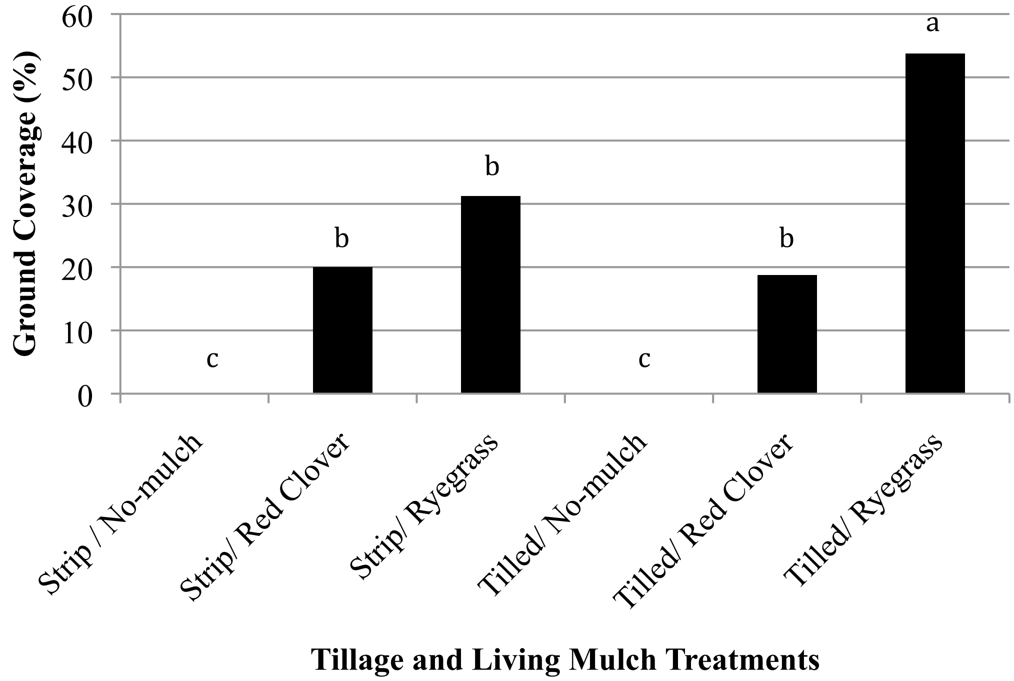

Figure B.4 Tillage by living mulch interaction at the buttoning growth stage of broccoli in 2009

Ground coverage from living mulches (annual ryegrass and red clover) within tillage treatment at the buttoning growth stage in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Ground coverage was measured on 29 June, corresponding with the buttoning growth stage of broccoli. Letters represent a significant difference by LSD mean separation; $P < 0.10$, F=3.81, LSD mean=16.28, N=20.

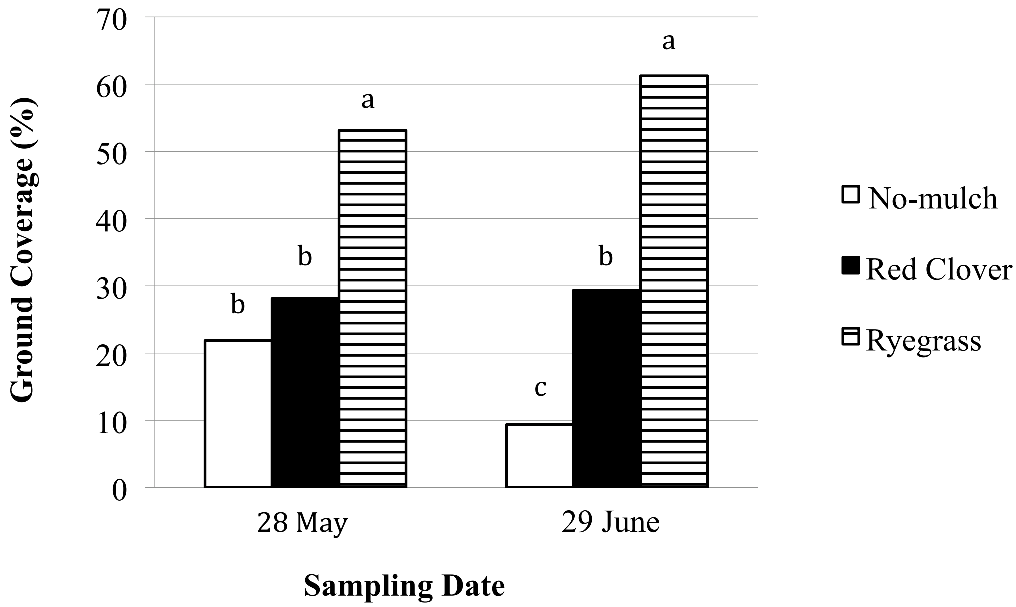

Figure B.5 Total ground coverage for non-marketable crops among living mulch treatments in 2009

Total ground coverage by non-marketable crops represents the sum of coverage by cover crops (Austrian winter pea and triticale) and living mulches (annual ryegrass and red clover) in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Ground coverage was measured on 28 May and 29 June, corresponding with the vegetative and buttoning broccoli growth stages, respectively. Letters represent a significant difference by LSD mean separation within each sampling date. For 28 May, $P < 0.01$, F=19.20, LSD mean=11.62, N=20; for 29 June, $P < 0.01$, F=69.92, LSD mean=9.63, N=20.

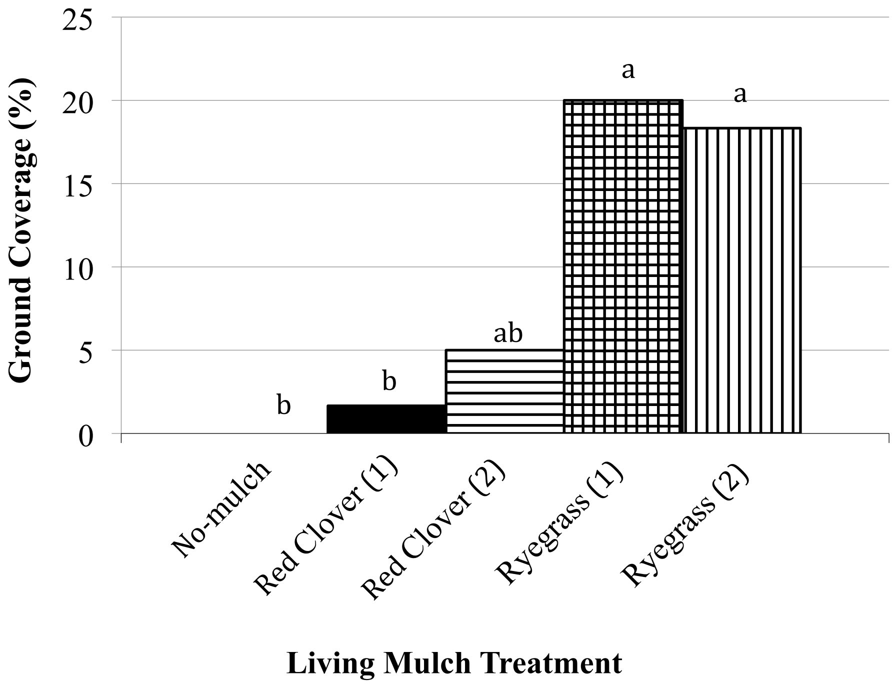

Figure B.6 Ground coverage among living mulch treatments sampled at the buttoning growth stage of broccoli in 2010

Ground coverage among living mulch treatments (no-mulch, red clover and annual ryegrass) sampled at the buttoning growth stage (19 May) in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Indications of (1) and (2) represent living mulch planting dates one month prior to transplanting broccoli and 5 DAT, respectively. Letters represent a significant difference by LSD mean separation; $P < 0.10$, F=3.67, LSD mean=16.12, N=20.

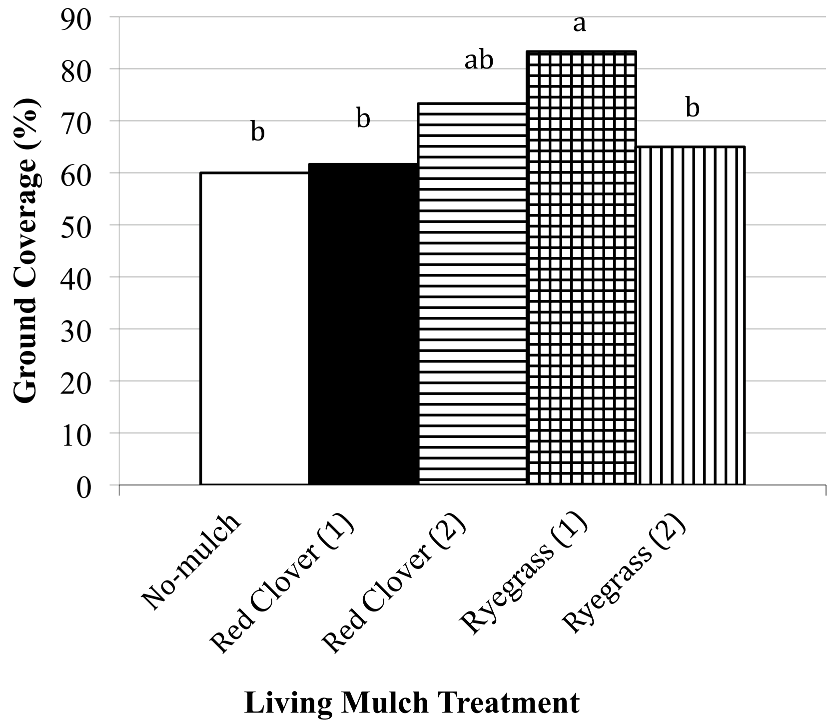

Figure B.7 Total ground coverage for non-marketable crops sampled at the buttoning growth stage of broccoli in 2010

Total ground coverage by non-marketable crops represents the sum of ground coverage by living mulches (annual ryegrass and red clover) and cover crops (winter oats and crimson clover) among living mulch treatments sampled at the buttoning growth stage (19 May) in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Indications of (1) and (2) represent living mulch planting dates one month prior to transplanting broccoli and 5 DAT, respectively. Letters represent a significant difference by LSD mean separation; $P < 0.05$, F=3.90, LSD mean=15.98, N=20.

Chapter Three: Growth and physiological response of broccoli to tillage regime and interplanted living mulch crops

Abstract

The adoption of reduced tillage programs for organic vegetable crop production has the potential to enhance soil quality, ameliorating damage caused by excessive tillage and mechanical cultivation. Strip tillage is a method of reduced tillage well suited to vegetable crop production, and the inclusion of cover crops and living mulches between rows provides a viable weed management option. In the current study, petiole sap nitrate concentration, photosynthetic rate, crop growth (plant height and stalk diameter) and above-ground biomass were assessed at the transplant, vegetative, buttoning and pre-harvest broccoli growth stages to determine the impacts of strip tillage and the inclusion of living mulch crops on the productivity of early-season broccoli in an organic system. Alterations to the soil environment through reduced tillage and the placement of crop residues at the soil surface can impact nutrient availability as a result of delayed decomposition. Additionally, the inclusion of a living mulch creates the opportunity for interspecific competition between mulch and cash crops, altering the status of plant available water, nutrients and sunlight. Significant differences in broccoli sap nitrate concentration were observed between tillage treatments at each sampling date in 2010. While sap nitrate concentrations remained relatively consistent in tilled treatments, concentrations decreased over time in strip tilled treatments. Higher photosynthetic rates were observed at the pre-harvest growth stage in 2010. Seasonal trends for photosynthetic activity in 2010 were the inverse of those observed for petiole sap nitrate. Crop growth and biomass were reduced for plants in strip tilled and annual ryegrass living mulch treatments in both years. The tallest plants and highest weights were observed within tilled, no-mulch treatments. Reductions in crop growth and delayed maturity appear to be due to insufficient fertility, demonstrated by sub-optimal sap nitrate concentrations, and may be due to decreased mineralization and competition from established cover crops and spring-seeded living mulches.

Introduction

Strip tillage is a conservation tillage practice that is well suited to the production of transplanted vegetables. While the planting area is tilled, cover crop residues remain between rows providing weed control and protection from soil erosion. Living mulches are interplanted cover crops established alongside a cash crop during the growing season. Strip tillage separates the vegetable crop from the immediate growing area of the living mulch limiting competition; planting into a tilled strip maximizes root growth allowing for improved plant setting (Biazzo and Masiunas, 2000; Wilhoit et al., 1990). Spring seeded living mulch crops maintain the integrity of a reduced tillage system by replacing decaying cover crop residues (Infante and Morse, 1996).

The utilization of cover crop residues and living mulches enhances soil quality, providing benefits such as reduced rates of erosion, decreased soil temperature fluctuations, increased soil organic matter, improved water infiltration rates, increased microbial activity and improved soil structure (Sullivan, 2004; Wani et al., 1994). Thus, incorporating reduced tillage methods into organic systems can provide more sustainable methods of crop production. Living mulches also provide a viable alternative for weed management (DeGregorio and Ashley, 1985, 1986; Ilnicki and Enache, 1992) and insect pest control (Costello and Altieri, 1995; Frank and Liburd, 2005; Hooks and Johnson, 2006; Hooks et al., 2007) that can make reduced tillage programs more feasible in organic systems.

Ongoing research with living mulches for reduced tillage has been primarily focused on interspecific competition between living mulch and vegetable crops. Competition is influenced by environmental conditions, resource levels and growth characteristics of both the cash and mulch crops (Wiles et al., 1989). Alterations in planting date (Brainard and Bellinder, 2004), mechanical suppression (Biazzo and Masiunas, 2000; Ilnicki and Enache, 1992) and mulch screening and selection have been assessed as potential methods to limit competition. However, results have been inconsistent, with vegetable yields either similar to (Infante and Morse, 1996) or lower than clean cultivation (Biazzo and Masiunas, 2000).

While differences in vegetable yield have been studied (Hooks et al., 2007; Swenson et al., 2004), information on the physiological responses of vegetable crops to reduced tillage and living mulches is lacking. Mineral nutrient deficiencies tend to reduce photosynthetic rate. Additionally, mineral deficient plants tend to weigh less than plants of the same age growing under optimal conditions (Theriault et al., 2009).

Nitrogen (N) is a key element in plant nutrition that limits production when the inorganic supply in soil is low (Al-Kaisi et al., 2004). Greater long-term N storage may be achieved by implementing conservation tillage practices; however, inorganic soil N is expected to be greater under conventional tillage in the short-term. This expectation of greater plant-available N in plowed soils is due to soil mixing, which increases the exposure of crop residues and organic matter to a more favorable environment for decomposition by the soil microbial community (Al-Kaisi et al., 2004). In reduced tillage systems, total N content is greatest in the 0-15 cm (0-6 in.) soil depth and may result from slowed rates of decomposition due to the placement of crop residues at the soil surface (Franzluebbers et al., 1995).

Nitrogen uptake by plants in different tillage systems is influenced by the amount of available soil N and is expected to follow mineralization trends. Mineralization is faster when organic residues are incorporated, as compared to remaining at the soil surface, due to greater organic matter decomposition, allowing growing crops to accumulate more N (Johnson and Hoyt, 1999).

The concentration of nitrate nitrogen (NO_3^--N) in broccoli midribs is significantly correlated with broccoli yield (Gardner and Roth, 1989), and provides a valuable method for assessing fertility status in the field. Optimal rates of NO_3^--N in broccoli leaves are: 800-1,000 ppm at the six leaf stage, 500-800 ppm one week prior to the first harvest and 300-500 ppm at first harvest (Hochmuth, 1994). When midrib NO_3^--N remains above these levels, maximum yields may be obtained.

Photosynthetic rates correlate closely with leaf N content because low N supply results in a low concentration of photosynthetic enzymes, causing decreased rates of photosynthesis (Chapin, 1991). However, low photosynthetic potential does not appear to cause slow growth in N deficient plants. Instead, changes in plant-water relations have been suggested as the physiological mechanism by which N causes reductions in growth. Water and osmotic stress cause changes in hormonal balance, affecting cell wall extensibility and limiting shoot growth. Slow growth is the central feature of plants adapted to a low-resource environment (Chapin, 1991).

An ample supply of available N has been demonstrated to increase marketable yield of broccoli (Gardner and Roth, 1989; Makus, 1997; Tremblay, 1989; Zebarth et al., 1995). High levels of N fertility (150-400 kg N/ha) (Tremblay, 1989; Zebarth et al., 1995) are generally required for high broccoli yields, and increased applications of N have resulted in linear increases in total above ground biomass (Zebarth et al., 1995) affecting vegetative growth and shoot weight but not head diameter (Tremblay, 1989).

When living mulches are interplanted with a vegetable crop, increases in fertilizer applications may not benefit the cash crop. Muller-Scharer (1996) observed that N storage by interplanted living mulches reduced fertilizer allocation to the cash crop.

Surplus amounts of fertilizer, intended to counteract yield reductions due to nutrient competition from a living mulch of ryegrass, were found to only slightly increase N allocation to a leek crop.

Research has demonstrated that the inclusion of reduced tillage and living mulches can impact the growth and yield of a vegetable crop; however, information on the physiological responses of vegetable crops within these systems is lacking. The objective of this study was to determine the effects of reduced tillage and overwintered cover crops and spring-seeded living mulches on the growth and physiological status of organic spring broccoli. Petiole sap nitrate, photosynthetic rate, plant growth and crop biomass were measured to determine overall plant health.

Materials and Methods

The experiment was conducted on a Dewey Silt Loam at the East Tennessee Research and Education Center Organic Crops Unit, in Knoxville, TN, on 0.07 ha (0.18 A.) of land. Two treatments were assessed within the experiment. The tillage treatment was comprised of tilled and strip tilled plots; tillage occurred only once prior to transplanting broccoli as a method of establishing the research plot. Additionally, two living mulches, red clover (*Trifolium pratense* cv. Cinnamon Plus) and annual ryegrass (*Lolium multiflorum* cv. Marshall), were assessed relative to a no-mulch control. A bi-culture of triticale (*x. Triticosecale* spp.), sown at 90 kg/ha (80 lbs./A.), and Austrian winter pea (*Pisum sativum)*, sown at 90 kg/ha (80 lbs./A.), was seeded on 5 Nov. 2008 for the 2009 growing season. A bi-culture of crimson clover (*Trifolium incarnatum*), sown at 28 kg/ha (25 lbs./A.), and winter oats (*Avena sativa)*, sown at 123 kg/ha (110 lbs./A.), was seeded on 20 Sept. 2009 for the 2010 growing season. Cover crops were drilled both years.

In 2009, the research trial was established on a tract of land previously planted to an assortment of vegetable crops. The trial was moved to a different tract of land for the 2010 season, previously planted in cucurbits (summer squash, watermelon and pumpkin). In the spring prior to tillage, the field was flail mowed to a height of 5 cm (2 in.). Tilled plots were established to a depth of 15 cm (6 in.) using a rototiller. Strip tilled plots were established using a Maschio Multivator (Maschio Group, Eldridge, Iowa) leaving a 15 cm

(6 in.) strip tilled to a depth of 15 cm. In 2009, broccoli (*Brassica oleracea* cv. Belstar F1) was transplanted on 13 Apr.; in 2010, broccoli was transplanted on 7 Apr. Plants were set 45 cm (18 in.) apart within rows and 91 cm (36 in.) between rows, with four rows per experimental treatment. Each treatment plot was 3.6 m x 3.6 m (12 ft. x 12 ft.). In 2009, four replicates were sampled. In 2010, three replicates were sampled; pressure from *Rhizoctonia spp*. greatly reduced the number of transplants within the fourth replicate, which was discarded from the study.

In 2009, living mulches of annual ryegrass and red clover were broadcast two days after transplanting (DAT) broccoli, on 15 Apr. In 2010, living mulches in tilled plots were broadcast 5 DAT, on 12 Apr. Strip tilled plots had two living mulch planting dates: 1) one month prior to broccoli transplanting on 8 Mar. 2010 and; 2) 5 DAT on 12 Apr. 2010. In both years, annual ryegrass was sown at a rate of 33 kg/ha (30 lbs./A.) and red clover was sown at a rate of 11 kg/ha (10 lbs./A.). Mulch crops were mowed to a height of 7 cm (3 in.) as they reached the broccoli canopy. In 2009, living mulch plots were mowed once (9 June); in 2010, the plots were mowed three times (19 Apr., 6 May and 2 June). In both years, all plots were spot-hoed weekly to manage weeds. In tilled and strip tilled plots, all observed weeds in the planting row and between rows were removed.

A drip irrigation system was established to provide supplemental water when soil moisture readings, measured with Watermark soil moisture sensors sensors (Irrometer 200SS; Riverside, CA, US), rose above 30 cb indicating limited availability of plant-accessible water. In both years, all treatment combinations received equivalent amounts of supplemental water on all irrigation events. Monthly rainfall and temperature averages are reported in Table C.1.

Petiole sap nitrate was measured using a handheld Cardy nitrate meter (2305G, Spectrum Technologies, Plainfield, Illinois). Measurements were taken on the youngest, fully expanded leaf between 8:00 and 11:00 AM. The petiole and midrib were crushed using a garlic press, and two or three drops of sap were placed directly on the sensor (Kubota et al., 1997). Three plants per treatment were sampled. Samples were collected in the field and immediately measured indoors to ensure proper calibration of the Cardy nitrate meter. In 2009, measurements were taken at pre-harvest (23 June) only. In 2010, measurements were taken at three growth stages: vegetative (30 Apr.), buttoning (18 May) and pre-harvest (13 June).

Photosynthetic rate was measured using a LiCor portable photosynthesis meter (LI-6400, Li-Cor Biosciences, Lincoln, Nebraska). Measurements were taken on the youngest, fully expanded leaf between 8:00 and 11:00 AM. Measurements at each growth stage were collected over a period of three days. Samples were taken on three plants per treatment combination. A reference CO_2 of 380 ppm and a PAR of 1350 mol were utilized across all samples. In 2009, measurements were taken at pre-harvest (30 June) only. In 2010, measurements were taken at three growth stages: vegetative (5 May), buttoning (24 May) and pre-harvest (16 June).

Broccoli height (cm) was measured as the distance from the soil surface to the crown of the plant. In 2009, broccoli was measured on two dates corresponding with the vegetative (29 Apr.) and pre-harvest (29 June) growth stages. In 2010, plants were measured on three dates corresponding with the vegetative (28 Apr.), buttoning (18 May) and pre-harvest (14 June) growth stages. In 2010 only, stalk diameter (mm), measured at mid-stalk using a digital caliper, was also assessed at pre-harvest.

Plant biomass (kg) was measured for five randomly sampled plants in each treatment combination at pre-harvest (6 July 2009 and 18 June 2010). A total fresh weight per treatment was calculated by summing the weight of each plant sample. The plants were dried in a forced air oven at 49 °C (120 °F) for 72 hours and a total dry weight for each treatment was calculated.

The experimental design was a randomized complete block with a split-plot arrangement of treatments. Tillage treatments (tilled and strip tilled) comprised the main plot. In 2009, the living mulch sub-plot had three levels: red clover, annual ryegrass and no-mulch. In 2010, main and sub-plots remained the same with the addition of an early planting date for living mulch treatments (one month prior to transplant) added to the strip-tilled treatment only. All data were analyzed by mixed model ANOVA using SAS (SAS 9.1, SAS Institute Inc., Cary, NC). Tillage and living mulch treatments were analyzed as fixed effects; replicate was analyzed as a random effect. In 2009, fixed effects were analyzed using a factorial design. In 2010, the addition of early sown living mulches within the strip tilled treatment created imbalance in the sub-plot, and fixed effects were analyzed using a nested design, providing comparisons between tillage treatments and between living mulch levels within each tillage treatment. A probability level of $P < 0.05$ or below was accepted.

Results

Physiological Status

Petiole sap nitrate concentrations in 2009 were not affected by tillage or living mulch treatments (data not shown). No trends were observed between tillage treatments; however, a trend towards greater sap nitrate concentrations was observed in the red clover living mulch plots, with the least in the annual ryegrass plot. In 2010, a significant difference ($P < 0.01$) in petiole sap nitrate concentration was observed between tillage treatments at each growth stage: vegetative, buttoning and pre-harvest (Fig. C.1). At the vegetative growth stage, greater sap nitrate concentrations were observed in plants in strip tilled (368 ppm NO_3^--N) plots compared to plants in tilled (244 ppm NO_3^--N) plots. At the buttoning growth stage, greater sap nitrate concentrations were observed in plants in tilled (308 ppm NO_3^--N) compared to plants in strip tilled (243 ppm NO_3^--N) plots. At pre-harvest, greater concentrations of sap nitrate were observed in plants in tilled (259 ppm NO_3^--N) compared to plants in strip tilled (118 ppm NO_3^--N) plots. A significant difference ($P < 0.01$) in petiole sap nitrate concentration was also observed among broccoli growth stages within strip tilled plots, with the highest concentrations (368 ppm NO_3^--N) at the vegetative growth stage and the lowest (118 ppm NO_3^--N) at pre-harvest (Fig. C.1).

Neither tillage type nor living mulch species affected broccoli photosynthetic rates during the 2009 growing season (data not shown). In 2010, higher photosynthetic rates ($P < 0.05$) were observed in plants in strip tilled (23.7 μmol CO2 m-2 s-1) compared to tilled (20.6 μmol CO2 m-2 s-1) plots at the pre-harvest growth stage (Fig. C.2). No difference was found at the vegetative or buttoning growth stages; however, at the vegetative growth stage, a trend toward higher photosynthetic rates was observed in plants in tilled plots (data not shown).

Plant Growth

In 2009, a significant difference in plant height was observed between tillage treatments ($P < 0.01$), and also among living mulch treatments ($P < 0.01$). Broccoli plants in tilled plots were taller than in strip tilled at the vegetative (tilled=17.9 cm, strip=14.1 cm) and pre-harvest (tilled=26.6 cm, strip=22.8 cm) growth stages (Fig. C.3). Plots with a living mulch of annual ryegrass had shorter plants (vegetative=15.2 cm, pre-harvest=21.9 cm) than red clover (vegetative=16.5 cm, pre-harvest=25.8 cm) or no-mulch (pre-harvest=26.4 cm) plots (Fig. C.4).

In 2010, taller plants were observed in strip tilled (11.1 cm) compared to tilled (7.4 cm) plots at the vegetative growth stage ($P < 0.01$); however, at the pre-harvest growth stage, taller plants were observed in tilled (32.1 cm) compared to strip tilled (26.7 cm) plots (Figure C.5). No difference in plant height was observed between tillage treatments at the buttoning growth stage. No clear trends in plant height were observed in living mulch treatments. A significant difference ($P < 0.01$) between tillage treatments was observed for stalk diameter at the pre-harvest growth stage, with the widest diameter in tilled (30.5 mm) compared to strip tilled (19.6 mm) plots (Fig. C.6).

Biomass

In 2009, a significant difference in fresh and dry weights was observed among living mulch treatments ($P < 0.01$) (Fig. C.7). The highest fresh (1.92 kg) and dry (0.32 kg) weights were observed in no-mulch plots, with the lowest weights (dry=0.11 kg, fresh=0.72 kg) in plots with a living mulch of annual ryegrass. Fresh weights for red clover plots (1.48 kg) did not differ significantly from no-mulch plots, but dry weights in red clover plots (0.22 kg) were significantly lower than no-mulch and higher than ryegrass plots. No trends in fresh and dry weight were observed between tillage treatments in 2009, with similar weights in tilled and strip tilled plots (data not shown). In 2010, greater broccoli weights ($P < 0.01$) were observed in tilled (fresh=3.68 kg, dry= 0.87 kg) compared to strip tilled (fresh=1.07 kg, dry=0.44 kg) plots (Fig. C.8). Trends in fresh and dry weight among living mulch treatments in 2010 indicate greater weights in no-mulch plots compared to plots with a living mulch of annual ryegrass or red clover (data not shown).

Discussion

In 2009, neither plants in tilled nor strip tilled treatments produced harvestable heads. In 2010, head production in the tilled treatment was variable, providing a minimal harvest, while no heads were produced within the strip tilled treatment. Yield data was not collected in either year.

In 2009 and 2010, petiole sap nitrate concentrations were below the levels critical for optimum broccoli yields at all growth stages, across tillage and living mulch treatments. Optimal rates of NO_3^--N in broccoli leaves are: 800-1,000 ppm at the six leaf stage, 500-800 ppm one week prior to the first harvest and 300-500 ppm at first harvest (Hochmuth, 1994). Sub-optimal nitrate concentrations may indicate legume cover crops of Austrian winter pea (2009) and crimson clover (2010) did not provide sufficient levels of N. Fertility status is significantly correlated with crop yield and increased plant biomass (Chapin, 1991; Tremblay, 1989; Zebarth et al., 1995); therefore, nutrient deficiency is one explanation for the poor yield, suppressed growth and reductions in biomass observed in both 2009 and 2010.

A stand of Austrian winter pea is expected to contribute 101-168 kg N/ha (90-150 lbs./A.); crimson clover is expected to contribute 78-168 kg N/ha (78-168 lbs/A.) (Clark, 2007). When incorporated into the soil, sixty percent of the total N provided by a leguminous cover crop is anticipated to become available for uptake by plants; forty percent of N contributed is anticipated to be plant-available when cover crops remain at the soil surface (Sullivan, 2003). Greater inorganic soil N has been observed under conventional tillage in the short-term due to soil mixing, which increases the exposure of crop residues and organic matter to a more favorable environment for decomposition by the soil microbial community (Al-Kaisi et al., 2004). Decreased or delayed mineralization is one explanation for the observed decreases in broccoli petiole sap nitrate concentrations in strip tilled plots.

In 2009, broccoli was sampled once at pre-harvest and no differences in sap nitrate were observed. In 2010, broccoli was sampled at the vegetative, buttoning and pre-harvest growth stages; a significant difference was observed among growth stages. Within each growth stage, a difference in sap nitrate concentration was observed between tillage treatments. At the vegetative growth stage, sap nitrate concentrations were highest within the strip tilled treatment; however, at the buttoning and pre-harvest growth stages, concentrations were highest in tilled treatments.

While sap nitrate concentrations remained relatively consistent in plants in tilled treatments across sampling dates, concentrations decreased over time in plants in strip tilled treatments. Decreases in petiole sap nitrate concentration are expected as the broccoli crop matures and head formation begins (Hochmuth, 1994). The pattern observed in strip tilled treatments follows this trend; however, nitrate concentrations were below optimal levels at all growth stages. Though fertility was below critical levels for optimal growth and yield, consistent amounts of plant-available N were available in tilled treatments throughout the broccoli production period. Decreases in sap nitrate in strip tilled treatments may indicate decreases in mineralization over time; this may be due to the reduced amount of crop residues incorporated into the soil with strip tillage (Johnson and Hoyt, 1999).

Additionally, analysis of ground coverage by cover crops demonstrated no significant difference in crop stand among broccoli growth stages within strip tilled plots (data not shown), indicating comparable levels of ground coverage by cover crops throughout the broccoli production period. The presence of triticale (2009) and winter oat (2010) small grains within the strip tilled treatment may indicate that established, overwintered cover crops also competed with the broccoli crop (in addition to interseeded living mulch crops) by assimilating available N, reducing the pool of plant-available N within the soil (Muller-Scharer, 1996).

In 2009, data indicate that photosynthesis did not differ significantly between tillage treatments or among spring-seeded living mulch treatments of red clover and annual ryegrass at pre-harvest. This may have been due to poor plant health at the time of sampling, resulting from damage caused by elevated insect pressure (Neves et al., 2006) and plant pathogens (Berger et al., 2004; Prokopova et al., 2010). In 2010, significantly higher photosynthetic rates were measured in strip tilled compared to tilled plots at the pre-harvest growth stage only. However, though non-significant, a trend toward higher photosynthetic rates in tilled plots was observed at the vegetative growth stage.

Previous research suggests low N supply results in decreases in photosynthetic enzymes, causing low rates of photosynthesis per gram of leaf (Chapin, 1991). Photosynthetic rate is therefore expected to be closely correlated with leaf N content. Research by Zhao et al. (2003) supports this theory; reduced growth and photosynthesis were observed in N deficient corn.

The relationship observed between photosynthetic rate and petiole sap nitrate in the current study is contrary to these observations. In 2010, no significant difference was observed in petiole sap nitrate concentration across broccoli growth stages within tilled plots; however, significantly greater concentrations of petiole sap nitrate were observed at the vegetative growth stage within strip tilled plots, with the lowest concentrations at pre-harvest. The inverse was true for photosynthetic rate in 2010. No significant difference in photosynthetic rate across broccoli growth stage was observed within strip tilled plots, while higher photosynthetic rates were observed at pre-harvest in tilled plots, with the lowest observations occurring at the vegetative growth stage. These results are in line with observations by Lu and Zhang (2000); N deficiency had little effect on PSII primary photochemistry or photoinhibition in corn under natural illumination. Insect herbivory (Neves et al., 2006) is another plausible explanation for decreases in photosynthetic activity of broccoli within the tilled treatment throughout the growing season. Greater densities of herbivorous insects were observed within tilled plots in the 2010 growing season (data not shown).

In addition to decreasing photosynthetic activity, N deficiency can also result in decreased plant growth (Zhao et al., 2003). Changes in plant-water relations have been suggested as the physiological mechanism by which N causes a reduction in growth. Water and osmotic stress disrupt hormonal balance, altering the flexibility of cell walls and suppressing growth (Chapin, 1991). It is unlikely that water and osmotic stress, caused by sub-optimal soil moisture status, are responsible for the observed decreases in plant growth and total above-ground biomass within strip tilled plots. In both 2009 and 2010, soil moisture was monitored and supplemental irrigation was provided via drip tape when soil moisture readings fell below 30 cb, the level of ample plant-available water.

In 2009 and 2010, strip tillage resulted in shorter plants; in 2009, shorter plants were also observed in plots with a living mulch of annual ryegrass. Reduced above ground biomass was observed for plants in annual ryegrass living mulch plots in 2009 and strip tilled plots in 2010. Additionally, thinner stalks were observed for plants in strip tilled plots in 2010. Research assessing the impact of reduced tillage and living mulches on vegetable crop growth and yield has produced variable results. Living mulches have been demonstrated to result in reductions in plant growth and crop yield (Biazzo and Masiunas, 2000; Brainard and Bellinder, 2004; Swenson et al., 2004). The primary cause of reduced vigor in vegetable crops when planted with living mulches has been interspecific competition (Muller-Scharer, 1996). Aggressive species, such as annual ryegrass, have been shown to cause reductions in crop yield when utilized as a living mulch (Brainard and Bellinder, 2004).

Additionally, living mulches may compete with a vegetable crop for space and sunlight. Living mulches are intended to create a second canopy below the cash crop, directly reducing sunlight availability to understories (DeGregorio and Ashley, 1985, 1986). A closed crop canopy can exclude the growth of plants beneath it (Morse, 1999). While these characteristics are beneficial for reducing weed emergence, when the living mulch crop reaches or exceeds the broccoli canopy it can decrease the amount of sunlight intercepted by the broccoli leaves. In the current study, cover crops and living mulches were suppressed throughout the broccoli production period by mowing. While the living mulch crops of annual ryegrass and red clover remained beneath the broccoli canopy, the triticale cover crop frequently overtopped the broccoli canopy between mowing events. This shading may have negatively impacted the broccoli crop.

Reduced tillage and living mulch systems have produced yields comparable to those of crops grown in tilled, cultivated soil under specific circumstances. Infante and Morse (1996) observed no effect on yield of Fall broccoli when overseeding living mulch crops into a reduced tillage system. However, Hoyt (1999) reported reduced yields of early-season broccoli, compared to long-season crops, caused by decreased soil temperatures in reduced tillage plots; production systems with a high degree of tillage resulted in the greatest yields of short-season vegetables. Thus, reduced tillage may hinder early-season broccoli production, though warmer soils in fall have not been demonstrated to delay crop growth.

Greater vegetable yields due to the inclusion of living mulches have been reported relative to reductions in weed biomass (Masiunas, 1998). It has also been demonstrated that planting of living mulches at least 10 DAT results in no yield reductions (Brainard and Bellinder, 2004). Living mulch planting dates within 10 DAT may enhance competition between living mulch and vegetable crops, accounting for reductions in plant height and above-ground biomass observed in the annual ryegrass living mulch treatments in this study.

Conclusions

In this study, the implementation of strip tillage and spring-seeded living mulches of annual ryegrass and red clover limited the growth and maturity of organic, early-season broccoli.

Petiole sap nitrate readings were below critical levels at all sampling dates, indicating that fall-sown bi-cultures of Austrian winter pea and triticale, and crimson clover and winter oat did not provide a sufficient source of fertility for early-season broccoli. The difference observed between tillage treatments at each sampling date indicated reduced amounts of plant-available N in strip tilled treatments over time. It is likely this is due to reduced mineralization caused by cover crop residues remaining on the soil surface as opposed to incorporated in the soil through tillage. Additionally, overwintered cover crops may have competed with the broccoli crop by decreasing the pool of plant-available soil N.

At the pre-harvest growth stage, higher photosynthetic rates were observed in strip tilled treatments. The trends in photosynthetic activity across the broccoli production period in 2010 are contrary to those expected. Decreases in photosynthetic activity within tilled treatments over time may be the result of insect herbivory.

In 2009, a living mulch of ryegrass resulted in smaller plants with less above-ground biomass than red clover or no-mulch plots; in 2010, strip tillage resulted in smaller plants with less above ground biomass than tilled plots. No yield measurements were taken in either year due to variable head formation. Strip tillage and the use of annual ryegrass as a living mulch appear to hamper crop growth and delay maturity. Competition for space and sunlight may have occurred as interseeded cover crops and living mulches approached the broccoli canopy, requiring mechanical suppression. Poor fertility, however, as indicated by sub-optimal petiole sap nitrate concentrations, due to insufficient N contributions from leguminous cover crops and competition for plant-available Nfrom established cover crops and spring-seeded living mulches is the most plausible explanation for reductions in crop vigor.

Further research should be conducted to determine which mulch and tillage methods are best suited to organic vegetable production for spring, summer and fall production periods. Studies focused on cover crop and mulch selection, method of living mulch establishment, time of seeding, and vegetable crop production period should be conducted to better determine the proper application of strip tillage and living mulches. Additionally, research on the uptake of nutrients by cover and living mulch crops, level of fertility supplied by leguminous and graminaceous cover crops and soil mineralization trends would provide greater insight into the availability of plant-essential nutrients provided by cover crop residues, and their uptake by vegetable, cover and living mulch crops. Lastly, studies focused on the effects of living mulches on the photosynthetic activity of vegetables in intercropping systems should be further explored. This information could provide better explanations for interspecific competition between living mulch and cash crops, and may provide insight into how this competition can be ameliorated.

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Appendix C

Table C.1 Mean monthly rainfall and temperature for 2009 and 2010

Year	*Month*	*Mean Temperature (°C)*	*Mean Temperature (°F)*	*Mean Rainfall (cm)*	*Mean Rainfall (in)*
2009	*Mar.*	8.16	46.7	7.39	2.91
	Apr.	16.22	61.2	6.04	2.38
	May	20.61	69.1	10.97	4.32
	June	25.38	77.7	4.64	1.83
2010	*Mar.*	10.50	50.9	8.53	3.36
	Apr.	14.38	57.9	7.64	3.01
	May	19.27	66.7	17.19	6.77
	June	23.55	74.4	10.51	4.14
	July	22.83	73.1	19.58	7.71

Mean monthly rainfall and temperature during the early-season broccoli production period in 2009 and 2010 at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN.

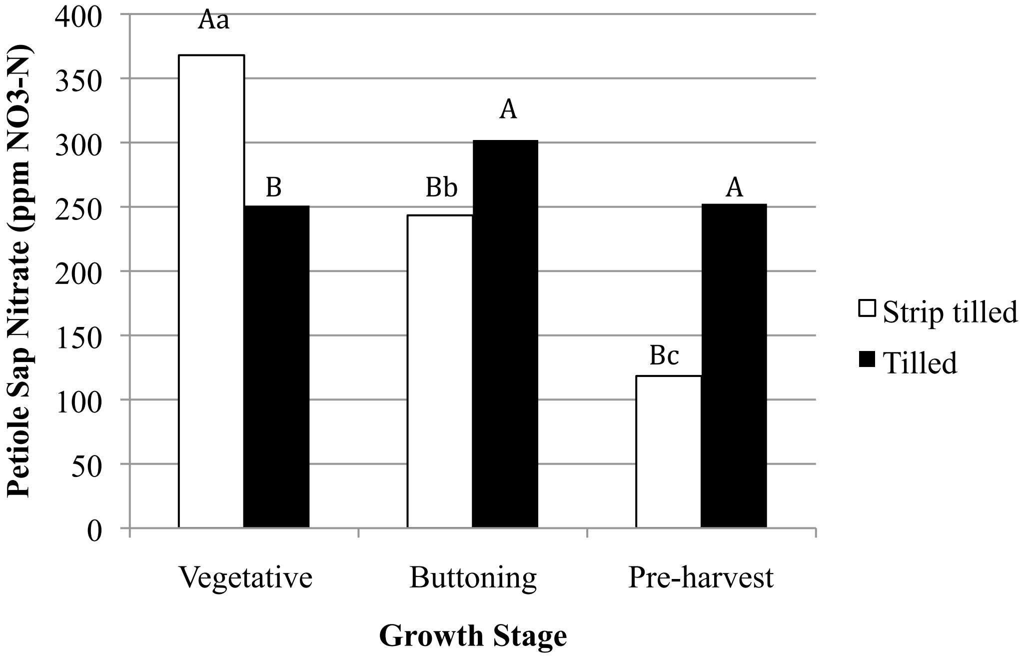

Figure C.1 Petiole sap nitrate concentration between tillage treatments at three broccoli growth stages in 2010

Petiole sap nitrate concentration between tillage treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Petiole sap nitrate was measured at the vegetative (30 Apr.), buttoning (18 May) and pre-harvest (13 June) growth stages. LSD mean separation indicates a significant difference between tillage treatments within each growth stage (noted with capital letters), and among growth stages within strip tilled plots (noted with lower case letters). At the vegetative growth stage, $P < 0.01$, F=12.02, LSD mean=75.89, N=3; at the buttoning growth stage, $P < 0.01$, F=10.89, LSD mean=39.17, N=3; and at the pre-harvest growth stage $P < 0.01$, F=29.16, LSD mean=55.29, N=3. Within the strip tilled plot across growth stages, $P < 0.01$, F=73.26, LSD mean=42.23, N=3.

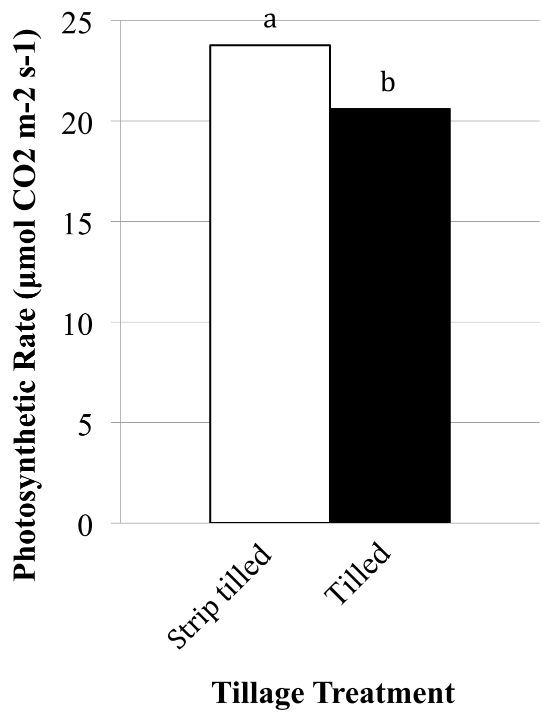

Figure C.2 Photosynthetic rate between tillage treatments at the pre-harvest growth stage of broccoli in 2010

Photosynthetic rate between tillage treatments at the pre-harvest growth stage (16 June) in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Letters represent a significant difference by LSD mean separation; $P < 0.05$, F=8.79, LSD mean=3.64, N=3.

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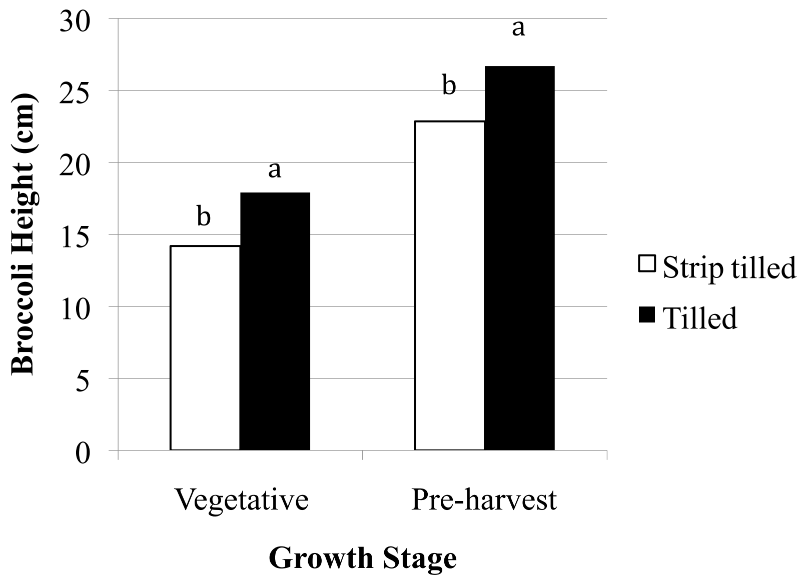

Figure C.3 Plant height between tillage treatments at two broccoli growth stages in 2009

Plant height between tillage treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Broccoli height was measured on two dates corresponding with the vegetative (29 Apr.) and pre-harvest (29 June) growth stages. Letters represent a significant difference by LSD mean separation within each growth stage. At the vegetative growth stage, $P < 0.01$, F=54.26, LSD mean=1.26, N=10; at the pre-harvest growth stage, $P < 0.01$, F=17.84, LSD mean=2.37, N=10.

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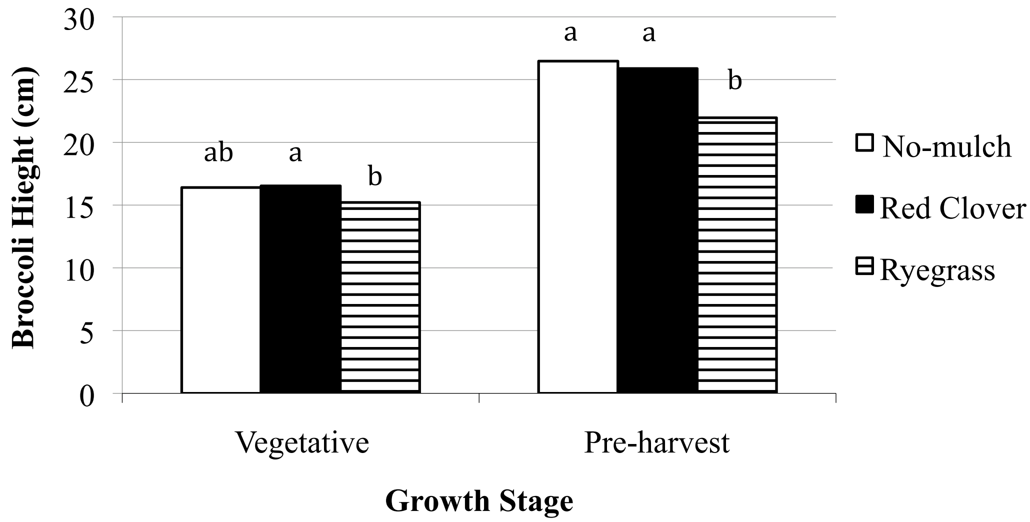

Figure C.4 Plant height among living mulch treatments at two broccoli growth stages in 2009

Plant height among living mulch treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Broccoli height was measured on two dates corresponding with the vegetative (29 Apr.) and pre-harvest (29 June) growth stages. Letters represent a significant difference by LSD mean separation within each growth stage. At the vegetative sampling date, $P < 0.01$, F=3.12, LSD mean=1.23, N=10; at the pre-harvest sampling date, $P < 0.01$, F=9.71, LSD mean=1.93, N=10.

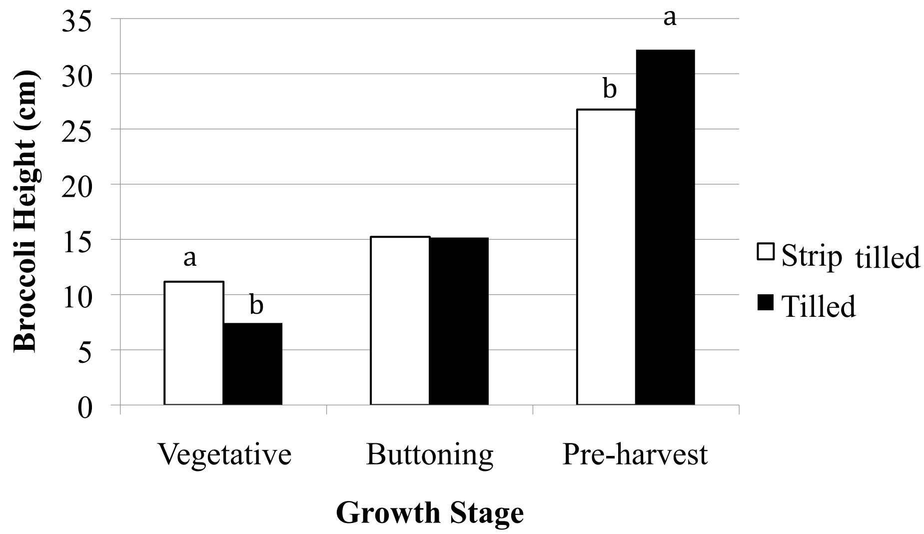

Figure C.5 Plant height between tillage treatments at three broccoli growth stages in 2010

Plant height between tillage treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Broccoli height was measured on three dates corresponding with the vegetative (28 Apr.), buttoning (18 May) and pre-harvest (14 June) growth stages. Letters represent a significant difference by LSD mean separation within each growth stage. At the vegetative growth stage, $P < 0.01$, F=45.36, LSD mean=1.53, N=10; at the pre-harvest growth stage, $P < 0.01$, F=46.07, LSD mean=2.61, N=10.

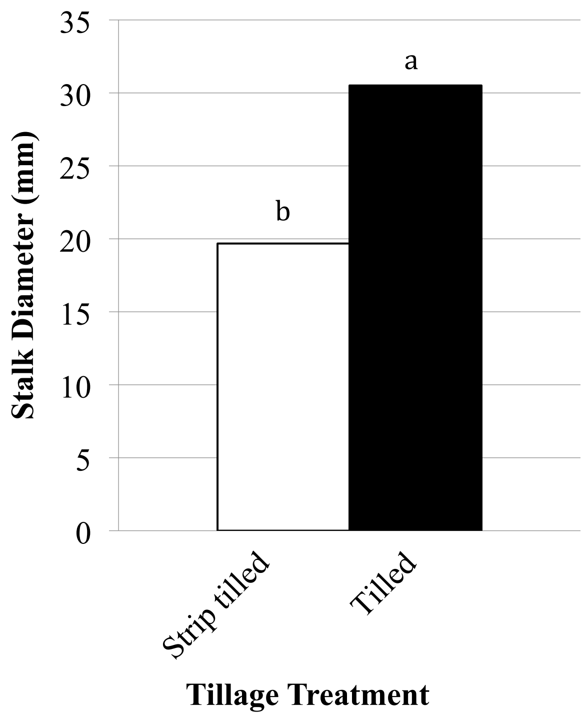

Figure C.6 Stalk diameter between tillage treatments at the pre-harvest growth stage of broccoli in 2010

Stalk diameter between tillage treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Stalk diameter was measured at the pre-harvest (14 June) growth stage. Letters represent a significant difference by LSD mean separation; $P < 0.01$, F=80.31, LSD mean=2.56, N=10.

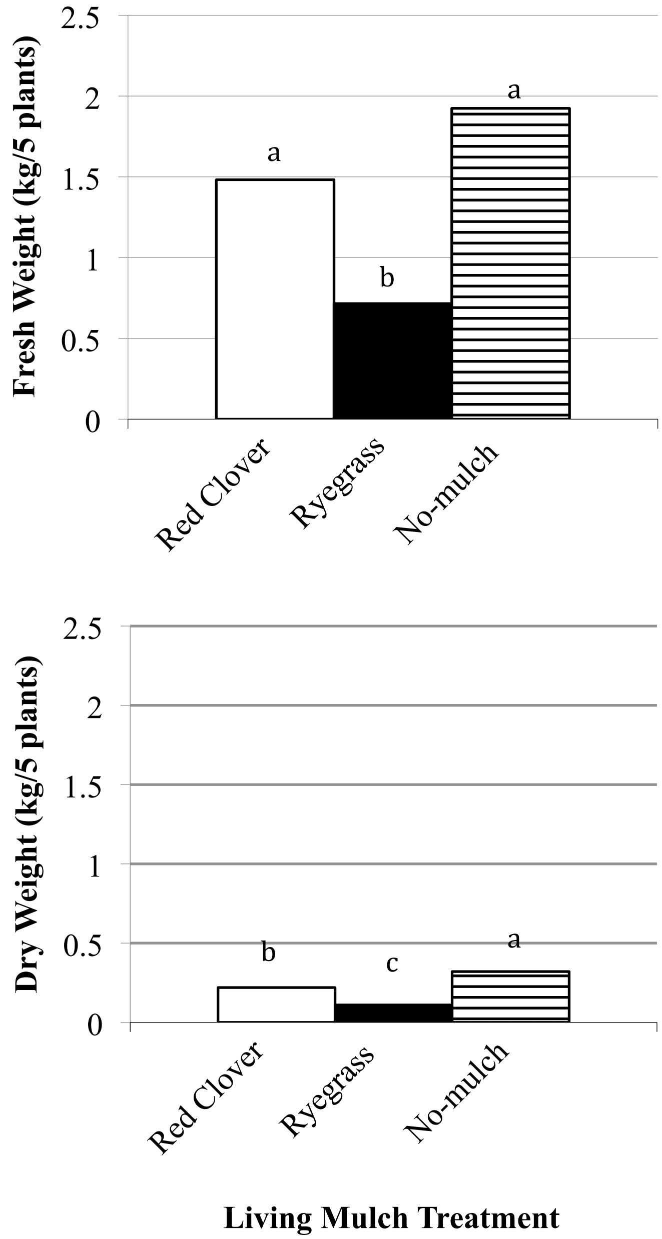

Figure C.7 Fresh and dry weights among living mulch treatments at the pre-harvest growth stage of broccoli in 2009

Fresh and dry weights among living mulch treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Fresh weight was measured at the pre-harvest growth stage (6 July); plants were dried in a forced-air oven at 49 °C (120 °F) for 72 hours and a dry weight measured. Letters represent a significant difference by LSD mean separation. For fresh weight, $P < 0.01$, F=16.15, LSD mean=0.42, N=5; for dry weight, $P < 0.01$, F=20.94, LSD mean=0.06, N=5.

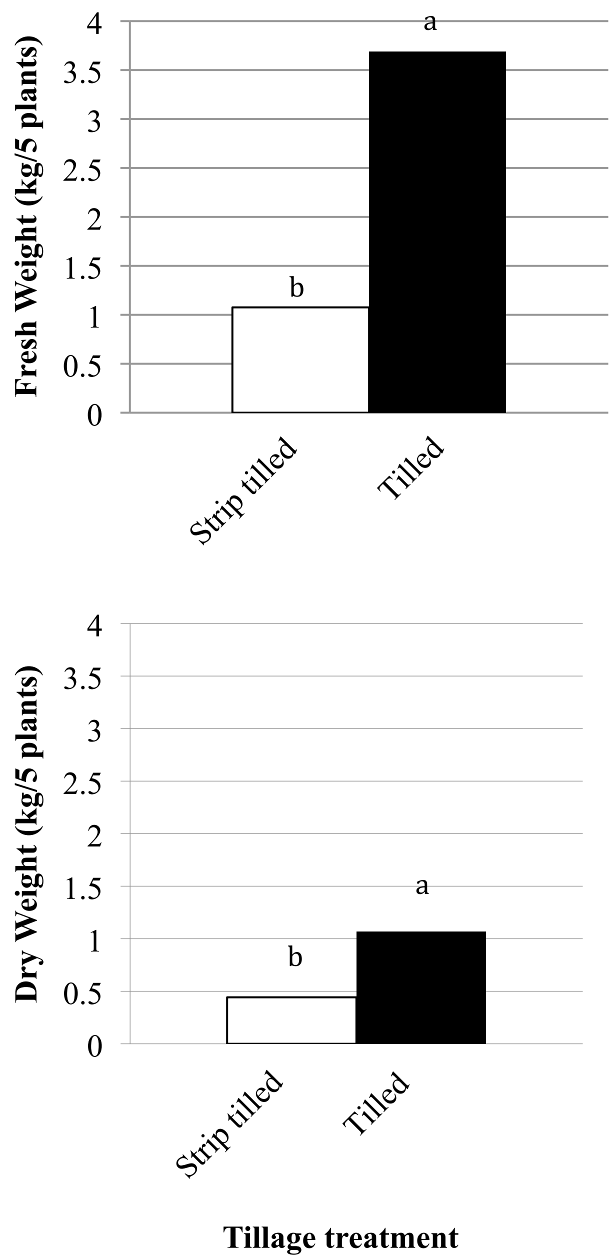

Figure C.8 Fresh and dry weights between tillage treatments at the pre-harvest growth stage of broccoli in 2010

Fresh and dry weights between tillage treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Fresh weight was measured at the pre-harvest growth stage (18 June); plants were dried in a forced-air oven at 49 °C (120 °F) for 72 hours and a dry weight measured. Letters represent a significant difference by LSD mean separation. For fresh weight, $P < 0.01$, F=301.66, LSD mean=0.31, N=5; for dry weight, $P < 0.01$, F=276.25, LSD mean=0.05, N=5.

Chapter Four: Weed relative abundance, insect density and disease incidence and severity in organic spring broccoli grown using strip tillage and living mulches

Abstract

Living mulches and cover crops have been indicated as methods to suppress weeds, reduce damage from insect pests and boost beneficial insect populations. Additionally, increases in crop residues may increase native microbial populations in surface layers of the soil, naturally suppressing disease-causing pathogens. However, research results on weed, insect and disease suppression by reduced tillage and living mulches have been variable, depending upon soil quality, climate, cash crop and intercropped species. The relative abundance of weeds, insect density and disease incidence and severity were assessed in an organic spring broccoli production system to determine the efficacy of strip tillage, overwintered cover crops and spring-sown living mulches as pest management strategies. Decreases in crabgrass abundance were observed in strip tilled plots, but greater presence of overwintered cool-season weeds (wild pansy) were observed in undisturbed soil. Annual ryegrass utilized as a living mulch reduced carpetweed and prickly sida populations compared to tilled plots. Decreases in herbivore density were observed in strip tilled and ryegrass living mulch plots, with no differences in predator or parasitoid densities. The greatest severity of plant pathogens (*Alternaria* spp.) occurred in tilled plots; the greatest incidence of plant pathogens (*Rhizoctonia* spp.) occurred in strip tilled plots. Results indicate that the use of strip tillage and living mulches may offer an alternative control strategy for grassy weed species, as well as decrease pest organisms. However, the impact of reduced tillage on disease incidence and severity depends upon the infecting pathogen.

Introduction

The integration of conservation tillage practices into organic production systems provides an alternative to conventional tillage, offering benefits to soil quality and protection against erosion. However, the implementation of reduced tillage creates additional challenges for pest control, such as weed management, within these systems. Conventionally managed reduced tillage systems are maintained using synthetic herbicides for clean cultivation. The utilization of cover crop residues and living mulches in reduced tillage systems has demonstrated potential in decreasing weed emergence (DeGregorio and Ashley, 1985, 1986; Ilnicki and Enache, 1992), providing a viable alternative to herbicides for the inclusion of reduced tillage programs into organic systems. Cover crops and living mulches also have been demonstrated to decrease injury from insect pests (Hooks and Johnson, 2006), increase beneficial insect populations (Costello and Altieri, 1995) and promote natural disease suppression (Sturtz et al., 1997), further enhancing natural pest suppression within the farm system.

Reduced tillage systems evaluated for vegetable crops have produced variable results depending upon crop, location, soil moisture and soil temperature. Wilhoit et al. (1990) reported increased cabbage yields due to reduced tillage in years with limited rainfall; however, yields were higher in conventionally tilled plots when rainfall was not limiting. Additionally, in some circumstances, the inclusion of overwintered cover crops and living mulches has resulted in significant levels of competition, decreasing vegetable yield (Muller-Scharer, 1996). Brassica crops specifically are slow growing and do not compete well with background vegetation (Hooks et al., 2007).

Strip tillage may provide a conservation tillage practice that is well suited to the production of transplanted vegetables. While the planting area is tilled, cover crop residues and living mulches remain between crop rows, providing weed control and protection from soil erosion. The separation between the main crop and the growing area of the living mulch may limit competition while allowing maximum root growth and optimal plant establishment (Biazzo and Masiunas, 2000; Wilhoit et al., 1990). Overseeding helps to maintain the integrity of a reduced tillage system by replacing decaying cover crop residues with a living mulch (Infante and Morse, 1996). When cool-season cover crops have not yet matured, these living mulches can provide an alternative method of weed control in organic, reduced tillage systems for early-season vegetable production.

Living mulches suppress weeds by competing for water, light and nutrients. However, the use of living mulches for weed control has provided mixed results. Living mulches have provided excellent control without adversely affecting the yield of corn, soybean, summer squash, spring cabbage, tomatoes and snap bean (Ilnicki and Enache, 1992). In other instances, they have been less successful at suppressing weeds or have negatively affected the vegetable (broccoli) crop (Chase and Mbuya, 2008). To avoid competition, seed size, aggressiveness, and time of planting should be assessed. Desirable grass and legume species for use as living mulches are those that rapidly establish a closed canopy or impede weed establishment through allelopathy (Chase and Mbuya, 2008). Small seeded species, such as clovers, typically have minimal impact on weeds, whereas more aggressive species, such as ryegrass, have been shown to cause reductions in crop yield (Brainard and Bellinder, 2004).

Mechanical suppression (Biazzo and Masiunas, 2000; Chase and Mbuya, 2008) and time of seeding (Brainard and Bellinder, 2004) have been evaluated as methods of managing living mulch crops to prevent competition. Chase and Mbuya (2008) found mowing to be an ineffective means of management for grasses. Further, delayed planting may not provide successful results if mulch crops have not established during the critical weed-free period (Brainard and Bellinder, 2004).

The application of reduced tillage alone may help reduce weed pressure. Soil disturbance can profoundly affect weed emergence. Tillage promotes the germination of seeds in the soil seed bank by exposing them to light, improving soil aeration, and moving seeds to sites that are more favorable for germination (Myers et al., 2005). Tillage also alters the placement of surface crop residues, which shade the soil surface and reduce temperatures, inhibiting weed seed germination (Myers et al., 2005).

Living mulch crops also alter insect populations, and may suppress pests while fostering predators and parasitoids. The presence of a non-marketable crop diversifies the cropping system; agroecosytems simplified by human action, such as monoculture crop stands, exhibit higher vulnerability to invasion and pest outbreak than more complex communities. Living mulches have been demonstrated to reduce damage imposed by herbivores, increasing total marketable yield (Hooks et al., 1998). Lepidopterans, aphids and flea beetles, among the primary pests of broccoli crops, have all been found at lower numbers on broccoli intercropped with a living mulch (Hooks et al., 2007; Hooks et al., 1998; Costello and Altieri, 1995).

In addition to pest and weed control, the use of cover crops and living mulches, in tandem with alterations in tillage regime, may affect natural disease suppression within the soil. With the adoption of reduced tillage, changes to environmental parameters, such as the placement of crop residues and application of nutrients at the soil surface, modify the responses of the microbial community responsible for decomposing organic matter (Bockus and Shroyer, 1998). The incorporation of crop residues through tillage fosters rapid degradation. When left on the soil surface, crop residues decompose more slowly, promoting the survival of pathogens (Bockus and Shroyer, 1998). Increased levels of crop residues, decreased soil temperatures and compaction, characteristics frequently found in soils maintained using reduced tillage, are potential constraints to the regulation of plant pathogens by native soil microbiota (Sturtz et al., 1997).

The environmental conditions found under reduced tillage systems, however, do not only promote plant pathogens, and colonization is not by deleterious microorganisms alone. Reduced tillage systems utilizing organic amendments and mulches may have an increased propensity towards disease suppression as a result of increased microbial activity, resulting in competition. Root zone microflora can stimulate plant growth, improve stress tolerance, induce disease resistance in plants and/or suppress disease development (Sturtz et al., 1997). Thus, a balanced, competitive soil microbial environment colonized by a community of disease antagonists appears to be a key factor affecting disease prevalence.

Strip tillage can provide enhancements in soil quality that are beneficial to organic crop production; however, the application of reduced tillage practices in organic systems provides challenges with weed management. The addition of living mulches is a viable method for weed suppression, with the additional benefit of reducing pest populations and pathogen prevalence. The objective of this study was to determine the effects of reduced tillage, overwintered cover crops and spring-seeded living mulches on weed communities, beneficial and pest insect density and disease incidence and severity in an organic, spring broccoli cropping system.

Materials and Methods

The trial was conducted on a Dewey Silt Loam at the East Tennessee Research and Education Center Organic Crops Unit, in Knoxville, TN, on 0.07 ha (0.18 A.) of land. Two treatments were assessed within the experiment. The tillage treatment was comprised of tilled and strip tilled plots; tillage occurred only once prior to transplanting broccoli as a method of establishing the research plot. Additionally, two living mulches, red clover (*Trifolium pratense* cv. Cinnamon Plus) and annual ryegrass (*Lolium multiflorum* cv. Marshall), were assessed relative to a no-mulch control. A bi-culture of triticale (*x. Triticosecale* spp.), sown at 90 kg/ha (80 lbs./A.), and Austrian winter pea (*Pisum sativum)*, sown at 90 kg/ha (80 lbs./A.), was seeded on 5 Nov. 2008 for the 2009 growing season. A bi-culture of crimson clover (*Trifolium incarnatum*), sown at 28 kg/ha (25 lbs./A.), and winter oats (*Avena sativa)*, sown at 123 kg/ha (110 lbs./A.), was seeded on 20 Sept. 2009 for the 2010 growing season. Cover crops were drilled both years.

In 2009, the research trial was established on a tract of land previously planted to an assortment of vegetable crops. The trial was moved to a different tract of land for the 2010 season, previously planted in cucurbits (summer squash, watermelon and pumpkin). In the spring prior to tillage, the field was flail mowed to a height of 5 cm (2 in.). Tilled plots were established to a depth of 15 cm (6 in.) using a rototiller. Strip tilled plots were established using a Maschio Multivator (Maschio Group, Eldridge, Iowa) leaving a 15 cm (6 in.) strip tilled to a depth of 15 cm. In 2009, broccoli (*Brassica oleracea* cv. Belstar F1) was transplanted on 13 Apr.; in 2010, broccoli was transplanted on 7 Apr. Plants were set 45 cm (18 in.) apart within rows and 91 cm (36 in.) between rows, with four rows per experimental treatment. Each treatment plot was 3.6 m x 3.6 m (12 ft. x 12 ft.). In 2009, four replicates were sampled. In 2010, three replicates were sampled; pressure from *Rhizoctonia spp*. greatly reduced the number of transplants within the fourth replicate, which was discarded from the study.

In 2009, living mulches of annual ryegrass and red clover were broadcast two days after transplanting (DAT) broccoli, on 15 Apr. In 2010, the living mulch seed in the tilled plots was broadcast 5 DAT, on 12 Apr. Strip tilled plots had two living mulch planting dates: 1) one month prior to broccoli transplanting on 8 Mar. 2010 and; 2) 5 DAT on 12 Apr. 2010. In both years, annual ryegrass was sown at a rate of 33 kg/ha (30 lbs./A.) and red clover was sown at a rate of 11 kg/ha (10 lbs./A.).

Mulch crops were mowed to a height of 7 cm (3 in.) as they reached the broccoli canopy. In 2009, living mulch plots were mowed once (9 June); in 2010, the plots were mowed three times (19 Apr., 6 May and 2 June). In both years, all plots were spot-hoed weekly to manage weeds. In tilled and strip tilled plots, all observed weeds in the planting row and between rows were removed. In 2009, Pyganic Crop Protection EC 1.4II (a.i. pyrethrins), applied at a rate of 2.35L/ha (2 pt./A.), was utilized for control of flea beetle in tilled plots on 11 May and strip tilled plots on 26 May. Before application in the tilled treatment, flea beetle counts reached 390 individuals per plot, approximately 49 individuals per plant. On the 11 May sampling date, the highest flea beetle count in strip tilled plots was 8 individuals per plot; on 26 May, flea beetle counts in strip tilled plots reached 450 individuals per plot, approximately 56 individuals per plant. In 2010, Dipel DF (a.i. *Bacillus thuringiensis*, subsp. Kurstaki), applied at a rate of 0.31 ml/L (0.04 oz./gal.) was utilized on 3 June for control of imported cabbageworm. Cabbageworm counts ranged from 60 – 230 individuals per plot (7.5 – 28.8 individuals per plant) with the highest counts obvserved in tilled treatments. A floating row cover (Agribon AG-19, 0.55oz./sq. ft.) was utilized for insect management in both years; in 2009, it was installed after treatment with Pyganic, and in 2010 it was installed as transplants were set.

A drip irrigation system was established to provide supplemental water when soil moisture readings, measured with Watermark soil moisture sensors (Irrometer 200SS; Riverside, CA, US), rose above 30 cb, indicating limited availability of plant-accessible water. In both years, all treatment combinations received equivalent amounts of supplemental water on all irrigation events. Monthly rainfall and temperature averages are reported in Table D.1.

Weed pressure was evaluated as the number of weed stems present per species within a random quarter-meter squared area. Three random quarter-meter squared samples were assessed per treatment combination. Plots were sampled weekly from 5 May to 29 June in 2009, and 12 Apr. to 11 June in 2010. All plots were hoed following sampling to ensure only new weed stems were counted. Relative abundance values for each species were calculated at each sampling date in each treatment to determine differences in species composition between treatments. In addition, a total relative abundance value for each species was calculated on each sampling date across all treatments to determine which species were the most prevalent. Relative abundance provides a value of a species abundance, or presence, relative to all other species occurring within a defined area. This value can be utilized as a rank, to determine the contribution of an individual species to the weed community. Calculations were made as follows:

Relative abundance=
(frequency of a particular species/sum of frequency values for all species)

+

(uniformity of a particular species/sum of uniformity values for all species)

+

(density of a particular species/sum of density values for all species)(Thomas, 1985; Thomas et al., 1994)

Frequency represents the number of plots (treatment combinations) in which a species occurred, expressed as a percentage of the total number of plots sampled. Frequency gives an estimate of the geographic extent of infestation. Uniformity is the number of sampling locations in which a particular species occurred, expressed as a percentage of the total number of samples. Uniformity is used to estimate the area infested. Density is the number of individuals of a given species located within a quarter-meter squared area of land. Density indicates the magnitude of infestation. Frequency, uniformity and density values are expressed as proportions. Relative abundance, calculated as the sum of these three values, has a maximum possible value of 300 (Thomas, 1985; Thomas et al., 1994).

Insect counts were taken on eight randomly selected broccoli plants per plot. The whole plant, including stems and tops and bottoms of leaves, was inspected. All organisms (arthropods and mollusks) present, at all life stages (egg, larva, pupa, adult), on a selected plant were recorded by taxon. Taxa were placed into guilds (herbivore, predator and parasitoid) based on feeding habit. Plots were sampled weekly between 8:00 and 11:00 AM from 5 May to 29 June in 2009, and 12 Apr. to 11 June in 2010. Herbivore, predator and parasitoid density values are reported for each treatment combination as the number of individuals per plant. At each sampling date, density was calculated for each guild by summing counts for the taxa observed, and dividing this value by the number of plants sampled; this calculation provided a density value for each treatment.

In 2009, the predominant disease-causing organisms were *Alternaria* spp., and one assessment was made at the height of disease severity (25 June) during the pre-harvest growth period. Disease severity was assessed based on symptomology; a percentage of chlorotic and necrotic leaf area was estimated within the center two rows (16 plants) of each treatment plot. In 2010, the predominant disease-causing organisms were *Rhizoctonia* spp.; one assessment was made at the height of disease severity (5 May) during the vegetative growth stage. Disease incidence was assessed as the number of dead plants within the center two rows (16 plants) of each treatment plot.

The experimental design was a randomized complete block with a split-plot arrangement of treatments. Tillage treatments (tilled and strip tilled) comprised the main plot. In 2009, the living mulch sub-plot had three levels: red clover, annual ryegrass and no-mulch. In 2010, main and sub-plots remained the same with the addition of an early planting date for living mulch treatments (one month prior to transplant) added to the strip-tilled treatment only.

All data were analyzed by mixed model ANOVA using SAS (SAS 9.1, SAS Institute Inc., Cary, NC). Tillage and living mulch treatments were analyzed as fixed effects; replicate and sampling date were analyzed as random effects. In 2009, fixed effects were analyzed using a factorial design. In 2010, the addition of early sown living mulches within the strip tillage treatment created imbalance in the sub-plot and fixed effects were analyzed using a nested design, providing comparisons between tillage treatments and between living mulch levels within each tillage treatment. A probability level of $P < 0.05$ or below was accepted.

Transformations were required during data analysis. In 2009, a square root transformation was utilized during the analysis of insect density. In 2010, a log transformation was utilized in the analysis of prickly sida uniformity and Pennsylvania smartweed density; a square root transformation was utilized in the analysis of mean total relative abundance. Reported statistical values are based on transformed data, while backtransformed means are presented.

Results

Relative Abundance of Weeds

In 2009, analysis of the relative abundance of weeds across all treatments indicated a significant difference ($P < 0.01$) in species abundance (Table D.2). Sixteen species were observed. The five most prevalent species were: crabgrass (*Digitaria sanguinalis)*, wild pansy (*Viola tricolor)*, henbit (*Lamium amplexicaule)*, carpetweed (*Mollugo verticillata)* and morning glory *(Ipomoea* spp.*)*. Of these five species, crabgrass was the most abundant and morning glory was the least abundant. In 2010, fifteen weed species were observed across all treatments. Analysis of relative abundance indicated a significant difference ($P < 0.01$) in species presence (Table D.2); the five most prevalent species were: crabgrass, wild pansy, Pennsylvania smartweed *(Polyganum pennsylvanicum)* carpetweed and prickly sida (*Sida spinosa*). Of these five species, crabgrass was the most abundant and prickly sida was the least abundant.

Of the five most prevalent species in 2009, only crabgrass showed a significant difference ($P < 0.01$) in relative abundance when analyzed by tillage treatment (Table D.3). Relative abundance of crabgrass was greater in tilled (142.3) compared to strip tilled (55.1) plots (Table D.3). Additionally, significantly greater ($P < 0.01$) values of crabgrass were observed in tilled treatments for frequency, uniformity and density (Table D.3). Though no significant difference in relative abundance was observed for wild pansy in 2009, significantly greater uniformity ($P < 0.01$) and density ($P < 0.05$) values were observed in strip tilled plots (Table D.3). A trend towards greater relative abundance of henbit, carpetweed and morning glory was observed in strip tilled plots.

In 2010, relative abundance of carpetweed was significantly different ($P < 0.05$) between tillage treatments, with greater values found in tilled (22.1) compared to strip tilled (8.5) treatments (Table D.3). Significantly greater frequency values of carpetweed were also observed in tilled plots. Relative abundance of crabgrass in 2010 was significantly different ($P < 0.01$) between tillage treatments. Greater relative abundance values were observed in tilled (193.4) compared to strip tilled (124.8) treatments (Table D.3). Relative abundance was significantly different between tillage ($P < 0.01$) treatments for wild pansy in 2010. Greater relative abundance values were observed in strip tilled plots (94.9), with no observations of wild pansy in tilled plots (Table D.3); greater frequency, uniformity and density values were also observed in strip tilled plots. In 2010, there was a trend towards greater relative abundance of smartweed in strip tilled plots, and prickly sida in tilled plots.

No significant differences in relative abundance were observed among living mulch treatments for the top 5 weed species in 2009 (Table D.4). A trend towards lower relative abundance values was observed in no-mulch treatments for crabgrass; there was a trend for lower relative abundance values of henbit and carpetweed in plots with a living mulch of annual ryegrass. In 2009, differences in frequency (*P* < 0.01), uniformity (*P* < 0.05) and density (*P* < 0.01) of carpetweed were observed among living mulch treatments, with the lowest values in annual ryegrass living mulch treatments (Table D.4). Though no significant difference in relative abundance was observed for wild pansy in 2009, significantly greater (*P* < 0.01) density values were observed in annual ryegrass living mulch plots (Table D.4). Crabgrass density was significantly (*P* < 0.05) greater in ryegrass plots (45.4) versus no-mulch plots (34.0) (Table D.4).

Significant differences in density (*P* < 0.01) and relative abundance (*P* < 0.05) of crabgrass were observed among living mulch treatments in 2010 (Table D.5), with the greatest density and relative abundance values in ryegrass and no-mulch plots within tilled treatments; the lowest density and relative abundance values were observed in early-sown red clover and ryegrass within strip tilled treatments. Relative abundance of wild pansy was significantly different (*P* < 0.05) among living mulch treatments in 2010. The relative abundance of wild pansy in the early-sown red clover (126.3) plots was significantly greater than all other treatments except for early-sown ryegrass; within the strip tilled plot, the lowest values were observed in late-sown red clover (52.6) (Table D.5). Frequency (*P* < 0.01), uniformity (*P* < 0.05) and density (*P* < 0.01) were also significantly greater in early-sown red clover. Relative abundance of prickly sida was significantly different (*P* < 0.05) among living mulch treatments. The highest values were observed in red clover within tilled plots (29.7), and the lowest in early-sown ryegrass plots within strip tilled treatments (3.2), though this was not significantly different from early-sown red clover or the tilled no-mulch treatment (Table D.5). A significant difference (*P* < 0.01) was also observed in the frequency of prickly sida among living mulch treatments in 2010; the greatest values were observed in red clover living mulch treatments within tilled plots. Values in tilled, red clover treatments, however, only differed significantly from tilled plots with no-mulch, and early-sown ryegrass and red clover plots within the strip tilled treatment. The density (*P* < 0.01) of Pennsylvania smartweed was significantly greater in early-sown ryegrass plots within the strip tilled treatment than all other plots, except no-mulch plots within the strip tilled treatment (Table D.5). The relative abundance of Pennsylvania smartweed was greatest (*P* < 0.05) in early-sown ryegrass plots within the strip tilled treatment, though only significantly different from ryegrass plots in the tilled treatment and early-sown ryegrass plots in the strip tilled treatment (Table D.5). Though not significantly different, there was a trend toward lower relative abundance values of carpetweed in no-mulch and living mulches sown at transplant within strip tilled plots, versus tilled and strip tilled plots sown early.

Significant differences in the relative abundance of lesser-abundant species were observed in tillage and living mulch treatments. These data are not reported as total relative abundance values for these species were low.

Herbivore, Predator and Parasitoid Guild Density

In 2009, 12 total arthropod taxa were observed; 7 herbivores, 3 predators and 2 parasitoids (Table D.6). In 2010, 16 total organisms (arthropods and mollusks) were observed; 9 herbivores, 4 predators and 3 parasitoids. In both years, aphid mummies were counted as an indication of parasitoid activity, and were included in parasitoid counts; in 2010, parasitized diamondback moths were also included within parasitoid counts.

Though not significantly different, a trend towards greater herbivore density was observed in tilled plots in 2009 (Table D.7). In 2010, herbivore density was significantly different ($P < 0.05$) between tillage treatments. Lower densities were observed in strip tilled (26.7 individuals/whole plant) compared to tilled (53.5 individuals/whole plant) plots. In both 2009 and 2010, predator and parasitoid densities were low and did not differ between tillage treatments.

In 2009, herbivore density was significantly different ($P < 0.01$) among living mulch treatments (Table D.8). Lower densities were observed in living mulch plots of annual ryegrass (54.7 individuals/whole plant) compared to red clover (125.0 individuals/whole plant) and no-mulch plots (115.9 individuals/whole plant). Predator and parasitoid densities were low and did not differ among living mulch treatments.

In 2010, predator density was significantly different ($P < 0.05$) among living mulch treatments (Table D.9). Predator densities in red clover plots within tilled treatments (4.3 individuals/whole plant) were significantly higher than red clover sown at transplant within strip tilled treatments (1.3 individuals/whole plant) and ryegrass within tilled treatments (1.8 individuals/whole plant) (Table D.9). A trend towards lower herbivore density was observed in no-mulch treatments in 2010; the lowest value observed was in no-mulch plots within the strip tilled treatment (18.4 individuals/whole plant). A trend towards greater parasitoid density in red clover plots was also observed, with the highest values occurring in red clover sown at transplant within the strip tilled treatment (7.2 individuals/whole plant).

In 2009, flea beetles were the most prevalent pest organisms. The total count of flea beetles was 4,661 individuals, comprising 73.76% of all organisms observed throughout the duration of the trial (Table D.6). Trends in flea beetle densities throughout the broccoli production period mirrored those observed for the herbivore guild in 2009 (Fig. D.1).

In 2010, imported cabbageworm was the most prevalent pest species. The total count of cabbageworm was 1,755 individuals, comprising 54.26% of all organisms observed throughout the duration of the trial (Table D.6). Trends in imported cabbage worm densities throughout the broccoli production period mirrored those observed for the herbivore guild in 2010 (Fig. D.2).

Observation of guild densities throughout the sampling period from 5 May to 29 June in 2009, and 12 Apr. to 11 June in 2010 indicated fluctuations in insect populations at the time of pesticide application and mowing. There was a trend towards decreases in population densities after pesticide application, while densities increased following mowing events. These trends were observed for each insect guild regardless of treatment (Figs. D.1 – D.6)

Disease Incidence and Severity

In 2009, broccoli became severely infected with *Alternaria* spp. Disease severity was assessed at the height of infection (25 June) during the pre-harvest growth stage as the percentage of leaf area within the center two rows (16 plants) showing chlorotic and necrotic symptomology. Disease severity was significantly different ($P < 0.01$) between tilled (44%) and strip tilled (6.6%) treatments (data not shown).

In 2010, infection by *Rhizoctonia* spp. caused death of infected transplants. Disease incidence was assessed at the height of infection (5 May) as the number of dead plants within the center two rows (16 plants). Disease incidence was significantly different ($P < 0.05$) among tillage treatments only. The highest incidence was observed in strip tilled plots (5.6%) with less than 1% observed in tilled plots (data not shown).

Discussion

In the 2009 season, poor cover crop establishment in early spring resulted in a lack of difference in ground coverage between tillage treatments (data not shown); strip tillage treatments provided no greater ground coverage than tilled treatments. In the 2010 season, spring-seeded living mulch crops were unable to compete with weed emergence. Significant pressure from crabgrass in the tilled treatment required management as living mulches began to germinate, negatively impacting living mulch establishment. Insufficient ground coverage from fall-seeded cover crops in 2009 and poor establishment of spring-seeded living mulches in 2010 may have affected insect, weed and disease populations and distribution.

Insect pest densities may have been impacted by the time of day in which they were sampled. Sampling occurred between 8:00 and 11:00 AM. Pest organism sampling was conducted before other weekly sampling tasks to ensure that activity within the research plot did not disturb or alter pest presence and location. However, the internal temperature of insects varies with the ambient environmental temperature. Higher temperatures cause a direct metabolic effect, resulting in greater and faster locomotion (Abdullah, 1961). Thus, greater pest organism densities may have been observed at later sampling times as temperatures warmed, and observations at early sampling dates may not account for movement into the research plot as insect activity increased.

Relative Abundance of Weeds

Relative abundance provides a value for the presence of one species relative to all other species occurring within a defined area; this value is based on the density and spatial distribution of each species within the area. Relative abundance can therefore be used as a rank to determine the contribution of an individual species to the weed community (Thomas, 1985; Thomas et al., 1994). In the 2009 season, reduced tillage, and red clover and annual ryegrass living mulches were unable to provide greater weed suppression than the tilled, no-mulch control for four of the top five weed species observed.

In 2009 and 2010, relative abundance values of crabgrass were significantly greater in tilled treatments, indicating that reduced tillage may provide a successful method of significantly reducing pressure from this species. This observation counters results by Treadwell et al. (2007) which demonstrated greater pressure from grass species in reduced tilled compared to conventionally tilled plots. Greater frequency, uniformity and density values of crabgrass in tilled treatments (2009 and 2010) also suggest that this species is more likely to emerge in disturbed soil. As crabgrass was the most abundant weed species observed in both years, it is likely that living mulch crops in tilled treatments were unable to compete. Pressure from crabgrass early in the 2010 growing season, as living mulches were germinating, required mechanical management that negatively impacted mulch stand. Infante and Morse (1996) observed that overseeded living mulches may only provide adequate weed suppression when weed pressure is low; under heavy weed growth, living mulches may have no significant impact on reducing weed biomass. These results are supported by the present study.

Wild pansy was the only species in both years observed to have significantly greater relative abundance values in strip tilled plots. The highest frequency, uniformity and density values of wild pansy among living mulch treatments occurred in early-sown red clover within the strip tilled treatment (2010). Within strip tilled plots, red clover sown at transplant provided the greatest suppression of wild pansy. Total ground coverage by cover crops and living mulches was significantly greater in red clover plots sown at transplant (73.3%) compared to red clover sown one month prior to transplant (61.6%). However, it does not appear this difference in total ground coverage was due to red clover. While there was a trend for greater ground coverage from red clover sown at transplant (5%) compared to one month prior to transplanting broccoli (1.6%), no significant difference in ground coverage by red clover was observed between sowing dates (data not shown).

Wild pansy is a cool season annual that overwinters in the cover crop. As an established, mature plant, it is likely that wild pansy had a competitive advantage over spring-sown living mulch crops. While able to suppress the emergence of warm-season weeds, strip tillage may promote the survival of cool season weeds as these plants are left undisturbed in the untilled area between rows. With decreased populations of newly emerging weeds in strip tilled treatments, it is likely that soil disturbance created an environment favorable for the germination of weed seeds in tilled treatments while strip tilled treatments did not. Tillage regime has been demonstrated to influence weed species composition within the cropping area (Myers et al., 2005).

Based on the results from this study, the greatest benefits for reduced tillage may be seen in areas with high populations of crabgrass. Strip tillage reduced the emergence of warm-season species in spring, but may promote the survival of cool-season weeds that are left undisturbed. Weed suppression by living mulch treatments appears to be variable, depending upon the mulch and weed species.

Herbivore, Predator and Parasitoid Guild Density

In 2009, herbivore density was lower in annual ryegrass living mulch plots compared to red clover and no-mulch plots; in 2010, herbivore density was lower in strip tilled plots. Results suggest that the application of strip tillage and a living mulch of annual ryegrass may decrease the prevalence of crop pests, decreasing feeding damage. In 2010, the greatest density of predators was observed in red clover plots within the tilled treatment; however, results are conflicting as red clover (sown at transplant) within the strip tilled treatment contained the lowest density of predators. No differences were observed for parasitoids in tillage or living mulch treatments either year; low parasitoid density values may explain this lack of difference. Nonetheless, though not significant, lower numbers of herbivores were observed as the numbers of parasitoids (2009 and 2010) and predators (2009) increased in tillage treatments.

The results of the present study support data presented by previous research, indicating that interplanted cover crops and living mulches decrease the numbers of pest organisms (Costello and Altieri, 1995; Hooks et al., 1998, Hooks et al., 2007). "Certain insect pests associated with *Brassica* crops (e.g. flea beetles, aphids, and cabbage root flies) are consistently found at lower densities on *Brassica* plants in the presence of non-host vegetation (Hooks and Johnson, 2006)."

Predator and parasitoid densities may have been decreased on host vegetation as a result of increased complexity in plant structure. Vegetative diversity, though beneficial in decreasing pest populations, may present challenges that deter beneficial organisms. The interconnection of plant surface areas (of the vegetable crop, cover crop and living mulch) may interfere with the ability of these organisms to find their hosts due to the masking of chemical cues or the inability to recognize host plant vegetation. Random searching can cause predators and parasitoids to spend more time on vegetation that does not harbor a host and less time on the vegetable crop where the pest organisms are located (Costello and Altieri, 1995).

Changes in insect densities were often linked with management practices. Timelines of insect densities throughout the growing season show a trend towards increased densities after mowing, while the application of insecticide decreased population densities (Figs. D.1 – D.6) regardless of treatment or insect guild. These trends suggest that herbivorous insect densities may be reduced when living mulch crops are taller, as mowing tended to increase insect density. However, taller mulch crops may also result in reductions to predatory and parasitic organisms, suggesting that interseeded crops may inhibit the ability of both pest and beneficial organisms to locate the vegetable crop.

Disease Incidence and Severity

In 2009, greater leaf area in tilled plots showed symptoms of infection by *Alternaria* spp. when assessed at the height of severity (25 June). Rainfall was abundant in spring (Table D.1), and pathogens may have been spread by raindrop splash. Loose soil is vulnerable to detachment by falling raindrops (Hartwig and Ammon, 2002), and could transport inoculum to neighboring plants. A second plausible mechanism of spread is the movement of water and condensation along the floating row cover utilized for insect management.

In 2010, the greatest number of dead plants, infected with *Rhizoctonia* spp., were observed in strip tilled plots when disease incidence was assessed at the height of infection (5 May). Plant disease in humid climates has been a major impediment to the adaptation of conservation tillage programs due to continuous moist soil conditions, changes in crop reside management, and the interaction of pathogens with soil. The cooler, wetter conditions found in reduced tillage soils may favor survival of soilborne pathogens, such as *Rhizoctonia* spp. In compacted soils, pathogens remain closer to the soil surface, and crop residues provide protection from microbial degredation in addition to furnishing a food source that promotes pathogen survival between crops (Bockus and Shroyer, 1998). Additionally, a cool, moist soil environment and compacted soil may hinder growth and increase plant stress, providing a more host that is more vulnerable to pathogen attack (Bockus and Shroyer, 1998; Sturtz et al., 1997). However, as *Rhizoctonia* spp. typically start in the greenhouse, it is also possible that an infected flat could have been planted solely in the strip tilled plot.

Conclusions

Greater frequency, uniformity, density and relative abundance values of crabgrass were observed in tilled treatments; greater values of wild pansy were observed in strip tilled treatments. It appears that tillage provided a successful means of killing cool-season weed species, but disturbed soil is more hospitable to weed emergence in the spring and may create greater weed pressure. While undisturbed soil suppressed newly emerging weeds, cool-season weeds that overwintered within the cover crop were left unmanaged. Thus, strip tillage may be the most beneficial in areas where the weed population is predominantly composed of crabgrass or other monocot species.

Lower frequency, uniformity, and density values of carpetweed (2009) and prickly sida (2010) were observed in annual ryegrass living mulch treatments. Lower relative abundance values were also observed for prickly sida. Ryegrass was able to suppress two of the top weed species observed, indicating that it may have successful application as a living mulch. However, decreases in abundance were dependent upon weed community composition, and overall suppression may be variable.

Observations also demonstrate that living mulch crops may not establish quickly enough to prevent weed emergence when pressure is high. The combination of weed pressure and the required management tactics may negatively impact living mulch establishment, decreasing overall mulch stand. The time of living mulch planting may be important in determining mulch establishment. In 2009, adequate coverage was provided by living mulches when sown two days after broccoli was transplanted; however, in 2010, living mulches sown five days after planting were unable to compete with weed seedlings, and establishment was severely impeded due to competition and mechanical weed management.

Results suggest that the suppression of weeds by living mulches is dependent upon both the living mulch and weed species, accounting for variability in previous research. Further studies trialing various living mulch species under different levels of weed pressure and species composition could allow for the successful pairing of a living mulch crop to the weed population.

Herbivorous pest density was significantly reduced by strip tillage and an annual ryegrass living mulch. Predator density was variably impacted by a red clover living mulch in 2009; the highest predator density was observed in red clover plots within the tilled treatment, with lowest in red clover plots within the strip treatment. Strip tillage and interplanted cover crops and living mulches therefore appear to decrease pest pressure, but may not increase beneficial insect populations. Additionally, observation of pest density throughout the growing season suggests that beneficial and pest insect densities may be reduced when living mulch crops are taller, as mowing tended to increase insect density.

The investigation of arthropod presence on interplanted cover crops and living mulches would enhance future research by providing an estimation of populations and their location within the plot on the cash crop or interplanted species. Previous research has demonstrated that beneficial organisms are increased with the inclusion of a living mulch; however, in the present study, predator and parasitoid densities were not significantly increased due to living mulch treatments. If the density of beneficial organisms observed on the vegetable crop is reduced, resulting from the decreased ability of predators and parasitoids to find host vegetation, greater densities may be expected on intercropped species relative to host vegetation.

Greater disease severity, caused by *Alternaria* spp., was observed in tilled treatments in 2009; greater disease incidence, caused by *Rhizoctonia* spp., was observed in strip tilled treatments in 2010. These results indicate that the impact of strip tillage on disease incidence and severity depends upon the infecting pathogen. Differences in treatment effects were observed dependent upon the method by which inoculum is spread. Tilled soil may enable the spread of disease inoculum as soil particles move in wind and water runoff; however, the cool, moist conditions found in untilled soil may provide a more hospitable environment for soilborne pathogens. Further research focused on the spread of diseases and method of infection, relative to reduced tillage and living mulches, may provide insights into enhanced disease prevention within these systems.

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Appendix D

Table D.1 Mean monthly rainfall and temperature for 2009 and 2010

Year	*Month*	*Mean Temperature (°C)*	*Mean Temperature (°F)*	*Mean Rainfall (cm)*	*Mean Rainfall (in)*
2009	*Mar.*	8.16	46.7	7.39	2.91
	Apr.	16.22	61.2	6.04	2.38
	May	20.61	69.1	10.97	4.32
	June	25.38	77.7	4.64	1.83
2010	*Mar.*	10.50	50.9	8.53	3.36
	Apr.	14.38	57.9	7.64	3.01
	May	19.27	66.7	17.19	6.77
	June	23.55	74.4	10.51	4.14
	July	22.83	73.1	19.58	7.71

Mean monthly rainfall and temperature during the early-season broccoli production period in 2009 and 2010 at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN.

Table D.2 Total relative abundance of all weed species observed in 2009 and 2010

	Mean Total Relative Abundance	
Weeds Observed	*2009*	*2010*
Carpetweed (*Mollugo verticillata*)	22.4 bc	3.1 cde
Clover (*Trifolium* spp.)	2.4 ef	_____
Common bermuda grass (*Cynodon dactylon*)	17.6 bcde	0.4 ef
Common dandelion (*Taraxacum officinale*)	6.4 cdef	4.6 cd
Corn speedwell (*Veronica arvensis*)	_____	0.4 ef
Crabgrass (*Digitaria sanguinalis*)	96.0 a	70.0 a
Henbit (*Lamium amplexicaule*)	21.8 bc	0.9 def
Morning glory (*Ipomoea* spp.)	19.3 bcd	0.1 f
Pennsylvania smartweed (*Polyganum pennsylvanicum*)	6.9 cdef	7.3 cd
Pigweed (*Amaranthus* spp.)	_____	0.2 f
Prickly sida (*Sida spinosa*)	3.1 def	15.6 cd
Prostrate knotweed (*Polyganum arenastrum*)	16.6 bcdef	0.1 f
Prostrate spurge (*Euphorbia maculata*)	13.1 cdef	1.1 cdef
Purslane (*Portulaca oleracea)*	10.9 cdef	0.2 f
Sunflower (*Helianthus annus*)	14.7 cdef	_____
Vetch (*Vicia* spp.)	0.6 f	_____
Wild pansy (*Viola tricolor*)	32.3 b	56.3 ab
Yellow wood sorrel (*Oxalis stricta*)	14.5 cdef	0.5 ef

Mean total relative abundance across tillage and living mulch treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. In 2009, sampling occurred between 5 May and 29 June; in 2010, sampling occurred between 12 Apr. and 11 June. Letters represent a significant difference by LSD mean separation between weed spp. within each year. In 2009, mean total relative abundance $P < 0.01$, F=14.35, LSD mean=16.47, N=3. In 2010, mean total relative abundance $P < 0.01$, F=6.98, LSD mean=1.98, N=3. A square root transformation was utilized during analysis in 2010. Statistical values are based on transformed data while backtransformed means are reported.

Table D.3 Frequency, uniformity, density and relative abundance of the top five weed species in 2009 and 2010 between tillage treatments

	2009				2010			
Species	*Frequency (%)*	*Uniformity (%)*	*Density (%)*	*Relative Abundance*	*Frequency (%)*	*Uniformity (%)*	*Density (%)*	*Relative Abundance*
Carpetweed								
Tilled	5.8	4.5	3.7	16.0	11.5 a*	7.0	3.5	22.1 a*
Strip tilled	8.2	9.8	9.4	24.8	4.0 b	2.7	1.7	8.5 b
F	*0.7*	*2.8*	*3.0*	*2.2*	*9.5*	*4.4*	*1.3*	*6.2*
LSD mean	*6.6*	*7.3*	*7.7*	*14.8*	*6.6*	*4.7*	*3.2*	*12.5*
Crabgrass								
Tilled	38.2 a**	46.1 a**	61.4 a**	142.3 a**	49.9 a**	63.7 a**	80.3 a**	193.4 a**
Strip tilled	20.3 b	16.9 b	17.0 b	55.1 b	29.9 b	34.5 b	60.5 b	124.8 b
F	*10.0*	*48.0*	*50.0*	*27.1*	*12.5*	*23.5*	*14.9*	*18.6*
LSD mean	*12.0*	*9.0*	*13.4*	*36.0*	*11.4*	*13.8*	*11.3*	*37.1*
Henbit								
Tilled	6.4	7.5	2.2	15.8	_____	_____	_____	_____
Strip tilled	9.9	6.7	10.5	28.9	_____	_____	_____	_____
F	*0.2*	*0.0*	*1.1*	*0.4*				
LSD mean	*15.3*	*7.9*	*18.7*	*46.6*				
Morning Glory								
Tilled	3.3	2.3	1.0	7.3	_____	_____	_____	_____
Strip tilled	9.9	13.3	7.8	30.8	_____	_____	_____	_____
F	*3.9*	*3.9*	*5.2*	*3.7*				
LSD mean	*7.7*	*13.12*	*7.0*	*26.0*				
Prickly Sida								
Tilled	_____	_____	_____	_____	10.8	1.3	2.7	22.6
Strip tilled	_____	_____	_____	_____	5.8	0.3	2.0	12.9
F					*3.4*	*48.4*	*0.7*	*3.4*
LSD mean					*6.1*	*1.5*	*1.6*	*11.9*

Table D.3 Frequency, uniformity, density and relative abundance of the top five weed species in 2009 and 2010 between tillage treatments. Continued.

	2009				2010			
Species	*Frequency (%)*	*Uniformity (%)*	*Density (%)*	*Relative Abundance*	*Frequency (%)*	*Uniformity (%)*	*Density (%)*	*Relative Abundance*
Smartweed								
Tilled	_____	_____	_____	_____	4.5	2.5	0.0	7.3
Strip tilled	_____	_____	_____	_____	6.0	3.8	0.2	11.3
F					*0.4*	*0.6*	*7.1*	*1.1*
LSD mean					*6.1*	*3.6*	*0.8*	*8.7*
Wild Pansy								
Tilled	9.2	6.9 b**	4.6 b*	22.8	0.0 b**	0.0 b**	0.0 b**	0.0 b**
Strip tilled	14.1	16.3 a	17.8 a	43.1	32.5 a	37.6 a	24.9 a	94.9 a
F	*2.8*	*12.5*	*11.1*	*3.4*	*55.6*	*2.9*	*17.6*	*42.1*
LSD mean	*6.7*	*6.2*	*9.3*	*26.0*	*9.1*	*11.3*	*12.3*	*30.7*

Frequency, uniformity, density and relative abundance between tillage treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Relative abundance values represent the sum of frequency, uniformity and density, providing an indication of one species' presence relative to all others. In 2009, sampling occurred between 5 May and 29 June; in 2010, sampling occurred between 12 Apr. and 11 June. Letters represent a significant difference by LSD mean separation between weed spp. * $P < 0.05$ ** $P < 0.01$, N=3. In 2010, a log transformation was used during analysis for uniformity of prickly sida and density of Pennsylvania smartweed; statistical values are based on transformed data while backtransformed means are reported.

Table D.4 Frequency, uniformity, density and relative abundance of the top five weed species in 2009 among living mulch treatments

Frequency, uniformity, density and relative abundance among living mulch treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Relative abundance values represent the sum of frequency, uniformity and density, providing an indication of one species' presence relative to all others. Annual ryegrass was sown at a rate of 33 kg/ha, red clover was sown at a rate of 11 kg/ha. In 2009, sampling occurred between 5 May and 29 June. Letters represent a significant difference by LSD mean separation among living mulch treatments within weed spp. * $P < 0.05$ ** $P < 0.01$, N=3.

Table D.4 Frequency, uniformity, density and relative abundance of the top five weed species in 2009 among living mulch treatments. Continued.

Species	*Frequency (%)*	*Uniformity (%)*	*Density (%)*	*Relative Abundance*
Carpetweed				
Red clover	7.3 ab**	11.7 a*	7.1 ab*	22.6
Ryegrass	2.9 b	2.5 b	2.3 b	10.7
No-mulch	10.7 a	11.7 a	10.2 a	27.9
F	*5.6*	*8.0*	*4.0*	*2.9*
LSD mean	*4.5*	*4.6*	*7.7*	*14.5*
Crabgrass				
Red clover	30.7	29.5	38.3 ab*	98.4
Ryegrass	29.9	36.0	45.4 a	108.4
No-mulch	27.0	29.0	34.0 b	89.2
F	*0.4*	*1.9*	*4.2*	*1.6*
LSD mean	*7.9*	*8.2*	*8.0*	*20.7*
Henbit				
Red clover	10.1	10.4	7.0	27.7
Ryegrass	5.4	5.1	3.9	14.1
No-mulch	9.0	5.7	8.1	25.2
F	*0.8*	*1.7*	*1.0*	*1.2*
LSD mean	*8.0*	*6.3*	*6.0*	*19.3*
Morning Glory				
Red clover	5.9	6.7	4.5	17.2
Ryegrass	8.6	7.7	5.1	21.4
No-mulch	5.1	9.1	3.7	18.5
F	*1.0*	*0.4*	*0.1*	*0.2*
LSD mean	*5.2*	*5.0*	*4.9*	*13.7*
Wild pansy				
Red clover	9.4	10.3	10.3 b**	25.3
Ryegrass	15.6	15.5	15.5 a	44.8
No-mulch	10.1	8.9	7.7 b	28.7
F	*2.5*	*2.9*	*5.5*	*3.1*
LSD mean	*6.1*	*5.8*	*4.8*	*17.4*

Table D.5 Frequency, uniformity, density and relative abundance of the top five weed species in 2010 among living mulch treatments

Species	*Frequency (%)*	*Uniformity (%)*	*Density (%)*	*Relative Abundance*
Carpetweed				
Tilled – No-mulch	12.5	7.2	2.2	22.0
Tilled – Red clover	12.3	7.4	4.9	24.6
Tilled – Ryegrass	9.7	6.5	3.3	19.4
Strip – No-mulch	3.3	2.3	1.0	6.7
Strip – Red clover (sown early)	5.9	4.3	3.7	13.9
Strip – Red clover (sown late)	3.1	2.3	1.4	6.9
Strip – Ryegrass (sown early)	4.8	3.0	2.1	9.8
Strip – Ryegrass (sown late)	2.8	1.4	0.9	5.2
F	*0.4*	*0.4*	*0.7*	*0.6*
LSD Mean	*5.6*	*4.8*	*5.1*	*13.2*
Crabgrass				
Tilled – No-mulch	49.5	64.4	82.8 a**	196.7 a*
Tilled – Red clover	43.4	58.0	75.2 ab	176.8 b
Tilled – Ryegrass	56.7	68.5	82.8 a	206.7 a
Strip – No-mulch	26.9	37.2	63.2 bcd	127.5 cd
Strip – Red clover (sown early)	31.4	32.6	50.7 e	114.7 d
Strip – Red clover (sown late)	31.0	36.9	70.9 abc	138.9 bc
Strip – Ryegrass (sown early)	30.9	32.5	62.7 de	118.6 d
Strip – Ryegrass (sown late)	29.5	33.1	54.2 cd	124.4 cd
F	*2.0*	*1.2*	*3.0*	*2.7*
LSD Mean	*12.9*	*12.4*	*15.1*	*30.2*
Pennsylvania Smartweed				
Tilled – No-mulch	6.9	3.9	0.0 d**	11.0 abc*
Tilled – Red clover	5.0	2.9	0.0 d	8.1 abc
Tilled – Ryegrass	1.8	0.7	0.0 d	2.7 bc
Strip – No-mulch	7.5	4.8	0.4 ab	14.0 ab
Strip – Red clover (sown early)	7.0	3.8	0.2 bc	12.0 ab
Strip – Red clover (sown late)	5.0	4.2	0.2 bc	10.1 abc
Strip – Ryegrass (sown early)	9.3	5.1	1.7 a	18.2 a
Strip – Ryegrass (sown late)	1.2	0.9	0.0 d	2.1 c
F	*2.2*	*1.7*	*4.0*	*2.5*
LSD Mean	*5.0*	*4.0*	*1.7*	*10.5*

Table D.5 Frequency, uniformity, density and relative abundance of the top five weed species in 2010 among living mulch treatments. Continued.

Species	*Frequency (%)*	*Uniformity (%)*	*Density (%)*	*Relative Abundance*
Prickly Sida				
Tilled – No-mulch	7.5 bcd**	1.0	1.7	15.6 bcd*
Tilled – Red clover	13.9 a	1.3	4.2	29.7 a
Tilled – Ryegrass	10.9 ab	1.7	2.1	22.5 abc
Strip – No-mulch	8.5 abc	1.1	3.0	20.0 ab
Strip – Red clover (sown early)	3.1 cd	0.2	1.3	7.0 cd
Strip – Red clover (sown late)	8.9 ab	0.9	3.0	19.0 abc
Strip – Ryegrass (sown early)	1.8 d	0.0	0.0	3.2 d
Strip – Ryegrass (sown late)	6.9 abcd	0.5	2.4	15.2 abc
F	*2.6*	*2.8*	*1.5*	*2.5*
LSD Mean	*6.5*	*2.1*	*3.5*	*14.2*
Wild Pansy				
Tilled – No-mulch	0.0 d**	0.0 c*	0.0 c**	0.0 d*
Tilled – Red clover	0.0 d	0.0 c	0.0 c	0.0 d
Tilled – Ryegrass	0.0 d	0.0 c	0.0 c	0.0 d
Strip – No-mulch	33.8 ab	34.5 a	24.2 b	92.6 b
Strip – Red clover (sown early)	42.5 a	47.3 a	36.4 a	126.3 a
Strip – Red clover (sown late)	19.6 c	24.6 c	8.2 c	52.6 c
Strip – Ryegrass (sown early)	34.9 ab	45.1 ab	30.2 ab	109.7 ab
Strip – Ryegrass (sown late)	31.8 ab	36.5 abc	25.0 b	93.4 b
F	*3.8*	*1.5*	*3.9*	*4.9*
LSD Mean	*9.1*	*14.0*	*16.5*	*33.8*

Frequency, uniformity, density and relative abundance among living mulch treatments in 2010 in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Relative abundance values represent the sum of frequency, uniformity and density, providing an indication of one species' presence relative to all others. Living mulches were planted one month prior to transplanting broccoli (sown early) and 5 DAT (sown late). Annual ryegrass was sown at a rate of 33 kg/ha, red clover was sown at a rate of 11 kg/ha. Sampling occurred between 12 Apr. and 11 June. Data were analyzed using a nested design, due to the addition of a second living mulch planting date, and living mulches are reported within tillage treatment. Letters represent a significant difference by LSD mean separation among living mulch treatments within weed spp. * $P < 0.05$ ** $P < 0.01$ N=3. A log transformation was used during analysis of uniformity of prickly sida and density of smartweed. Statistical values are based on transformed data while backtransformed means are reported.

Table D.6 Distribution of organisms into herbivore, predator and parasitoid guilds and total counts in 2009 and 2010

	2009		*2010*	
Organisms by Guild	*Total Count*	*% of Total*	*Total Count*	*% of Total*
Herbivore				
Aphid	53	0.83	641	19.82
Armyworm	______	______	67	2.07
Cabbage looper (*Trichoplusia ni*)	9	0.14	42	1.29
Diamondback moth (*Plutella xylostella*)	294	4.65	111	3.43
Flea beetle	4661	73.76	90	2.78
Harlequin bug (*Murgantia histrionica)*	977	15.46	______	______
Imported cabbageworm (*Pieris rapae*)	54	0.85	1755	54.26
Slug	______	______	1	0.03
Virginian tiger moth (*Spilosoma virginica)*	______	______	39	1.20
Whitefly	4	0.06	6	0.18
Predator				
Lacewing	9	0.14	9	0.27
Lady beetle	139	2.19	116	3.58
Spider	65	1.02	73	2.25
Stink bug	______	______	13	0.40
Parasitoids				
Aphid mummy	50	0.79	230	7.11
Braconid wasp	4	0.06	3	0.09
Parasitized diamondback moth	______	______	38	1.17

Total counts of the observed herbivore, predator and parasitoid taxa across tillage and living mulch treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. In 2009, sampling occurred between 5 May and 29 June; in 2010, sampling occurred between 12 Apr. and 11 June. Total count represents the total number of individuals observed across tillage and living mulch treatments throughout the duration of the trial. Percentage of total indicates what proportion of the total population each taxon comprised. N=8.

Table D.7 Density of individuals classified by herbivore, predator and parasitoid guilds between tillage treatments in 2009 and 2010

	Density (No./whole plant)	
Guild	*2009*	*2010*
Herbivore		
Tilled	132.7	53.5 a*
Strip tilled	64.7	26.7 b
F	*2.0*	*8.8*
LSD mean	*5.2*	*20.8*
Predator		
Tilled	1.8	3.2
Strip tilled	2.9	2.7
F	*1.3*	*7.9*
LSD mean	*0.5*	*2.0*
Parasitoid		
Tilled	0.0	1.6
Strip tilled	0.0	4.2
F	*0.4*	*3.8*
LSD mean	*0.2*	*3.0*

Density of individuals classified by herbivore, predator and parasitoid guilds between tillage treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. In 2009, sampling occurred between 5 May and 29 June; in 2010, sampling occurred between 12 Apr. and 11 June. Density is reported as individuals per plant. Letters represent a significant difference by LSD mean separation between tillage treatments within each guild and year. ** $P < 0.01$, N=8. In 2009, a square root transformation was utilized during data analysis; statistical values are based on transformed data while backtransformed means are reported.

Table D.8 Density of individuals classified by herbivore, predator and parasitoid guilds among living mulch treatments in 2009

Guild	*Density (No./whole plant)*	
Herbivore		
Red clover	125.0	a**
Ryegrass	54.7	b
No-mulch	115.9	a
F	*12.6*	
LSD mean	*1.6*	
Predator		
Red clover	2.4	
Ryegrass	2.2	
No-mulch	2.4	
F	*0.0*	
LSD mean	*0.6*	
Parasitoid		
Red clover	0.0	
Ryegrass	0.0	
No-mulch	0.0	
F	*0.1*	
LSD mean	*0.2*	

Density of individuals classified by herbivore, predator and parasitoid guilds among living mulch treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Sampling occurred between 5 May and 29 June. Density is reported as individuals per plant. Letters represent a significant difference by LSD mean separation among living mulch treatments within each guild. ** $P < 0.01$, N=8. A square root transformation was used during data analysis. Statistical values are based on transformed data while backtransformed means are reported.

Table D.9 Density of individuals classified by herbivore, predator and parasitoid guilds among living mulch treatments in 2010

Density of individuals classified by herbivore, predator and parasitoid guilds among living mulch treatments in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Data were analyzed using a nested design, due to the addition of a second living mulch planting date, and living mulches are reported within tillage treatment. Sampling occurred between 12 Apr. and 11 June. Density is reported as individuals per plant. Letters represent a significant difference by LSD mean separation among living mulch treatments within each guild. * $P < 0.05$, N=8.

Table D.9 Density of individuals classified by herbivore, predator and parasitoid guilds among living mulch treatments in 2010. Continued.

Guild	*Density (No./whole plant)*
Herbivore	
Tilled – No-mulch	47.1
Tilled – red clover	60.5
Tilled – ryegrass	52.8
Strip – No-mulch	18.4
Strip – Red clover (sown early)	26.7
Strip – Red clover (sown at transplant)	28.7
Strip – Ryegrass (sown early)	38.2
Strip – Ryegrass (sown at transplant)	21.2
F	*1.1*
LSD mean	*22.4*
Predator	
Tilled – No-mulch	3.5 abc*
Tilled – red clover	4.3 a
Tilled – ryegrass	1.8 bc
Strip – No-mulch	2.7 abc
Strip – Red clover (sown early)	3.5 ab
Strip – Red clover (sown at transplant)	1.3 c
Strip – Ryegrass (sown early)	3.1 abc
Strip – Ryegrass (sown at transplant)	3.1 abc
F	*2.4*
LSD mean	*2.1*
Parasitoid	
Tilled – No-mulch	0.8
Tilled – red clover	3.0
Tilled – ryegrass	1.1
Strip – No-mulch	3.4
Strip – Red clover (sown early)	3.5
Strip – Red clover (sown at transplant)	7.2
Strip – Ryegrass (sown early)	3.3
Strip – Ryegrass (sown at transplant)	3.4
F	*2.1*
LSD mean	*3.4*

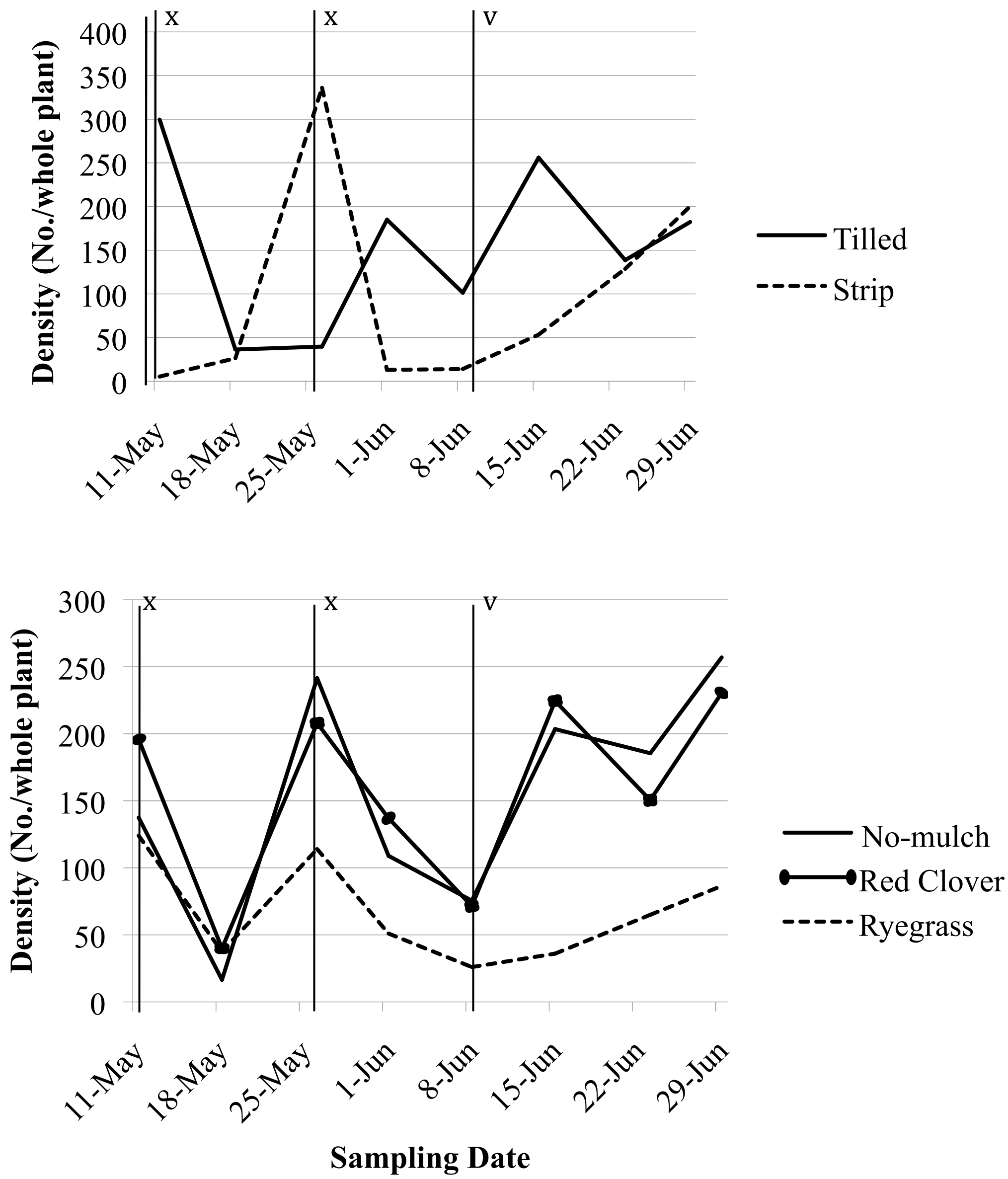

Figure D.1 Mean herbivore density for weekly samplings throughout the broccoli production period within tillage and living mulch treatments in 2009

Herbivore density in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Herbivore density was monitored weekly throughout broccoli production, providing 8 sampling dates between 5 May and 29 June in 2009. Density is reported as individuals per plant. Pyganic Crop Protection EC 1.4II 9 (a.i. pyrethrins) was applied at a rate of 2.34 L/ha (2 pts/A.) in tilled plots on 11 May and strip tilled plots on 26 May. All plots were mowed on 9 June. Vertical lines represent pesticide application (x) and mowing events (v). N=8.

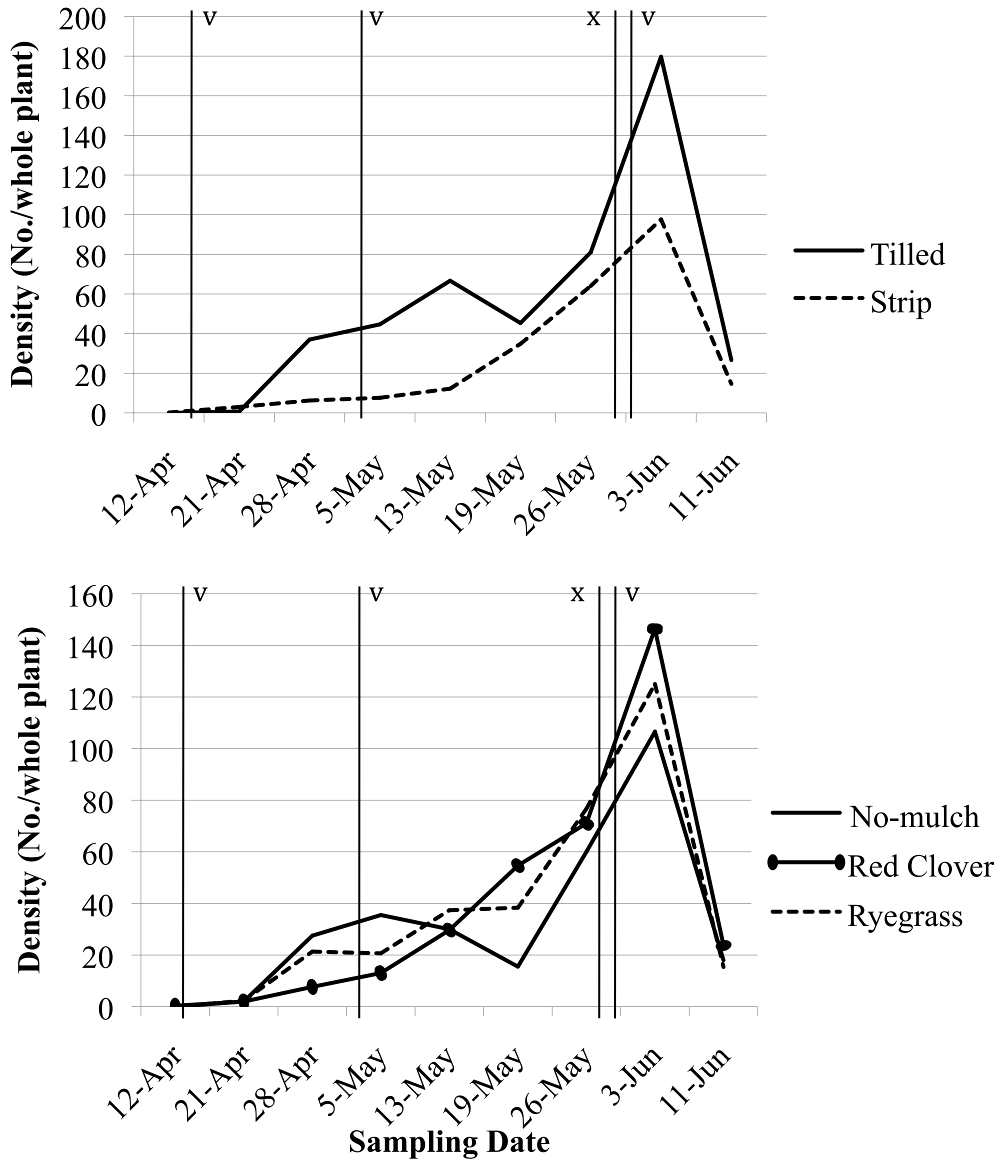

Figure D.2 Mean herbivore density for weekly samplings throughout the broccoli production period within tillage and living mulch treatments in 2010

Herbivore density in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Herbivore density was monitored weekly throughout broccoli production, providing 9 sampling dates between 12 Apr. and 11 June in 2010. Density is reported as individuals per plant. Dipel DF (a.i. *Bacillus thuringiensis* sbusp. kurstaki) was applied at a rate of 0.31 ml/L (0.04 oz./gal.) on 3 June in all plots. All plots were mowed on 19 Apr., 6 May and 2 June. Vertical lines represent pesticide application (x) and mowing events (v). N=8

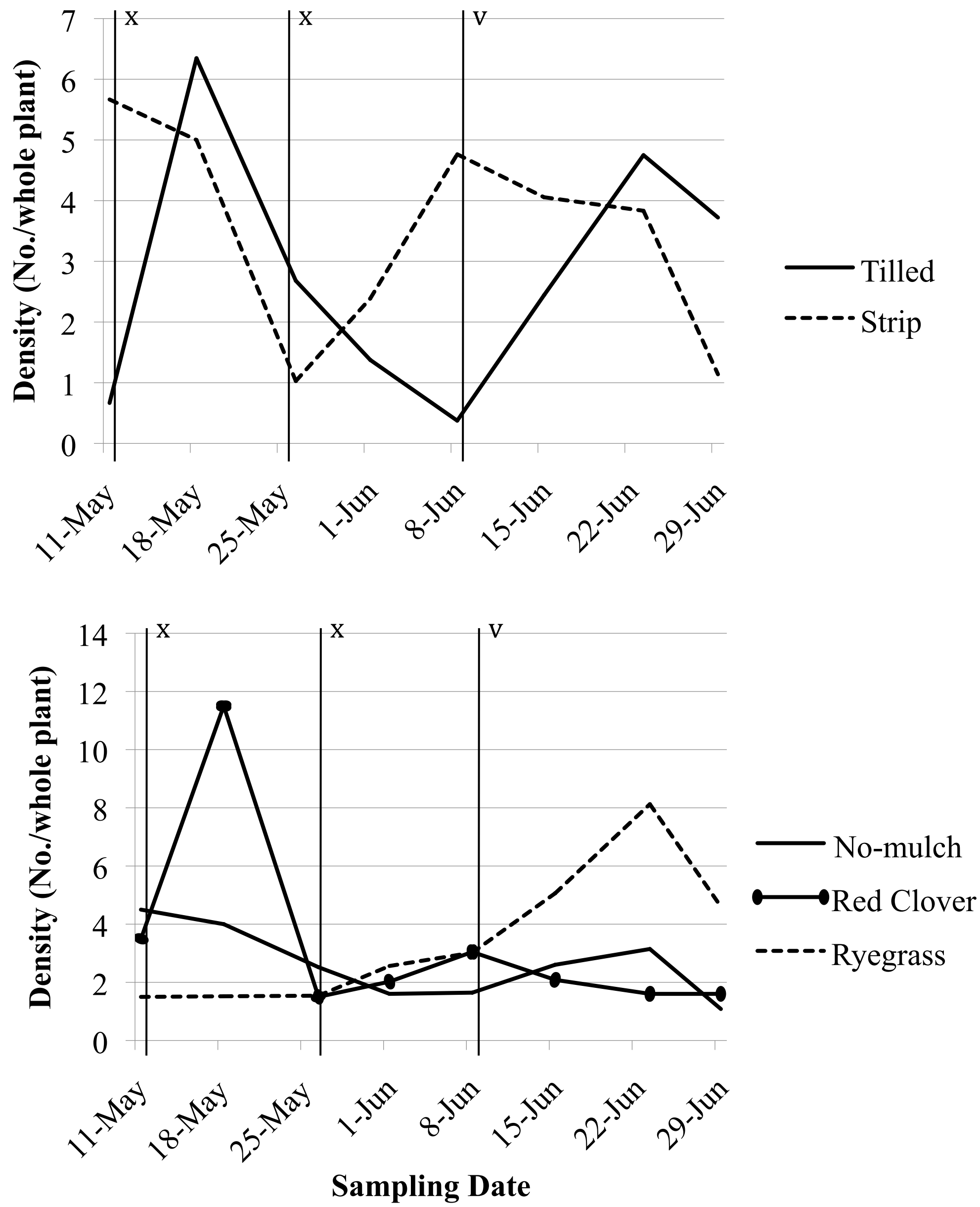

Figure D.3 Mean predator density for weekly samplings throughout the broccoli production period within tillage and living mulch treatments in 2009

Predator density in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Predator density was monitored weekly throughout broccoli production, providing 8 sampling dates between 5 May and 29 June in 2009. Density is reported as individuals per plant. Pyganic Crop Protection EC 1.4II 9 (a.i. pyrethrins) was applied at a rate of 2.34 L/ha (2 pts/A.) in tilled plots on 11 May and strip tilled plots on 26 May. All plots were mowed on 9 June. Vertical lines represent pesticide application (x) and mowing events (v). N=8.

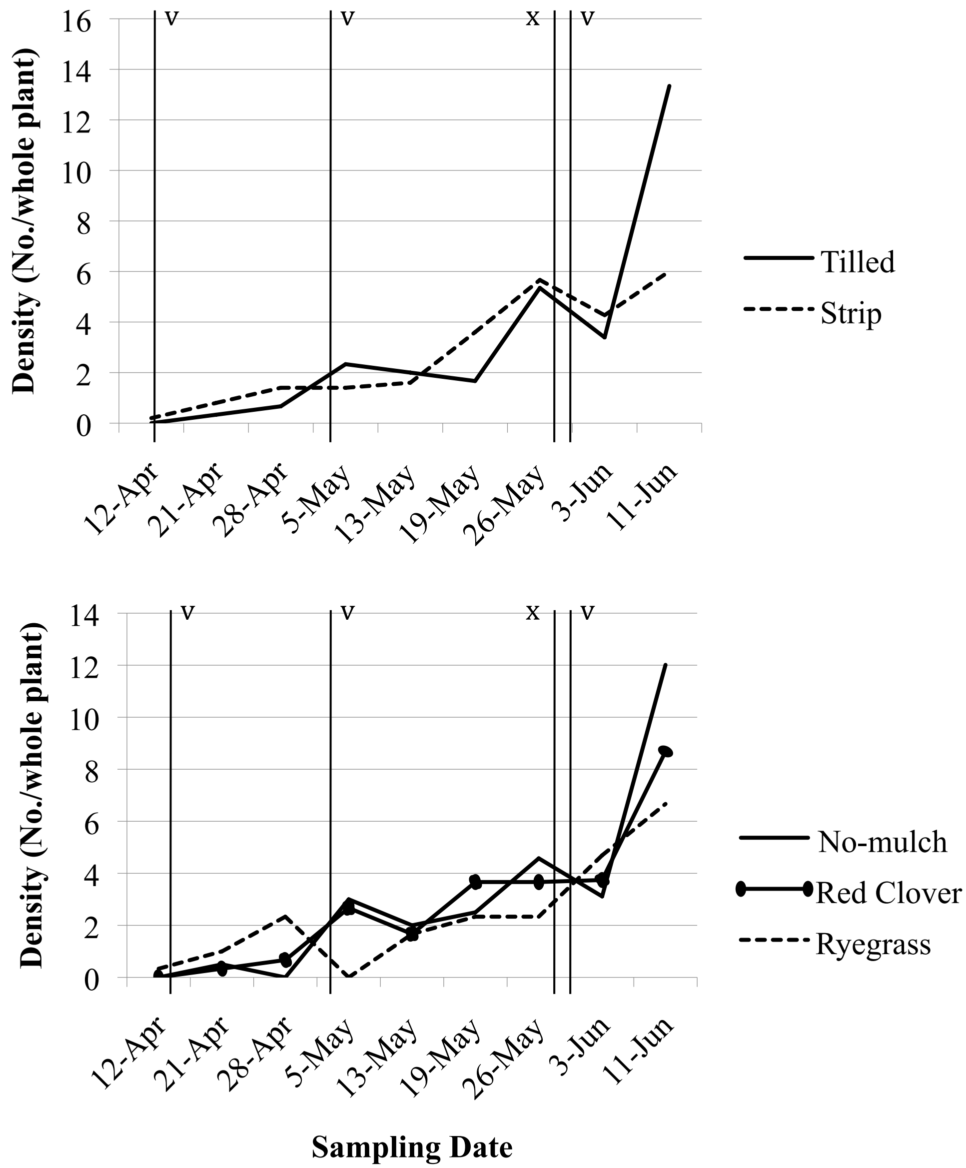

Figure D.4 Mean predator density for weekly samplings throughout the broccoli production period within tillage and living mulch treatments in 2010

Predator density in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Predator density was monitored weekly throughout broccoli production, providing 9 sampling dates between 12 Apr. and 11 June in 2010. Density is reported as individuals per plant. Dipel DF (a.i. *Bacillus thuringiensis* sbusp. kurstaki) was applied at a rate of 0.31 ml/L (0.04 oz./gal.) on 3 June in all plots. All plots were mowed on 19 Apr., 6 May and 2 June. Vertical lines represent pesticide application (x) and mowing events (v). N=8.

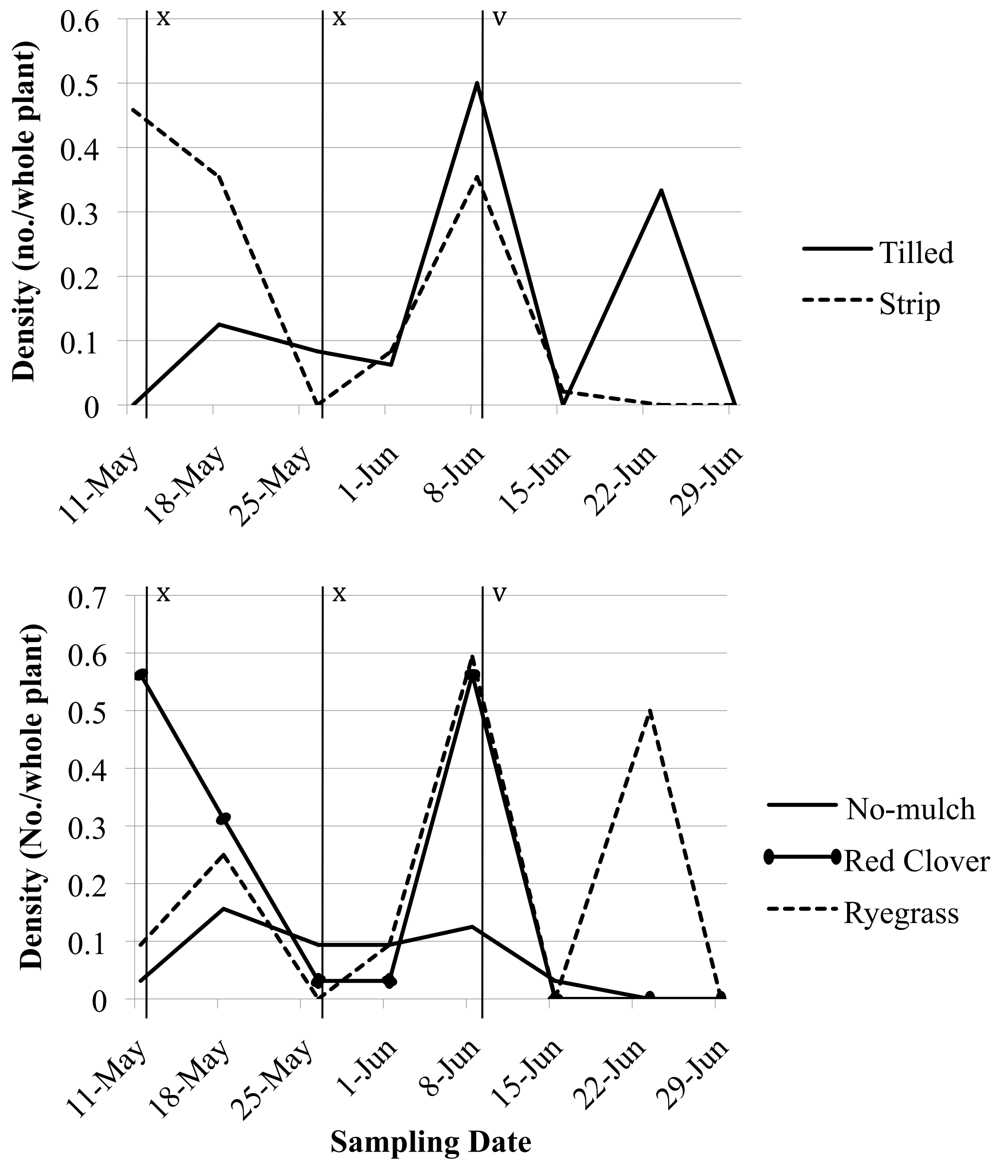

Figure D.5 Mean parasitoid density for weekly samplings throughout the broccoli production period within tillage and living mulch treatments in 2009

Parasitoid density in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Parasitoid density was monitored weekly throughout broccoli production, providing 8 sampling dates between 5 May and 29 June in 2009. Density is reported as individuals per plant. Pyganic Crop Protection EC 1.4II 9 (a.i. pyrethrins) was applied at a rate of 2.34 L/ha (2 pts/A.) in tilled plots on 11 May and strip tilled plots on 26 May. All plots were mowed on 9 June. Vertical lines represent pesticide application (x) and mowing events (v). N=8.

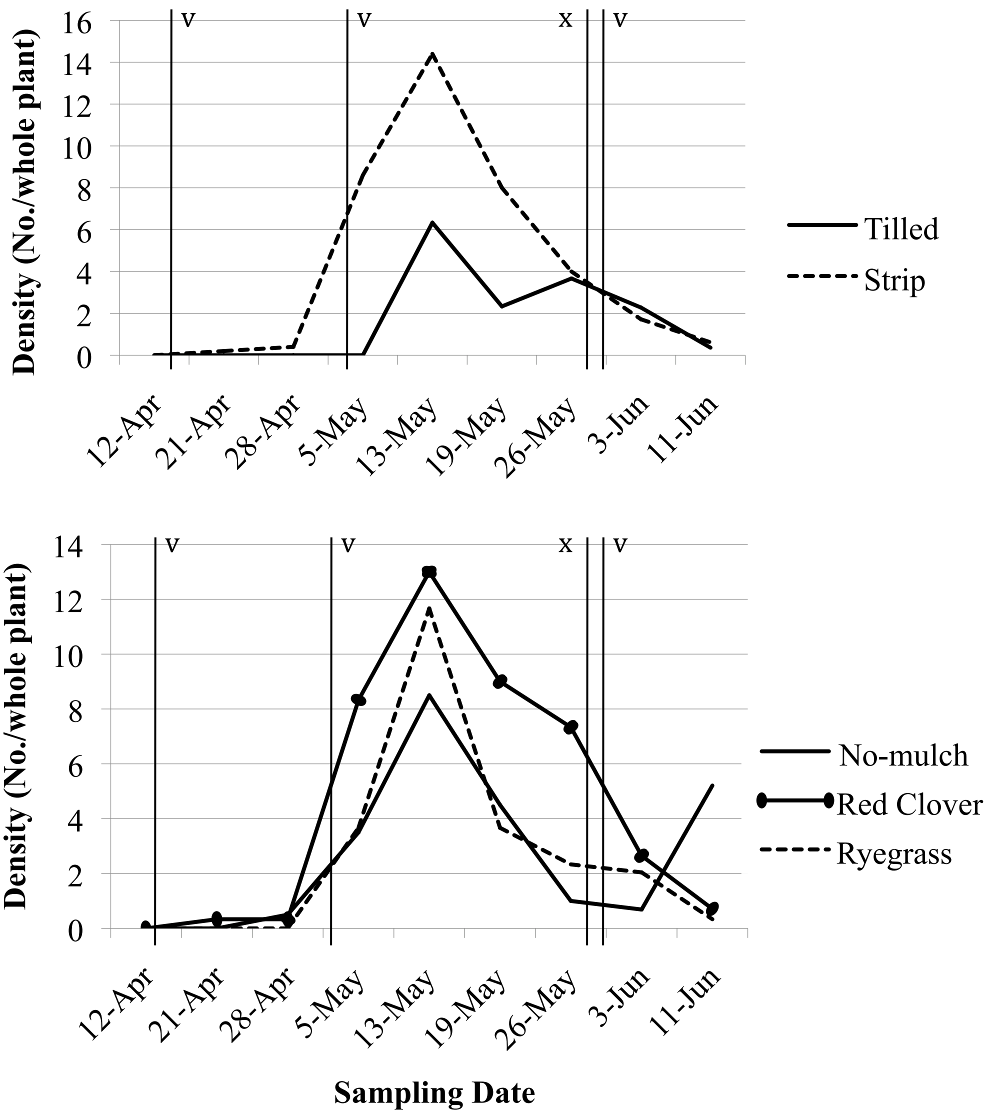

Figure D.6 Mean parasitoid density for weekly samplings throughout the broccoli production period within tillage and living mulch treatments in 2010

Parasitoid density in an organic, broccoli production system at the University of Tennessee, East Tennessee Research and Education Center Organic Crops Unit in Knoxville, TN. Parasitoid density was monitored weekly throughout broccoli production, providing 9 sampling dates between 12 Apr. and 11 June in 2010. Density is reported as individuals per plant. Dipel DF (a.i. *Bacillus thuringiensis* sbusp. kurstaki) was applied at a rate of 0.31 ml/L (0.04 oz./gal.) on 3 June in all plots. All plots were mowed on 19 Apr., 6 May and 2 June. Vertical lines represent pesticide application (x) and mowing events (v). N=8.

Chapter Five: Conclusions

Strip tillage is a method of reduced tillage that is well suited to vegetable crop production; while the planting area is tilled, cover crop residues remain between rows providing weed control and protection from soil erosion (Biazzo and Masiunas, 2000; Wilhoit et al., 1990). Additionally, the utilization of cover crop residues and living mulches enhances soil quality, providing benefits such as reduced rates of erosion, decreased soil temperature fluctuations, increased soil organic matter, improved water infiltration rates, increased microbial activity and improved soil structure (Sullivan, 2004; Wani et al., 1994). Thus, incorporating reduced tillage methods into organic systems can provide more sustainable methods of crop production. The inclusion of living mulches also offers an alternative to chemical weed (DeGregorio and Ashley, 1985, 1986; Ilnicki and Enache, 1992) and insect pest (Costello and Altieri, 1995; Frank and Liburd, 2005; Hooks and Johnson, 2006; Hooks et al., 2007) management that can make the application of reduced tillage programs more feasible in organic systems.

Modifications to production systems, such as the implementation of a reduced tillage program, changes in crop residue management and the addition of living mulches, can have significant impacts on crop growth and pest control in organic cropping systems. The addition of interseeded crops, utilized to increase ground coverage, creates the opportunity for interspecific competition, altering the status of water, nutrients and sunlight available to the cash crop (Muller-Scharer, 1996; Theriault et al., 2009; Wiles et al., 1989). In order to determine the impact of strip tillage, overwintered cover crops and spring-seeded living mulches on organic, spring broccoli production, ground coverage by cover crops and living mulches, crop growth (plant height, stalk diameter and weight of above ground biomass), physiological status (petiole sap nitrate and photosynthetic rate) and pest pressure (weed relative abundance, insect density and disease incidence and severity) were assessed relative to a tilled, no-mulch control in which fall-sown cover crops were utilized as a green manure.

It is important to determine the impact of tillage system and living mulch species on the level of ground coverage within management systems utilizing these techniques as ground coverage effects erosion and weed abundance. In this study, the implementation of strip tillage limited the growth and establishment of living mulch crops. In 2009, poor cover crop (triticale and Austrian winter pea) establishment provided insufficient ground coverage at the beginning of the broccoli production period. Spring-seeded living mulches increased total ground coverage by non-marketable crops. However, greater than thirty percent total ground coverage, which is necessary to reduce erosion, was only achieved in annual ryegrass plots. In 2010, cover crop (crimson clover and winter oat) biomass was greatly increased, providing high levels of ground coverage; however, ground coverage by living mulches was low, suggesting that a dense cover crop may hinder living mulch establishment. It appears that the greatest application of living mulch crops is in boosting total ground coverage when cover crop establishment is poor. When a dense cover crop provides a high level of ground coverage, living mulch crops may be of little benefit. Additionally, annual ryegrass established the quickest and provided greater ground coverage than red clover within strip tilled plots in both years.

In 2010, a second planting date for living mulches was added to the strip tilled plots only. It was hypothesized that warmer temperatures at the time of transplanting broccoli, beyond the suggested period for optimal establishment of the living mulch crops, may result in decreases in biomass and ground coverage of the living mulches. In 2010, annual ryegrass and red clover were sown one month prior to transplanting broccoli and five days after broccoli was transplanted. No differences in planting date were observed for either living mulch species, indicating that earlier seeding of living mulch species, before broccoli transplanting, may not increase ground coverage.

Research has demonstrated that the inclusion of reduced tillage and living mulches can impact the growth and yield of vegetable crops; however, information on the physiological responses of vegetable crops within these systems is lacking. In this study, the implementation of strip tillage and spring-seeded living mulches of annual ryegrass and red clover limited the growth and maturity of organic, spring broccoli. Petiole sap nitrate readings were below critical levels at all sampling dates, indicating that fall-sown bi-cultures of Austrian winter pea and triticale (2009), and crimson clover and winter oat (2010) did not provide a sufficient source of fertility. Data indicate the amount of plant-available nitrogen (N) in strip tilled treatments decreased over time. It is likely this decrease is due to reduced mineralization caused by cover crop residues remaining on the soil surface as opposed to incorporating the residues in the soil through tillage. Additionally, overwintered cover crops may have decreased the pool of plant-available soil N, thus competing with the broccoli crop. Higher photosynthetic rates were observed in strip tilled treatments at the pre-harvest growth stage in 2010. The trends in photosynthetic activity across the broccoli production period in 2010 are contrary to those expected, with decreasing photosynthetic rates in tilled treatments over time. These decreases in photosynthetic activity within tilled treatments may have been the result of insect damage.

Strip tillage (2010) and a living mulch of annual ryegrass (2009) resulted in smaller plants with less aboveground biomass. No yield measurements were taken in either year due to variable head formation. Poor fertility, as indicated by sub-optimal petiole sap nitrate concentrations, due to insufficient N contributions from leguminous cover crops and competition from established cover crops and spring-seeded living mulches for plant-available N, is the most plausible explanation for reductions in crop vigor.

The application of reduced tillage practices in organic systems provides challenges with weed management. The addition of living mulches is a viable method for weed suppression, with the additional benefit of augmenting pest populations and pathogen prevalence. In the current study, greater frequency, uniformity, density and relative abundance of crabgrass were observed in tilled treatments; greater values of wild pansy were observed in strip tilled treatments. It appears that tillage provided a successful means of killing cool-season weed species, but disturbed soil was more hospitable to weed emergence in the spring creating greater weed pressure. While undisturbed soil suppressed newly emerging weeds, cool-season weeds that overwintered within the cover crop were left unmanaged. Thus, strip tillage may be the most beneficial in areas where the weed population is predominantly composed of crabgrass or other monocot species.

A living mulch of annual ryegrass was able to suppress two of the top weed species observed, carpetweed (2009) and prickly sida (2010), indicating that it may have successful application as a living mulch. In both years, however, decreases in abundance were dependent upon weed species; thus overall suppression may be variable.

Observations also demonstrate that living mulch crops may not establish quickly enough to prevent weed emergence in tilled soil when pressure is high. The combination of weed pressure and the required management tactics may negatively impact living mulch emergence, decreasing overall mulch stand.

Herbivorous pest density was significantly reduced by strip tillage and a living mulch of annual ryegrass. Interplanted cover crops and living mulches therefore appear to decrease pest pressure. Additionally, observations of insect density throughout the growing season suggests that beneficial and pest insect densities may be reduced when living mulch crops are taller, as mowing tended to increase overall insect density.

Greater disease severity, caused by *Alternaria* spp., was observed under tilled treatments in 2009; greater disease incidence, caused by *Rhizoctonia* spp., was observed in strip tilled treatments in 2010. The impact of strip tillage on disease incidence and severity appears to depend upon the pathogen and the method by which inoculum is spread.

Based upon the observed results, spring-seeded living mulches appear to be most beneficial when fall-sown cover crops show poor establishment in spring. As observed by Infante and Morse (1996), spring-seeded living mulches can help to maintain the integrity of reduced tillage systems. A spring-seeded living mulch of annual ryegrass shows the most benefit in increasing ground coverage, decreasing weed pressure and increasing herbivorous pest density. However, combined with strip tillage, annual ryegrass caused decreases in broccoli growth, sap nitrate, photosynthesis and yield. Annual ryegrass appears to be too aggressive and competitive for use as a living mulch in organic, spring broccoli production. It may be best fitted for use with a different crop where interspecific competition may be reduced.

The current study has raised several questions for the focus of new research. Ground coverage of thirty percent has been suggested as the amount necessary to slow rates of erosion; further research should be conducted to determine the level of ground coverage necessary for optimal weed control. In order to determine an optimal beneficial level of ground coverage, it is important to understand the impact of varying levels of interseeded living mulch crops on weed management and marketable crop establishment and yield. With an understanding of the recommended species and level of ground coverage necessary to reduce erosion and control weed populations, growers would be better able to make necessary decisions regarding the usage of cover crops and living mulches and more likely benefit from the integration of interseeded crops. Additionally, thresholds will vary among living mulch species; to provide suggestions for successful production systems using interseeded crops, different cover crop and living mulch combinations should be trialed in multiple climate regimes. Different weed management techniques and frequencies should be assessed to determine the effects on cover crop and living mulch biomass and ground coverage in order to properly manage weeds within these systems.

Further research should be conducted to determine which mulch and tillage methods are best suited to organic vegetable production for spring, summer and fall growing periods. Studies focused on cover crop and mulch selection, method of living mulch establishment, time of seeding, and vegetable crop production period should be conducted to determine the best application of strip tillage and living mulches. Additionally, research on the uptake of nutrients by cover and living mulch crops, level of fertility supplied by leguminous and graminaceous cover crops and soil mineralization trends would provide greater insight into the availability of plant-essential nutrients provided by cover crop residues, and their uptake by vegetable, cover and living mulch crops. This information could allow stronger explanations for interspecific competition between living mulch and cash crops, and may provide insight into how this competition can be ameliorated.

Results in the current study suggest that the suppression of weeds by living mulches is dependent upon both the living mulch and weed species, accounting for variability in previous research. Further studies trialing various living mulch species under different levels of weed pressure and species composition could allow for the successful pairing of a living mulch crop to the weed population.

The investigation of arthropod densities on interplanted cover crops and living mulches would enhance future research by providing an estimation of populations and their location on the cash crop or interplanted species. Previous research has demonstrated that beneficial organisms are increased with the inclusion of a living mulch; however, in the present study, predator and parasitoid densities were not significantly increased due to living mulch treatments. If the density of beneficial organisms observed on the vegetable crop is reduced, resulting from the decreased ability of predators and parasitoids to find host vegetation, greater densities may be expected on intercropped species.

Differences in treatment effects on disease incidence and severity were observed dependent upon the method by which inoculum is spread. Tilled soil may enable the spread of pathogens as soil particles move in wind and water runoff; however, the cool, moist conditions found in untilled soil may promote infection by soil borne pathogens. Further research focused on the spread of diseases and method of infection, relative to reduced tillage and living mulches, may provide insights into enhanced disease prevention within these systems.

The application of reduced tillage offers the potential to alleviate excessive tillage commonly found in organic vegetable production systems. In addition to decreasing erosion, reduced tillage can enhance overall crop production. The inclusion of living mulch species in strip tillage appears to provide benefits in weed and insect management, reducing the constraints of reduced tillage programs within organic systems. Further research should be conducted to determine the best pairing of cover crop and living mulch species within these programs to allow for optimum crop performance and yield.

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Vita

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