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Weeds, nitrogen, and yield: Measuring the effectiveness of an organic no-till system

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WEEDS, NITROGEN, AND YIELD:
MEASURING THE EFFECTIVENESS OF AN ORGANIC NO-TILL SYSTEM

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ABSTRACT

Previous research in the mid-Atlantic and midwestern USA has identified advantages and drawbacks of “organic no-till” vegetable production, but few studies have been conducted in the warmer southeastern region. The purpose of this study was to examine the effects of tillage [no-till (NT) vs. conventional tillage (CT) of a cereal rye/crimson clover cover crop] and three nitrogen fertilization rates on organic tomato (*Solanum lycopersicum* L.) and summer squash (*Cucurbita pepo* L.) yield, weed suppression, and soil N dynamics in two years in a soil series in Clemson, SC. Squash yields were similar between tillage treatments in both years. NT tomato yields were 43% greater than CT yields in 2014, whereas CT tomato yields were 46% greater than NT yields in 2015. Squash and tomato yields per unit of management labor (time) were significantly greater in NT compared to CT treatments for both years. There were no statistical differences in squash and tomato yields between N fertilization treatments in either year. Pre-season soil N levels were significantly higher in NT tomato plots in 2014 but similar between tillage treatments in tomato plots in 2015 and in squash plots both years. Post-season soil N levels in tomato plots were similar between tillage treatments both years. Post-season soil N levels were significantly higher in NT squash plots in 2014 and in CT squash plots in 2015. Roller-crimped NT mulches provided adequate early-season weed suppression in both years and saved considerable weed management and seedbed preparation labor. Overall, the results demonstrated that organic no-till is a viable method for reduced tillage summer vegetable production in the South Carolina Piedmont region.

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TABLE OF CONTENTS

LIST OF TABLES

CHAPTER ONE: INTRODUCTION AND LITERATURE REVIEW

Organic Agriculture

Representing just over four percent of overall U.S. food sales and roughly about 0.5% of total U.S. cropland, organic production is a small but steadily growing segment in U.S. agriculture (Greene et al., 2009; USDA ERS, 2015). Among organic food sales, fresh fruits and vegetables are a top selling category, accounting for 43% of organic food sales. (USDA ERS, 2015). Organic food sales quintupled between 1997 and 2007 with consumer demand for organics often outstripping supply (Greene et al., 2009). The growth in demand is largely driven by consumer concerns over the health and environmental impacts of food choices (USDA ERS, 2014). Similarly, organic agriculture has been lauded for pesticide reduction, improvements in soil heath, carbon sequestration, and enhanced biodiversity (Greene et al., 2009). Concurrent to the rising popularity of organic foods is the growth of direct-to-consumer marketed foods, with a strong consumer preference for local organically produced foods (Low et al., 2015; USDA ERS, 2014). Forty percent of organic farms in the U.S. market food through direct-to-consumer channels (Low et al., 2015). Organic foods demand a higher price premium than conventionally produced food, which can be a strong marketing incentive for farmers to switch to organic practices (Greene et al., 2009; USDA ERS, 2014).

Organic farming, at its core, is soil-health centric (Kuepper, 2010). Early organic farmers, promoted traditional agricultural practices such as animal and green manuring, composting, crop rotation and diversified cropping to build and feed the “soil food web” (Kuepper, 2010). These traditional practices are codified in the National Organic Program (NOP), the governing document for organic agriculture, which emphasizes soil health by requiring organic producers to use cover crops, crop rotations and application of plant and animal materials (NOP, 2015). Weed management, though, is one of the biggest challenges to organic crop production (Sooby et al., 2007; Riemens et al., 2007), and the prohibition of synthetic herbicides and lack of effective organic alternatives makes weed management more complex in organic systems compared to conventional ones (DeDecker et al., 2014).

Weed management strategies in organic farming include cultural practices such as cover cropping, crop rotations, diversified cropping as well and stale seedbed/delayed planting techniques and mechanical practices such as mowing and tilling (Morse and Creamer, 2006; Sooby et al., 2007; Schonbeck and Morse, 2007). Despite the widely known deleterious effects of soil disturbance on soil health organic farmers, out of necessity, rely heavily on soil tillage for weed management (Schonbeck and Morse, 2007; Morse and Creamer, 2006). Indeed, organic farmers are confounded by the seasonal paradox of both improving and damaging soil health (Schonbeck and Morse, 2007).

A growing number of organic farmers, though, have begun finding success managing weeds while concomitantly improving soil health by blending traditional cover cropping for weed management with reduced tillage techniques (Leavitt et al., 2011; Mirsky et al., 2013).

Advantages of No-till Systems

Background

No-till is a reduced tillage practice in which soil disturbance is all but eliminated between harvest and the subsequent season's planting (Köller, 2003). No-till and other reduced tillage practices spread gradually in the United States in the wake of technological innovations during and after World War II (Lal et al., 2007; Magdoff & Van Es, 2009). Chemical advancements such as the broadleaf herbicide 2-4,D (1945), and the non-selective herbicide paraquat (1962), created tillage alternatives for farmers who, prior to their invention, relied on primary (moldboard plow) and secondary tillage (chisel and/or disc plow) for weed management and seedbed preparation (Lal et al., 2007; Magdoff & Van Es, 2009; Coughenour and Chamala, 2000). Farmer adoption of reduced tillage practices spread gradually in the second half of the 20th century (Coughenour and Chamala, 2000). Currently, over 40% of agronomic crop acreage in the U.S. is managed using some form of conservation tillage, mostly no-till (CTIC, 2004). Several decades of no-till research, primarily regarding conventionally grown agronomic crops, has demonstrated a number of beneficial attributes associated with reduced tillage management.

Soil Organic Matter

No-till practices leave abundant residue on the soil surface resulting in slower residue decomposition than when incorporated (Magdoff and Weil, 2004; Franzluebbers, 2004). Surface-concentrated organic matter is better protected within soil macro-aggregates from consumption by soil fauna and microbes (Franzluebbers, 2004). Eventually, all residues left in the field will decompose to some degree, losing the majority of their carbon (C) to the atmosphere via microbial respiration (Franzluebbers, 2004), but by slowing down the process of decomposition, the rate of C loss can be lessened and soil organic matter (SOM) better preserved (Magdoff and Weil, 2004). Over time, continually adding residues while limiting or eliminating tillage altogether (i.e. no-till) can gradually increase SOM levels (Franzluebbers, 2004). Decades of research have demonstrated that no-till increases SOM. Longer-term studies in different climatic zones in North America demonstrated higher SOM levels in no-till systems compared to conventionally tilled systems: barley (Arshad et al., 1990); maize and soybeans, (Dick, 1983); maize (Blevins et al., 1977); wheat (Bauer and Black, 1981); and maize and soybean (Edwards et al., 1992).

Soil Biology

Microorganism diversity and functional diversity are greatly affected by soil disturbance (Kennedy et al., 2004; Altieri, 1999). Tillage disrupts at least the top 15-25cm of the soil profile and distributes organic matter more evenly throughout the plow zone creating a less stratified, more homogenous surface layer with reduced soil microbial biomass and soil microbial species density (Franzluebbers, 2004; Altieri, 1999; Seiter and Horwath, 2004). In contrast, no-till systems, which increase and concentrate SOM in the upper centimeters of the soil profile increase microbial biomass and diversity in surface soils (Franzluebbers, 2004; Seiter and Horwarth, 2004) and generally have higher fungi-to-bacteria ratios (Frey et al., 1999; Andrade et al., 2003). A number of studies (Aslam et al., 1999; Hubbard et al., 1999; Jordan et al., 1997; Kladivko et al., 1997) also have demonstrated earthworm populations are generally larger in no-till compared to tilled systems.

Andrade et al. (2003) reviewed 40 short- and long-term no-till/conventional tillage comparison studies and reported that soil microbial biomass generally was higher in no-till systems regardless of study site and crop rotation. Further, they documented that differences between microbial biomass in the two tillage treatments became more pronounced as the duration of the studies increased (Andrade et al. 2003). Increased microbial biomass and SOM, in turn, increase the mineralization potential of the soil resulting in greater plant available nutrients (Seiter and Horwath, 2004). Over time, no-till systems, therefore, tend to accumulate greater biologically active fractions of SOM such as mineralizable C and nitrogen (N) than conventionally tilled systems (Pekrun et al., 2003; Kennedy et al., 2004; Seiter and Horwath, 2004). Overall, no-till imparts less stress on soil micro- and macrobiota and creates a soil environment closely resembling undisturbed, natural ecosystems (Andrade et al., 2003).

Nutrient Cycling

No-till residues decompose slower than those incorporated into the soil through tillage, thus the timing of nutrient release can be different between tilled and no-till systems (Magdoff and Weil, 2004). Conventional tillage triggers oxidative processes, which accelerate the mineralization of nutrients such as N, P, and S for plant uptake (Franzluebbers, 2004; Magdoff and Weil, 2004). With no-till and other reduced tillage practices, mineralization of N generally is slower (Franzluebbers, 2004). In the short term, after transitioning from intensive cultivation to no-till management practices, additional N fertilizer may be required to account for slower N mineralization (Pekrun et al., 2003). However, after a transition period – which could last several years to a decade depending on soil conditions – a new equilibrium can be reached in no-till systems wherein increased SOM and microbial biomass lead to greater mineralized N, reducing the need for additional N fertilizer amendments (Magdoff and Weil, 2004; Pekrun, 2003). Increases in SOM and microbial biomass in long-term no-till management, in essence, compensate for slower N mineralization and can lead to increased net N mineralization compared to conventionally tilled systems (Pekrun et al., 2003).

Agronomic Crop Yields

Franzluebbers (2004) reviewed over 80 agronomic crop studies comparing no-till, shallow tillage, and deep inversion tillage and found that no-till systems produced no consistent yield advantage compared to tilled systems – yields tended to be comparable between the systems. No-till has also been associated with yield reduction, particularly with direct-seeded crops in poorly drained soils that are slow to warm up in the spring (Cannell and Hawes, 1994; Dick et al., 1991; Van Doren et al., 1976; Lal et al., 1989). Yet, longer-term agronomic crop studies revealed more distinct yield advantages conferred by no-till management when compared to conventional tillage. Dick et al.

(1991) and Ismail et al. (1994), 25-yr and 20-yr maize studies, respectively, reported that yields tended to increase with time under no-till management compared with conventional tillage.

Soil and Water Conservation

In general, returning plant residue to the soil surface tends to increase soil water entry and storage (Magdoff and Weil, 2004). Residues left on the soil surface also protect the soil from the erosive forces of rainfall and wind (Pimentel et al., 1995). Franzluebbers et al. (1999) reported that no-till practices resulted in significant reductions in both water runoff and soil loss in land that had previously been under conventional tillage. SOM enhances the soil's ability to retain water by way of direct absorption and by promoting stronger aggregation (Magdoff and Weil, 2004). Thus, soils with a high SOM content have significantly higher available water capacity than soils with similar texture but with less SOM (Hudson, 1994). No-till practices, which maximize soil coverage with residues and increase SOM, tend to result in more erosion-resistant soils with greater soil water content compared conventional tillage (Blevins and Frye, 1993).

Carbon Sequestration

Agricultural soil conservation practices such as no-till, which increases soil C long term, serve as a potential mitigation strategy to curb greenhouse gas emissions and thus combat accelerated global climate change (Lal, 2010; West and Post, 2002; Six et al., 2004). Estimates of how effective no-till farming could potentially be to reducing global warming, though, are highly variable and complex due to variations in crop residue, climate, and soil properties (Lal, 2010). Franzluebbers (2010), reviewed 147 long-term no-till/conventional tillage comparison studies from the southeastern U.S. and reported that the agricultural soils in this region alone hold the potential to sequester 0.45 Mg C ha^{-1} yr^{-1} if converted to no-till management. Six et al. (2004) reported that an estimated 0.031 Mg C ha^{-1} yr^{-1} of greenhouse gas emissions could be realized by using no-till, mainly by way of reduced fuel consumption.

Cover Cropping for Soil Health and Weed Management

Teasdale et al. (2007) defined cover crops as "a wide range of plants that are grown for various ecological benefits other than as a cash crop." Cover crops are commonly are used to fill a between-season temporal and/or spatial niche that otherwise would be occupied by unmanageable weed populations in the absence of cash crops (Lal et al., 1991; Teasdale, 1996). Cover crops provide a number of beneficial ecosystem functions: cover crops add organic C and N to the soil, uptake nutrients and recycle them, improve soil aggregation, increase macropore formation, enhance water infiltration, conserve soil moisture, protect the soil surface from wind and water erosion, improve soil tilth, and, in general, enhance soil biological diversity (Seiter and Horwath, 2004; Lal et al., 1991; Schonbeck and Morse, 2006; Schonbeck and Morse, 2007, Clark, 2007; Creamer and Baldwin, 2000).

Regarding weed management, cover crops cover the soil surface with living plant tissue and outcompete weeds for sunlight, water, and nutrients (Mohler and Teasdale, 1993; Balkcom et al., 2007; Teasdale, 1996). A number of studies also have shown that cover crops suppress weeds to a varying degree through phytotoxic allelochemicals (e.g. phenolic acids, coumarins, benzoquinones, terpenoids, glucosinolates, and tannins) released into the soil (Reberg-Horton et al., 2005; Barnes and Putnam, 1983; Putnam and DeFrank, 1983; Chung et al. 2002; Seigler 1996; Swain, 1977). In addition to outcompeting weeds while growing, cover crops can be terminated and their residues left on the soil surface as an *in situ* mulch to suppress weed growth early in the growing season (5-7 weeks), commonly known as the "critical weed-free period", when cash crops have yet to establish dense canopies to out-compete weeds (Schonbeck and Morse, 2007). Surface-placed residues suppress weeds by intercepting and reflecting light transmittance, which stymies weed seed germination (Mohler and Teasdale, 1993; Teasdale and Mohler, 2000). Further, the physical presence of mulch on the soil surface impedes the emergence of germinated weeds (Teasdale and Mohler, 1993). Mulch can also alter soil temperature conditions, delaying the emergence of weed seeds by keeping soil temperatures sub-optimal early in the season (Teasdale and Mohler, 1993).

Organic No-till

Background

Conventional no-till, an agricultural practice that relies heavily on chemically based weed suppression, is not practicable in organic production systems (Schonbeck and Morse, 2007; Moyer, 2011). Organic farmers are prohibited from using synthetic substances, such as herbicides, in organic production and handling (NOP, 2015)

However, in the last several decades, advancements in cover crop research and improvements in no-till equipment have led to a growing interest among organic farmers in developing no-till strategies that are compatible with organic systems (Moyer, 2011; Schonbeck, 2015; Schonbeck and Morse, 2007). "Organic no-till", as it is known, is a cover crop centric reduced tillage system whereby an *in situ* cover crop mulch alone provides weed suppression and enables farmers to reduce tillage in organic systems (Moyer, 2011; Schonbeck, 2015; Schonbeck and Morse, 2007).

In an organic no-till system, a cover crop – normally a winter annual (e.g. cereal rye, hairy vetch, crimson clover) – is planted in the fall at a dense seeding rate and overwintered until mature in the spring (Moyer, 2011; Schonbeck and Morse, 2007, Schonbeck, 2015). Variances of this cropping schedule exist. For instance, faster maturing, short-season crops (e.g. cowpeas, millet, sorghum-Sudan grass, buckwheat and sunn hemp) can be planted in the summer for fall cropping or planted in the fall and "frost" killed for early spring cropping (Schonbeck and Morse, 2007, Schonbeck, 2015). However, most published research regarding organic no-till has focused on fall-planted over-wintering cover crops. Large amounts of plant biomass are favorable when using cover crop *in situ* mulches for in-season weed suppression (Schonbeck and Morse, 2007). Mohler and Teasdale (1993) demonstrated that normal cover crop biomass levels, approximately 3,000 kg ha^{-1} or less, did not provide adequate weed suppression. They reported that biomass levels two and four times the natural amount were needed for adequate suppression of annual grasses and annual/perennial broadleaf weeds, respectively (Mohler and Teasdale 1993).

No-till Cover Crops

Cereal rye (*Secale cereale* L.) is a fall-planted cover crop that is adaptable for most USDA plant hardiness zones (Clark, 2007). Rye, which has well-documented allelopathic properties, can produce a large amount of aboveground biomass (>9,000 kg ha^{-1}), and is an optimal cool-season cover crop for organic no-till cropping systems in the southeastern U.S. (Mirsky et al., 2009; Reberg-Horton et al., 2012; Schonbeck and Morse, 2006). Cereal rye, especially as it matures, has a high C/N ratio and is thus slower to decompose than other cover crops, such as legumes (Teasdale and Abdul-Baki, 1998; Mohler and Teasdale, 1993). Mohler and Teasdale (1993) demonstrated that cereal rye maintains weed suppression over a longer growing season compared to legume cover crops, which generally have lower C/N ratios. Rye also is a scavenger or "catch" crop for residual N in the fall and winter, reducing the quantity of leachable NO_3^- in the soil (Clark, et al., 1994; Meisinger, 1991; Shipley, et al., 1992).

The high C/N ratio of mature cereal rye (25:1 to 55:1), which increases markedly later in the growing season as it matures, can lead to immobilization of N in the soil (Clark, et al., 1994; Creamer et al., 1997; Teasdale and Abdul-Baki, 1998). To reduce N immobilization while maintaining adequate biomass for weed suppression, rye is often planted with a companion winter legume such as crimson clover (*Trifolium incarnatum* L.) or hairy vetch (*Vicia villosa* Roth) (Schonbeck and Morse, 2007). Hairy vetch is better adapted to slightly cooler climates (USDA zones 5-7) than crimson clover and is winter hardy to USDA zones 3-4 (Clark, 2007). Compared to vetch, crimson clover is better adapted to warmer U.S. climates (USDA zones 8-10) including much of the southeastern U.S. (Clark, 2007). Both hairy vetch and crimson clover can contribute considerable N to the soil (75-100 kg ha^{-1} N fertilizer equivalence), which reduces N immobilization in rye cover crop systems (Fageria et al., 2005; Hargrove, 1986; Clark et al., 1994; Creamer et al., 1997). Another advantage of using a cover crop biculture (grass + legume) is that it can accumulate more “topgrowth” N than either cover crop grown alone because by depleting the soil of N, the grass, in essence, drives greater biological N fixation on behalf of the legume (Creamer et al., Clark et al., 1994).

Cover Crop Termination

Proper mechanical termination of cover crops is necessary to make organic no-till systems work (Schonbeck and Morse, 2007; Creamer and Dabney, 2002; Moyer, 2011). Organic no-till cover crops can be killed mechanically with a number of farm implements (e.g. mowers, cultipackers, undercutters, rolling stalk choppers, crop rollers) but optimal results have been documented with specialized roller-crimping devices – heavy, often water-filled cylinders with welded steel blades – that crush cover crop tissue and press the crop residue flat onto the soil surface (Schonbeck and Morse, 2007; Moyer, 2011, Mischler, et al., 2010, Ashford and Reeves, 2003; Morse, 1999). Mischler et al. (2010) and Mirsky et al. (2009) demonstrated that roller-crimpers provide consistent cover crop control comparable to herbicides. Ashford and Reeves (2003) demonstrated that roller-crimping was more economical than chemical weed control.

Unlike mowing, which tends to shred residues finely and distribute them unevenly, roller-crimping keeps residues intact and in place, leaving behind a thick weed barrier that persists longer in season than when mowed (Schonbeck and Morse, 2007; Mirsky et al. 2009, Creamer and Dabney, 2002; Moyer, 2011). Further, roller-crimped cover crop residue is uniformly pressed in the direction of travel, which reduces the risk of hairpins and clogged equipment if followed with no-till planting equipment (Moyer, 2011; Creamer and Dabney, 2002). Roller-crimpers also are more cost-effective compared to other methods of cover crop termination, such as mowing. Roller-crimpers can be operated at faster speeds than when mowing and do not require an energy-intensive power take-off (PTO) drive (Mirsky et al., 2013). Ashford and Reeves (2003) reported that energy requirements for roller-crimper operation were one tenth that of a rotary mower.

Timing of the cover crop termination is critical in organic no-till systems (Moyer, 2011; Mirsky et al., 2009; Mischler et al., 2010; Creamer and Dabney, 2002). The cover crop needs to have time to generate sufficient biomass – if killed too early, not enough biomass has accumulated for lasting weed suppression (Schonbeck and Morse, 2007; Moyer, 2011, Mirsky et al., 2013). In experiments examining cover crop kill-date effects, Clark et al. (1994), Clark et al. (1995), Wagger (1989), and Mirsky et al. (2011) demonstrated that significant increases in cover crop biomass could be achieved by delaying spring termination by just 2-4 weeks. In general, mechanical control of cover crops improves with increasing plant maturity (Mirsky et al., 2012). Conversely, if the cover crop is left in the field too long and viable seed is formed, the seed from the cover crop can create weed problems in future cropping seasons (Moyer, 2011).

For optimal biomass production with little risk of carry-over weed seed, mechanically killed cover crops for organic no-till are best terminated at anthesis or greater but before viable seed has been produced (Moyer, 2011; Schonbeck, 2015; Mirsky et al., 2009). In an organic no-till study examining roller-crimped cereal rye, Mirsky et al. (2009) found that cereal rye regrowth was consistently controlled by terminating the crop at anthesis (Zadoks growth stage 61) or greater. Ashford and Reeves (2003) had similar findings: 85% and 95% cover crop control when rye was terminated at anthesis and soft dough stages, respectively. Another concern regarding the timing of cover crop termination is regrowth of a cover crop that was too immature at time of termination. Cover crop regrowth can create a carryover weed problem in the field as lingering cover crops can compete with cash crops for water and nutrients much like weeds do (Moyer, 2011; Mischler et al., 2010). Waiting until anthesis or greater before terminating the cover crop diminishes the chance for regrowth of the cover crop (Mischeler et al., 2010; Mirsky et al., 2009).

Vegetable Yields

Similar to the aforementioned conventional no-till agronomic crop studies, yield results in organic no-till vegetable production have been mixed. Yield reductions associated with no-till rye and/or vetch mulches were documented in squash (Leavitt et al., 2011), bell pepper (Diaz-Perez et al., 2008; Leavitt et al., 2011), and tomato production (Leavitt et al., 2011). On the contrary, comparable or positive yield responses in organic no-till systems compared to conventionally tilled systems were reported in tomatoes (Abdul-Baki et al., 1996; Madden et al., 2004; Delate et al., 2012). Abdul-Baki et al. (1996) documented higher tomato yields with lower N fertilizer inputs using mowed hairy vetch, crimson clover, and rye + hairy vetch mulches compared to black polyethylene mulch (plasticulture) treatments. They also demonstrated that using cover crop mulches instead of plastic mulches potentially could save growers an estimated $1850/ha in reduced fertilizer, herbicide and equipment costs (Abdul-Baki et al., 1996). Indeed, one of the biggest potential advantages to using organic no-till practices is the potential for greater economic returns through lessened production and management costs (Moyer, 2011).

Future Challenges

Organic no-till, though, is not without its share of pitfalls. Common problems researchers have identified regarding organic no-till production include: sub-optimal soil temperatures early in the season and decreased degree growing days due to the cooling effect of cover crop mulches; loss of earliness due to a lack of synchrony between cover crop maturity and optimal cash crop planting dates; N immobilization when using high C/N cover crops (i.e. rye); increased weed pressure particularly when cover crop stands are inadequate; and reduced N mineralization due to a lack of cover crop incorporation (Leavitt et al., 2011; Schonbeck and Morse, 2007; Schonbeck, 2015; Moyer, 2011; Creamer et al., 1997; Morse, 1999; Mirsky et al., 2011). To keep weeds (particularly perennial weeds) in check, continuous no-till is not recommended in organic no-till systems – eventually some tillage is required between cropping seasons to manage weed pressure (Schonbeck and Morse, 2007). Therefore, organic no-till is viewed not a as "zero" tillage system but more of a rotational tillage method – a means to eliminate most, but not all, tillage events from crop production (Schonbeck and Morse, 2007; Mirsky et al., 2012).

Research Objective

The purpose of this research is to evaluate organic no-till production for weed management, vegetable yield, and nutrient management compared to a conventionally tilled system.

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CHAPTER TWO: WEEDS, NITROGEN, AND YIELD: MEASURING THE EFFECTIVENESS OF AN ORGANIC NO-TILL SYSTEM

Abstract

Previous research in the mid-Atlantic and midwestern USA has identified advantages and drawbacks of “organic no-till” vegetable production, but few studies have been conducted in the warmer southeastern region. The purpose of this study was to examine the effects of tillage [no-till (NT) vs. conventional tillage (CT) of a cereal rye/crimson clover cover crop] and three nitrogen fertilization rates on organic tomato (*Solanum lycopersicum* L.) and summer squash (*Cucurbita pepo* L.) yield, weed suppression, and soil N dynamics in two years in a soil series in Clemson, SC. Squash yields were similar between tillage treatments in both years. NT tomato yields were 43% greater than CT yields in 2014, whereas CT tomato yields were 46% greater than NT yields in 2015. Squash and tomato yields per unit of management labor (time) were significantly greater in NT compared to CT treatments for both years. There were no statistical differences in squash and tomato yields between N fertilization treatments in either year. Pre-season soil N levels were significantly higher in NT tomato plots in 2014 but similar between tillage treatments in tomato plots in 2015 and in squash plots both years. Post-season soil N levels in tomato plots were similar between tillage treatments both years. Post-season soil N levels were significantly higher in NT squash plots in 2014 and in CT squash plots in 2015. Roller-crimped NT mulches provided adequate early-season weed suppression in both years and saved considerable weed management and seedbed preparation labor. Overall, the results demonstrated that organic no-till is a

viable method for reduced tillage summer vegetable production in the South Carolina Piedmont region.

Introduction

Weed management and the associated labor inputs are consistently some of the biggest challenges to organic crop production (Riemens et al., 2007; Sooby et al., 2007). Organic farmers, out of necessity, rely heavily on soil tillage and other forms of labor-intensive soil cultivation for weed management despite the well-known disadvantages to soil health associated with intensive soil disturbance (Schonbeck and Morse, 2007; Morse and Creamer, 2006).

A small but growing number of organic farmers have begun adopting reduce tillage techniques, which blend the soil-conserving and labor-saving methods of conventional no-till systems with traditional soil building practices (i.e. cover cropping) used in organic production (Leavitt et al., 2011; Mirsky et al., 2013). In organic no-till, an *in situ* mulch is created by mechanically terminating mature cover crops. Subsequent cash crops are direct seeded or transplanted into the mulch-covered soil. The cover crop mulch manages weeds in place of mechanical cultivation through physical impedance, light interception, and allelopathy (Mohler and Teasdale, 1993; Teasdale and Mohler, 1993; Teasdale and Mohler, 2000).

Weed suppression in no-till systems is achieved with high biomass (>3000 kg ha^{-1}) cover crops (Mohler and Teasdale, 1993). Organic no-till research has focused primarily on fall-planted, winter annual cover crops that establish quickly, are competitive with weeds during the winter and spring, produce large amounts of biomass, and are terminated easily using mechanical methods (Delate et al., 2012). Good results have been found using monocultures or combinations of cereal rye (*Secale cereale* L.), hairy vetch (*Vicia villosa* Roth), and crimson clover (*Trifolium incarnatum* L.) (Delate et al., 2012; Mischler et al., 2010; Duzy et al., 2014; Abdul-Baki et al., 1996).

Adequate termination of cover crops is essential to organic no-till (Schonbeck and Morse, 2007; Creamer and Dabney, 2002). Optimal results have been documented with specialized roller-crimping devices that crush cover crop tissue and press the intact crop residue onto the soil surface (Creamer and Dabney, 2002; Mischler, et al., 2010, Ashford and Reeves, 2003; Morse, 1999; Moyer, 2011). Mirsky et al. (2009), Mischler et al. (2010), and Ashford and Reeves (2003) found good control of roller-crimped no-till cover crops with lasting weed suppression.

Despite the demonstrated weed suppression of no-till mulches, organic no-till vegetable production systems have produced mixed results (Delate et al., 2012). Yield reductions associated with no-till mulches were documented in squash (Leavitt et al., 2011), bell pepper (Diaz-Perez et al., 2008; Leavitt et al., 2011), and tomato production (Leavitt et al., 2011). On the contrary, comparable or positive yield responses in organic no-till systems compared to conventionally tilled systems were reported in tomatoes (Abdul-Baki et al., 1996; Madden et al., 2004; Delate et al., 2012).

Common problems researchers have identified regarding organic no-till production include: sub-optimal soil temperatures early in the season and shortened degree growing days caused by the cooling effect of cover crop mulches; loss of earliness due to a lack of synchrony between cover crop maturity and optimal cash crop planting dates; N immobilization when using high C/N cover crops (i.e. rye); increased weed pressure particularly when cover crop stands are inadequate; and reduced N mineralization and poor N synchrony due to a lack of cover crop incorporation (Leavitt et al., 2011; Schonbeck and Morse, 2007; Schonbeck, 2015; Moyer, 2011; Creamer et al., 1997; Morse, 1999; Mirsky et al., 2011; Parr, et al., 2014).

The purpose of this research is to compare an organic no-till vegetable production system to a conventionally tilled system on a Toccoa sandy loam soil in Clemson, SC along the following parameters: vegetable yield, soil N dynamics, and weed management inputs.

Materials and Methods

Field Experiment

The experiment was initiated in October 2013 at the Clemson University Student Organic Farm, a 5-acre USDA certified organic farm on the Calhoun Field Research Area on the Clemson University campus. The soil at the study site is a moderately well drained Toccoa sandy loam (Coarse-loamy, mixed, active, nonacid, thermic Typic Udifluvents) with an average organic matter content of 4.6%. Although the experiment began in 2013, observations were taken only from 2014 to 2015. The experimental design for both years was a 2 by 3 factorial randomized complete block design replicated three times. The treatments consisted of two levels of tillage [no-till (NT) and conventional tillage (CT)] of a cereal rye/crimson clover cover crop biculture and three levels of N fertilization (0, 58, and 116 kg ha^{-1} N) for tomato and summer squash production. Conventional tillage was accomplished with a disk harrow to a depth of 15 cm. The recommended N fertilizer rate (116 kg ha^{-1}) was based on Clemson Agricultural Service Lab soil fertility recommendations from a standard soil analysis of composited 0-15 cm soil samples taken in March 2014 from the year one experiment site. In 2014, soil at the experiment plot was amended with P (from 0-10-0 bone meal) at a rate of 448 kg ha^{-1} and K (from 0-0-50 potash) at a rate of 60 kg ha^{-1} according to soil test recommendations. No P and K amendments were needed in 2015. The treatments were arranged in a split-split plot design. Tillage treatment split plots (6 m x 7.5 m) were established for each vegetable crop with 2 m alleys between each plot. Alleys were flail mowed, tilled, and planted to a buckwheat (*Fagopyrum esculentum*) cover crop in both years. Split-plots were divided into three split-split plots (vegetable rows) spaced 1.5 m apart for the N fertilization treatment. The treatments were replicated three times for each vegetable crop.

On 4 October, 2013 and 13 September, 2014 experiment plots were seeded with a mixture of cereal rye (VNS) and crimson clover (VNS in 2013 and 'Dixie' in 2014) using a tractor-mounted overseeder attachment with 10 cm row spacing. Two-year cropping history for the 2014 experiment plot included maize (*Zea mays*) and summer squash cash crops and Japanese millet (*Echinochloa esculenta*), sunn hemp (*Crotalaria juncea*), cereal rye, crimson clover, and cowpea (*Vigna unguiculata*) cover crops. The 2015 plot cropping history included garlic (*Allium sativum*), carrot (*Daucus carota*), cole crops (*Brassica oleracea*) and beet (*Beta vulgaris*) cash crops and cereal rye, crimson clover, cowpea, and sudex (*Sorghum bicolor* × *S. bicolor var. sudanese*) cover crops. Prior to cover crop seeding, the plots had been disked to remove weeds and level the field. In 2013, a seeding rate of 112 kg ha^{-1} rye and 39 kg ha^{-1} clover was used. The high rate of clover was due to calibration problems with the overseeder's seed shoot. In 2014, the same rate of rye was used, but the clover rate was reduced to a more appropriate rate of 12 kg ha^{-1}. Cover crops in CT plots were flail mowed on 5 May, 2014 and 6 May, 2015 and the plots were disked repeatedly the following day in both years to incorporate cover crop residue. NT termination was accomplished on 6 May, 2014 and 11 May, 2015 with a rear-mounted 2.4 m I & J (Gap, PA) roller-crimper that had been filled with 225 kg of water for a total weight of 860 kg. The drum could have accommodated more water, but the tractor's lifting capacity was a limiting factor. In both years crimping was done in one direction with roughly 0.3 m of roller-crimper overlap with each pass. In 2014, the initial round of crimping did not fully terminate the rye crop, which by 7 May, had begun to rebound. The NT plots were re-crimped on 8 May with a small-plot 0.7 m roller-crimper mounted to a two-wheel walk-behind tractor. (The farm's larger category 1 tractor was not operational at the time.) An additional 113 kg of weight was added to the small-plot crimper for a total weight of 230 kg. In 2015, two back-to-back passes with the 2.4 m roller-crimper were made over the cover crop (same direction) on 11 May to ensure adequate rye termination. At time of crimping, the rye had reached Zadoks stage 69 (anthesis complete) in 2014 and stage 75 (medium milk) in 2015. Crimson clover maturity was not noted in either year.

Five-week old 'Celebrity' tomato and two-week old 'Success' squash seedlings were transplanted by hand in the corresponding CT and NT tomato and squash plots on 09 May, 2014 (both crops) and on 14 May (tomatoes) and 18 May (squash) in 2015. Vegetable plots consisted of three rows 4.5 m in length with 0.3 m spacing between plants and 1.5 m spacing between row centers. Drip irrigation was installed on top of mulch in NT and on bare soil in CT prior to transplanting; plants were watered immediately after transplantation. In the NT plots, the cover crop mulch was spread 12-15 cm apart by hand creating a narrow planting slit in the row prior to transplanting. The mulch was then pushed back against the plants after transplantation to cover the soil surface. All plants had been started in the farm's greenhouse using on-farm generated potting soil [50% compost (2, 0.02, and 0.02 kg t^{-1} N, P, and K, respectively): 25% perlite: 25% peat moss] with 120 ml lime and 710 ml powderized 8-5-5 feather meal fertilizer added per 0.3 m^3 of potting soil mix. Tomatoes were seeded in 128-count seed trays and then transplanted after 3 weeks into grow out pots measuring 10 cm in diameter. Squash were seeded in 72-count seed trays. Squash seedlings had reached the second true-leaf stage prior to transplantation. All vegetable transplants were fertilized with a powderized 8-5-5 feather meal fertilizer while in the greenhouse and were hardened off prior to transplantation. Immediately after transplantation, plants were fertilized according to N fertilization treatment with a side-dressed split application of a slower release, pelletized 13-0-0 feather meal fertilizer. A second split application of 13-

0-0 was made at flowering stage for each crop. Tomatoes were trellised using the "Florida weave" technique.

Cover Crop Data

Aboveground cover crop biomass was sampled in three 0.5m^2 quadrants in 2014 and five 0.5 m^2 quadrants in 2015 from the alleys between vegetable plots immediately prior to CT plot flail mowing. The biomass samples were oven dried for 72 hrs at 55°C and then weighed. Additionally, subsamples from each biomass sample were sent to the Clemson University Agricultural Service Lab where they were dried at 70-80°C for 12-24 hrs, ground to pass through a 2 mm sieve, and analyzed for total N by combustion using a LECO® FP528 Nitrogen Combustion Analyzer. Cover crop N contribution to the following vegetable crops was estimated as 0.40 × total cover crop biomass × cover crop %N (Baldwin and Creamer, 2006). Four weeks after termination, NT plots were assessed visually for percentage cover crop regrowth (Leavitt et al., 2011).

Weeding and Labor Inputs

CT plots were weeded approximately every 1-2 weeks in 2014 and approximately every 2-3 weeks in 2015. Weeding in tilled plots consisted of rototilling, flame weeding, and hand hoeing. NT plots were weeded every 2-3 weeks in both years. Weeding in NT plots consisted of rotary and string mowing weeds that had emerged through the cover crop residue and hand-pulling of perennial weeds. Weed management labor (hours) was recorded for each vegetable crop by tillage treatment for both years. Additionally, a visual assessment of all NT plots was made 6 weeks after crimping to estimate average percent ground coverage by weeds (Creamer et al., 1997). Labor (hours) spent preparing no-till (crimping) and tilled (mowing + disking) cover crop plots prior to transplanting was also recorded both years.

Soil Analysis

Prior to transplantation of vegetable crops and N fertilization (9 May, 2014 and 13 May, 2015), six 0-15 cm soil samples were taken from each of the 36 split-split plots. Soil samples were composited by split-split plot and subsamples were sent to the USDA-ARS Grassland Soil and Water Research Laboratory, Temple, TX for soil health analysis using the Soil Health Tool (SHT) ver. 4.4. (Haney, n.d.). Another series of soil samples, same protocol, were taken at the end of the each growing season (30 July, 2014 and 31 July, 2015). The samples were dried at 50°C, ground to pass through a 2 mm sieve, extracted with DI water and H^3A, and analyzed on a Seal Analytical rapid flow analyzer for NO_3-N and NH_4-N (Haney et al., 2008). The water extract was analyzed on a Teledyne-Tekmar Apollo 9000 C:N analyzer for water-extractable organic C and total N and 40 g of each dried soil sample was re-wetted with DI water and incubated with a Solvita® paddle in a 237 ml glass jar for 24 hours (Haney et al., 2008). At the end of 24-hour incubation, the paddle was removed and placed in the Solvita® digital reader for CO_2-C analysis. The SHT couples inorganic N (NO_3-N and NH_4-N), water-extractable organic C and N, and CO_2-C measurements to estimate plant available N in the soil.

Vegetable Yield

Yield data (weight) were recorded for marketable tomatoes (USDA grades 1-3) and marketable squash (USDA grades 1 and 2) in each row for every harvest (USDA 1997a, 1997b). Squash were harvested 3-4 times per week and tomatoes 2-3 times per week in both years.

Tissue Mineral Analysis

In 2015, leaf tissue samples (excluding petioles) were taken from the most recently mature leaf of each plant in every row for both crops at early the early flowering stage. Samples were composited by row and sent to the Clemson Agricultural Service Lab where they were dried at 70-80°C for 12-24 hrs, ground to pass through a 2 mm sieve, and analyzed for total N by combustion using a LECO® FP528 Nitrogen Combustion Analyzer.

Statistical Analysis

Statistical analyses were performed with analysis of variance (ANOVA) using the Fit Model procedure of JMP® (version 11.0) to determine the effects of tillage and N fertilization on vegetable yield and soil N. Fisher's least significant difference tests ($P \leq 0.05$) were used to separate means. To compare inputs between the two tillage treatments, an analysis of labor was compiled by recording the total labor hours required to prepare the seedbed for planting and manage weeds during the vegetable growing season for each crop (Leavitt et al, 2011). Additionally, an ANOVA was performed to determine the effects of tillage and N fertilization on vegetable yield per unit of labor.

Results

Cover crops

Cover crop biomass averaged 8,400 kg ha^{-1} in 2014 and 8,960 kg ha^{-1} in 2015. Based on the average total N content of the cover crop samples, 1.74% (2014) and 1.72% (2015), total cover crop N content was approximately 146 kg ha^{-1} in 2014 and 154 kg ha^{-1} in 2015. Total N contribution to the vegetable crops (0.40 × total cover crop biomass × cover crop %N) was 58 kg ha^{-1} (2014) and 61 kg ha^{-1} (2015). Roller-crimping provided adequate control of cover crops. Cover crop regrowth at 4 weeks after termination was minimal (<1%) in both years.

Weeding and Labor Inputs

Seedbed preparation labor was higher both years in CT plots (Table 1). Mowing + disking required 191% and 300% more labor in 2014 and 2015, respectively, compared to NT roller-crimping (Table 1). Managing weeds was also more labor-intensive in CT plots. Weed labor was 400% and 338% greater in CT tomato and squash plots, respectively, compared to NT plots in 2014 (Table 1). In 2015, weed labor was 45% greater in CT tomato plots compared to NT; squash plot weed management was comparable between tillage treatments. NT cover crop plots did become weedy later in the season particularly in 2014 when regrowth of the previous summer's cover crop (Japanese millet) required routine mowing to keep the millet from overwhelming the NT plots. Average percent ground cover by weeds at 6 weeks after termination in NT plots was 35% (tomatoes) and 25% (squash) in 2014 and 10% (tomatoes) and 10% (squash) in 2015.

Soil Analysis

Pre-season analysis

Average plant available N and total N were significantly greater in NT tomato plots compared to CT in 2014 (Table 2). There were no significant differences in available and total N between tillage treatments in 2015. There were no significant differences in CO_2-C levels between tillage treatments in tomato plots in either year. Average plant available N and total N in squash plots were not statistically different between tillage treatments for either year studied (Table 2). Average squash plot CO_2-C was significantly higher with NT in 2014 but similar between tillage treatments in 2015.

Post-season analysis

Tomato plant available N and total N levels were similar both years regardless of tillage treatment (Table 3a). Average CO_2-C was significantly higher in 2014 with NT but similar between CT and NT in 2015. Average plant available N and total N were significantly greater in NT squash plots in 2014 and in CT plots in 2015 (Table 3b). Average CO_2-C was significantly higher in CT squash plots in 2015. Based on post-season soil analysis, N fertilization treatments did not significantly affect plant available N, total N, or CO^2-C in either year for either crop studied.

Tissue Mineral Analysis

Based on mid-season analysis, there appeared to be no effect of either tillage or fertilization on leaf tissue N. Average leaf tissue total N values were similar between tillage and N fertilization treatments for both crops in 2015 (Table 4). Average %N for both CT and NT were within the sufficiency ranges for both tomato (3.5-5.0%) and squash (4.0-6.0%) crops (Campbell, 2000).

Vegetable Yield

Average NT tomato yields were significantly greater than CT yields in 2014; in 2015 CT yields were significantly greater than NT (Table 5). Squash yields were similar between tillage treatments for both years studied (Table 5). Nitrogen fertilization treatments did not significantly affect vegetable yield in either year for either crop studied nor were there significant tillage x fertilization interactions. Vegetable yields per unit of labor (seedbed preparation + weeding) were significantly greater in both NT crops in both years studied (Table 6).

Discussion

The significant reduction in CT tomato yield in 2014 was likely due to disease. CT tomatoes were severely damaged by a combination of Southern blight (*Sclerotium rolfsii)* and Pythium root rot (*Pythium spp.*). Plant pathogen diagnosis was confirmed by the Clemson University Plant Problem Clinic. Both pathogens thrive in moist conditions found in poorly drained sites (Kluepfel et al., 2014). Because of the no-till component of the study, we did not create raised beds in either tillage treatment. The roller-crimper, we found, provides optimal cover crop termination on level terrain, although there are roller-crimping devices designed for use in raised-bed systems (Reberg-Horton et al., 2012; Moyer, 2011). Normal farm CT practices include post-tillage raised-bed making to improve field drainage for cultural management of soil-borne diseases. In all, roughly 14% of the CT tomato plants in 2014 were lost to disease, which impacted average row yields. However, when row yield data were transformed from yield per row to yield per plant (by dividing row yields by number of plants per row) and analyzed using the same statistical model, there were no significant differences between tillage treatments (data not shown). NT tomatoes remained disease free in 2014, which was notable because: 1) CT and NT crops were grown in spatially similar parts of the field with identical cropping histories; 2) soil conditions with high levels of available carbon (i.e. poorly decomposed plant tissue) such as those found in reduced tillage systems are conducive to Southern blight (diagnostician's notes; Averre, 2009). A different field at the farm was used in the second year of the study and both CT and NT crops remained disease free.

Seedbed prep and weed management labor were much higher in CT plots in 2014 compared to 2015. Mowing and incorporating the cover crop residue took longer in 2014. More in-field tractor turns and repositioning were required in 2014 during mowing and subsequent tillage because of plot proximity to adjacent crop fields. Regarding 2015, roughly 75% of the cover crop at the study site (visual estimation) was lodged by severe rain and wind events three weeks prior to cover crop termination. At termination, approximately 20% of the cover crop stand in CT plots remained lodged – only 20% of the crop was left standing at its original height. The lack of a fully erect cover crop made mowing less time intensive in 2015. Regarding in-season weeding, field conditions in 2014 were generally wetter in the first several weeks of the vegetable-growing season compared to 2015. In 2015, there were no rain events for the first 2.5 weeks after transplanting, which decreased the amount of early-season weeding that had to be done in CT plots after transplantation.

Overall, we found that the labor required to establish and manage weeds in CT plots was considerably greater when compared to NT. When yields were similar (squash, in both years) or even greater using CT practices (i.e. tomatoes in 2015), the management savings associated with NT translated to significantly greater yields per unit of labor input. Further, having a 5-7 week relatively weed-free window early in the growing season where little weeding was needed in newly transplanted crops – as was our experience with no-till – was particularly advantageous on a small, diversified farm such as ours where labor demands are high in the early summer growing season with 20+ crops growing in the fields at any given time.

N levels were high across all treatments each year. N fertility treatments had no significant effect on vegetable yield. Thus, soil N was likely not a limiting factor in either year probably as a result of high soil organic matter content and residual N from previous cover crops. Plant available N, total N, and CO_2-C were generally higher in soil from the 2015 site.

Because of the short duration of the study, we were unfortunately unable to identify any discernible trends regarding differences in soil health across tillage treatments. Longer-term, mostly conventional agronomic-crop no-till studies, though, have demonstrated significant advantages to soil health (increased SOM) after multiple (>5) years of conventional no-tillage management (Arshad et al., 1990; Dick, 1983; Blevins et al., 1977; Bauer and Black, 1981; Edwards et al., 1992).

Regarding greater farmer adoption of organic no-till, one potential drawback we recognized is weediness later in the growing season, which we experienced particularly in year one of the study. Repeated hand weeding or "rouging" of no-till plots can be especially labor intensive and could negate the early season weed management savings realized with no-till mulches. We found adequate weed management later in the growing season using string and rotary mowing to keep emerged weeds in check but not necessarily controlled. Unrelated to this study, the Student Organic Farm has also experimented with adding off-farm mulches (e.g. leaf litter) to no-till mulches for longer season summer vegetable (e.g. pepper and eggplant) production in an attempt to compensate for decomposition of no-till mulches over the course of the growing season. Further research into cost-effective weed management strategies in organic no-till systems is warranted.

One main disadvantage we found using no-till was loss of earliness, which is an identified problem with spring/early-summer organic no-till vegetable cropping systems (Schonbeck and Morse, 2007). By prolonging the cover crop growing season until the rye had matured to a stage where it could be managed by either tillage treatment, vegetables were not available for market until late June (squash) and mid-July (tomatoes). In order to produce tomatoes and squash for the early summer market period, the cover crops would had to have been terminated in early April, which would not have been compatible with no-till practices – the cover crop is too immature at this stage to be crimped and has not produced nearly enough biomass for effective no-till mulch. Thus, we found no-till vegetable production is perhaps best used for mid-to-late season summer crops. In future work, we would like to explore earlier fall planting/spring termination dates with faster maturing cover crop varieties to improve reduced tillage vegetable cropping earlier in the season.

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Table 1. Total labor inputs by tillage treatment.

		Seedbed preparation (hrs)		Weeding (hrs)	
Tomato	Treatment	2014	2015	2014	2015
	NT	0.9	0.3	1.3	1.1
	CT	2.75	1.2	6.5	1.6
Squash	Treatment	2014	2015	2014	2015
	NT	0.9	0.3	1.3	0.9
	CT	2.75	1.2	5.7	0.9

Table 2. Effects of tillage (NT and CT) on average plant available N, total N, and CO_2-C, pre-season[x] analysis.

		Plant Available N (kg ha^{-1})		Total N (kg ha^{-1})		CO_2-C (ppm)	
Tomato	Tillage	0 DBT[y] 2014	1 DBT 2015	0 DBT 2014	1 DBT 2015	0 DBT 2014	1 DBT 2015
	NT	61.36a[z]	94.98a	74.12a	102.57a	132.34a	242.57a
	CT	51.89b	100.07a	61.34b	113.44a	128.61a	189.50a
		$P = 0.0222$	$P = 0.5483$	$P = 0.0197$	$P = 0.2731$	$P = 0.7757$	$P = 0.2335$
Squash	Tillage	0 DBT 2014	4 DBT 2015	0 DBT 2014	4 DBT 2015	0 DBT 2014	4 DBT 2015
	NT	65.21a	90.60a	78.56a	99.99a	65.01a	217.76a
	CT	54.97a	91.78a	65.92a	103.84a	44.21b	172.32a
		$P = 0.0699$	$P = 0.8377$	$P = 0.0846$	$P = 0.5761$	$P = 0.0493$	$P = 0.3342$

[x] After cover crop termination but before vegetable transplantation.
[y] DAT=Days after transplantation.
[z] Mean separation within tillage and year by Fisher's lease significant difference test, $P \leq 0.05$.

Table 3a. Effects of tillage (NT and CT) and N fertilization (0, 58, and 116 kg ha^{-1}) on average plant available N, total N, and CO_2-C, post-season[x] analysis.

		Plant Available N (kg ha^{-1})		Total N (kg ha^{-1})		CO_2-C (ppm)	
Tomato	Tillage	82 DAT[y] 2014	78 DAT 2015	82 DAT 2014	78 DAT 2015	82 DAT 2014	78 DAT 2015
	NT	68.80a	89.48a	78.14a	104.03a	161.56a[z]	315.98a
	CT	59.99a	89.41a	67.22a	104.76a	97.29b	250.40a
	Fertilization						
	0	69.45a	84.62a	78.11a	98.45a	94.83b	272.02a
	58	61.26a	88.83a	69.23a	103.97a	162.67a	278.43a
	116	62.57a	94.88a	70.69a	110.77a	130.77ab	299.12a
	Tillage	$P = 0.1383$	$P = 0.9925$	$P = 0.1441$	$P = 0.9358$	$P = 0.0260$	$P = 0.0823$
	Fert	$P = 0.4601$	$P = 0.5047$	$P = 0.5495$	$P = 0.5366$	$P = 0.1288$	$P = 0.7972$
	Tillage x Fert	$P = 0.7432$	$P = 0.4997$	$P = 0.7638$	$P = 0.5544$	$P = 0.4815$	$P = 0.4051$

[x] After all harvesting completed for the season.
[y] DAT=Days after transplantation.
[z] Mean separation within tillage or fertilization and within year by Fisher's least significant difference test, $P \leq 0.05$.

Table 3b. Effects of tillage (NT and CT) and N fertilization (0, 58, and 116 kg ha^{-1}) on average plant available N, total N, and CO_2-C, post-season[x] analysis.

		Plant Available N (kg ha^{-1})		Total N (kg ha^{-1})		CO_2-C (ppm)	
Squash	Tillage	82 DAT 2014	74 DAT 2015	82 DAT 2014	74 DAT 2015	82 DAT 2014	74 DAT 2015
	NT	70.92a	80.56b	82.31a	93.89b	180.94a	202.80b
	CT	59.88b	94.26a	67.89b	112.06a	130.67a	305.19a
	Fertilization						
	0	65.84a	91.47a	75.39a	106.78a	154.97a	253.68a
	58	64.38a	86.85a	73.79a	103.53a	171.05a	245.22a
	116	65.98a	83.90a	76.12a	98.60a	141.39a	263.08a
	Tillage	$P = 0.0239$	$P = 0.0099$	$P = 0.0232$	$P = 0.0138$	$P = 0.0843$	$P = 0.0105$
	Fert	$P = 0.9413$	$P = 0.3880$	$P = 0.9372$	$P = 0.5629$	$P = 0.6638$	$P = 0.9055$
	Tillage x Fert	$P = 0.8259$	$P = 0.3235$	$P = 0.8481$	$P = 0.4375$	$P = 0.5631$	$P = 0.9274$

[x] After all harvesting completed for the season.
[y] DAT=Days after transplantation.
[z]Mean separation within tillage or fertilization and within year by Fisher's least significant difference test, $P \leq 0.05$.

Table 4. Effects of tillage (NT and CT) and N fertilization (0, 58, 116 kg ha^{-1}) on average leaf tissue N (2015).

		Total N (kg ha^{-1})
Tomato	Tillage	
	NT	4.18a[z]
	CT	4.01a
	Fertilization	
	0	4.09a
	58	4.14a
	116	4.05a
	Tillage	P = 0.2710
	Fert	P = 0.8676
	Tillage x Fert	P = 0.3072
Squash	Tillage	
	NT	4.95a
	CT	4.56a
	Fertilization	
	0	4.76a
	58	4.82a
	116	4.67a
	Tillage	P = 0.0853
	Fert	P = 0.8200
	Tillage x Fert	P = 0.7217

[z]Mean separation within tillage or fertilization by Fisher's least significant difference test, $P \leq 0.05$.

Table 5. Effects of tillage (NT and CT) and N fertilization (0, 58, 116 kg ha^{-1}) on average marketable vegetable yields per row.

		Yield (kg)	
Tomato	Tillage	2014	2015
	NT	13.74a[z]	14.79b
	CT	9.27b	21.55a
	Fertilization		
	0	10.91a	15.89a
	58	10.60a	18.85a
	116	13.02a	19.80a
	Tillage	$P = 0.0440$	$P = 0.0029$
	Fert	$P = 0.5609$	$P = 0.2019$
	Tillage x Fert	$P = 0.8515$	$P = 0.5212$
Squash	Tillage	2014	2015
	NT	30.37a	23.32a
	CT	32.21a	25.14a
	Fertilization		
	0	27.56a	22.46a
	58	32.79a	26.45a
	116	33.52a	23.78a
	Tillage	$P = 0.5459$	$P = 0.4830$
	Fert	$P = 0.2459$	$P = 0.4404$
	Tillage x Fert	$P = 0.9747$	$P = 0.7050$

[z]Mean separation within tillage or fertilization and within year by Fisher's least significant difference test, $P \leq 0.05$.

Table 6. Effects of tillage (NT and CT) on average marketable vegetable yield per unit of effort.

		Yield per Unit of Effort[y] (kg/hr)	
Tomato	Tillage	2014	2015
	NT	57.26a[z]	92.46a
	CT	9.00b	69.52b
		$P < 0.0001$	$P = 0.0371$
Squash	Tillage	2014	2015
	NT	126.54a	179.40a
	CT	34.27b	109.29b
		$P < 0.0001$	$P = 0.0003$

[y] Rate determined by dividing labor input totals for each tillage treatment by number of rows (9) to determine hours of labor input per row of crop by tillage treatment. Crop row yields were then divided by hours of labor per row to determine yield per unit of effort rate for each row.
[z]Mean separation within tillage and year by Fisher's least significant difference test, $P \leq 0.05$.