2013

Conservation Tillage Techniques for Mixed Vegetable Production in Southern New England

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Recommended Citation

Pieper, Jeffrey Ross, "Conservation Tillage Techniques for Mixed Vegetable Production in Southern New England" (2013). *Open Access Master's Theses.* Paper 69.
https://digitalcommons.uri.edu/theses/69

CONSERVATION TILLAGE TECHNIQUES FOR MIXED VEGETABLE PRODUCTION IN SOUTHERN NEW ENGLAND

BY

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
BIOLOGY AND ENVIRONMENTAL SCIENCE

UNIVERSITY OF RHODE ISLAND

2013

MASTER OF SCIENCE THESIS

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2013

ABSTRACT

Vegetable farming is an intensive practice that typically relies on several tillage passes to prepare fields for production. Repeatedly tilling the soil, however, is unsustainable and has been shown to decrease soil structure and organic matter while increasing erosion rates. A 3-year experiment was conducted in a mixed vegetable production system in southern New England to determine how crop yield, weed abundance, and soil health were affected by conservation tillage practices. Three conservation tillage systems were compared to conventional tillage to determine the effects on yields of six vegetable crops, weed abundance, and soil health.

Six 50 m planting beds were created within each treatment with the four middle rows planted to vegetable crops. In every treatment group, six vegetable crops were grown. These included tomato, cabbage, carrot, melon, cucumber, and lettuce. Two of the four rows were planted with the tomato and cabbage crops while melon / cucumbers, and lettuce / carrots were planted together in the remaining rows. Drip tape, with 30 cm emitter spacing, was used to irrigate to each crop in each treatment at a rate of 2.54 cm per week. All vegetables received one line of drip tape except the carrot / lettuce row, in which two lines were used. Crops were fertilized at recommended rates using organic fertilizers applied at planting and through fertigation.

To determine the conservation tillage treatments effects on yield, marketable yields were harvested throughout the season. Marketable yield totals were used to establish $kg \cdot ha^{-1}$ estimates for all crops in all years. These

estimates were used to gauge the conservation tillage treatments' ability to produce yields comparable to the conventional treatment. Due to large amount variability across replications, marketable yields were transformed using a log (x) +1 transformation to normalize the data.

To determine differences in weed abundance among treatments, counts were taken four times in both the 2011 and 2012 seasons. Tallies determined total weed populations and species compositions within each treatment. In 2012, dried biomass measurements were collected for broadleaf and grass weeds, in addition to cover crops.

Soil samples were collected in April every year and sent to the Cornell Nutrient Analysis Laboratory for the comprehensive Soil Health Test to measure the effects of the treatments on soil health. Additionally, in 2011 and 2012 soil respiration and nitrate levels were measured biweekly during the growing season. Six 15 cm soil cores were collected from four locations in each replication of each treatment. The soil was dried and then analyzed for soil respiration and nitrate levels

The conventional tillage (CT) system was managed as follows: In the spring, fall seeded (123 $kg \cdot ha^{-1}$) winter rye was incorporated using a moldboard plow and disked twice. Weeds within the treatment were controlled with tractor-mounted and walk-behind rototillers. In the fall, plots were disked twice before seeding winter rye.

Establishment of the rolled crimped zone builder (RCZB) treatment: After the fall vegetable harvest, the plots were plowed and disked prior to seeding the winter rye with a seed drill. The winter rye was seeded at a rate of 123 $kg \cdot ha^{-1}$. In the spring, when the rye reached anthesis, it was rolled and crimped. A zone builder was then used to strip till planting beds into the treatment. The winter rye seeding rate was increased to 184 $kg \cdot ha^{-1}$ in 2012 after a low biomass of winter rye was observed in 2011. The winter rye biomass was expected to provide adequate weed control between the strip-tilled rows throughout the season. Hand weeding was used to control weeds in the strip-tilled rows.

Raised planting beds and a cover crop mixture of perennial ryegrass (27.20 $kg \cdot ha^{-1}$) and Dutch white clover (2.72 $kg \cdot ha^{-1}$) seeded in the aisles between the beds made up the PLM treatment. Post harvest, the raised beds were seeded with winter rye (123$kg \cdot ha^{-1}$). The following spring, the rye was mowed and the beds were rototilled with a walk-behind tiller to prepare them for planting. A walk behind mower was used to control weeds between the beds, while hand weeding was used in the planted rows.

The crimson clover (CC) treatment was established as follows: The plots were plowed and disked twice before planting the vegetable crops. Following vegetable crop planting, crimson clover seed was mixed with pelletized lime at a 1:2 ratio and seeded at a rate of 25 $kg \cdot ha^{-1}$ using a drop seeder. Mowing was used to prevent the crimson clover from competing with the vegetables. Hand weeding was used to control weeds that the cover crop was unable to control.

Yield, weed abundance, and soil health analysis results varied by treatment. Redroot pigweed, crabgrass, purslane, and lady's thumb were the most abundant weeds in our fields. Soil respiration rates, nitrate levels, and soil health test results found the active carbon, nitrate, and biological activity in our soils to be lacking. Individual results between treatments varied.

CT - Vegetable yields were consistently higher than or equal to the other treatment yields over all three years. Weed abundance in 2011 was not significantly different from the other treatments, however, an additional tillage pass in 2012 reduced the weed populations by 42%. The reduction in abundance lead to no significant differences between the CT and PLM treatments. Organic matter levels were reduced over the three-year study. The 2012 nitrate levels were higher than the RCZB and PLM treatments, however, the soil respiration rates were lower than the conservation tillage treatments

RCZB – Yields throughout all three years, for all vegetables, were severely reduced in this treatment. The rolled and crimped winter rye failed to control weeds effectively and demonstrated reduced nitrate levels. The 2012 respiration levels, however, were the highest of any treatment.

PLM – Yield results varied by crop in this treatment. The melon, cucumber, and carrot yields were similar to the CT treatment yields, while the tomato, lettuce and cabbage yields were reduced. This treatment was very effective at broadleaf weed control, however, it was not effective against crabgrass. Soil respiration rates were higher than in all other treatments in 2011 and were greater than the CT treatment in 2012. Soil nitrate levels were lower than in the CT treatment in 2012.

CC – Vegetable and cover crop plant residue was left on the soil surface until the following spring. This treatment's yields were comparable to or greater than those of the CT treatment for all crops and all years, except cabbage 2011.

Conclusion

Each of the conservation tillage treatments showed one or more attributes that could potentially increase on-farm sustainability. The conservation tillage treatments have a higher average soil health score, reduced weed abundance, and produced yields similar to or greater than the conventional treatment. The CC treatment, however, was the only conservation tillage treatment comparable to the CT treatment in all three categories. Further experimentation is needed to improve upon these treatments and should include a greater emphasis on nutrient cycling in conservation tillage systems.

ACKNOWLEDGEMENTS

I sincerely thank Dr. Rebecca Brown for providing me with this opportunity; your patience, understanding, and willingness to assist me in my pursuit of this degree will not be forgotten. I also thank Dick Casagrande, Jose Amador, and Pat Logan for their keen guidance and sage advice throughout my journeys at URI. To the Greene H. Gardner farm managers Carl Sawyer and Tim Sherman, I appreciate your willingness to teach me new farming skills and your ability to bring levity into difficult situations. A big hug goes to Mina Vescera, the best office mate anyone could ever wish for! I still have no idea how you put up with me and my dirty desk, wet bike and stinky jackets for three years, but I am glad you did. To Emily Cotter, I am not sure I could have done this without your help! Your two years of hard work and enthusiasm really helped to keep me on track. I also want to thank my family for their support, encouragement, and editing. To Emma Kaiser, I owe you so much! Thanks for encouraging me to pursue this opportunity, and for being there through the difficult times. Your calming presence has made this experience much easier. Thank you to Northeastern SARE for providing the funding that allowed me the opportunity to be a part of this study. To the rest of the faculty, staff, and graduate students, thank you for your support and assistance making me feel at home in the department. I would not have been able to do any of this work with out the members of the dedicated farm crew who stuck with me through all the sweat and hard work; your efforts are truly appreciated – now let's go weed the cabbage!

PREFACE

A total of three chapters are written in manuscript format for publication in the journal HortScience.

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Chapter 1

LITERATURE REVIEW

History and Implications of Conventional Agriculture.

Crop production uses an intensive system that typically relies on tillage. Tillage can be defined as any cultivation practice that disturbs the soil surface, usually inverting or incorporating the top layer deeper into the soil profile. Historically, tillage was used to prepare the soil for seeding. This practice increased germination and gave seedlings an advantage over weeds (Magdoff and van Es, 2009). While there are many tillage devices, the Chinese were the first to develop the metal moldboard plow, a modified version of which is still heavily relied upon today (Temple, 1998). Today, most growers continue to use conventional tillage practices to plant their crops and control weeds (Hoyt et al., 1994).

While it has been the standard practice for some time now, excessive tillage in the modern agricultural system has become unsustainable. Tillage breaks down soil aggregates, making them more susceptible to wind and water erosion (Holland, 2003). In the last 50 years, one fifth of the world's topsoil and farmland has been lost due to excessive tillage (Raven, 2002). In 1990, Lal and Stewart estimated that 12×10^6 ha of arable land has been lost to erosion due to unsustainable practices. In addition, the United States of America Department of Agriculture's Natural Resource Conservation Service (USDA NRCS) conducted a twenty-five year National Resource Inventory (NRI) on erosion in the United States, concluding that 1.73 billion tons of arable cropland were lost due to erosion in 2007. While this was a 43% decrease from the amount of land lost to erosion in 1982, this figure is still above the soil loss tolerance threshold, the rate at which new soil can be formed (NRI, 2008). While erosion in the United States is not as severe as it is in other parts of the world, arable soil lost to erosion in the United States is still above the soil formation rate of 1 ton ha^{-1} $year^{-1}$ (Troeth and Thompson, 1993). This net loss of soil leads to land that is less fertile and ultimately reduces the total farmland available for crop production. Tillage practices also have a dramatic effect on soil health and structure. Excessive tillage decreases organic matter and affects the biological, physical, and chemical structure of the soil (Canell and Hawes, 1994). Tillage homogenizes soil particles and destroys soil macropores, which can restrict movement and interaction between soil macrofauna. This also disrupts fungal hyphae and nitrogen transformation (Young and Ritz, 1999). Excessive tillage can also lead to spatial variation in soil nutrients within fields, leading to pockets of lower productivity (Schumaker *et al*., 1999). These pockets are difficult to correct and can cause substantial yield losses for growers. Conservation tillage techniques have been shown to improve physical characteristics of the soil. Leaving organic residues at the soil surface leads to higher amounts of organic matter (Arshad et al., 1990). Cover crop residue also lowers soil temperature and conserves soil moisture (Licht and Al-Kaisi, 2005).

Coupling the consequences of excessive tillage with the current and growing demand for food demonstrates further reasoning why additional sustainable farming practices need to be developed. Even though many crop yields continue to increase (Tester and Langridge, 2010), there are more than 800 thousand people in the world who are currently facing a food shortage (von Grebmer and Klaus, 2008). The demand for food is steadily rising and is expected to double by 2050 (Walker *et al.*, 2005). Production in our present agricultural system is failing to meet our needs, while at the same time polluting our environment. To bolster yields in the current system, additional chemical fertilizers and pesticides will be necessary, thus adding even more pollutants to the environment (Licker *et al.*, 2010). Run-off from excess fertilizer creates hypoxic zones in water bodies all around the world, the number of which doubles in size every decade (Diaz and Rosenberg, 2008). These crops will also take more water to produce. Water is a limited resource in many parts of the world, and is being depleted faster than it can be replenished from many key production areas such as the Ogallala aquifer in the Midwest region of the United States (Sophocleous, 2005). The world's food production system presently faces many challenges, at the forefront of which is sustainability. In order to maintain sustainability, growers need to find ways to produce greater quantities of food more efficiently without enlarging agriculture's current footprint (Hobbs, 2007).

Conservation tillage

To overcome the unsustainable practices associated with conventional tillage, conservation tillage practices have been developed. Several studies have cited the severe environmental impacts of conventional tillage practices and have recommended reduced tillage practices to combat them (Unger et al., 1991; Gomez et al., 1999). Realizing the potential for loss of soil productivity and health, growers are considering alternative techniques that rely on lower impact tillage practices than those they currently use (Cannell and Hawes, 1994). Responding to unsustainable tillage practices, growers experimented with conservation tillage techniques while the government provided incentives to adopt them. In 1985, the Food Security Act, part of the US farm bill, contained the Conservation Security Program, which encouraged conservation practices that improve water, soil, air, energy, plant and animal life. From these policies, conservation agriculture techniques were further developed to limit erosion and balance soil nutrients, simultaneously minimizing greenhouse gas emissions and water usage (Hobbs, 2007; Powlson *et al.*, 2011). Growers were encouraged to use methods that sustain soil, water and other natural resources (Food Security Act, 1985). While there are myriad techniques to prevent soil loss, the most effective methods incorporate the use of vegetation to cover bare soil and the adoption of reduced tillage practices (Pimental et al, 1995). Conservation tillage practices are rooted in maintaining or building soil health through cover cropping and minimizing soil disturbance (Hobbs, 2007). There are many philosophies on conservation tillage, but practices that maintain soil coverage on 30% or more of a field are generally accepted (Hoyt, 1999). There is still tremendous potential and need for improved techniques in this sector of agriculture worldwide, as conservation tillage practices are only being used on five percent of global farmland (Montgomery, 2007).

Conservation Tillage Practices

Despite being underutilized, many different conservation tillage techniques have been investigated. The most widely adopted form of conservation tillage is the no-till technique. Arshad (1999) has labeled no-till methods the most practical technique to maintain food production and a healthy environment while restoring soil health. No-till methods do not always employ cover crops, but often involve leaving all cash crop residues on the soil surface (Anderson, 2010). Seeding the subsequent cash crop is often done directly into the previous crop’s stubble (Anderson, 2010). Many studies using no-till techniques have proven effective for commodity crops such as corn, wheat, and soybeans (Hoyt, 1999; Licht and Al-Kaisi, 2005). The use of herbicide resistant crops has helped to facilitate the increase in acreage of no-till techniques in the US (Brainard et al., 2013). This resistance allows growers to chemically control weeds and cover crops without sacrificing return on cash crops (Brainard et al., 2013). Continuous no-till studies have shown better erosion control, an increase in organic matter, and increased yields when compared to intensive tillage practices (Cannell and Hawes, 1994).

More recently, many of the same conservation tillage techniques and equipment used for agronomic crops have been modified for vegetable production (Hoyt et. al, 1994). Large seeded vegetable crops such as pumpkins and summer squash have been successfully grown when planted directly into cover crop residue (Hoyt, 1999; Licht and Al-Kaisi, 2005). Winter-hardy cover crops such as winter rye (*Secale cereale* L.) or hairy vetch (*Vicia villosa* L.) have served as mulch residues in which no-till vegetable production has been studied (Leavitt et al., 2011). Yield results in no-till vegetable production systems have varied. Hairy vetch was determined to be the best cover crop for no-till tomato production (Abdul-Baki et al., 1996). Leavitt et al. (2011) found that no-till tomato, pepper and zucchini yields were reduced. When evaluating strip tillage for tomato production, Kornecki and Arriga (2011) determined a cover crop of winter rye was able to produce enough biomass to suppress weeds and maintain yield; thus making it a viable alternative to plastic mulch. Crimson clover (*Trifolium incarnatum*), however, did not produce the biomass necessary to suppress weeds and resulted in decreased yields

Vegetable growers have to weigh several factors when contemplating the adoption of cover cropping and reduced tillage systems. Contradicting yield results and heavy reliance on herbicides in no-till systems have resulted in slower adoption of no-till techniques for many vegetable growers. Soils in no-till systems have been shown to be wetter and have lower temperatures early in the season (Licht and Al-Kaisi, 2005). This makes the no-till system a poor choice for mixed vegetable growers who rely on warmer soil temperatures to plant their warm season crops. If soil temperatures are lowered, or cool temperatures linger late into the season, growers may miss market opportunities or premium pricing. Other factors compounding the lack of cover crop use on vegetable farms includes potential loss of profits, as cash crops often have to be terminated early in order to establish winter cover crops. Furthermore, successful no-till methods often rely on the application of herbicides to control weeds, which many small-scale, sustainability-minded growers prefer not to use (John Holscher, personal communication, June 25, 2012).

Alternatives to no-till for vegetable production

With a desire to develop conservation tillage techniques that are better suited to vegetable production, growers have developed new equipment and techniques that attempt to overcome some problems associated with no-till systems. Strip tillage and living mulches are conservation tillage techniques that may be more suitable for vegetable growers. By tilling small rows within the existing cover crops, strip tillage has been shown to alleviate some of the problems vegetable growers have faced with no-till systems (Brainard et al., 2013). Tilling narrow planting beds within the cover crop increases soil temperature, leading to improved plant emergence when compared to no-till systems (Licht and Al-Kaisi, 2005). The warmer soil also allows growers to transplant crops earlier, which may lead to an earlier harvest and higher returns. Strip tillage also lowers input costs, and conserves soil in cool season crop production (Haramoto and Brainard, 2012). Strip tillage has maintained yield levels while reducing fuel and labor costs in many vegetable crops including sweet corn, winter squash, snap beans, cucumber, cabbage, broccoli and carrots (Brainard et al., 2013).

Cover crop management is an important aspect of conservation tillage. In no-till and strip-till systems, growers rely on mechanical or chemical methods to terminate growth of cover crops, which limits competition between cover and cash crops. As the terminated cover crops break down, their effectiveness in controlling weeds wanes. To counteract this loss of effectiveness, living mulches can be used. Living mulches, however, can cause problems with cash crop production as they compete for nutrients and light, making them well suited to production systems where the cash crop plants are larger and interference is limited. In vegetable production, this competition can be a problem as living mulch cover crops have been found to out-compete cash crops. Living mulches are best suited to use in combination with strip tillage techniques in vegetable production systems (Masiunas, 1998). In this strip-till design, the cash crop row is kept cultivated and free of both weeds and cover crops, and the living mulch is grown between the planted rows. Living mulch cover crops are usually chosen for their ability to form a dense stand that competes well with weeds, and often include clover and grass mixtures. In Hawaii, Hooks and Johnson (2004) found that several clover species sown into broccoli plantings resulted in yields similar to those of broccoli grown on bare ground. Growing broccoli in New York, Brainard and Bellinder (2004) interseeded winter rye as living mulch.. They found when they seeded the winter rye at transplanting, weed emergence and crop yield were significantly reduced. In Indiana, clover seeded between transplanted tomato rows was shown to reduce weed biomass, but also reduced tomato yield when compared to tomatoes grown in black plastic mulch (Butler, 2012). Living mulch mixtures of Dutch white clover (*Trifolium repens*) and perennial ryegrass (*Lolium perenne* L.) also show potential for controlling weeds. Although this cover crop does not have the biomass of winter rye, when the two cover crops are grown together, the biomass is increased compared to when either one is grown alone (Hogh-Jensen and Schjoerring, 2010). The turf-like nature of perennial ryegrass, and the stoloniferous nature of the Dutch white clover allows it to form a dense ground cover that also prevents erosion. As a legume, Dutch white clover is able to fix nitrogen at a rate of 90 - 145 kg $N \cdot ha^{-1}$ (Balkcom et al., 2009). It is also highly resistant to trampling, making it a good selection for high traffic aisle ways between planting beds (Balkcom et al., 2009). In combination, each of these two plant species is able to compensate for the other if growth is retarded by disease or insect pressure (Hogh-Jensen and Schjoerring, 2010).

Soil health

To further understand the benefits of conservation tillage techniques, it is important to understand the effects tillage can have on the soil. Examining the physical, biological and chemical properties of soil can be used to further understand the effects. Within the soil, all three characteristics are closely intertwined and can influence each other. When determining soil structure pore space, the space between soil particles, and its relationship to root penetration, water storage, movement of air, water, and soil fauna are critical factors to consider (Hermavan and Cameron, 1993; Langmaack, 1999). Soil with healthy physical characteristics, or good tilth, possesses structure that allows for water penetration and air flow within the soil profile. This structure also allows soil fauna and plant roots to easily move through the soil. Identifying loss of soil structure is the key to understanding how management practices are impacting soil health (Danielson and Sutherland, 1986). A 32-year study comparing conventional and conservation tillage methods found that conservation tillage improved several physical, biological and chemical soil traits (Moebius et al., 2008). The improved physical traits included aggregate stability, plant available water capacity, bulk density, permeability, and infiltration capacity.

Fewer disruptions of the soil led to greater populations of soil fauna, building the biological components of the soil (Linn and Doran, 1984; Hendrix et al., 1987). The residual organic matter left on the soil surface in no-till systems provides a carbon and nitrogen source for microorganisms, increasing potentially available nitrogen and cellulose decomposition rates over time (Moebius et al., 2008). In turn, soil structure is improved by the biological components of the soil as mucilaginous secretions from plant roots, soil fungi and earthworms bind soil particles together and help build soil aggregates (Young and Ritz, 1999).

The choice of tillage practice also has an effect on nutrient cycling. When investigating systems transitioning into no-till practices, Rice et al. (1986) found that the initial surface nitrogen lost from conventional tillage systems was three times higher than from no-till systems. The increased mineralization rates led to higher inorganic nitrogen levels and greater yields in the conventional treatment. McCarthy et al. (1998) found similar results when transitioning from plow tillage to no-till systems. Over time, the accumulation of organic matter in the no-till system helped to increase mineralization rates, correcting the differences between the two treatments (Rice et al., 1986).

Monitoring soil respiration rates can help us understand organic matter decomposition rates. Tillage aerates the soil and increases decomposition of organic matter, resulting in an increase of soil respiration levels. Soil respiration rates can be monitored to help determine the conversion of organic matter into plant available nutrients (Parkin et al., 1996). Haney and Haney, (2004) found that soil respiration rates measured by the Solvita health kit were comparable to 7 and 28 day titration levels of organic carbon, potentially mineralizable nitrogen and phosphorus. Organic matter and carbon mineralization rates, however, have been found to be highly variable among adjacent sampling sites in old-field soils (Amador et al., 2000). They suggest that the assumption of identical physical and biological properties between soil samples may not be valid due to spatial variation of these characteristics within the soil.

Benefits of Cover Crops

Cover cropping is a key component in conservation tillage. Cover crops are defined as any crop that is not grown for commercial sale. They reduce erosion rates by keeping soil surface covered when or where cash crops are not being produced. Cover crops provide greater benefits than simply reducing erosion rates. By covering the soil, they also add organic matter, suppress weeds, add nutrients, decrease nutrient loss, and suppress crop pests (Magdoff and van Es, 2009). Cover crops have been used for over 2,500 years (Newman et al., 2012). Historically, farmers in China, India, and Europe are known to have used legumes to help them maintain soil nutrients and achieve higher yields (Ingles and Klonsky, 2003).

Cover cropping allows growers to produce their own on-farm resources, making it one of the best ways a farm can maximize sustainability. Cover crops suit a variety of needs and their use is largely determined by the requirements of the soil, the goals of the grower, and the time of year the cover crop is to be grown.

Many different plants can be used as cover crops, and each species has its own specific benefits. For example, legumes form a symbiotic relationship with soil bacteria that have the ability to fix nitrogen from the air and make it available to the plant. Nitrogen fixation rates vary widely between legume cover crops, ranging from 33 to 168 kg $N \cdot ha^{-1}$ (Hoyt, 1999). The low carbon to nitrogen (C:N) ratio of legume cover crops allows legumes to decompose quickly, adding nitrogen to the soil (Magdoff and van Es, 2009). This nitrogen helps to reduce the amount of fertilizer needed for the next crop, but does little to change organic matter levels in the soil (Snapp et al., 2005).

Clover is widely used as a leguminous cover crop, as the wide variation of varieties make it highly adaptable and useful for a multitude of conditions on the farm. Crimson clover (*Trifolium incarnatum*) is a summer annual legume that is able to scavenge as well as fix nitrogen at rates ranging from 65 to 168 kg N·ha^{-1} (Balkcom et al., 2009). Early spring or late summer plantings can result in suitable ground cover. When grown as a summer cover crop in temperate regions, below zone 5, it will reliably winter kill, making it easier to manage in the spring (Balkcom et al., 2009). Fall seeded cover crop mixtures, including crimson clover, have also been shown to be more effective at controlling weeds than hairy vetch alone (Teasdale and Abdul-Baki, 1998). Studies in Maryland have shown summer seeded crimson clover acquired 680 – 907 kg of dry matter and fixed 65 kg N·ha^{-1} (Balkcom et al., 2009). In the South, crimson clover has been used as a winter cover crop in vegetable production systems. Studies in Georgia have found that the use of crimson clover produced a greater number of roots and increased nitrogen uptake in tomato production (Sainju et al., 2001).

Unable to fix nitrogen, cereal cover crops like winter rye are able to provide other benefits. The ability to seed winter rye late is of great benefit to vegetable growers who often have late maturing cash crops that need to be harvested in the fall. Winter rye reduces the amount of residual nitrogen lost from the soil profile by effectively scavenging nitrogen from the soil (Balkcom et al., 2009). Winter rye is also able to bring potassium from deep in the soil profile up to the soil surface, increasing the levels of exchangeable potassium (a key to crop quality), protein and starch synthesis, and water and nutrient transport (Balkcom et al., 2009).

Weeds can be a major concern for growers who choose not to use herbicides (Anderson, 2010). Traditionally herbicide free vegetable systems relied on tillage to control weeds in all aspects of production. Using cover crops can help growers reduce weed populations while decreasing the amount of tillage. Many cover crops are grown for their ability to suppress weeds by physical or chemical inhibition. Cover crops that produce large amounts of biomass can limit light penetration of the soil surface and reduce weed seed germination (Teasdale and Mohler, 1993). Anderson (2010) found weed seedling density was reduced by 15% for each 1000 kg·ha^{-1} of cover crop residue in conservation tillage systems. Cereals such as rye, oats, and wheat are known to produce large amounts of biomass, which help to increase soil organic matter, but also contain higher amounts of lignin that can lead to slower breakdown (Snapp et al., 2005). This biomass can be used as mulch on the soil surface to further reduce weed populations when cash crops are planted (Teasdale and Mohler, 2000).

Known for its cold hardiness, winter rye (*Secale cereale* L.) has been widely used as a winter cover crop in temperate regions. Its hardiness allows it to be seeded later in the fall than other cereal crops. Even when seeded late, winter rye is able to produce ample biomass, providing weed suppression and erosion control (Balkcom et al., 2009). Biomass accumulations from 3,345 to 4,482 kg N·ha^{-1} of winter rye can be expected in the Northeast (Balkcom et al., 2009). Properly managed, the resulting biomass can be used as a mulch layer that can be very effective at limiting light to the soil surface and preventing germination of weeds such as chickweed, redroot pigweed, lambsquarters, and foxtail (Balkcom et al., 2009). Smith et al. (2011) found that 9,000 $kg \cdot ha^{-1}$ rye biomass was enough to suppress weeds and maintain soybean yields. In a three state study conducted by Masiunas et al. (1995), rye dry biomass averaged 6,763 $kg \cdot ha^{-1}$ in Kentucky, Illinois, and Indiana. Winter rye biomass production in Alabama averaged 9,725 kg dry biomass ha^{-1} (Ashford and Reeves, 2003), while three sites in North Carolina averaged 7,652, 5,140, and 4,540 kg dry biomass ha^{-1} (Smith et al., 2011; Yenish et al., 1996). Winter rye dry biomasses between 4,400 $kg \cdot ha^{-1}$ and 6,600 $kg \cdot ha^{-1}$ did not reduce weeds effectively, decreasing soybean yield by 29% and 38%, respectively (Smith et al., 2011). Winter rye also produces an allelopathic chemical, benzoaxazoline, in its roots that has been shown to inhibit germination, affect metabolic processes in seedlings, and even cause death of certain species (Schulz et al., 2013).

Conservation Tillage in New England

The National Agricultural Statistics Service (NASS) in 2007 showed that roughly two thousand vegetable farms of an average size of 9.7 hectares in southern New England produce 10% of the market value of all agricultural products sold in the region. Many of these farms are still using conventional tillage to incorporate debris, prepare beds, and remove weeds. As a result of these tillage practices, an average of 16.3 $Mg \cdot ha^{-1} \cdot year^{-1}$ of soil are lost to erosion in New England (NRI, 2009). To curtail erosion rates on their farms, a number of these growers would like to incorporate more sustainable practices into their production system, but they are unsure how to incorporate conservation tillage practices within their existing management systems. Their concerns revolve around the idea that reducing tillage will lead to increased weed populations and that the timing associated with cover crop seeding dates will interfere with their cash crops, lowering their return. Many growers do not want to spend money on new equipment that they are not familiar with, or are not sure how to use in their fields. Identifying systems that are easy to establish and incorporating cover cropping and tillage practices that maximize low input techniques is key to improving farm sustainability in New England. Finding a combination of cover crops and tillage techniques that can build soil health and reduce weed populations while maintaining yield would greatly increase farm sustainability, as growers would have to rely less on off-farm inputs in order to produce a successful harvest.

Chapter 2

CONSERVATION TILLAGE TECHNIQUES AND THEIR ABILITY TO MAINTAIN MIXED VEGETABLE YIELDS WHEN COMPARED TO CONVENTIONAL METHODS

This chapter has been formatted for submission to HortScience.

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Introduction

Various types of tillage are used in vegetable production systems. Tillage, or flipping, digging or turning of the soil, has become the primary method used to incorporate plant debris and prepare the soil for planting. For growers who do not use herbicides, tillage has also become a valuable tool to control weeds. This reliance on tillage to prepare, plant, and cultivate fields, in addition to controlling weeds, led Magdoff and van Es (2009) to conclude that modern vegetable growers have developed an “addiction to tillage.”

Realizing the negative effects tillage has on the soil has created a desire among vegetable growers to become more sustainable. This desire led vegetable growers to adopt the use of conservation tillage techniques that had primarily been used to produce commodity crops (Hoyt, 1994). Conservation tillage techniques were designed to improve soil health through the use of cover crops and by minimizing tillage. While there have been many studies conducted on conservation tillage techniques for vegetable production (Abdul-Baki et al., 1996; Adbul-Baki and Teasdale, 2007; Brennan and Boyd, 2012; Kornecki and Arriaga, 2011), several concerns still exist about their ability to control weeds and maintain acceptable yield levels. Growing vegetables for direct retail sale requires an intensive production system where crops are planted early in the spring and harvested late into the fall. This intensive system offers little opportunity for growers to establish or maintain typical winter cover cropping systems as they do not want to risk adopting a conservation tillage system that may lower their profit potential by requiring early termination of crops, or delaying entry into their fields. Furthermore, few of the conservation tillage studies have been modeled on mixed vegetable systems. A study that encompasses various types of both transplanted and direct seeded crops together, emulating a direct sales, market garden system, would prove beneficial to many growers in southern New England, where most growers are still using conventional tillage to incorporate debris, prepare beds, and remove weeds.

The objective of this study is to evaluate possible cover crop and tillage regimes that could be adopted by southern New England vegetable growers. To do so, we evaluated the effects that various cover crops and tillage systems have on a mixed vegetable system. To emulate a mixed vegetable system, six vegetables were grown in each treatment: tomato, cabbage, muskmelon, cucumber, carrot, and lettuce. We used three treatments: (1) rolled-crimped fall seeded winter rye (*Secale cereale* L.) with zone tilled planting beds (RCZB), (2) a perennial living mulch of perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) grown between strip tilled raised beds (PLM), and (3) crimson clover (*Trifolium incarnatum* L.) seeded after vegetable establishment (CC). Marketable and total yields were compared to conventional tillage (CT) practices to determine their effectiveness.

Methods

Plot establishment. This three-year study on conservation tillage techniques was established in the fall of 2009, with all data collection beginning in 2010. Our experiment was conducted at the Greene H. Gardener field experiment station in Kingston, Rhode Island. The experiment was carried out on roughly one half hectare of Bridgehampton silt loam soil. A randomized complete block design with three conservation tillage treatments and one conventional treatment was used. Each of the four treatments was replicated three times. The individual treatments within the blocks were 10 X 30 m. Within each treatment, six 1.5 m wide rows were established. The two outside rows were maintained as buffers between plots, while the four interior rows were planted to vegetables. Each year the vegetable crops shifted one row to the east with the fourth row becoming the first to eliminate the use of the same beds for the same crops over multiple years. In 2011 and 2012, the melon / cucumber rows in all treatments except roller crimper zone builder (RCZB) were covered with black plastic mulch. A Rain-flo Irrigation® Series II #2550 plastic mulch layer was used to prepare these planting beds. Drip tape with 30 cm emitter spacing was used to irrigate each crop. All vegetables received one line of drip tape except the carrot / salad row, in which two lines were used.

Treatments

Conventional (CT). Each fall, winter rye was planted at a rate of 123 $kg \cdot ha^{-1}$. Seeding dates for each field season were the 20th, 21st, and 24th days of October (2009, 2010, and 2011), respectively. The following spring, the winter rye stand was incorporated using a moldboard plow. After plowing, the plots were disked twice. Five planting beds, each 1.5 m in width, were created using the tractor wheelbase as aisles. After planting, weeds were controlled with a tractor-mounted tiller for the empty rows, and an 8hp walk-behind tiller for the walkways and shoulders of the beds. Various hand-weeding tools were used for additional weeding around the crops. Each replication was tilled a total of 3 times in 2011 and 4 times in 2012.

Rolled crimped / zone builder (RCZB). Each fall, winter rye was planted at a rate of 123 $kg\cdot ha^{-1}$ on the 20th and 21st days of October (2009 and 2010) respectively. In 2011, the seeding rate was increased to 184 $kg\cdot ha^{-1}$ to increase cover crop biomass. The 2011 seeding date was the 24th of October. In the spring, the winter rye was rolled at anthesis using a front mounted roller crimper (I & J Manufacturing). After flattening the rye, a zone builder (Monroe Tufline™ 2S-24-60 subsoiler with Unverferth® zone strip coulters and roller basket) was used to make 30 cm wide planting beds within the treatment. Each planting bed, except for the cabbage, was made with one tractor pass using a single shank set 30 cm into the ground. For the cabbage, two zones spaced 75 cm apart were made.

Perennial ryegrass and Dutch white clover perennial living mulch (PLM). In the spring of 2010, a mixture of turf-type perennial ryegrass (27.20 $kg\cdot ha^{-1}$) and Dutch white clover (2.72 $kg\cdot ha^{-1}$) was seeded in the aisles between four raised beds. This cover crop was designed to provide perennial soil coverage between the planting rows throughout the course of the three-year experiment. The 2010 tomato and all melon and cucumber plantings were covered with black plastic mulch to help control weeds, warm the soil, and preserve soil moisture. Post harvest, the planting beds were rototilled with a walk-behind tiller and seeded with winter rye at a rate of 123 kg·ha^{-1} using a drop seeder. The following spring, the rye was mowed and the beds were rototilled with a walk-behind tiller to prepare them for planting. Each spring, the PLM treatment was reseeded as needed.

Crimson clover annual living mulch (CC). In the spring of 2010 the CC plots were plowed and disked twice before planting the vegetable crops. Following vegetable crop planting, in June, the crimson clover was seeded throughout the plot. The crimson clover seed was mixed with pelletized lime at a 1:2 ratio and seeded at a rate of 25 kg·ha^{-1} using a drop seeder. Vegetable and cover crop plant residue was left on the soil surface until the following spring when the plot was plowed and disked before being planted.

Vegetable Crops

Tomato. All of the 2010 tomato transplants were provided by Confreda's Greenhouses and Farms (Hope, RI). In 2011 and 2012, the tomatoes were grown in the URI greenhouse. Seeds were started on the 17th and 21st of April (2011 and 2012) respectively. The tomatoes were transplanted by hand during the last week of May (2011) and first week of June (2010 and 2012). In 2011, sparrows in the greenhouse damaged several flats of transplants. To make up for the loss, new seeds were started on the 27th of April, and additional tomato transplants were obtained from Confreda's Greenhouses and Farms. The additional plants led to an increase in the number of varieties planted. In 2012, three varieties, 'Celebrity', 'Polbig' and 'Valley Girl,' were chosen for production. Kocide® 3000 and Bravo

Weather Stik® were used as needed to control fungal outbreaks. In 2012 Dipel® DF was used to control Lepidoptera species.

Brassicas. The first year of the study (2010), broccoli was directly seeded in the spring. Late in the season, cross-striped cabbageworms became a large problem in the crowns of the crop. To prevent this problem from recurring, broccoli was replaced with cabbage for the 2011 and 2012 seasons. The 2011 cabbage crop was hand seeded on the 3rd of June. A double row of 150 plants (300 plants total) spaced 30 cm apart was established in each treatment. Heavy weed pressure in 2011 led us to grow transplants for the 2012 season. The 2012 cabbage crop was started in the URI greenhouse on the 15th of May, before being transplanted into two rows of 150 plants on the 18th of June. The brassicas were sprayed with Dipel® DF as needed to control Lepidoptera species.

Melon / Cucumber. In 2010, several melon varieties including Sarah's Choice, Honey Orange, Delicious 51 PMR, and Halona were planted. In the following years, Diplomat (melon) and Marketmore (cucumber) were seeded into 38-cell trays at the URI greenhouse on the 5th and 7th days of May 2011 and 2012, respectively. For the 2011 and 2012 seasons, the row was divided into 6 subplots, alternating melon and cucumber down the row. A total of 54 melons and 42 cucumbers were planted per row in 2011, and 45 melons and 33 cucumbers per row in 2012. Both melons and cucumbers were planted with 60 cm between plants.

Lettuce / Carrot. In 2010, the 50 m row was equally divided into lettuce and carrot plantings. For 2011 and 2012, 15.5 m and 10 m of carrots were seeded, respectively. Carrot seeding was done using an Earthway® (1001 –B) seeder in 2010 and 2011, and a Jang (Jang Automation Co., JP-1) seeder in 2012. In all three years, four rows of carrots were seeded in each treatment. To seed the salad, two passes, each 15.5 m in length, were made using a Johnny's six-row seeder. In 2011 and 2012, 10 m sections of lettuce were seeded to start the season. The initial seeding was followed by biweekly plantings that were 3 m in length. Both crops were hand weeded and thinned as necessary. A hand held weed burner was used to manage the succession planting areas in 2012. Each week, six meters of bed space was burned. For each 3 m planting, weeds were burned twice prior to seeding. After seeding, the beds were watered, and covered with floating row cover. Plots were watered daily until the first true leaf was visible.

Statistical Analysis

The harvested crops were graded as marketable or non-marketable, weighed, and counted. Produce that was determined to be saleable at a farmers market or other direct sales venue was labeled as marketable. Marketable yield results were evaluated for significant difference from the conventional (CT) treatment. Due to the high variability between replications within treatments, all yield data was transformed using log (x+1) to normalize the distribution. Repeated measures analysis of variance (ANOVA) procedure in Statistical Analysis System (SAS Inst., Cary, NC) was used to determine statistical differences. Treatment means were separated (α = 0.05) using Fisher's LSD.

Results

There was a significant interaction between treatment and years (*P* < 0.0001) for marketable yield. Therefore, differences between treatments were analyzed separately by crop and year. Marketable yields in kilograms per hectare were estimated for each treatment. Effectiveness of the treatments was evaluated by comparing treatment yields with yield of the CT treatment.

Tomato. There was no significant difference between marketable yields of the CT, RCZB, and CC treatments in 2010 (Fig. 1). The average marketable yields in these treatments ranged from 13,258 kg·ha^{-1} to 126,299 kg·ha^{-1}. The 2010 PLM treatment was significantly different, and yielded 61% more than the CT treatment.

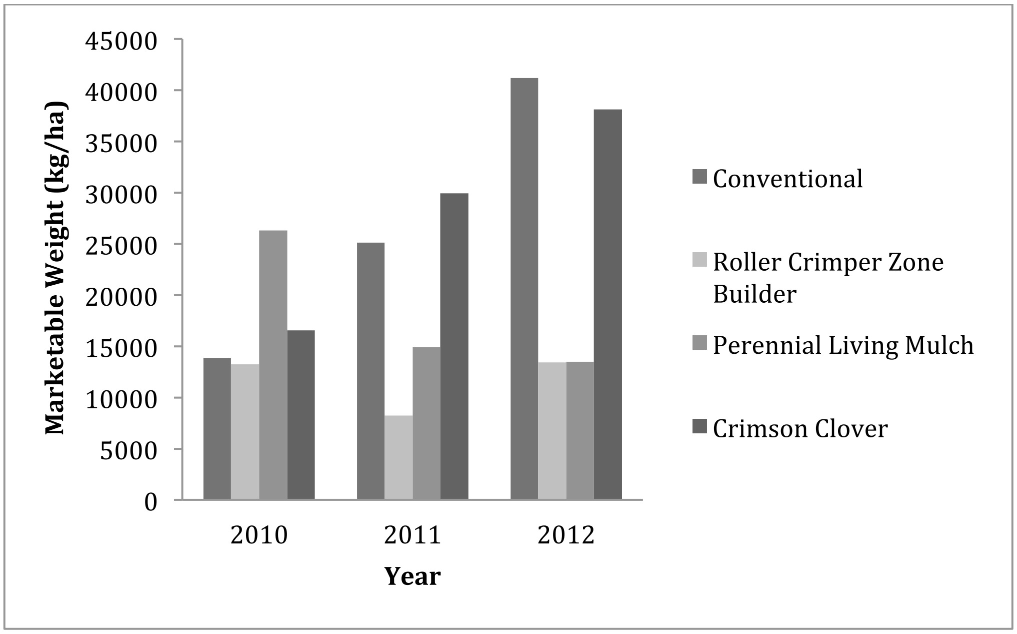

Fig. 1. Average marketable tomato yield for 2010, 2011, and 2012.

In 2011, the marketable weight of the RCZB treatment was 58% lower than, and significantly different (*P* = 0.0201) from the CT treatment. The PLM and CC treatments were not significantly different from the CT treatment. The data from 2012 were similar to the results of 2011, with both the RCZB and PLM treatments differing significantly from the CT treatment. Marketable yields in the RCZB treatment increased while the PLM treatment yields decreased; both were 33% of the CT treatment yields. The CC treatment was not significantly different from the CT treatment.

Melon. The marketable yields from the CT, PLM, and CC treatments in all three years were not significantly different. Yield averages over the three years ranged from 17,400 to 32,994 kg·ha^{-1} (Fig. 2). The RCZB treatment yield was significantly different (*P* = 0.0044) and totaled 5% of the CT treatment yield in 2010.

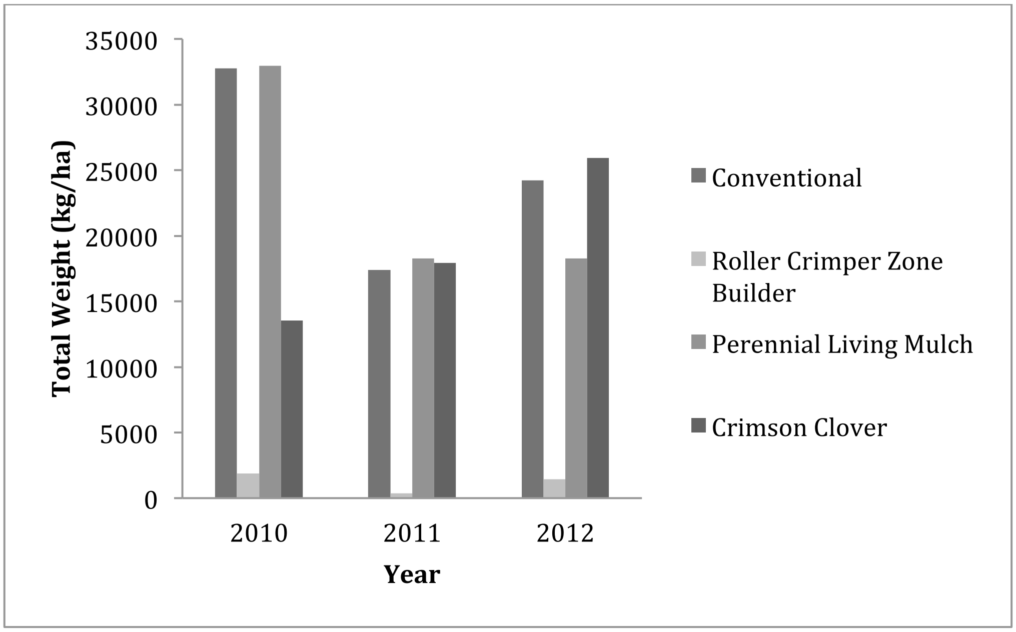

Fig. 2. Averaged marketable melon yield for 2010, 2011, and 2012.

The marketable yield of RCZB treatment was also significantly different from the CT treatment in 2011 ($P < 0.0001$) and 2012 ($P = 0.0113$). Marketable yield in the RCZB treatment was 0% to 5% of the CT treatment's yields over the final two years of the study.

Lettuce. There was no marketable lettuce harvested in the RCZB treatment in 2010. Among the CT, PLM, and CC treatments, there were no significant differences in marketable yield (Fig. 3). Averaged marketable values for these treatments ranged from 3,976 to 4,914 kg·ha^{-1}. Poor establishment led to a failed lettuce crop for the 2011 season; evidence suggested that seed and seedling predation by mice and voles was the culprit.

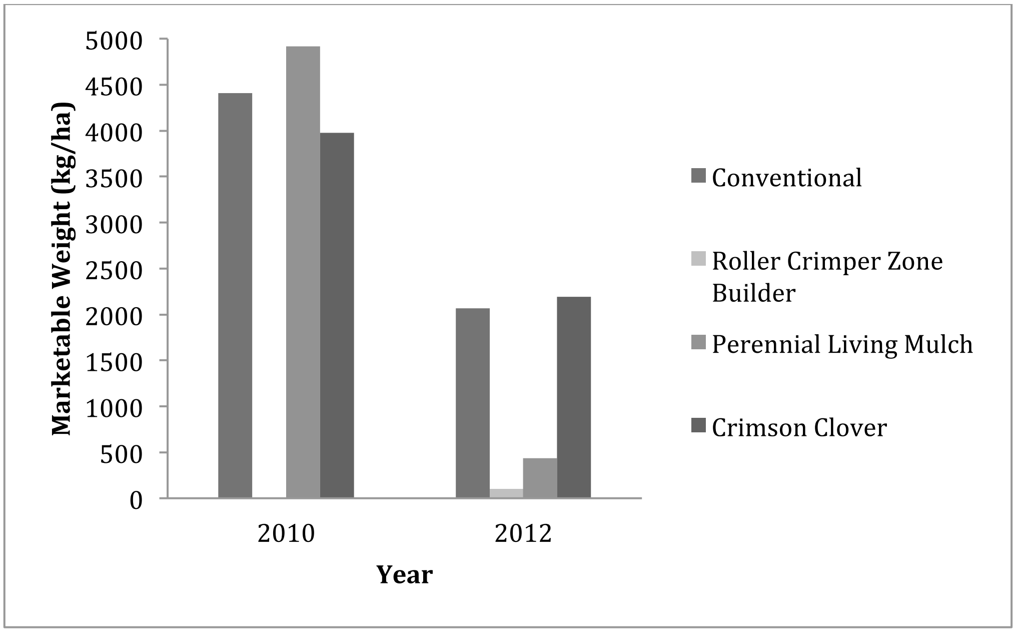

Fig. 3. Averaged marketable lettuce yield for 2010 and 2012.

The 2012 marketable yield for the CC treatment was 6% greater than, but not significantly different from, the CT treatment. The marketable yields in both the

PLM and RCZB treatments were significantly different (*P* = 0.0010) and were 5% and 21% of the CT treatment, respectively.

Cucumber. The marketable yield for the RCZB treatment in 2011 was significantly lower (*P* = 0.0017) than the CT treatment (Fig. 4). No significant differences were observed between the PLM, CC, and CT treatments. Average marketable yields ranged from 25,127 to 31,823 kg·ha^{-1} within the treatments. There were no significant differences in marketable yield between treatments in 2012. Marketable yields averaged between 18,113 to 27,297 kg·ha^{-1}.

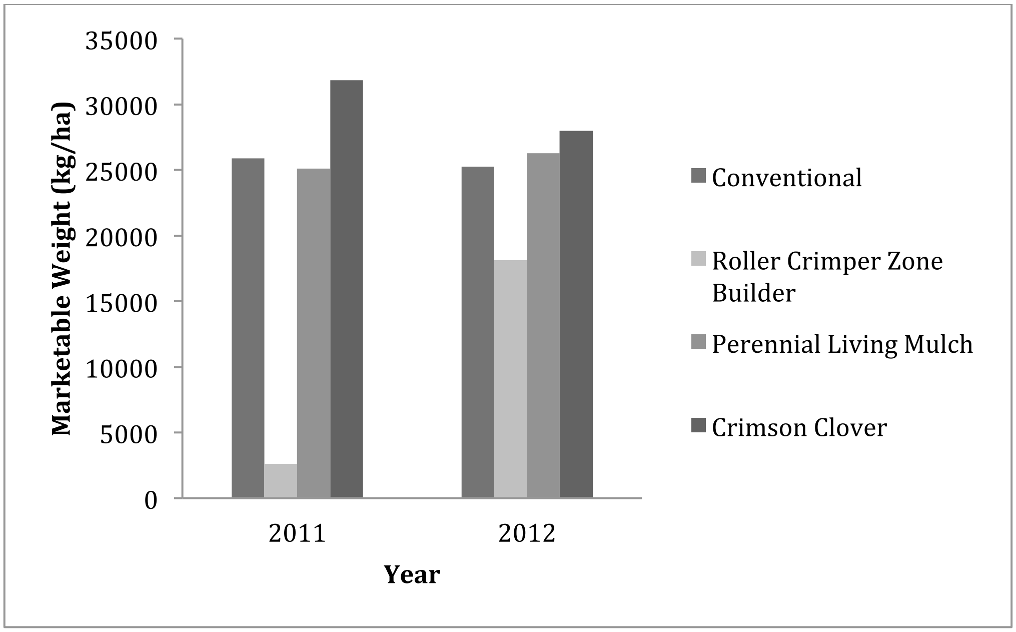

Fig. 4. Averaged marketable cucumber yield for 2011 and 2012.

Carrot. In 2010, the RCZB treatment failed to produce a marketable yield. There were no significant differences between the other three treatments, with marketable yield averages ranging between 5,815 and 9,461 kg·ha^{-1}. Seed predation by mice and voles and poor germination resulted in a failed carrot crop for the 2011 season. The 2012, RCZB marketable yield was only 40% of the CT treatment. There were no significant differences between the PLM, CC, and CT treatments. Marketable yield averages ranged from 7,293 to 7,269 kg·ha^{-1}.

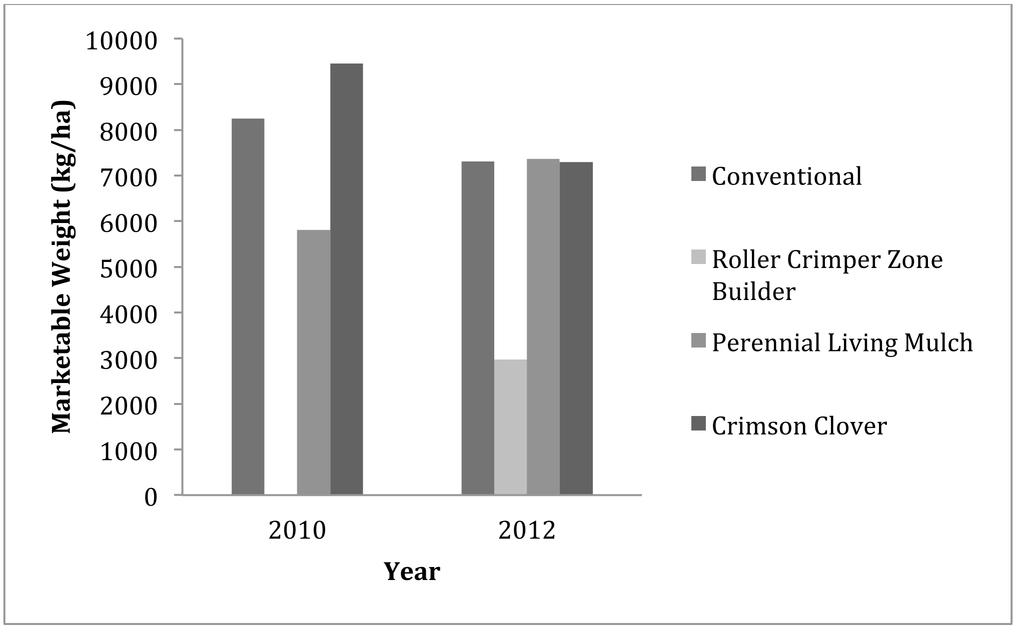

Fig. 5. Averaged marketable carrot yield for 2010 and 2012.

Brassica. There were no significant yield differences between CT, PLM and CC treatments in the 2010 broccoli harvest. Yield for these treatments ranged from 1,432 to 1,736 kg·ha^{-1} (Fig. 6). The RCZB treatment's marketable yield was significantly different (P = 0.0061) and was 2% of the CT yield. In 2011, no significant difference was found between the marketable cabbage yields of the CT, PLM and RCZB treatments. The average marketable yields for those treatments ranged from 9,185 to 11,942 kg·ha^{-1}. The CC treatment's marketable yield was significantly reduced (P = 0.0061), producing only 2% of the CT treatment's marketable yield. For 2012, CT and CC marketable cabbage yields were not significantly different. Marketable yields for these treatments averaged 38,272 and 39,141 kg·ha^{-1} for each treatment, respectively. The RCZB and PLM treatments' marketable and total yields were significantly reduced compared to the CT treatment. The marketable yield averages (5,398 and 8,364 kg·ha^{-1}) for each treatment were 16% and 25% of the CT treatment yield.

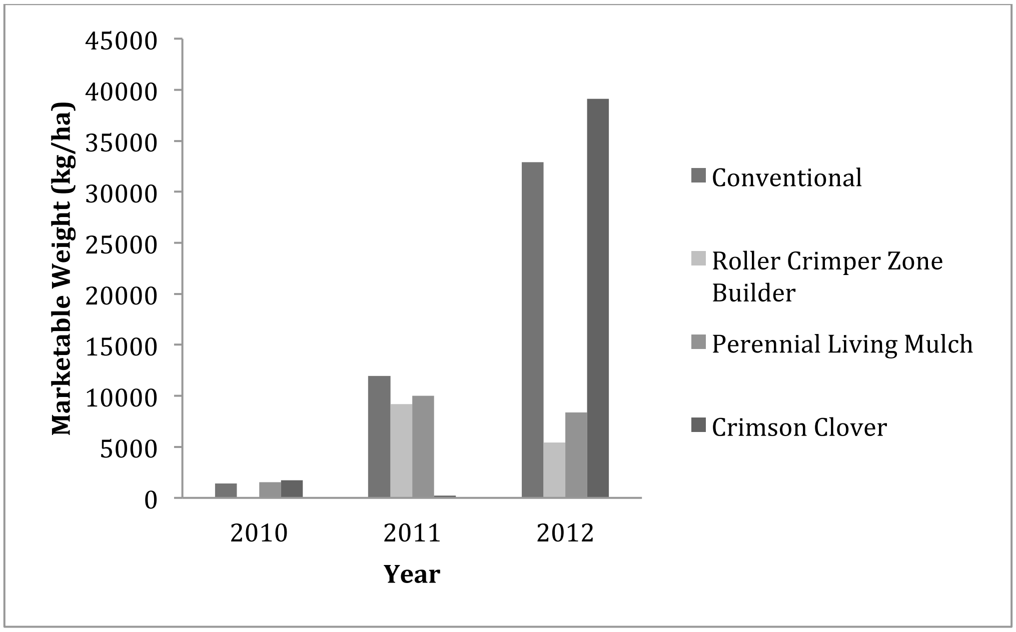

Fig. 6. Averaged marketable brassica yield in 2010, 2011, and 2012. Broccoli was grown in 2010, and cabbage in 2011 and 2012.

Discussion

By Crop

Brassica. After experiencing problems with establishment in some treatments, we decided to abandon direct seeding and transplanted the cabbage crop in 2012. This turned out to be very beneficial in all treatments, as our starts had a large advantage over the germinating weeds. While all crops established nicely, the weed pressure in RCZB and PLM treatments was still a problem and led to reduced head sizes (Fig. 6), which decreased the yield.

Melon / Cucumber. A large infestation of striped cucumber beetle (*Acalymma vittatum)* in May and June 2012 greatly reduced the vigor of the plants. The beetle damage was particularly severe in the third replication of treatments CT and CC, as the plots were located directly downwind of a former squash field. Striped cucumber beetle damage on the melons led to dramatic reductions in yield, obscuring much of the treatment effect. While the cucumbers did not sustain as much damage as the melon crop, the damage was enough to cause reduced yields in the third replications of the CT and CC treatments. This resulted in the yield averages for the 2012 season being greatly reduced. Removal of the third replication from the 2012 yield averages (Fig. 2) raised the yield averages in the CT and CC treatments by 23% and 29%, respectively. In addition, without black plastic mulch, the vegetable crops in the RCZB treatment struggled to compete with the weed populations, and resulted in significantly reduced yields over all three years.

Salad / Carrots. A change of row management practices in 2012 led to nearly weed- free plantings of salad, and greatly reduced the weed pressure within the carrot rows. Reducing weed cover on the bed edges in 2012 eliminated mouse and vole predation. Our 2012 findings align with Haramoto and Brainard (2012), who found that carrots grown in a strip tilled system had yields that were equal to or greater than carrots produced using a full width tillage system. Their study, however, included the use of herbicides and their results could have been partially due to the effective weed control within the treatment

Tomatoes. Marketable yields ranging from 38,156 to 41,202 kg·ha^{-1}, and total yields ranging from 63,752 to 65,992 kg·ha^{-1} in the CC and CT treatments were similar to those reported by Kornecki *et al.* (2011). In Alabama, they found that a winter rye mulch layer was a suitable alternative to black plastic mulch for weed control. Rye and crimson clover cover crops, however, produced lower tomato yields in two out of three field seasons. Swenson et al. (2004) reported that conservation tillage methods, including strip tillage and living mulches, when given sufficient moisture, produced marketable yields similar to conventional tillage practices. Hoyt (1999) found that the total marketable yield in strip tillage, no-till, and strip tillage with a sub-soiler was greater than conventional tillage yields. Results contradictory to this were found in our RCZB and PLM treatments. Frissen (1979) found that keeping tomato transplants weed-free for the first 24 to 36 days after transplanting was critical to production of a proper yield. Total yields in RCZB and PLM treatments were likely significantly smaller than CT because of weed pressure. Conversely, the initial tillage in the CC treatment provided sufficient weed control for the tomatoes to produce total yields comparable to CT yields.

By Treatment

RCZB. The winter rye biomass averaged 1.7Mg·ha^{-1} and 2.1Mg·ha^{-1} in 2011 and 2012, respectively. Other studies have shown cover crop residue to be sufficient and as effective as herbicide applications in controlling weeds, with control levels contingent on cover crop biomass. Morse (2001) and Hoyt et al. (1994) concluded cover crop biomass of 9.8 - 10.5 and 6.7 - 13.4 Mg·ha^{-1}, respectively, controlled weeds as effectively as plots that had herbicides applied to them. Teasdale and Mohler (2000) showed an exponential relationship between rye mulch biomass and weed populations, concluding that weed suppression is increased by 15% for every 1000kg of cover crop biomass. After noticing low biomass in our 2011 winter rye cover crop, and hearing from several other regional growers that our seeding rate was too low, we increased our winter rye-seeding rate to 184kg·ha^{-1}. Others, however, found that seeding rate did not affect rye biomass (Masiunas *et al.*, (1995). The higher seeding rate increased our biomass by 0.4 megagrams per hectare (Mg·ha^{-1}); but this was still less than one-third of the amount needed for substantial weed suppression. Despite the increased seeding rate, we still ended up with a mulch layer that appeared very similar to the previous year. Weeds continued to be a problem throughout the 2012 growing season. The rye mulch layer slowed weed seed germination for a month after planting, but by July we resorted to mowing to control weed height. Mowing was used for weed control in the treatment for the remainder of the season. Weeds, especially crabgrass, dominated the treatment and stunted the crops. The yield data collected suggests that the RCZB treatment would not be a suitable alternative to the CT treatment. In a study on seeding rate in California, Boyd et al. (2009) found that increasing winter rye seeding rate increased dry biomass early in rye development, but not in the final dry biomass measurements. A similar study by Leavitt el al. (2011) in Minnesota found that winter rye seeded at 51 kg·ha^{-1} reduced weed populations by 95% but also led to reduced yields.

PLM. Where the perennial ryegrass and white clover living mulch was present, it successfully limited and smothered broadleaf weeds. As the experiment progressed, however, it became difficult to control weeds in the transition zone between the PLM and the raised bed. This area saw an increase in weeds, many of which competed with crop production. In 2012, potato leafhopper (*Empoasca fabae*) predation on the clover allowed crabgrass to flourish in late summer. The use of black plastic mulch in the tomato beds for the 2010 season resulted in significantly higher tomato yields than the other three treatments however, the process of installing the plastic had negative effects on the treatment. The use of the plastic mulch layer cut through the perennial living mulch and left a 15 cm swath of bare soil on both sides of the planting bed. Due to these problems, no plastic mulch was used in the tomato plantings after the 2010 season. The subsequent reduction in tomato yields after the 2010 season may suggest the plastic mulches ability to reduce weed pressure led to the higher yields. To overcome the problems with the plastic mulch in the melon and cucumber beds we laid the plastic mulch by hand. This method, while time consuming, proved to be a more effective way of installing the plastic mulch without destroying the perennial living mulch.

There may be two factors contributing to the yield discrepancies between treatments. One possibility is weed pressure. Many studies have investigated various conservation tillage techniques to control weeds (Smith et al., 2011; Brainard et al., 2013; Anderson, 2010; Schulz, 2013). Several studies have found conservation tillage techniques have reduced weed populations, but they have also been found to be associated with yield reductions (Leavitt et al., 2011; Kornecki, 2011). Weed control proved to be a significant factor in our treatments as well. Extensive research has been done on the importance of a critical period of weed interference, and how it affects harvest yields (Swanton et al., 2010; Weaver and Tan, 1983; Knezevic et al., 2002). Our research investigated the cover crop's ability to control weeds between rows, but we did not record data on weeds in the row. In 2011 and 2012, the RCZB was found to have the highest weed populations of any treatment. While these results reflect the inability of a low biomass of winter rye to control weeds, they also show how difficult weed control in a RCZB system can be without herbicides. The PLM treatment however, had the lowest weed populations in 2011, and was not different from the CT treatment in 2012. While these data show the PLM treatment's effectiveness between the rows, weeds within the rows were difficult to control. Weed populations in the CT and CC treatments were reduced by tillage at the beginning of each season. These tillage passes may have been enough to allow the vegetables to get ahead of the weeds and to produce better crops.

Difference in soil health is the other factor that could have had an effect on yield discrepancies. Even though each treatment was fertilized at the same rates, 2012 nitrate levels in the CT and CC treatments were significantly higher than in the RCZB and PLM treatments. Research on no-till systems by Rice et al. (1986) has shown an initial immobilization of nitrogen during the first few years of transitioning to no-till practices. While not a no-till system, the RCZB treatment could have experienced a similar fate when the winter rye was rolled to the soil surface. Soil health reports from Cornell University showed levels of active carbon in the soil were very low in all treatments during all three years of the study. This lack of active carbon slows biological activity in the soil and leads to lower rates of mineralization. Over the course of the three-year experiment, the organic matter levels in the RCZB treatment increased 8% while all other treatments lost 2% to 15% of their organic matter. The loss of organic matter in the CC and CT treatments most likely occurred when treatments were plowed, disked and rototilled. Tillage increases organic matter decomposition by chopping debris into smaller particles and aerating the soil. The tillage passes in the CT and CC treatments could have increased mineralization while the winter rye mulch layer in the RCZB treatment was immobilizing nutrients.

Our data suggests that the crimson clover treatment may serve as a suitable alternative to the conventional treatment. The roller crimper zone builder and perennial living mulch treatments, however, need further exploration to determine a more effective use in mixed vegetable systems. Weed control at the edges of the strip tilled crop row in the roller crimper zone builder and perennial living mulch treatments was very difficult. Further investigation with these treatments should include alternative cultivation techniques that allow for improved weed control at the cover crop and strip till interface.

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Chapter 3

INVESTIGATING DIFFERENCES IN WEED ABUNDANCE BETWEEN CONSERVATION TILLAGE TECHNIQUES AND THE CONVENTIONAL METHOD IN MIXED VEGETABLE PRODUCTION SYSTEMS

This chapter has been formatted for submission to HortScience.

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Introduction

Weed pressure can reduce crop yield and quality, making weed control one of the largest obstacles to a grower's success (Brainard et al., 2013). There are three ways growers can control weeds on their farms: mechanical, cultural, and chemical. Typically, growers use herbicides (chemical) and repeated tillage (mechanical) to control weeds. However, over-reliance on these techniques has led many to question the sustainability of the industrial food system (Montgomery, 2007; Raven, 2002; Reganold et al., 2011). Excessive tillage destroys soil structure, which affects nutrient cycling, microbial habitats, and water infiltration, and reduces organic matter content (Marques da Silva and Alexandre, 2004; McCarthy et al., 1998).

In an attempt to create a more sustainable vegetable production system, conservation tillage methods have recently been studied. Conservation tillage techniques combine the use of cover crops with reduced tillage practices to limit erosion, build healthier soils, and suppress weeds. Cover crops help to provide a year-round cover for the soil and also improve nutrient management. While maintaining soil coverage reduces soil erosion and nutrient runoff, this physical barrier also helps to prevent weed establishment (Teasdale and Mohler, 2000). Cover crops shade the soil, preventing light from reaching weed seeds on the soil surface (Teasdale and Mohler, 1993). Without light, many weeds are not able to germinate. Leavitt et al. (2011) found that rolled winter rye provided effective control of lambsquarter, foxtail, redroot pigweed, and shepherd's purse. Winter rye also produces alleolopathic chemicals that inhibit germination, limit growth, and cause death of certain species (Schulz et al., 2013).

Many studies have been conducted using conservation tillage techniques to reduce weed populations in agronomic crops (Al-Kaisi and Licht, 2004; Brainard et al., 2013; Smith et al., 2011). Agronomic studies, however, often use herbicides to terminate cover crops and control weeds (Smith et al., 2011). Therefore, when vegetable growers began to adopt conservation tillage techniques, many of them continued to use herbicides in this fashion. The yield and weed control results in such studies, however, have been inconsistent. In Alabama, Saini et al. (2008) reported that conservation tillage systems using crimson clover, winter rye, and turnip were unable to control crabgrass, and concluded herbicide use in this system resulted in higher tomato yields. Yield losses were also reported for snapbeans in a no-till and strip-till system in Illinois where herbicide was applied to control the cover crop and weeds (Bottenberg et al., 1999). In contrast, Swenson et al. (2013) found that no-till and strip-till systems using winter rye and wheat as living mulch cover crops produced greater marketable tomato yield than no-till and strip till systems using herbicides. In a no-till system in Kentucky, Cline and Silvernail (2002) reported that no-till, herbicide controlled, winter rye, and hairy vetch/winter rye biculture resulted in 17% and 35% reductions in sweet corn density. The yield per plant in that study, however, was not reduced.

For organic and sustainably-minded vegetable growers, who do not want to use herbicides, conservation tillage techniques need further development. Weed control will be paramount if these growers are to successfully implement such a system. As noted above, studies on no-till methods have shown that cover cropping can reduce weed populations, but that it has also led to reduced yields. Leavitt et al. (2011) found that yields of tomato, bell pepper, and zucchini were reduced by 41% to 92% in a no-till, rolled rye system. Delate et al. (2008), however, observed that organic pepper yields were equal to or greater than conventional production when strip tilled plots were side dressed with additional nitrogen. Ultimately, an effective conservation tillage system would be able to control weeds without sacrificing yields.

The objective of this study is to evaluate three conservation tillage techniques for their ability to effectively control weeds without herbicides. To evaluate the overall effectiveness of the conservation tillage treatments, weed populations and biomasses were compared to the conventional tillage practices. In addition to monitoring the conservation tillage treatments' effectiveness on weed populations, we also evaluated them for their ability to produce yields that are comparable to those of the conventional treatment.

Methods

Plot establishment. This three-year study on conservation tillage techniques was established in the fall of 2009, with weed data collected in 2011 and 2012. Our experiment was conducted at the Greene H. Gardener field experiment station in Kingston, Rhode Island. The experiment was carried out on roughly one half of a hectare of Bridgehampton silt loam soil. A randomized complete block design with three conservation tillage treatments and one conventional treatment was used. Each block of the four treatments was replicated three times. The individual treatments within the blocks were 10 X 30 m. Within each treatment, six 1.5 m wide rows were established. The two outside rows were maintained as buffers between plots, while the four interior rows were planted to vegetables. Each year the vegetable crops shifted one row to the east with the fourth row becoming the first to eliminate the use of the same beds for the same crops over multiple years. In 2011 and 2012 melon / cucumber rows in all treatments except roller crimper zone builder (RCZB) were covered with black plastic mulch. Rain-flo Irrigation® Series II #2550 plastic mulch layer was used to prepare these planting beds. Drip tape with 30 cm emitter spacing was used to irrigate to each crop. All vegetables received one line of drip tape except the carrot / salad row, in which two lines were used.

Treatments

Conventional (CT). Each fall, winter rye was planted at a rate of 123 kg·ha^{-1}. Seeding dates for each field season were the 21st, and 24th days of October 2010 and 2011, respectively. The following spring, the winter rye stand was incorporated using a moldboard plow. After plowing, the plots were disked twice. Five planting beds, 1.5 m in width, were created using the tractor wheelbase as aisles. After planting, weeds were controlled with a tractor-mounted tiller for the empty rows, and an 8hp walk-behind tiller for the walkways and shoulders of the beds. Various hand-weeding tools were used for additional weeding around the crops. Each replication was tilled a total of 3 times in 2011, and 4 times in 2012.

Rolled crimped / zone builder winter rye (RCZB). Each fall, winter rye was planted and overwintered. Winter rye growth the following spring was rolled and crimped as a mulch layer for that season. The 2010 winter rye was seeded at a rate of 123 kg·ha^{-1} on the 20th of October. In 2011, the seeding rate was increased to 184 kg·ha^{-1} to improve cover crop biomass. The 2011 seeding date was the 24th of October. In the spring, the winter rye was rolled at anthesis using a front mounted roller crimper (I & J Manufacturing). After flattening the rye, a zone builder (Monroe Tufline™ 2S-24-60 subsoiler with Unverferth® zone strip coulters and roller basket) was used to make 30 cm wide planting beds within the treatment. Each planting bed, except for the cabbage, was made with one tractor pass using a single shank set 30 cm into the ground. For the cabbage, two zones spaced 30 inches apart were made.

Perennial ryegrass and Dutch white clover perennial living mulch (PLM). In the spring of 2010, a mixture of turf-type perennial ryegrass (27.20 kg·ha^{-1}) and Dutch white clover (2.72 kg·ha^{-1}) was seeded in the aisles between four raised beds. This cover crop was designed to provide perennial soil coverage between the planting rows throughout the course of the three-year experiment. Post harvest, the planting beds were rototilled with a walk-behind tiller and seeded with winter rye at a rate of 123kg·ha^{-1} using a drop seeder. The following spring, the rye was mowed and the beds were rototilled with a walk-behind tiller to prepare them for planting. Each spring, the PLM treatment was reseeded as needed.

Crimson clover annual living much (CC). Each spring the CC plots were plowed and disked twice before planting the vegetable crops. Following vegetable crop planting in June, crimson clover was seeded throughout the plot. The crimson clover seed was mixed with pelletized lime at a 1:2 ratio and seeded at a rate of 25 $kg \cdot ha^{-1}$ using a drop seeder. The crimson clover cover crop was left in place until the following spring when the plot was plowed and disked before being planted.

Vegetable Crops

Tomato. The tomatoes were grown in the URI greenhouse. Seeds were started on the 17th and 21st of April in 2011 and 2012, respectively. The tomatoes were transplanted by hand during the last week of May (2011) and first week of June (2010 and 2012). In 2011, sparrows in the greenhouse damaged several flats of transplants. To make up for the loss, new seeds were started on the 27th of April, and additional tomato transplants were obtained from Confreda's Greenhouses and Farms. The additional plants led to an increase in the number of varieties planted. In 2012, three varieties, 'Celebrity', 'Polbig' and 'Valley Girl,' were chosen for production. Kocide® 3000 and Bravo Weather Stik® were used as needed to control fungal outbreaks. In 2012 Dipel® DF was used to control Lepidoptera species.

Brassicas. The 2011 cabbage crop was hand seeded on the 3rd of June. A double row of 150 plants (300 plants total) spaced 30 cm apart was established in each treatment. Heavy weed pressure in 2011 led us to grow transplants for the 2012 season. The 2012 cabbage crop was started in the URI greenhouse on the 15th of May, before being transplanted into two rows of 150 plants on the 18th of June. The brassicas were sprayed with Dipel® DF as needed to control Lepidoptera species.

Melon / Cucumber. Diplomat (melon) and Marketmore (cucumber) were seeded into 38-cell trays at the URI greenhouse on the 5th and 7th days of May 2011 and 2012, respectively. The row was divided into 6 subplots, alternating melon and cucumber down the row. A total of 54 melons and 42 cucumbers were planted per row in 2011, and 45 melons and 33 cucumbers per row in 2012. Both melons and cucumbers were planted with 60 cm between plants.

Lettuce / Carrot. For 2011 and 2012, 15.5 m and 10 m of carrots were seeded, respectively. Carrot seeding was done using an Earthway® (1001 –B) seeder in 2011, and a Jang (Jang Automation Co., JP-1) seeder in 2012. Four rows of carrots were seeded in each treatment. To seed the lettuce, two passes, 15.5 m in length, were made using a Johnny's six-row seeder. The initial seeding consisted of 10 m sections; it was followed by biweekly plantings that were 3 m in length. Both crops were hand weeded and thinned as necessary. A hand-held weed burner was used to manage the succession planting areas in 2012. Each week, six meters of bed space was burned. For each 3 m planting, weeds were burned twice prior to seeding. After seeding, the beds were watered, and covered with floating row cover. Plots were watered daily until the first true leaf was visible.

Methods of weed control were similar within the crop rows, and relied upon hoeing and other forms of hand weeding. Weed control between the rows varied by treatment.

In the CT treatment, aisle ways were tilled with either a tractor-mounted or an 8hp walk behind tiller. There was not a weed control method designed for between the rows of the RCZB treatment, as the rolled and crimped rye was expected to be enough to smother the weeds. When it proved insufficient, the treatment was mowed at 6 cm to control weed height and seed development. The PLM treatment was mowed to 6 cm on a weekly basis using a walk behind mower. The CC treatment plots were disked and tilled prior to seeding the crimson clover. Post establishment, mowing at 6 cm was used to control crimson clover and weed height.

Weed Observation Data

Beginning at the end of June, monthly weed abundance measurements were calculated in four randomly assigned plots within each treatment. These sampling locations were maintained throughout the season to monitor potential changes to the weed communities within the treatments. Over the course of the year, weed counts were tallied four times for each treatment. Sampling dates were June 24th, July 19th, August 19th, and August 31st in 2011 and June 29th, July 31st, August 28th, and October 1st in 2012. A 1 X 0.5 m grid consisting of 50, 10 X 10 cm squares was used in each plot to determine the abundance of weed species (Fig. 1). Abundance totals were recorded as counts. When one or more plants of the same species appeared within a square, it counted as one occurrence for that species. In 2012, a total of sixteen randomly selected locations per treatment were measured for weed density and biomass. At these sites, a 0.25 X 0.25 m grid was used for species counts of broadleaf weeds present per plot. After this count, all above-ground plant matter was removed at the soil surface. The clippings were then separated into cover crop, grass, or broadleaf weeds, and placed in paper bags. The bags were placed in a drying oven at 50 °C for two weeks, after which a dry weight was recorded.

Fig. 1. A 1 X 0.5 m grid consisting of 50 squares was used to determine total and species abundance of weeds within treatments.

Statistical Analysis

Total population differences between treatments were determined using the repeated measures analysis of variance (ANOVA) procedure in SAS (Statistical Analysis System Inst., Cary, NC) with sampling time as the repeated variable. The PROC GLIMX function in SAS was used to determine differences in weed species populations between treatments. Treatment means were separated ($\alpha = 0.05$) using Fisher's LSD.

Results

Total Weed Abundance by Treatment

There was a significant interaction between treatment and years ($P < 0.0001$) for total weed observances. Therefore, statistical analysis was done individually by year. The total number of weeds observed across all treatments for both years were similar, with 16,187 observations in 2011 and 16,176 observations in 2012. Although the total number of observations in 2012 was similar to the total number of observations in 2011, eleven additional species were observed in 2012. In 2011, the average number of weeds observed per sampling date in the PLM treatment (56) was significantly lower than the CT treatment (118) (Fig. 2).

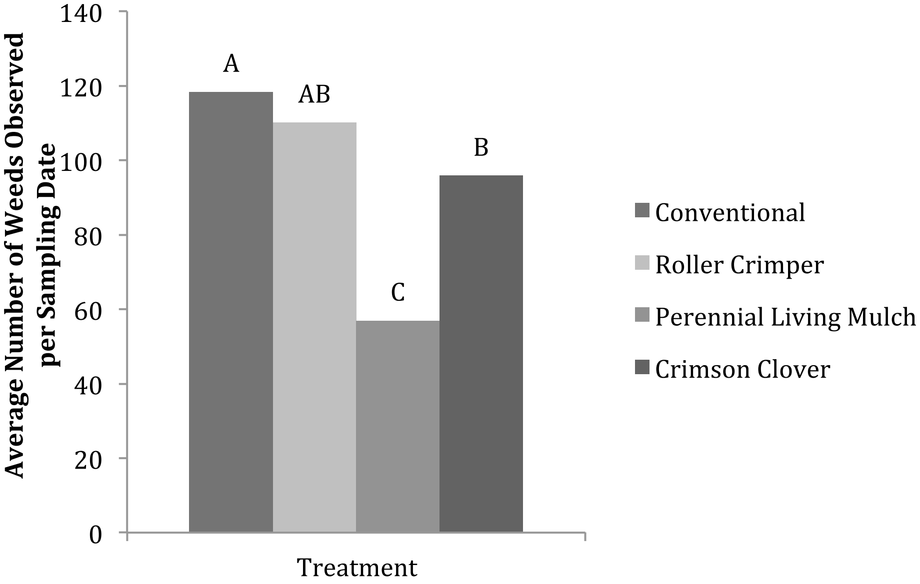

Fig. 2. Average total weed abundance per sampling date by treatment for 2011. Different capital letters show significant difference between treatments.

The number of weeds observed in the CC treatment (95) was also significantly less than in CT. The RCZB treatment (110) was not significantly different from the CT treatment. The 2012 averaged weed totals in the CT (68) and CC (79) treatments decreased 42.37% and 16.85%, respectively, when compared to the 2011 totals. The 2012 averaged weed totals for the PLM (68) treatment, however, increased 21.42% from the 2011 total (Fig. 3). The 2012 average number of weeds observed per sampling date in the RCZB treatment (122) was not different from the 2011 average weed counts. The 2012 average number of weeds observed per sampling date in the RCZB treatment was significantly higher ($P < 0.0001$) than the CT treatment. There were no differences in the average number of weeds observed per sampling date between the CT treatment and the PLM and CC treatments.

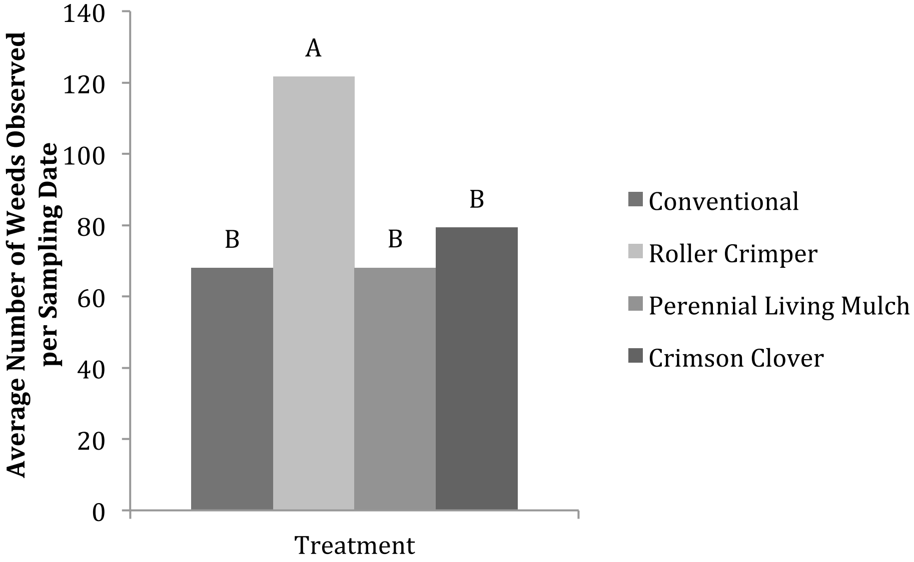

Fig. 3. Average total weed abundance per sampling date by treatment for 2012. Different capital letters show significant difference between treatments.

By Species

In 2011, a total of 23 species of weeds were observed, with the five most abundant species making up 75% of the total weeds observed. In 2012, a total of 34 weed species were observed, with the five most abundant species responsible for 70% of the total weed observations. The four most prevalent species for both years were: crabgrass (*Digitaria spp.* Haller), lady's thumb (*Polygonum persicaria* L.), purslane (*Portulaca oleracea* L.), and redroot pigweed (*Amaranthus retroflexus* L.). Carpetweed (*Mollugo verticillata* L.), and ragweed (*Ambrosia artemisiifolia* L.) were the fifth most prevalent weeds in 2011 and 2012, respectively (Table 1). Crabgrass was the overall most abundant weed in our fields, making up 42% and 44% of the total weed observations in 2011 and 2012, respectively.

Table 1. Average weed count in each treatment by species for the 2011 and 2012 growing seasons.

	Mollugo verticillata	*Digitaria spp.*	*Polygonum persicaria*	*Portulaca oleracea*	*Amaranthus retroflexus*	*Ambrosia artemisiifolia*
2011						
Conventional	12 a[z]	42 b	10 a	18 a	19 a	-
Roller Crimper	1 b	46 a	4 b	4 c	2 d	-
Perennial Living Mulch	1 b	27 b	10 a	1 d	3 c	-
Crimson Clover	9 a	46 a	11 a	9 b	7 b	-
2012						
Conventional	-	27 c	6 a	8 a	8 a	1 b
Roller Crimper	-	47 a	4 a	0 b	1 b	10 a
Perennial Living Mulch	-	40 b	5 a	1 b	2 b	2 b
Crimson Clover	-	36 b	11 a	9 a	6 a	0 c

[z] Different lower case letters denote significant difference between weed species by treatment.

The 2011 CT treatment had significantly higher carpetweed, purslane, and redroot pigweed observations than all other treatments. When compared to the CT treatment, the RCZB treatment showed significantly reduced populations of carpetweed, lady's thumb, purslane, and redroot pigweed. The RCZB crabgrass observations, however, were significantly higher than all other treatments. The PLM treatment effectively controlled all of the broadleaf species, tallying significantly lower numbers than CT and CC treatments in all species but lady's thumb. PLM crabgrass observations were the lowest of all treatments. The total was significantly lower than the RCZB and CC treatments. It was not, however, significantly different from the CT treatment's observations.

Broadleaf weed control in 2012 was similar to the 2011 results. No significant differences (*P* between 0.1631 and 0.4294) were found between the CT and the CC treatments weed counts of carpetweed, purslane, and redroot pigweed. The CT treatment had significantly larger ($P < 0.0001$) populations of these three weeds than the PLM and RCZB treatments. The PLM and RCZB treatments showed effective control of carpetweed, purslane, and redroot pigweed with average counts ranging from 1% to 25% of the CT treatments averages. Lady's thumb counts showed no significant difference (*P* between 0.3257 and 0.8831) between all treatments. The RCZB treatment, again, showed poor control of crabgrass and had a significantly higher amount than all other treatments. The 2012 CT treatment showed the best control of crabgrass and was significantly lower ($P < 0.0001$) than all other treatments. The RCZB, PLM, and CC treatments' crabgrass averages ranged from 36% (CC) to 77% (RCZB) greater than the CT treatment.

Weed and Cover Crop Biomass

The abundance counts obtained for broadleaf weeds in the 0.25 X 0.25 m plots were similar to those of the 1 X 0.5 m quadrat (Fig. 4). The average total broadleaf weed counts per treatment showed that the CT treatment had significantly more ($P = 0.3275$) broadleaf weeds than all other treatments, while the PLM treatment had the fewest. When evaluated for differences between treatments by species, the results were found to be similar to the larger quadrat. Five weed species continued to comprise the majority of the total weed counts. Four of the five – carpetweed, lady's thumb, purslane and redroot pigweed – were the same as those observed when using the 1 X 0.5 m quadrat. The smaller quadrat however, showed elevated populations of chickweed (*Stellaria media* L.). No significant differences were found between treatments in lady's thumb abundance.

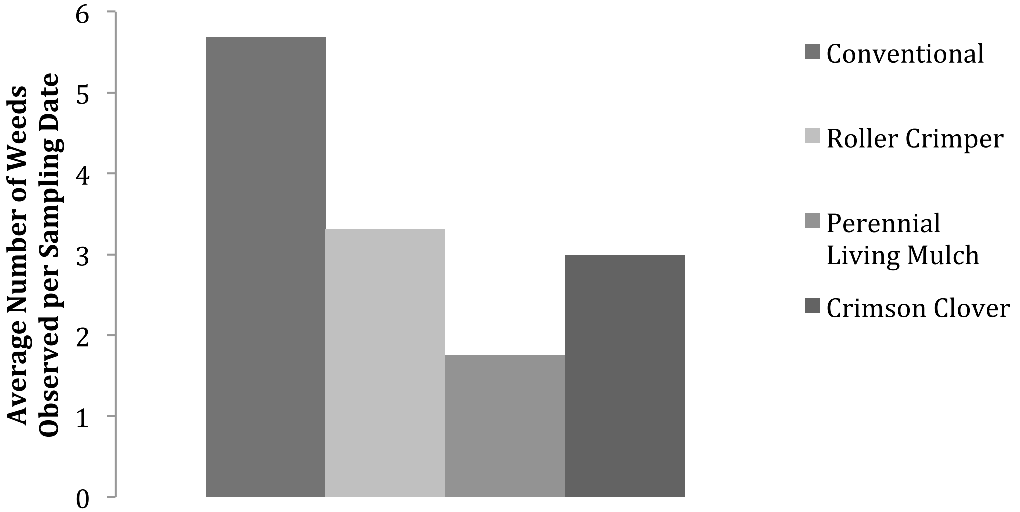

Fig. 4. Average total weed abundance per sampling date by treatment as observed in the 0.25 X 0.25 m grid. Total weed abundance in the CT treatment was significantly higher than the conservation tillage treatments.

The purslane population in both the PLM and the RCZB treatments was 9% and 24%, respectively, of the CT treatment total counts. No differences in purslane averages were found between the CC and CT treatments. Carpetweed and redroot pigweed populations in the PLM and the RCZB treatments were also lower, ranging from 0% to 3% of the averages in the CT treatment. The averages for carpetweed and redroot pigweed in the CC treatment were also significantly lower, 19% to 59% respectively, than the CT treatment. Differences in crab grass coverage were calculated using the biomass collected from each plot. Over the course of the season, the crabgrass biomass in the RCZB and CC treatments was significantly higher (*P* = 0.0006, and 0.0062) than that of the CT treatment (Table 2). The PLM crabgrass biomass was not significantly different (*P* =0.0952) from the CT treatment. The biomass of broadleaf weeds in the PLM treatment was significantly lower (*P* between 0.0084 and 0.0223) than that of all the other treatments. There were no significant differences (*P* between 0.6098 and 0.9682) between the broadleaf weed biomass of the RCZB, CC, and CT treatments.

Table 2. Average dry biomass measurements of broadleaf and grass weeds, and cover crops for 2012. Different lower case letters show significant differences between treatments.

	Grass (g)		Broadleaf (g)		Cover Crop (g)	
Conventional	6.59	c^z	3.54	a	0.00	c
Roller Crimper Zone Builder	11.54	a	4.02	b	14.22	a
Perennial Living Mulch	8.53	bc	1.12	a	10.12	b
Crimson Clover	10.14	ab	3.58	a	0.65	c

^{z} Lower case letters show significant differences in dry weights between treatments.

The cover crop biomass in the RCZB treatment was significantly greater than that of all other cover crop treatments. The cover crop dry weight in the PLM treatment was significantly higher (*P* < 0.0001) than that of the CC treatment. Poor establishment of crimson clover in the CC treatment in 2012 resulted in no significant differences (*P* = 0.3275) between the CC treatment cover crop biomass and the CT treatment, where no cover crop was used.

Discussion

The total weed abundance per plot can provide information on how well a treatment is able to control weeds. The total weed count averages per sampling date suggest that the CT and PLM treatments were more effective at controlling weeds than the CC and RCZB treatments. In 2012 the total weed count per sampling date was 68, for both the CT and PLM treatments. This was 17% and 79% lower than the CC (79) and RCZB (122) treatments, respectively. An additional tillage pass in the CT treatment in 2012 reduced total weed averages to nearly one half of their observed total from 2011. This reduction may have also played a significant role in reducing weed populations at the beginning of the season in the CC treatment.

Controlling weeds within the row was a problem in the RCZB treatment. The narrow strips were difficult to weed by hand once the crops began maturing. The RCZB treatment was able to effectively control the five most prevalent broadleaf weed species, but the total number of weeds within the treatment, both in the row and between the rows, likely had a large effect on yield.

When evaluating for total weed observations, the RCZB was ineffective in 2012, and although not significantly different from the CT or CC treatments in 2011, the treatment did not significantly reduce weed populations. Leavitt et al. (2011) found that a dried winter rye biomass of 5.3 $Mg \cdot ha^{-1}$ was sufficient to reduce weed populations by 96% at one site, while the other site showed no significant differences. The average weight of dried biomass for this experiment was 1.9 and 2.1 $Mg \cdot ha^{-1}$ in 2011 and 2012, respectively, suggesting a reason to explain why our RCZB treatment was not able to effectively control weeds. Teasdale and Mohler (2000) found an exponential relationship between weed suppression and cover crop mulch biomass, with greater levels of mulch resulting in greater weed prevention. Although the rye-seeding rate was increased in 2012, the resulting biomass was still insufficient for suitable weed control. Seeding winter rye earlier in the fall would prove to be a more appropriate method for producing a larger cover crop biomass. Researchers in New York concluded that winter rye over-seeded into fall cabbage resulted in no yield loss, accumulated 90 $kg \cdot ha^{-1}$ of nitrogen, and 3 - 5 $Mg \cdot ha^{-1}$ of dried biomass that covered 80% of between-row space (Balkcom et al., 2007).

The RCZB treatment was ineffective at *Digitaria spp*. control, with significantly greater occurrence than the CT treatment in 2011 and 2012. In general, *Digitaria spp*. was very difficult to control in all of our plots. In Alabama, problems with *Digitaria spp.* were also noted as a major concern in strip till systems where no herbicides were used (Saini et al., 2008). While no herbicides were used in our study, an application of grass-specific herbicide would have removed over 40% of our weed problem, and should be considered in areas that are known to have difficulties with *Digitaria* spp. and similar grass species.

The PLM treatment proved to be better than, or as effective as, the tillage weed control in the CT treatments. Although there were no biomass numbers for 2011, the PLM treatment seemed to decline in 2012, and may benefit from shorter growing intervals between reestablishment, especially in areas of high weed pressure. After three seasons of compaction from both the tractor and heavy foot traffic, the treatment seemed to develop small patches that failed to provide proper coverage. These areas were re-seeded in an attempt to re-establish the void patches, but this proved more difficult than we anticipated. The PLM treatment's raised beds excelled at diverting water from pooling around crops, and the cover crop provided an easy-to-identify traffic area for each aisle. If the raised beds are too high, however, it can become difficult to mow between them. Many times mowing in our plots had to be accomplished by raising one set of wheels onto the bed top while the other set of wheels remained in the bottom of the trough. Mowing in this manner caused a lot of scalping on the bed shoulders, removing the cover crop treatment from a critical area of weed control. In fact, the majority of the weeds that interfered with the crops originated from this scalped area. If the beds had been lower and the aisles wider, weed control on the shoulders of the bed may have been better and led to greater yields.

The importance of tillage has already been noted with weed control in the CT treatment, and this may have also been a factor with the weed control in the CC treatment. With the spring soil preparation being similar between the two treatments, it is plausible to conclude that the tillage to prepare the CC treatment for seeding the cover crop was sufficient to curtail weed development around the plants. Crimson clover has been shown to fix 78 to 168 kg $N \cdot ha^{-1}$ (Balkcom et al., 2007). This additional nitrogen could have provided extra nutrients, and led to increased yields in 2011 and 2012. The low biomass of the 2012 cover crop showed that difficulties do exist with the CC treatment. Timing of establishment proved to be the most challenging aspect. To avoid trampling and increased seedling death from workers and equipment, all of the vegetable crops were planted prior to seeding the crimson clover. While this method allows the vegetables a chance to establish and get a jump-start on the weeds and the cover crops, weather and scheduling delays have the potential to make this technique risky. While there were no problems with establishment in 2010 and 2011, a lack of rain in 2012 lead to poor crimson clover germination. The crop was re-seeded, but late spring temperatures had become too warm and caused poor germination, leading to the failure of a suitable cover. Establishing a strong stand prior to the time that the crops are planted may prove more effective however, competition between cover and cash crops can become a problem. Studies have shown that crimson clover is less tolerant of mowing than other clovers (Balkcom et al., 2009). Mowing or strip tillage to suppress crimson clover in the planting row may prove beneficial for spring planted vegetable production. Further experimentation should include seeding just after the danger of last frost passes to ensure a better crimson clover stand.

Crop yield reductions related to weed pressure have been studied extensively with the critical period for weed control (CPWC) evaluated for most crops. Weaver and Tan (1983) determined that transplanted tomatoes required 4 to 5 weeks without weed competition after transplanting. Transplants that were not sufficiently weeded showed significant reductions in plant dry weight and fruit number. The yield reductions in their study were attributed to shading, not water stress. Swanton et al. (2010) concluded the

CPWC for carrots was dependent on seeding date, with earlier seeding dates requiring longer periods of monitoring than those seeded later. While weed prevention through cover cropping and reduced tillage in the aisles is important and can limit soil loss, improve soil health, and save time and money by controlling weeds, our study did not collect data on weed pressure within the cropping rows, and how it may relate to crop productivity. Further investigation should incorporate both in-row and aisle weed pressure, as well as labor hours spent weeding, before making further recommendations on adoption or implementation of the treatments.

Based on our findings, the RCZB treatment was ineffective at controlling weeds when compared to the CT treatment. The PLM treatment was very effective at controlling weeds in the aisle way, although improved techniques for weed management at the aisle and planting bed interface are needed. This could be achieved by lowering the raised bed height, and/or widening the aisle ways between planting rows. The PLM cover crop also needs to be monitored for spots of poor establishment. This treatment was found to be a suitable replacement for the CT treatment in cucumber, melon and lettuce production systems. The CC treatment, despite the poor cover crop establishment in 2012, showed that it was a suitable replacement for the CT treatment for all the vegetables grown in this trial. A technique embracing earlier cover crop seeding dates is encouraged, however, as it may help to improve the cover crop stand, which would offer better weed control.

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Chapter 4

COMPARING SOIL HEALTH, RESPIRATION, AND NITRATE BETWEEN CONSERVATION TILLAGE AND CONVENTIONAL TILLAGE METHODS IN MIXED VEGETABLE PRODUCTION SYSTEMS

This chapter has been formatted for submission to HortScience.

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Introduction:

Tillage is used in a variety of ways in vegetable production systems. In the spring, growers often use primary tillage, such as a moldboard plow, to turn the soil, incorporating crop and weed debris. Primary tillage is then followed by secondary tillage, such as disking, to further prepare the soil for planting. After planting, roto-tillers and cultivators are used to control weeds throughout the season. This repetitive tillage regime can lead to poor soil conditions, making the soil less productive over time. Tillage adversely affects soil structure, breaking down soil aggregates and increasing potential for erosion. Pagliai et al. (2004) found that conventional tillage systems reduced soil porosity at both the surface and lower cultivation depths, which resulted in less stable aggregates and soils that were more prone to surface crusting. They found that this reduced porosity and surface crusting affects water infiltration, which decreases seed germination rates.

Sustainable agriculture techniques were developed to address problems associated with excessive tillage. By using cover crops and minimizing the amount of tillage to help reduce erosion rates, growers can increase soil fertility and improve the sustainability of their farms. Large-scale commodity growers were the first to adopt sustainable agriculture techniques, but recent advances in equipment have led to greater use in vegetable production systems (Hoyt, 1999). For example, strip tillage practices have helped to overcome many of the initial problems vegetable growers were having with sustainable techniques. Strip tilling creates a small planting area within the suppressed cover crops. The tilled strip allows the soil to dry more quickly and warm more quickly than no-till system (Licht and Al-Kaisi, 2005), making soil conditions more suitable for vegetable production.

When combined with cover cropping, conservation tillage has been shown to be an effective technique to help reduce off-farm inputs, such as fertilizer, in addition to decreasing soil erosion, reducing nutrient runoff, and reducing weed populations (Newman et al., 2008). Conservation tillage techniques involve cover crops to preserve soil coverage, which affects the habitat and resources available to soil fauna. The large amount of biomass left on the soil surface from cover crops provides soil coverage and has a large effect on soil nutrient cycling and microbial populations. Reicosky et al. (1995) found organic matter levels in the first 5 cm of the soil were significantly increased in no-till systems. Higher levels of organic matter in no-till systems led to higher carbon levels, resulting in a larger microbial biomass and increased respiration rates at the soil surface (Doran, 1980). Increased carbon levels also led to larger communities of fungi, which dominate as the primary decomposers. They found this to be the opposite for conventionally tilled systems where bacteria tend to be more abundant in the soil (Coleman et al., 1994). Fewer disruptions to the soil in conservation tillage systems preserves soil structure and the macropore channels that healthy soil macrofauna create (Coleman et al., 2001). Understanding how conservation tillage practices influence biological and physical components of the soil can also help growers understand nutrient availability.

Nitrogen management on farms is very important as it is not only an essential component for plant growth and development, but if it is not managed correctly, nitrate run-off can lead to environmental impacts such as water pollution. With energy prices rising, nitrogen has become the most expensive input on the farm (Tester and Langridge, 2010). Understanding how to manage the carbon:nitrogen ratio in the soil is an important aspect of conservation tillage techniques. Research has shown that soil transitioning to no-till practices often results in a stratification of organic matter. McCarthy et al. (1998) found that this stratification happens rapidly, causing increases in total and biomass nitrogen, in addition to organic and biomass carbon on the soil surface, while also noting decreases of these same components at lower soil depths. In Michigan, Haramoto and Brainard (2012) found that inorganic nitrogen availability in conventional tillage plots was elevated for three weeks after tillage and was greater than the levels found in the strip tilled plots. They also observed that strip tilled plots with cover crops had the lowest levels of inorganic nitrogen in their trial.

Soil nutrient management is complex and can be a difficult for growers to monitor, and quick, inexpensive on-farm tools to assist growers with this management are scarce. In an attempt to assuage this need, universities and private companies have been developing techniques to help growers better understand their soil and nutrient needs. To offer a more complete picture of soil analysis, the Cornell Nutrient Analysis Laboratory (CNAL) has developed a soil health test that provides growers with physical, biological, and chemical analyses. The comprehensive results from this test provide results that help growers understand their soils’ needs and how a holistic management system could benefit their production methods.

Woods End Laboratory has developed the Solvita soil respiration test to address the need for analysis of biological activity in the soil. This test may be an important tool for growers looking for better ways to increase their sustainability by managing their soil fertility according to the crops’ needs. Haney et al. (2008) determined that Solvita test results were highly correlated with one-day titration and cumulative 28-day CO_2 respiration rates. Their data also suggested that the CO_2 measured using the Solvita test accurately reflected the carbon, nitrogen, and phosphorus titration levels in the soil. Knowing the soil respiration rates can also help to determine the fate of organic matter and nutrient availability in the soil.

Soil nutrient management is a key component to increasing sustainability in agriculture. Developing systems that maximize on-site inputs, such as cover crops, and cultivation techniques that reduce excessive working of the soil play a large role in this effort. The objective of this three-year study on cover cropping and reduced tillage techniques for mixed vegetable production in Southern New England is to determine the effects of various conservation tillage and cover crop treatments on (i) soil health, (ii) soil nitrate levels, and (iii) soil respiration throughout the growing season.

Methods:

Plot establishment. This three-year study on conservation tillage techniques was established in the fall of 2009, with all data collection beginning in 2010. Our experiment was conducted at the Greene H. Gardener field experiment station in Kingston, Rhode Island. The experiment was carried out on roughly one half hectare of Bridgehampton silt loam soil. A randomized complete block design with three conservation tillage treatments and one conventional treatment was used. Each block of the four treatments was replicated three times. The individual treatments within the blocks were 10 X 30 m. Within each treatment, six 1.5 m wide rows were established. The two outside rows were maintained as buffers between plots, while the four interior rows were planted to vegetables. Each year the vegetable crops shifted one row to the east with the fourth row becoming the first to eliminate the use of the same beds for the same crops over multiple years. In 2011 and 2012, melon / cucumber rows in all treatments except roller crimper zone builder (RCZB) were covered with black plastic mulch. Rain-flo Irrigation® Series II #2550 plastic mulch layer was used to prepare these planting beds. Drip tape with 30 cm emitter spacing was used to irrigate to each crop at a rate of 2.54 cm per week. All vegetables received one line of drip tape except the carrot / salad row, in which two lines were used.

Treatments

Seablend® fertilizer (7-5-5) was used to fertilize all treatments and vegetables in 2011 and 2012. In 2011, Seablend® was applied at a rate of 45 kg $N \cdot ha^{-1}$. The fertilizer rate for 2012 was increased to 70 kg $N \cdot ha^{-1}$. An additional 15 kg N·ha^{-1} was applied to all vegetable crops on the 10th of July. Each year, Organic Gem® (3-3-0.3) fish emulsion was used as supplemental fertilizer. The fish emulsion was applied every 7 to ten days at a rate of 47 l·ha^{-1} by fertigation.

Conventional (CT). Each fall, plots were disked twice and winter rye was planted at a rate of 123 kg·ha^{-1}. Seeding dates for each field season were the 20th, 21st, and 24th days of October (2009, 2010, and 2011) respectively. The following spring, the winter rye stand was incorporated using a moldboard plow. After plowing, the plots were disked twice. Five planting beds, 1.5 m in width, were created using the tractor wheelbase as aisles. After planting, weeds were controlled with a tractor-mounted tiller for the empty rows, and an 8hp walk-behind tiller for the walkways and shoulders of the beds. Various hand-weeding tools were used for additional weeding around the crops. Each replication was tilled a total of 3 times in 2011, and 4 times in 2012.

Roller Crimper Zone Builder (RCZB) In the fall of each growing season, the plots were disked twice and seeded with winter rye. Winter rye was seeded at a rate of 123 kg·ha^{-1} on the 20th and 21st days of October (2009 and 2010) respectively. In 2011, the winter rye was seed on the 24th of October. The seeding rate was increased to 184 kg·ha^{-1} to increase the cover crop biomass. Each spring, the winter rye was rolled at anthesis using a front mounted roller crimper (I & J Manufacturing). . After flattening the rye, a zone builder (Monroe Tufline™ 2S-24-60 subsoiler with Unverferth® zone strip coulters and roller basket) was used to strip till 30 cm wide planting beds within the treatment. After the strip till zones were established the treatment was not cultivated between the rows. Hand weeding was done to control weeds within the planting rows.

Perennial ryegrass and Dutch white clover perennial living mulch (PLM). In the spring of 2010, a mixture of turf-type perennial ryegrass (27.20 kg·ha^{-1}) and Dutch white clover (2.72 kg·ha^{-1}) was seeded in the aisles between four raised beds. This cover crop was designed to provide perennial soil coverage between the planting rows throughout the course of the three-year experiment. Post harvest, the planting beds were rototilled with a walk-behind tiller and seeded with winter rye at a rate of 123kg·ha^{-1} using a drop seeder. The following spring, the rye was mowed and the beds were rototilled with a walk-behind tiller to prepare them for planting. Each spring, the PLM treatment was reseeded as needed. Biweekly mowing was used to control weeds and cover crop height in the aisles during the growing season. Weed control within the planting beds was done by hand.

Crimson clover annual living much (CC). In the spring the CC plots were plowed and disked twice before planting the vegetable crops. Following vegetable crop planting, in June, crimson clover was seeded throughout the plot. The crimson clover seed was mixed with pelletized lime at a 1:2 ratio and seeded at a rate of 25 kg·ha^{-1} using a drop seeder. Vegetable and cover crop plant residue was left on the soil surface until the following spring when the plot was plowed and disked before being planted.

Vegetable Crops

Tomato. All of the 2010 tomato transplants were provided by Confreda's Greenhouses and Farms (Hope, RI). In 2011 and 2012, the tomatoes were grown in the URI greenhouse. Seeds were started on the 17th and 21st of April (2011 and 2012) respectively. The tomatoes were transplanted by hand during the last week of May (2011) and first week of June (2010 and 2012). In 2011, additional tomato transplants were obtained from Confreda's Greenhouses and Farms.. Kocide® 3000 and Bravo Weather Stik® were used as needed to control fungal outbreaks. In 2012 Dipel® DF was used to control Lepidoptera species.

Brassicas. A double row of 150 plants (300 plants total) spaced 30 cm apart was established in each treatment. In 2010, broccoli was directly seeded in the spring. For 2011, cabbage was hand seeded on the 3rd of June. The 2012 cabbage crop was started in the URI greenhouse on the 15th of May, before being transplanted on the 18th of June. The brassicas were sprayed with Dipel® DF as needed to control Lepidoptera species.

Melon / Cucumber. Melon and cucumber varieties were seeded into 38-cell trays at the URI greenhouse on the 9th, 5th, and 7th days of May 2010, 2011, and 2012, respectively. A total of 54 melons and 42 cucumbers were planted per row in 2011, and 45 melons and 33 cucumbers per row in 2012. Both melons and cucumbers were planted with 60 cm between plants.

Lettuce / Carrot. In 2010, the 50 m row was equally divided into lettuce and carrot plantings. For 2011 and 2012, 15.5 m and 10 m of carrots were seeded, respectively. Carrot seeding was done using an Earthway® (1001 –B) seeder in 2010 and 2011, and a Jang (Jang Automation Co., JP-1) seeder in 2012. After seeding, the beds were watered and covered with floating row cover. Plots were watered daily until the first true leaf was visible.

Cornell Soil Health Test:

Soil samples were collected each April (2010, 2011, 2012, and 2013) prior to the start of the growing season. The initial sampling in 2010 was conducted in the three replication blocks to provide a set of baseline conditions. For the remaining years, each treatment within each replication was sampled individually. All samples were sent to Cornell University's Nutrient Analysis Laboratory (CNAL) for soil health test evaluations. Analysis of soil nutrients, pH, and organic matter were also performed as part of the Cornell Soil Health Test. The soil was collected using the "W" method as suggested by CNAL. At each sampling site a hole, 15cm deep, was made using a hand trowel. The loosened soil was stirred to maximize homogeneity and 600 mL were extracted and placed in a one gallon interlocking plastic bag. The results from each sample were used to establish an understanding of the changes in physical, biological and chemical conditions of the soil over the course of this study.

Solvita:

Starting in 2011, biweekly soil samples were collected and analyzed for respiration using the Solvita soil health kit. Forty-eight sampling sites were established across the field, with each treatment having four sampling sites in each replication (12 total across all three replications). Within the treatments, two sampling sites were randomly selected in both the lettuce and tomato rows. Six soil core samples to a depth of 15cm were collected from each sampling site. The samples were combined in a paper bag, weighed and dried for 30 hours at 50 °C. The dried samples were weighed and then crushed using a mortar and pestle. The samples were then hand shaken through a 250 mm mesh sieve for twenty seconds.

Fig. 1. Emily Cotter weighing and measuring dried soil samples for the Solvita soil respiration test.

Forty grams of sieved soil were isolated from each sample (Fig 1). A small cellulose filter was placed in the bottom of a 50 mL plastic beaker that had three holes drilled in the bottom. 25 mL of de-ionized water was added to a screw top, 250 mL glass jar. The 40 g of soil were then poured into the plastic beaker and the plastic beakers were placed inside the glass jars. Solvita low soil CO_2 paddles were placed in the soil and the jars were sealed. The jars were placed out of direct light in a temperature-controlled room at 21 °C. After twenty-four hours, the Solvita paddles were removed and read with the Solvita digital color reader.

Five samples were randomly selected and sieved twice to test for any differences between different sieve sizes. First, we shook the pulverized soil through a 2mm mesh screen and separated 40 g from the sample. The remainder was sieved again using the 250 mm mesh screen and another 40 g of soil was isolated from this. Four additional, randomly selected samples were run through the 250 mm mesh screen as split samples for each biweekly test.

Nitrate:

An additional 20 g of sieved soil was set aside for nitrate analysis. The intent was to use an ion selective electrode to obtain soil nitrate levels. Soil Testing Procedures for the Northeastern United States (University of Delaware, 1995) suggests using a 0.04 M ammonium sulfate solution to extract the nitrate from the samples when using a nitrate selective probe. To extract the nitrate, 50 mL of extractant was added to the 20 g of soil. It was stirred for 15 minutes and then filtered (Fisher Scientific P4) twice. Approximately 25 mL samples were then frozen to be analyzed at a later date.

After experiencing a considerable amount of difficulty with the selective ion probe in 2011, a spectrophotometric analysis method was adopted. As all of the 2011 nitrate extraction was completed using the 0.04 $(NH_4)_2SO_4$ M solution, we continued using this extraction method for the 2012 samples. For spectrophotometric nitrate analysis a vanadium (III) acid solution was used. One hundred microliters of sample was pipetted into 96 well plates, each well having a 500 ml capacity. An additional 100 mL of the vanadium (III) solution was then added to each sample. The samples were allowed to sit at room temperature for five hours. The plates were then analyzed at 540 nm using KC Junior Nitrate analytical software.

Statistical Analysis

Statistical differences for Solvita and nitrate data were determined using analysis of variance (ANOVA) procedure in SAS (Statistical Analysis System Inst., Cary, NC), with sampling time as the repeated variable. Solvita tests comparing differences between smaller and larger screen sizes were compared using a one-way ANOVA in SAS. Treatment means were separated ($\alpha = 0.05$) using Fisher's LSD. Differences between treatments with the Cornell Soil Health Test results were evaluated by percent change over the three-year study.

Results:

Solvita:

There was a significant interaction ($P < 0.0001$) between treatments by year; therefore, differences between treatments were analyzed separately by year.

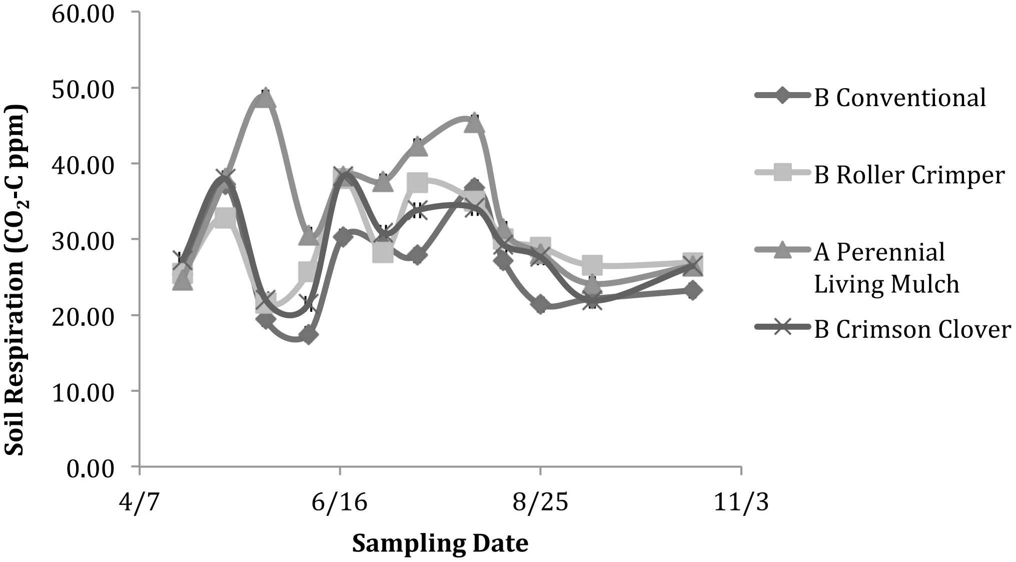

Fig. 2. Solvita soil respiration (CO_2-C ppm) curves for the 2011 growing season. Different capital letters in the legend show significant differences between treatments.

The CO_2 respiration rates in the PLM treatment averaged 34.62 ppm in 2011. This respiration rate was significantly higher than the CT treatment, which averaged 26.47 ppm over the same time period. The CO_2 respiration rates for the RCZB and CC treatments were 29.72 and 29.26 ppm, respectively, and were not significantly different from the CT treatment. In 2012 (Fig. 2), the CT treatment had significantly lower soil respiration rates (23.93 ppm) than the other three treatments. The 2012 CO_2 respiration rate (35.42 ppm) for the RCZB treatment was significantly higher than all other treatments. The CO_2 respiration rates for the PLM and CC treatments in 2012 were 31.50 and 28.42 ppm respectively, and were not significantly different from one another. Both of these values were, however, significantly higher than the CT treatment from the same year (Fig. 3).

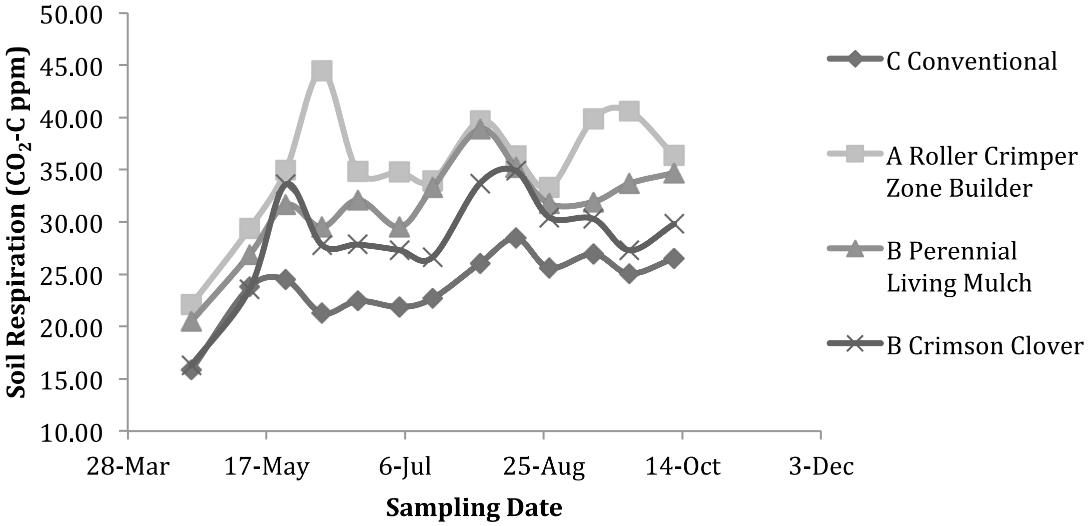

Fig. 3. Solvita soil respiration (CO_2-C ppm) curves for the 2012 growing season. Different capital letters in the legend show significant differences between treatments.

Cornell Soil Health Test:

Chemical indicator results showed little change over the three-year study. The levels of extractable potassium were of concern in 2010 but the following year levels increased to satisfactory and remained unchanged for the remainder of the study. The physical indicators, surface and subsurface hardness, were variable over the study. No treatments were found to have hardness levels that would have restricted plant growth. Aggregate stability was the physical indicator that had the largest difference between treatments. Average aggregate stability values in the RCZB treatment were 15% higher than the CT treatment. The aggregate stability in the CT treatment was not different from the PLM treatment, but the aggregate stability in the CC treatment was 10% lower than in the CT treatment. Available water holding capacity exceeded the CT treatment by 1% in the RCZB, 5% in the PLM, and

6% in the CC treatments, respectively, and was therefore not dramatically affected by treatment.

All biological indicators were found to vary across treatments (Table 1). Percent organic matter in the conservation tillage treatments was 12% (RCZB), 3% (PLM), and 6% (CC) higher than the organic matter in the CT treatment. Active carbon levels in the soil showed similar results as the levels in the conservation tillage treatments were 16% (RCZB), 9% (PLM), and 10% (CC) higher than in the CT treatment. In our soil, the amount of active carbon was found to be a constraint in all treatments in all years and treatments except the RCZB treatment in 2012. Potentially mineralizable nitrogen was another biological factor that was found to be low in all treatments. The potentially mineralizable nitrogen levels in the RCZB and PLM treatments were 54% and 16% higher, respectively, while the CC treatment was 15% lower than the CT treatment. Root health ratings in all three conservation tillage treatments were found to be 7% (RCZB), 10% (PLM), and 20% (CC) lower than the CT treatment. All three conservation tillage treatments were found to have better overall soil health characteristics than the CT treatment, and the RCZB treatment had the highest overall average score.

Table 1. Biological indicators for soil health as measured by the Cornell Nutrient Analysis Laboratory

	% Organic Matter	Active Carbon (ppm)	Potentially Mineralizable Nitrogen	Root Health Rating
2010				
Baseline averages of soil health sampled prior to establishing treatments	3.10	344.67	11.97	6.63
2011				
Conventional	3.30	379.50	7.70	3.75
Roller Crimper Zone Builder	3.37	389.33	9.07	4.27
Perennial Living Mulch	3.13	371.67	6.57	3.73
Crimson Clover	3.40	387.67	9.33	4.67
2012				
Conventional	2.90	379.33	15.27	4.77
Roller Crimper Zone Builder	3.27	414.33	22.57	4.70
Perennial Living Mulch	3.03	381.33	17.77	4.77
Crimson Clover	3.27	453.67	13.27	3.70
2013				
Conventional	2.63	333.67	7.80	5.27
Roller Crimper Zone Builder	3.37	451.00	17.67	5.27
Perennial Living Mulch	3.07	426.67	13.53	5.27
Crimson Clover	2.80	348.00	4.80	3.93

The RCZB treatment, the treatment with the least tillage, was the only treatment over the three-year study to maintain the baseline percent organic matter that was established in 2010. In 2013, all of the reduced tillage treatments had a greater percentage of organic matter (4-27% more) than the CT treatment.

Nitrate:

There were significant interactions ($P < 0.0001$) between treatment and year for nitrate levels, so nitrate levels were analyzed separately by year. Nitrate levels in 2011 averaged 1.44 ppm across all treatments, while 2012 nitrate levels averaged 4.54 ppm (Table 2).

Table 2. Average nitrate levels (NO_3-N ppm) for the 2011 and 2012 seasons.

Treatment	2011		2012	
Conventional	1.41	a[z]	4.64	a
Roller Crimper	1.25	a	2.84	b
Perennial Living Mulch	1.19	a	3.23	b
Crimson Clover	1.89	b	7.46	c
Avg. Seasonal Nitrate Levels Across Treatments	1.44		4.54	

[z] Different lower case letters show significant difference between treatments.

The highest recorded nitrate levels occurred in late June and early July. In 2011, the highest averaged nitrate level (4.62 ppm) of any date was on June 29th in the CC treatment (Fig. 5). The CC treatment had significantly higher nitrate levels than the other three treatments in 2011.

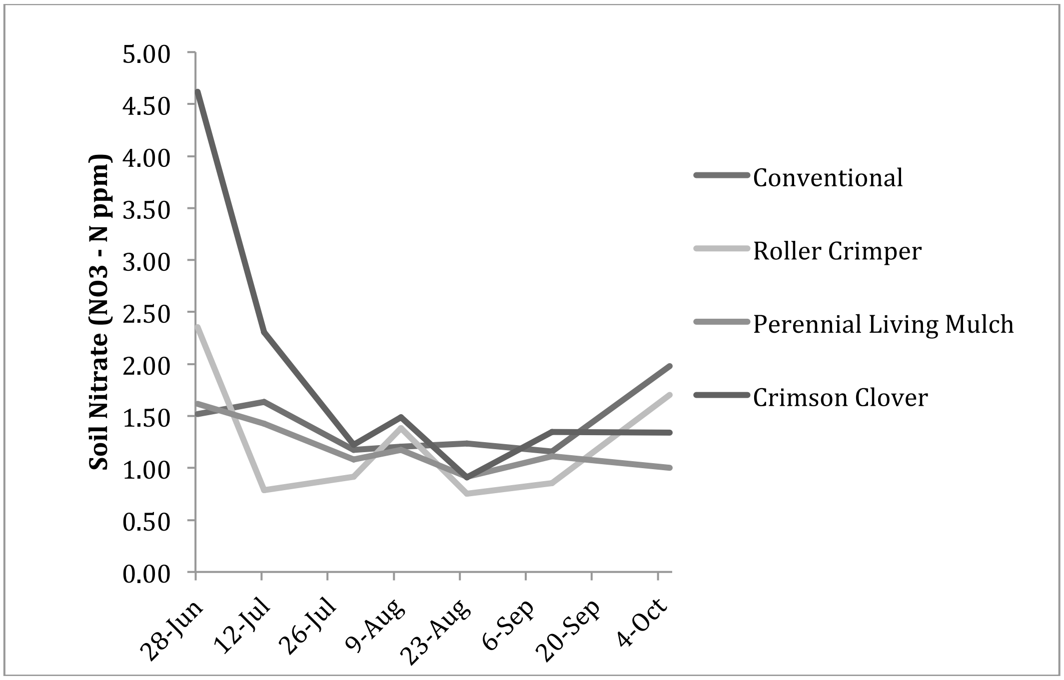

Fig. 4. Nitrate ($N0_3$ – N ppm) levels for the 2011 growing season.

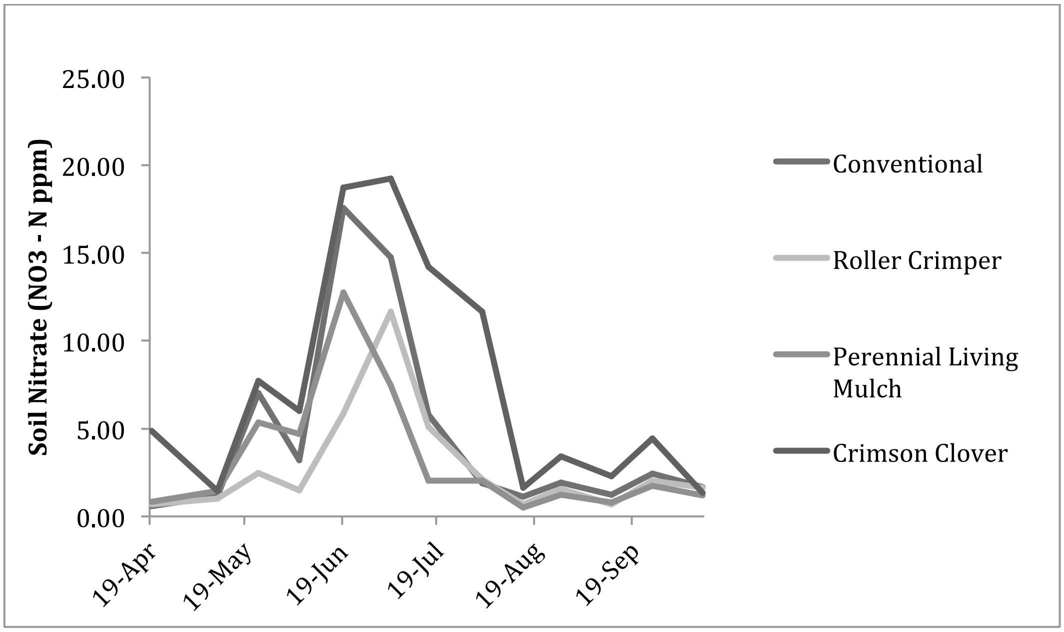

Fig. 5. Nitrate ($N0_3$ – N ppm) levels for the 2012 growing season.

The CC treatment had the highest averaged nitrate level (17.85 ppm) for all treatments on June 20, 2012 (Fig. 5). The nitrate levels for the CC and CT treatment in 2012 were not significantly different however, the CZB and PLM treatments nitrate levels were significantly lower than the CT nitrate levels. In 2011, no significant differences in nitrate levels were observed between the CT treatment and the RCZB and PLM treatments (*P* = 0.4127 and *P* = 0.2900,respectively). (Table 2). An elevated reading in late June made the CC significantly higher (*P* = 0.0006) than the CT treatment. In 2012, all treatments' nitrate levels were significantly different than the CT treatment. The RCZB and PLM treatments had significantly lower (*P* = 0.0095 and *P* = 0.0463, respectively) nitrate levels, while the CC treatment had significantly higher (*P* < 0.0001) nitrate levels than the CT treatment. The 2012 nitrate levels followed a similar trend to the 2011 nitrate levels. The average nitrate levels from the RCZB treatment in 2012 were 35% lower than the CT treatment's nitrate levels. Nitrate levels in the PLM treatment were 39% lower than the CT treatment's nitrate levels. The CC treatment had the highest nitrate levels of any treatment, averaging 7.46 ppm over the 2012 season; these levels were 60% higher than the CT treatment.

Discussion

Solvita:

The Solvita guidelines suggest that low CO_2-C respiration rates below 30 require supplemental nitrogen for most crops. The yearly CO_2-C respiration averages for 2011 and 2012 were 30.02 and 29.82 ppm, respectively, suggesting additional fertilizer was needed to ensure proper plant growth. Respiration rates after tillage have shown higher levels of CO_2, as the turning of the soil breaks up organic matter and aerates the soil. In addition, Briar et al. (2010) found that the destruction of soil macropores caused by tillage does not have negative effects on soil respiration, as bacterial communities are largely unaffected by the structural change. Respiration levels in 2012 correlated closely with the amount of tillage conducted within each treatment. The RCZB, which received the least amount of soil disturbance, had the highest levels of organic matter, and also had the highest respiration levels. These results are similar to those found by Doran (1980), who found that 10 cm deep soil sample respiration levels in no-till soils were significantly higher than those of conventionally tilled soils. The Cornell soil health test results, however, showed low active carbon rates across all treatments for all four years that samples were taken. These low levels could suggest low microbial activity, and respiration rates may have been a response to low carbon levels across all treatments.

Nitrate:

In 2011, an insufficient rate of fertilization resulted in low nitrate for the entire growing season. Fertilizer rates were increased in 2012 to correct these deficiencies. Nitrate rates for the 2012 season improved, but were still found to be lower than what is suggested for normal vegetable development. Timing fertilizer application to match maximum uptake periods of plant growth is a challenge for any grower. Not providing enough fertilizer, or applying it at the wrong time can lead to reduced plant growth or nutrient runoff. Heckman (2003) determined that soil nitrate levels between 20 and 30 ppm were sufficient for growth of most annual crops. Soil nitrate levels in our study failed to reach this level at any sampling period over both 2011 and 2012. While sidedress applications of fertilizer in 2012 raised nitrate levels in the CT and CC treatments, these levels were still below optimum levels. Rice et al. (1986) and McCarthy (1990) have shown that no-till systems can immobilize soil nitrogen at the soil surface. The 2012 nitrate levels from our study seem to suggest similar results, as the RCZB treatment had significantly lower nitrate levels than the CT treatment. Conventional tillage systems reduce organic matter levels by breaking down organic matter and aerating the soil. The 2012 nitrate levels in the CT and CC treatments had the highest nitrate levels in our study. The crimson clover cover crop in the CC treatment can fix between 78 and 168 kg N·ha^{-1} (Balkcom, 2009). The increased nitrate levels observed in the CC treatment could also have come from the spring incorporation of this cover crop into the soil, which may have led to improved yields in the treatment. It has been well documented that conservation tillage techniques that rely on large amounts of cover crop biomass to control weed populations can result in nitrogen immobilization (Al-Kaisi and Licht, 2004; McCarthy et al., 1998; Rice et al., 1986). Haramoto and Brainard (2012) observed that the nitrogen levels in a conventional tillage system were significantly higher than the strip till system for three to four weeks, and then eventually leveled out. The 2012 nitrate levels in our study showed a similar trend, rising in the CT and CC treatments while declining in the RCZB treatment. Rice et al. (1986) suggested that additional fertilizer needs to be applied in conservation tillage systems to make up for nitrogen immobilization. While we did increase our fertilizer application rates, additional fertilizer in all treatments would likely have led to improved yields.

Magdoff and van Es (2009) describe active carbon as fresh organic matter that can easily be used as a resource by soil microbes. A lack of active carbon would decrease microbial activity and decrease respiration rates. Active carbon levels in the CT treatment were 9% - 16% lower than the levels in the conservation tillage treatments. The low active carbon levels combined with tillage in the CT treatment could have led to decreased respiration levels. This lack of carbon could also be noted in the Solvita test, where 2012 respiration rates in the CT treatment were significantly lower than in the conservation tillage treatments. Conversely, higher organic matter levels at the soil surface and higher moisture levels in the RCZB treatment resulted in higher respiration rates.

Understanding the relationship between soil nutrient cycling and a crop’s nutrient needs can help growers increase sustainability on their farms. Three techniques designed to help growers understand these interactions were investigated in this study. Nitrate levels in both the 2011 and 2012 growing seasons were found to be lower than optimal levels. These low rates may have attributed to yield discrepancies between the years in the cabbage, carrot, and tomato crops. As previously stated, conservation tillage techniques have historically been found to increase organic matter and respiration rates at the soil surface, but they also lead to lower surface levels of nitrate (Doran, 1980; McCarthy et al., 1998; and Rice et al., 1986). Our data found similar results, showing increased organic matter and respiration levels (2012) in the RCZB treatment. Active carbon levels and Solvita respiration rates suggested low microbial activity in the soil across all treatments in all three years. There was no correlation between soil nitrate levels and Solvita respiration in both 2011 and 2012 (R = -0.00615 and -0.0756, respectively). The lack of correlation suggests the Solvita soil respiration test is not an accurate way for growers to monitor nitrate levels throughout the growing season. The Solvita respiration rate averages for both years averaged below 30 ppm CO_2-C, at these levels guidelines for the Solvita test recommend the addition of organic matter to increase soil fertility. Nitrate levels for both growing seasons were also low and suggest that an increase in nitrogen would have benefitted all treatments. While there was no correlation between the two tests, further investigation into increased fertility rates and how they may change soil test results would prove useful. Additional studies on soil health in mixed vegetable systems should address lower nutrient and microbial rates by experimenting with various fertilizer rates. Developing fertilizer rates that are able to overcome nitrogen immobilization in conservation tillage systems is critical to improving yield levels.

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CONCLUSION

Conservation tillage systems for mixed vegetable production in New England have the potential to limit soil erosion while maintaining soil health. Developing a conservation tillage system that best suits the needs of a grower can be difficult, as one system may not prove to be successful for all crops. This study experimented with three conservation tillage systems, each of which had specific benefits to the grower. The roller crimper zone builder (RCZB) treatment was designed to accumulate a large amount of biomass that would serve to increase the level of organic matter in the soil, while preventing weed establishment. The raised beds in the perennial living mulch (PLM) treatment helped separate the cover crop and vegetables, while the perennial nature of the treatment provided a low maintenance cover that suppressed weeds between the planted rows. The living mulch in the crimson clover (CC) treatment was designed to build up soil nutrients and provide competition against weeds. Results from data collected on weed distribution and biomass, soil health respiration and nitrate content, and total crop yields suggested that each of the treatments had benefits and pitfalls.

The RCZB treatment was ineffective at controlling weeds, and produced an inferior crop when compared to the conventional (CT) treatment. The biomass of the winter rye planted in the treatment was found to be one quarter of the amount that other studies have shown to be necessary to provide successful weed control without herbicides. Low yields could be attributed to both weed pressure and low nitrogen levels in the RCZB treatment. It has been shown that no-till and strip tillage systems have an increased amount of organic matter at the soil surface, which results in immobilization of nitrogen. It has been suggested that a greater number of nitrogen applications may help to overcome these losses. As discussed, weed pressure in the RCZB treatment was due to low winter rye biomass, but was also due to weed pressure within the planting rows. Weed control within the strip tilled zone proved very difficult to accomplish using hand weeding tools. Correcting winter rye biomass through increased fertilizer application may help to improve both weed control and yield levels.

The PLM treatment was found to be a suitable replacement for the CT treatment in cucumber, melon and lettuce production systems. This treatment was also very effective at controlling weeds in the aisle way, although improved techniques for weed management at the aisle and planting bed interface are needed. Lowering the raised bed height, and/or widening the aisle ways between planting rows to allow for less dramatic height differentials between the planting rows and the aisles could help to achieve this. The PLM cover crop also needs to be monitored for spots of poor establishment or possibly be re-established more frequently. Further investigation with this treatment should include alternative cultivation techniques that allow for improved weed control at the cover crop and strip till interface.

Our data suggest that the crimson clover (CC) treatment may serve as a suitable alternative to the CT treatment. Despite the poor cover crop establishment in 2012, the CC treatment’s yields were found to be equal to or greater than those for all vegetables grown in this trial. Nitrogen provided from the crimson clover in the 2010 and 2011 seasons was sufficient to raise soil nitrate levels to the highest of any treatment in 2011 and 2012. A technique utilizing an earlier crimson clover seeding date, however, could improve germination and lead to a better cover crop stand. The increased biomass in this stand would help to improve nitrogen fixation rates, and would also accomplish better weed control.

Active carbon levels from the Cornell Soil Health Test, and Solvita respiration rates suggested low microbial activity in the soil across all treatments for all three years of the study. Further research on soil health in mixed vegetable systems should address lower nutrient and microbial levels by experimenting with various fertilizer rates. Developing fertilizer rates that are able to overcome nitrogen immobilization in conservation tillage systems is critical for improving crop yield, and may help to improve the biomass in the cover crop stands. In 2012, trends in the soil respiration rates seemed to closely follow nitrate levels. These trends, however, were not found to be similar with the low nitrate levels of 2011. These contradictory findings warrant further experimentation before a correlation between Solvita soil respiration and nitrate levels can be established.

The use of conservation tillage for mixed vegetable production systems in southern New England has shown potential to improve farm sustainability in this region. This study served to show the benefits and limitations of using various conservation tillage techniques. Further development in the application of these techniques is needed to encourage greater adoption by vegetable growers.

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