Nitrogen Management and Weed Suppression in Organic Transition

by

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Abstract

The objectives of this research were: 1) to quantify the amount of supplemental nitrogen (N) to maximize organic broccoli (*Brassica olearcea var. italica*) on transition soils, 2) to evaluate the ability of leguminous cover crops lablab (*Dolichos lablab* L.), soybean (*Glycine max* L.), sunn hemp (*Crotalria juncea* L.) and a sunn hemp and cowpea mixture (*Vigna sinensis* Endl.) to supply N and suppress weeds and, 3) to compare the effect on N availability and broccoli yield potential of incorporating cover crops with conventional tillage (CT) or mulching cover crops with no-tillage (NT) practices. Broccoli was grown during the third year of organic transition in the spring and fall of 2006 at the Kentland Agricultural Research Farm in Blacksburg, VA. Supplemental N significantly increased broccoli yield up until 112 kg ha^{-1} with a quadratic correlation with leaf N. The NT treatment yielded no difference during the spring, but in the fall CT surpassed NT. On the other hand, N uptake, measured by leaf N, under NT conditions increased with supplemental N, which suggests NT has equivalent yield potential as CT when N is not limiting. Yields from leguminous residues did not differ, even though quality and quantity of cover crop biomass did. This suggests that N availability from cover crop legumes may be impacted other ecological process such as soil microbial activity. Also, cover crop residues differed in their ability to suppress weeds. The results from this study give organic growers in transition tools to maximize productivity and sustainability.

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Table of Contents

List of Tables

List of Figures

1. Literature Review

1.1 Challenges for Organic Agriculture

Organic agriculture faces a challenge when yields fail to compete with conventional agriculture (Trewavas, 2004). With the adoption of intensive practices, the modern agricultural revolution increased productivity and reduced labor requirements while keeping pace with the world food demand (Parayil, 2003). In comparison, more land would be needed to go under organic production to produce similar yields (Stanhill, 1990; Trewavas, 2001). In order to address this challenge, researchers have identified two main factors for restricted organic yields; nitrogen (N) availability (Berry et al., 2002; Clark et al., 1999a; Scow et al., 1994) and non-chemical weed control (Bàrberi, 2002; Ngouajio and McGiffen, 2002). Organic agriculture addresses these factors in a fundamentally different way compared to their conventional counterparts.

One percent of the world's energy supply is used to produce synthetic N fertilizer (Smil, 2001). These N sources play an essential role for world food supply because they are readily available for plant uptake and allow arable land to be continuously farmed (Eickhout et al., 2006). On the other hand, organic systems are reliant upon crop rotations and soil amendments for N-building (Berry et al., 2002). Herbicides are highly effective for weed control and facilitate the adoption of conservation tillage (Morse et al., 1993). Conversely, non-chemical weed control requires an appreciation for weed ecology and often requires a greater dependence on tillage (Bond and Grundy, 2001; Madden et al., 2004). Advancement in the understanding of organic N fertility and non-chemical weed control would aid the competitive capacity of organic agriculture.

High demand for organic produce has created favorable economic conditions for organic producers (Thompson, 2000). However, an expansion of organic farming based solely on economic gain may undermine goals for sustainability (IFOAM, 2002). Three year withdrawal phase of prohibited materials is mandatory, but during this time, nutrient and pest dynamics change often resulting in an initial reduction in yield (USDA, 2000; Zinati, 2002). In order to improve productivity, organic farmers may degrade soil quality with the excessive use of tillage (Bàrberi, 2006; Kasperczyk and Knickel, 2006). Ideally, organic farmers strive toward a complete systems change including input reduction, energy efficiency and prudent stewardship of the environment (Shennan et al., 2005). In order to balance productivity with sustainability, the use of cover crop rotations and the strategic use of tillage are indispensable.

1.2 Cover Crops and Sustainable Agriculture

Cover crops are important to agricultural sustainability. Diversified crop rotations using cover crops improve soil quality (Veenstra et al., 2006), provide biological N as green manures (Tonitto et al., 2006), reduce N leaching (Wyland et al., 1996) and suppress weeds (Teasdale, 1996). Also, cover crops can improve compacted soils and protect against soil erosion (Flach, 1990; Rosolem et al., 2002). Furthermore, the selection of cover crop species is diverse, which makes them versatile under multiple climactic conditions (Creamer and Baldwin, 2000; Pardini et al., 2003; Wagger, 1989). Though their services may be difficult to quantify, long-term rotations of cover crops offer farmers distinct advantages.

In order to facilitate the adoption of cover crop rotations and maximize their seasonal benefits, different species require different management techniques (Tonitto et al., 2006). For agronomic crops in temperate regions, cover crops are sown after harvest and grown during the winter and killed before planting (Wagger, 1989). For vegetable crops, the cover crop selection depends on the season. Similar to agronomic crops, winter cover crops are grown before spring and summer vegetables; they are often either frost-sensitive or frost-tolerant (Wyland et al., 1996). Summer cover crops, often of tropical origin, thrive under hot, humid conditions and are produced before fall vegetables (Creamer and Baldwin, 2000). Mechanical techniques such as plowing, mowing, and rolling have been developed instead of chemicals to kill living cover crops with success depending on species and its stage of development (Creamer and Dabney, 2002). Additional parameters for successful use of cover crops include planting date, cover crop stand, and kill date (Cline and Silvernail, 2001; Drinkwater et al., 2000; Wagger, 1989).

Cover crops have arisen to as an effective way to improve soil quality (Wander and Drinkwater, 2000). The most important indicator of soil quality is soil organic matter (SOM) or soil organic carbon (C), which includes decaying plant material, soil microbes and humified substances (Reeves, 1997). Decomposing cover crops and root exudates from living cover crops add significant amounts of organic C to the soil (Fageria et al., 2005). These C inputs improve soil aggregation, which maintains soil structure (Kavdir and Smucker, 2005; Liu et al., 2005), enhances water retention (Franzluebbers, 2002b) and reduces erosion (Flach, 1990). Organic matter from cover crops sustains soil microbial life (Lundquist et al., 1999a) and reduces the loss of C and N from the agroecosystem (Drinkwater et al., 1998). Furthermore, properly managed SOM may increase nutrient availability to plants, which may reduce fertilizer use (Reeves, 1997). As a result, incorporating cover crops into crop rotations improves physical, chemical and biological properties of the soil.

In coordination with SOM management, cover crops play an important role in the management of soil organic N. Rotations of leguminous cover crops or green manures are utilized to supplement synthetic N fertilizer (Peoples et al., 1995).

Furthermore, cover cropping systems dependent on the amount of legume biomass for productivity (Tonitto et al., 2006). In order to maximize legume nodulation and biological N fixation soil N concentrations need to be low (Giller and Cadisch, 1995). In comparison to legumes, grasses germinate earlier and develop root systems faster to absorb excess soil N (Ranells and Wagger, 1997). As a result, leguminous cover crops have the potential reach maximum biomass while excess soil N is retained in the system (Wyland et al., 1996). Hence, planting grass-legume bicultures offers the best cover cropping strategy.

1.3 Strategic Use of Tillage

The intensity of tillage practices has profound effects on the agroecosystem. Intensive farming methods that utilize conventional tillage (CT) can jeopardize land, air and water resources (Piovanelli et al., 2006). As a result, alternative systems utilizing reduced or no-tillage (NT) have been adopted for soil and water conservation (Hoyt et al., 1994). In spite of these benefits, the suitability of adopting NT practices depends on soil and climate conditions as well as yield potential and farmer's attitude for change (Lindwall et al., 1994; Mitchell et al., 2006). The underlying success of NT systems results in a systems change including not just an avoidance of tillage, but strategies for residue management (Morse et al., 2001). Finally and most importantly, tillage practices require a strategy to balance between productivity and sustainability (Morse and Creamer, 2006).

CT is a standard practice for high productivity, but with negative consequences. Continuous tillage compacts soil below the plow layer, which reduces drainage and increases soil crusting, affecting water infiltration and movement (Arvidsson and Bolenius, 2006). Moreover, during drought conditions, compacted layers of soil restrict root growth and development, which leads to plant stress and yield loss (Nidal and Abu-Hamdeh, 2003). Consequently, farmers use more tillage in order to break up soil compaction, leading to a continuous cycle of soil disturbance (Botta et al., 2006). Thus, standard practices need to be reevaluated to integrate more sustainable practices.

Often, problems arise with CT including the degradation of soil, air and water quality. Frequent tillage disturbs soil aggregation making soil particles susceptible to erosion (Drinkwater et al., 2000; Six et al., 1999). Surface runoff from unprotected soil leads to surface-runoff that damages water quality (Lal, 1994). Also, CT stimulates microbial activity that can decay organic matter, which reduces C sequestration and enhances gaseous losses of CO_2 (Calderon et al., 2001; Jackson et al., 2003; Piovanelli et al., 2006). A dependence on CT contributes to air pollution from airborne soil particles and fossil fuel combustion (Mitchell et al., 2006). Also, if tillage is not synchronized with plant uptake, N may leach to groundwater or be lost as gaseous N oxides (Paul et al., 1997). Therefore, CT practices should be reduced to save resources and reduce costs.

In order to overcome the problems associated with CT, researchers have promoted NT, the extreme form of conservation tillage. The adoption of NT practices can be limited by soil properties and climactic conditions (Lindwall et al., 1994). For example, NT is difficult on poorly drained, compacted, or fine-textured soils, which can lead to negative consequences (Hoyt et al., 1994). Some studies suggest conversion from CT to NT reduced porosity and increased bulk density (Kay and VandenBygaart, 2002; Piovanelli et al., 2006). In cooler climates, NT residues lower soil temperatures, which can affect maturity dates, thereby missing lucrative early markets (Creamer et al., 1996a; Phillips, 1984). Furthermore, in semi-arid climates NT soils that are not remixed lead to nutrient stratification, which may limit nutrient availability to deeper-rooting crops or contribute to salinity problems (Veenstra et al., 2006).

Despite it limitations, NT has gained validity as systems adapt. For instance, NT practices improve erosion control, water infiltration and nutrient conservation with increased organic matter on the soil surface in hot, wet climates with inherent low SOM (Franzluebbers, 2002a). Furthermore, NT residues aid systems without irrigation or reduce irrigation requirements with greater soil water conservation

(Morse, 1993). Also, NT soils with adequate porosity benefit biological activity that leads to improved nutrient cycling and disease suppression (Adl et al., 2006; Peters et al., 2002). Finally, the development of specialized equipment for farmers was facilitated the NT movement (Morse et al., 1993). In summary, these examples of NT systems provide insight into the continued role of conservation tillage.

Due to restriction on agrichemicals, organic production often depends heavily on tillage to manage soil fertility and weeds. As a result, organic farms can suffer greater soil losses than chemical-based no-till systems (Bruulsema et al., 2003; Madden et al., 2004). Integrated with a greater understanding of soil fertility and weed control, organic systems possess the potential to benefit from conservation tillage. Even though NT organic techniques are being developed (Ross, 2006), it is logical for farmers to adapt conservation tillage because in many cases it is more sustainable and cost effective.

1.4 Organic Nitrogen Fertility

During the transition from conventional to organic farming, yields can be limited by N availability (Berry et al., 2002; Clark et al., 1999a; Pang and Letey, 2000; Scow et al., 1994). In comparison to synthetic fertilizers, organic N sources are characterized by slow-release formulations regulated by microbial activity (Drinkwater, 2004; Tu et al., 2006). As a result, synchronizing crop N demand with microbial N release remains a challenge (Jackson, 2000). Strategies to increase N availability include managing soil microbes and depending on multiple N sources. In the short-term, organic production systems may require increased supplemental N to optimize yields (Clark et al., 1999b; Kramer et al., 2002; Tonitto et al., 2006). However in the long-term, building SOM retains N and increases the efficiency of its use by crops (Drinkwater, 2004).

Building SOM impacts microbial activities that regulate the cycling of C and N in the soil (Drinkwater, 2004; Wang et al., 2003). In order to sustain microbial life, continuous organic inputs are needed to balance C and N losses (Lundquist et al., 1999b; Veenstra et al., 2006). More importantly, during organic transition, practices that build SOM are essential to adapt soil microbes to the greater role of nutrient cycling (Scow et al., 1994). Accordingly, cover crops add organic matter, which increases microbial populations (Clark et al., 1998; Gunapala and Scow, 1998) and promotes microbial activity (Burger and Jackson, 2003). Therefore, microbes depend heavily on the maintenance and accumulation of SOM; however their immediate activity in conjunction with N availability deserves further investigation.

Microbial activity in relation to N cycling depends on the C:N ratio of cover crop residues. Microbes immobilize mineral N and assimilate organic C into soil aggregates when residues with high C:N ratios, such as grasses, are incorporated

(Haynes and Beare, 1997). Soil aggregation contributes to improved soil structure and C sequestration and N immobilization reduces leaching and retains soil N to act as a future pool of nutrients (Aulakh et al., 2001; Burger and Jackson, 2004; Drinkwater, 2004). As a result, grasses in cover crop rotations improve soil and environmental quality but, N immobilization during the production cycle leads to lower N availability (Hu et al., 1997).

Leguminous cover crops are essential to maintain organic N fertility by adding organic N and optimizing microbial activity (Drinkwater et al., 1998). When microbes assimilate C from low C:N residues, they met their N demand and release N more rapidly (Jackson, 2000). However, organic N inputs compared to synthetic fertilizers are released gradually later into the season (Burger and Jackson, 2003; Kramer et al., 2002). In effect, using leguminous cover crops as the sole organic N source depends on a number of factors. The amount of legume biomass and its C:N ratio determines total organic N inputs (Puget and Drinkwater, 2001; Quemada and Cabrera, 1995; Wagger, 1989). Crop N requirements (Abdul-Baki et al., 1997) and crop rooting characteristics (Rahn, 2002) also play a role. In conclusion, to maximize soil fertility and SOM building combinations of grass and legume cover crops are essential.

To ensure adequate N availability, systems low in SOM and microbial activity, such as those under transition to organic, require multiple sources of N. Tillage frees immobilized N by stimulating microbial activity (Calderon et al., 2000; Calderon et al., 2001). Research has shown that N is available earlier and at higher rates in tilled soils (Drinkwater et al., 2000). Furthermore, in organic and conventional systems, studies suggest applying additional N to supplement legume cover crop N (Clark et al., 1999a; Kramer et al., 2002; Tonitto et al., 2006). Although tillage and supplemental N are inputs that compromise goals for sustainability, cover crop rotations and strategic tillage improve SOM and microbial activity to offset the need for these inputs over time.

1.5 Non-chemical Weed Control

Without the aid of herbicides weed management is an important challenge for organic growers. Research has devoted little attention to the threat of weeds (Bàrberi, 2002). As a result, many producers are reluctant to undertake organic transition because of uncertainty over weed management (Ngouajio and McGiffen, 2002). Integrated weed management that relies on multiple weed control methods provides a holistic approach to managing weeds in organic systems (Bàrberi, 2002). Furthermore, an increase in the understanding of weed biology and ecology underpins long-term improvements in sustainable weed control (Bond and Grundy, 2001). Growers interested in converting to organic farming require more information about non-chemical weed control.

Direct weed control offers an effective method to eliminate weed pressure. Physical control like hand weeding and hoeing are effective, but labor costs restrict its wide spread use. Tillage is a direct, non-selective method for controlling established weeds. Tillage is highly effective, but energy dependent and tied to soil degradation. Also, tillage stimulates light-dependent weed seed germination, which increases competition after crop establishment (Aldrich, 1984). On the other hand, stimulating weed seed germination in between rotations is beneficial for exhausting the weed seed bank. Direct control, despite its limitations, is essential for an integrated weed management plan.

Multiple biological mechanisms prevent the growth and establishment of weeds. Cover crops out-compete weeds during fallow periods as smother crops and during the production cycle as living mulches (Infante and Morse, 1996; Morse and Creamer, 2006a). Mulched cover crops under NT conditions inhibit light needed for weed seed germination (Creamer et al., 1996b). Also, cover crops like sorghum and rye possess strong allelopathic chemicals that inhibit weed seed germination (Einhellig et al., 1993; Khanh et al., 2005; Schonbeck et al., 1991). Additional biological techniques have been investigated such fungal species of the genus *Trichoderma* (Heraux et al., 2005) and the use of microorganisms to manage the weed seedbank (Kremer, 1993). Clearly, potential for biological control is abundant due to the wealth of organisms to explore.

Non-chemical measures need to include cultural measures to maintain the weed populations at a manageable level (Bond and Grundy, 2001). Transplanting vegetable crops in a twin-row configuration with adequate spacing can hasten canopy closure shading competitive weed species (Jett et al., 1995). Keeping fields free of weeds during early production stages addresses weed-crop competition before it becomes a problem (Morse, 2005). Maintaining a low weed seed bank offers the best long-term solution to reduce weed pressure (Kremer, 1993; Teasdale et al., 2004). Fortunately, a few years of good weed control can rapidly reduce seed banks following years of imperfect weed control (Teasdale et al., 2003). In summary, the eradication of weeds is impossible, so weed management requires integrating multiple measures to bring weed pressure in balance with production goals.

1.6 Research Objectives

The most important challenges faced by organic growers are organic N fertility and non-chemical weed control. Cover crops, the strategic use of tillage, and multiple N sources are the key factors to be investigated, which will help to develop and refine integrated management practices. The objectives of the project are to evaluate cover crop combinations, to identify the strategic use of tillage by comparing

CT and NT, and to investigate different rates of supplemental N. The practical objective of this project is to aid organic growers and those interested in the transition to organic farming.

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2. Organic Broccoli Production on Transition Soils Comparing Cover Crops, Tillage and Supplemental N

2.1 Introduction

During transition from conventional to organic farming, yields can be limited by nitrogen (N) availability (Berry et al., 2002; Clark et al., 1999; Pang and Letey, 2000; Scow et al., 1994). In comparison to synthetic fertilizers, organic N are characterized by slow-release formulations regulated by microbial activity (Drinkwater, 2004; Tu et al., 2006). As a result, synchronizing crop N demand with microbial N release remains a challenge (Jackson, 2000; Pang and Letey, 2000).

Short-term N availability is essential for maximum productivity. Tillage increases the amount of N available for plants (Calderon et al., 2001). Soil microbial populations and their N cycling activities are stimulated and immobilized N within soil organic matter is made plant accessible after tillage activities (Drinkwater et al., 2000). Furthermore, low carbon-to-nitrogen organic residues, such as leguminous cover crops, supply organic N budgets with availability depending on cover crop biomass and quality (Drinkwater et al., 1998; Quemada and Cabrera, 1995). Finally, timely applications of properly placed supplemental N improve yields and guarantee fertilizer is used efficiently .

Beyond transition, organic systems depend on long-term N use efficiency to balance productivity with sustainability (Drinkwater, 2004). Reduced tillage hastens soil aggregation, which augments the capacity of the soil to act as a N reservoir (Hoyt et al., 1993). High carbon-to-nitrogen cover crops such as grasses nourish soil development with high organic inputs and scavenge and redistribute residual N above ground (Jackson, 2000). As a result, management strategies that include cover crop rotations and a strategic use of tillage result in sustainable and productive organic systems.

2.2 Materials and Methods

Experiments were conducted in the spring and fall of 2006 at the Virginia Polytechnic Institute and State University, Kentland Agricultural Research Farm, near Blacksburg, VA on a Hayter loam soil (fine-loamy mixed, mesic Ultic Hapludaf, pH 6.4). The field plots were in their third year of organic transition; conventional field corn in 2003 followed by a manure application and combinations of cover crops and vegetable crops in 2004 and 2005.

The experimental design was a randomized split-block. Spring treatments were cover crops as main plots (3.66 x 130 m), tillage system as subplots (3.66 x 65 m) and nitrogen (N) rate as sub-subplots (3.66 x 16.25), with two replications. Fall treatments were arranged differently, with tillage system as main plots (3.66 x 130 m), cover crop as subplots (3.66 x 43.33 m) and N rate as sub-subplots 3.66 x 7.62), with four replications. A schedule of operations is listed in Table 2.1. For both crops, tillage systems were conventional (CT), in which the cover crop residues were incorporated 15-cm deep using a tractor-drawn rotary tiller, and no-tillage (NT), in which the cover crops were flailed mowed and the residues left on the surface as an organic mulch. Two weeks after transplanting both crops, subplots received four different rates of hand-sidedressed organic N fertilizer (Table 2.2).

In both experiments, all plots consisted of two raised beds on 183 cm centers and 15 cm high each, over which cover crops were zone-seeded with a 10-row (18.3 cm) Tye drill (Agco Corporation, Duluth, GA). Legume species were seeded on bed tops (73 cm wide) where broccoli transplants were set (grow zones). Grass species were seeded in inter grow-zone areas or alleyways (110 cm wide) which included bed edges, sides and bottoms. For the spring crop, lablab (LL) (*Dolichos lablab* L.) and sunn hemp (SH) (*Crotalria juncea* L.) were seeded in grow zones and sorghum sudangrass (SSG) (*Sorghum vulgare var. sudanense* Hitchc.) in alleyways. For the fall crop, lablab, soybean (SB) (*Glycine max* L.) and a sunn hemp and cowpea mixture (SH-CP) (*Vigna sinensis* Endl.) were seeded in grow zones and pearl millet (PM) (*Pennisetum glaucum* L.) in alleyways. Seeding rates were 45, 40, 56, 45, 90 and 15/75 kg per ha equivalent for SSG, PM, LL, SH, SB and SH-CP, respectively.

Down pressure of each row was regulated separately to ensure a desirable seeding depth and subsequent uniform stand over the surface of the entire bed.

An early maturing broccoli cultivar (Major) was used for the spring crop, and a mid-season cultivar more suited to fall production (Gypsy) was grown (Seedway Seed Co., Elizabethtown, PA). Broccoli transplants were produced at the Virginia Tech Horticulture Greenhouse for six weeks in 72-cell trays (55 cc/cell) containing an organic potting mix (McEnroe Lite, Millerton, NY). The plants were transported to the farm and allowed to acclimate in the shade with daily watering for 10 days before transplanting.

Prior to transplanting, aboveground cover crop and weed biomass and weed population samples (0.25 m) were collected by hand-cutting at the soil surface, dried at 70 C for 14 days, cover crop samples were ground with a cyclone mill and analyzed for total N content using the Kjeldahl procedure (Peterson and Chesters, 1964). Broccoli transplants were set in twin rows on raised beds (50-cm apart and 37 cm in-row) with minimal disturbance of surface mulch or soil, using the Subsurface Tiller-Transplanter (SST-T) (Morse et al., 1993). Harmony organic fertilizer (5N-2.2P-2.5K—Harmony Products, Inc., Harrisonburg, VA) and drip tubing (T-Tape—Rainflo Irrigation, LLC East Earl, PA) were applied at planting along side each row using the SST-T. The same sources and rates of supplemental organic fertilizers were applied to both spring and fall broccoli crops (Table 2). All plots were drip irrigated as needed to supplement rainfall shortages. To ensure an adequate stand establishment, any wilted or dead plants were replaced up to one week after transplanting. Whole-leaves of broccoli were sampled during early heading to compare N uptake under the four N regimes. Leaves were dried and analyzed for N as described above.

Weeds and insect pests were kept below yield-limiting levels (Infante and Morse, 1996), using a combination of integrated management practices. Weeds were controlled in both crops by performing one critical hand cultivation approximately 5-10 days before canopy closure of the twin broccoli rows. Weeding methods included hand pulling and shallow cultivation with a hoe or push wheel hoe. Cover crop mulch in NT plots suppressed weed growth, resulting in less weed numbers and biomass than in CT (data not shown). A Multivator (Mitchell Equipment, Marysville, OH) was used 1 week after transplanting spring broccoli to cultivate alleyways between beds in both NT and CT plots.

Incidence of insect pests and diseases were kept low by 1) applying recommended nutrients and irrigation to maximize plant health and vigor; 2) planting beneficial habitat strips (farmscapes) adjacent to the broccoli rows; and 3) applying a single application of Dipel (*Bacillus thuringiensis*, Valent Corporation, Walnut Creek, CA) at 1.12 kg ha^{-1} 3 weeks before first harvest (Table 2.1).

The spring and fall production seasons varied in temperature and cultivar and thus rate of maturity. The harvest began 7 weeks after planting in the spring and 11 weeks in the fall and continued for 10 days and 14 days, respectfully. Bead tightness and uniformity were the primary selection criteria for harvest. Broccoli heads were cut to a uniform length of 20 cm and checked for hollow stem, counted and weighed for total yield, and sorted into marketable and cull yield. Culls included heads damaged or < 8 cm head diameter.

Mean separation (LSD) was conducted. Significant statistical differences between treatment means and treatment interactions were determined at $P < 0.05$. Percentage data were arcsin transformed prior to analysis to normalize variances of binomial data, with original data shown for presentation purposes (Little and Hills, 1978). Data were analyzed using SAS (SAS Institute Inc., Cary, NC).

Table 2.1 Calendar of Events

Operation	Spring	Fall
Sow cover crops	25 Jul*	15 Jun
Seed broccoli in greenhouse	17 Mar	10 Jul
Sample cover crop and weed biomass	19 Apr	14 Aug
Roll (spring) or flail-mow (fall) cover crop	10 Nov*	15 Aug
Incorporate cover crop residues in CT plots	20 Apr	15 Aug
Transplant broccoli seedlings	25 Apr	17 Aug
Apply base fertilizer	25 Apr	17 Aug
Critical hand weeding	26 Apr	8 Sep
Fertilize through drip irrigation	3 May	24 Aug
Apply supplemental N	9 May	7 Sep
Sample broccoli leaves for tissue N analysis	12 Jun	3 Oct
Apply Bt for pest control	---	11 Oct
Harvest first crop	13 Jun	1 Nov
Harvest second crop	22 Jun	10 Nov
Harvest third crop	---	14 Nov

*Signifies operation in 2005

Table 2.2 Sources and time of application of supplemental N to broccoli plots in spring and fall 2006

N fertilizer source (time of application)	N (kg ha^{-1})			
Base application (transplanting)				
Harmony organic 5N-2.2P-2.5K	45	45	45	45
Fertigation* (1 week after transplanting)	5	5	5	5
Supplemental N (2 weeks after transplanting)				
Sodium nitrate (16%)	0	22	34	45
Feathermeal (12%)	0	34	88	123
Total supplemental N	0	56	112	168
Total N = base + fertigation + supplemental	50	116	162	218

*Soluble organic fertilizer applied through drip lines: sodium nitrate (3.5 kg N ha^{-1}) and a mixture of hydrolyzed fish and seaweed extract (1.5 kg N ha^{-1})

2.3 Results and Discussion

Supplemental N effects: Higher rates of supplemental N fertilizer significantly increased yield in both experiments (Table 2.3). Applied N had a marked effect on yield in previous studies (Cutcliffe, 1971; Kahn et al., 1991). However, there was no significant difference between 112 and 168 kg ha^{-1}. This study indicated that the N requirement for broccoli was fulfilled at 112 kg ha^{-1}. Higher N rates statistically decreased cull yield and total yield correlated with average head weight. Our findings are consistent with Dufault and Waters (1985) who reported that increasing the N rate increased broccoli head weight and yield and decreased cull yield. Higher N rates increased the incidence of hollow stems, however interacted with the tillage treatment (Table 2.4). Stem hollowness has been reported to correlate with increased N rate and is considered a measurement for broccoli growth rate (Hipp, 1974). Supplemental N was needed to maximize the yield potential in our organic system.

Improved yield associated with higher N rates was correlated with the higher percentage of N accumulation in leaf tissue (Table 2.3). The reported leaf N values fell within the optimum range of 3.2 to 5.5 for broccoli production (Wolf, 1996). However, in our system the higher end of this range correlated with higher yields and there was a quadratic response between leaf N and broccoli yield (Fig. 1 and 2). Other studies have identified similar relationships as higher rates of N increased yield and leaf N (Everaarts and De Willigen, 1999; Zebarth et al., 1995). Kowalenko and Hall (1987) showed higher N fertilization rates significantly increased N in leaves and broccoli heads without stimulating vegetative growth. As a result, broccoli leaf N measurements can be utilized as an indication of broccoli yield potential.

Tillage effects: Organic NT and CT broccoli had equivalent yield potential when produced under comparable conditions. Yields of organic spring broccoli showed no significant difference between NT and CT treatments (Table 2.5). These results are consistent with broccoli yield data from other NT studies (Abdul-Baki et al., 1997; Infante and Morse, 1996; Morse, 1995). A limitation of NT was encountered during the fall experiment. Decreased stem hollowness found in the NT plots indicates that cover crop mulch reduced soil temperature and slowed broccoli development (Hoyt et al., 1994). Sudden, extreme low temperatures on the 15th of October (-5 C) at early heading caused uniform leaf damage in all plots and reduced fall broccoli yields. However, the less developed nature of NT plants at the onset of the frost event reduced yield potential of NT to greater extent than CT.

Tillage affects both seasonal and long-term N availability and thus can play an important role in determining yield potential. Tillage can aerate soil, increase net mineralization, and release immobilized N (Calderon et al., 2000; Calderon et al., 2001). Using tillage to loosen soil and incorporate plant residues can result in earlier release and higher rates of N compared to NT mulched soil (Drinkwater et al., 2000). In this study, a significant tillage x supplemental N interaction (*P*=0.0023) occurred for leaf N content of broccoli plants (Figure 2.3). Without additional supplemental N, availability and corresponding N uptake in NT plots were reduced. However, as rate of supplemental N increased, N uptake by NT plants approached levels of CT (Figure 2.3). Past research showed that supplemental N may be required to increase N availability in NT (Fox and Bandel, 1984).

Cover crop effects: The quantity and quality of cover crop residues determine their N contribution (Puget and Drinkwater, 2001; Quemada and Cabrera, 1995; Wagger, 1989). Planting a biculture of SH and CP creates an efficient use of differing plant architectures. Cowpeas are relatively low growing compared to tall-growing sunn hemp, resulting in high cover crop biomass (Table 2.6).

Apparently, rate of mineralization and broccoli yield were more affected by quality of cover crop residues than quantity. Both spring and fall broccoli yield was not influenced by cover crop species, even though the quantity of biomass and plant N in SH and SH-CP plots was higher than LL and SB (Table 2.6). The relative proportion of leaves and stems largely determine the quality of cover crop residues, rate of mineralization, and release of plant-available N (Quemada and Cabrera, 1995).

In general, LL and SB had more leafy and succulent residues than the SH-CP mixture. Several factors could explain the lack of yield response to cover crop species in these experiments. First, net mineralized N was the same in all cover crop plots because the quality differences compensated for the differences in biomass (Quemada and Cabrera, 1995). Second, net mineralized N was highest in SH (spring crop) or SH-CP (fall crop); however, N release was not synchronized with crop demand (Pang and Letey, 2000). Third, net mineralized N was highest in SH-CP plots, but the broccoli roots absorbed and assimilated plant-available N more readily in LL and SB than SH-CP. That last scenario could be attributed to a positive synergistic plant-microbe interaction occurring in the rhizosphere of the LL broccoli and SB broccoli rotations, but not in the SH-CP broccoli rotation (Peters et al., 2002).

Beyond organic transition: Large annual inputs of organic matter from cover crop rotations and a commitment to reduced tillage can improve soil quality (Coolman and Hoyt, 1993; Drinkwater et al., 1998). Increased soil organic matter and corresponding microbial activity can improve nutrient cycling capacity of the soil (Drinkwater, 2004; Wang et al., 2003). High levels of soil organic matter improves N retention (Aulakh et al., 2001; Burger and Jackson, 2004). Therefore, over time the reliance on supplemental N should decrease as the level of soil organic matter is increased.

Table 2.3 Supplemental N effects on broccoli yield, head weight, cull yield, stem hollowness and leaf N in spring and fall, 2006

N (kg/ha)	Yield ($t\ ha^{-1}$)	Head wt(g)	Cull[z] (%)	Hollow (%)	Leaf N (%)
		Spring			
0	3.9[y] c	197 d	28.1 a	3.9 c	3.21 c
56	5.6 b	272 c	19.6 b	21.4 b	3.95 b
112	6.5 a	307 b	11.5 c	45.4 a	4.58 a
168	6.7 a	330 a	9.9 c	51.3 a	4.82 a
P value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
		Fall			
0	5.0 c	207 c	13.2 a	50.4 c	3.35 d
56	5.9 b	247 b	9.9 ab	71.5 b	4.59 c
112	6.4 ab	268 a	7.1 b	87.1 a	5.52 b
168	6.7 a	281 a	8.4 b	87.6 a	5.91 a
P value	<0.0001	<0.0001	0.0473	<0.0001	<0.0001

[z] all heads >7.5 cm diameter

[y] Means within a column followed by different letters are significantly different at the 5% level according to the LSD test.

Table 2.4 Analysis of the variance

FALL

		P-value				
Source of Variation[z]	Df	Yield	Head wt	Cull	Hollow	Leaf N
T	1	**0.0001**[y]	**0.0001**	**0.0001**	**0.0001**	**0.0001**
CC	2	0.4450	0.3490	0.2044	0.7420	**0.0054**
T*CC	2	0.0761	0.0863	0.1276	**0.0002**	0.1075
N	3	**0.0001**	**0.0001**	**0.0043**	**0.0001**	**0.0001**
T*N	3	0.6189	0.6943	0.2759	**0.0275**	**0.0023**
CC*N	6	0.3596	0.1140	0.3544	0.4942	0.2859
T*CC*N	6	0.1221	0.1430	0.3182	**0.0227**	0.9203

SPRING

		P-value				
Source of Variation	Df	Yield	Head wt	Cull	Hollow	Leaf N
T	1	0.9483	0.2175	0.8571	**0.0238**	0.1523
CC	1	0.1427	**0.0118**	**0.0205**	**0.0001**	0.2852
T*CC	1	0.1374	**0.0150**	0.0559	**0.0415**	0.6669
N	3	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
T*N	3	0.6856	0.8093	0.7706	0.5688	0.0921
CC*N	3	0.2586	0.3580	0.2476	**0.0141**	0.9684
T*CC*N	3	0.3005	0.1005	0.6753	**0.0364**	0.7964

[z] T = tillage; CC = cover crop; N = nitrogen

[y] Values in **bold** are statistically significant (*P* value<0.050)

Table 2.5 Tillage effects on broccoli yield, head weight, cull yield, stem hollowness and leaf N in spring and fall, 2006

Tillage [z]	Yield ($t\ ha^{-1}$)	Head wt(g)	Cull [y] (%)	Hollow (%)	Leaf N (%)
		Spring			
CT	5.7 [x]	280	17.1	33.3	4.2
NT	5.7	274	17.4	27.7	4.08
p value	NS	NS	NS	0.0238	NS
LL		***Fall***			
CT	6.4	266	6.6	80.3	5.02 a
NT	5.5	236	12.8	68.0	4.66 b
p value	0.0001	0.0004	<0.0001	0.0106	<0.0001

[z] CT = conventional tillage; NT = no tillage

[y] all heads < 8 cm diameter

[x] Means within a column are significantly different at the 5% level according to the LSD test.

Table 2.6 Cover crop species, biomass and plant N percentage and their effects on broccoli yield and leaf N in spring and fall, 2006

Cover Crop				Broccoli	
Species[z]	Biomass ($t\ ha^{-1}$)	Plant N (%)	N ($kg\ ha^{-1}$)	Leaf N (%)	Yield ($t\ ha^{-1}$)
			Spring		
LL	2.0 b[y]	0.75 b	15 b	4.18	5.6
SH	3.5 a	0.92 a	32 a	4.10	5.8
P value	0.0052	0.0105	0.0015	NS	NS
			Fall		
LL	4.6 b	2.35	110 b	4.86	6.1
SB	5.2 b	2.17	112 b	4.69	5.8
SH-CP	7.0 a	2.19	153 a	4.97	6.1
P value	0.0004	NS	0.0068	NS	NS

[z] LL = lablab; SH = sunn hemp; SB = soybean; SH-CP = sunn hemp and cowpea mix

[y] Means within a column are significantly different at the 5% level according to the LSD test.

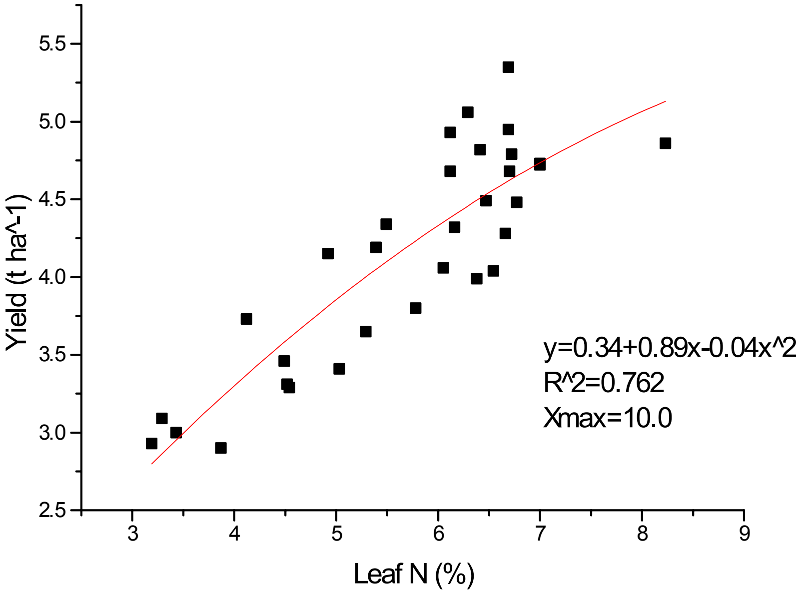

Figure 2.1 Quadratic correlation between leaf N and broccoli yield spring 2006

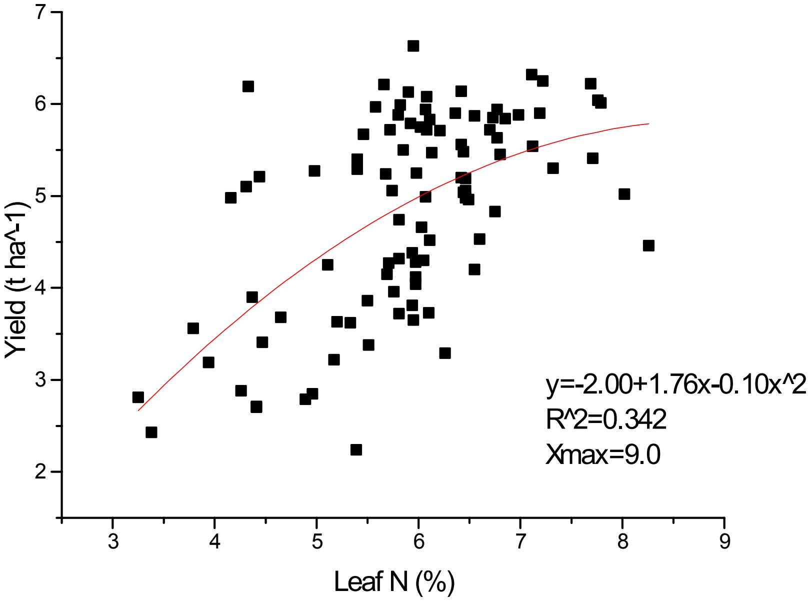

Figure 2.2 Quadratic correlation between leaf N and broccoli yield fall 2006

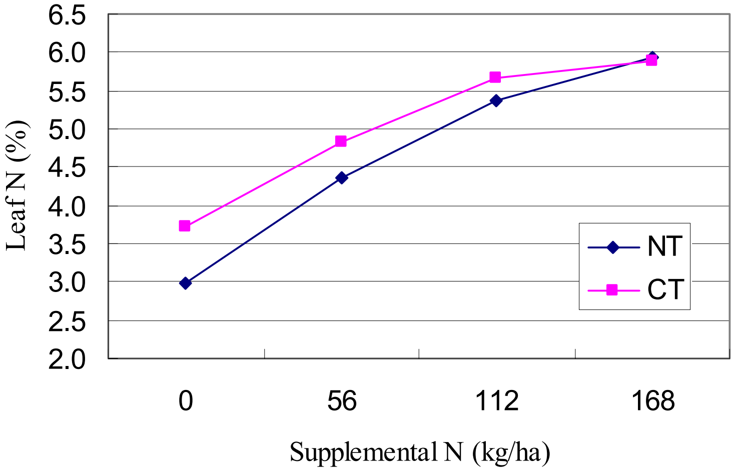

Figure 2.3 Tillage and supplemental N treatment interaction on broccoli leaf N (p=0.0023) fall 2006

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3. Non-chemical Weed Control Utilizing Cover Crops and Tillage

3.1 Introduction

Without the aid of herbicides weed management is one of the greatest challenges for organic growers. Research has devoted little attention to the threat of weeds in organic crop production (Bàrberi, 2002). As a result, many producers are reluctant to undertake organic transition because of uncertainty over weed population dynamics and management (Ngouajio and McGiffen, 2002). Integrated weed management that relies on multiple weed control methods provides a holistic approach to managing weeds in organic systems (Bàrberi, 2002). Furthermore, an increase in the understanding of weed biology and ecology underpins long-term improvements in sustainable weed control (Bond and Grundy, 2001). Growers interested in converting to organic farming require more information to meet this challenge.

Cover crop rotations and the strategic use of tillage offer an effective approach to non-chemical weed control. In the long-term, management strategies to reduce the weed seed bank is a practice to decrease weed pressure (Teasdale et al., 2003). Tillage can be an effective method for weed control, however soil inversion buries new weed seeds and brings buried seed to the surface (Carter and Ivany, 2006). Furthermore, both living and mulched (dead) cover crops physically obstruct weed growth (Creamer et al., 1996; Schonbeck et al., 1991; Teasdale, 1993). In addition, cover crops produce allelochemicals for chemical weed suppression (Einhellig et al., 1993; Ekelme et al., 2003; Khanh et al., 2005). The combination of mulched cover crops and tillage when necessary suppresses weeds and reduces the weed seed bank.

3.2 Materials and Methods

See section 2.2.

3.3 Results and Discussion

Compared to the other cover crops in both the spring and fall experiments, lab-lab (LL) had lower cover crop biomass. Killed cover crops have the capacity to physically obstruct light (Teasdale, 1993). Often, increased cover crop biomass is correlated with greater weed suppression (Creamer et al., 1996; Schonbeck et al., 1991). Where LL was grown the weed biomass measured (Table 3.1) and observed in the NT plots (Figure 3.1) was far less than the other species. Also, weed populations were lower in the LL plots (Table 3.1). In Nigeria, researchers have suggested LL has an allelopathic characteristic to suppress weeds (Ekelme et al., 2003). These ressults suggest that LL has a unique characteristic to suppress weeds.

A greater understanding of weed ecology underlies non-chemical weed control efforts. Knowledge of seasonal propagation of noxious species is required for effective control (Table 3.2).

Table 3.1 Average cover crop and weed biomass from spring and fall 2006

Cover Crop	Cover Crop Biomass (kg ha^{-1})	Weed Biomass (kg ha^{-1})	Weed Population (# ha^{-1})
	Spring		
LL	1985 b	18 b	-
SH	3506 a	301 a	-
P value	0.0100	0.0005	-
	Fall		
SB	5171 b	272	2764 a
LL	4642 b	114	936 b
CP/SH	6995 a	314	2196 ab
P value	0.0003	NS	0.0444

(LL) lab-lab, (SH) sunn hemp, (CP/SH) cowpea/sunn hemp mix

Table 3.2 Weed flora observations of spring and fall broccoli 2006

SPRING	
Life cycle	Common (*Scientific*)
Winter annuals	Henbit (*Lamium amplexicaule* L.)
	Purple deadnettle (*Lamium purpureum* L.)
	Common chickweed (*Stellaria media* L.)
Perennials	Canada Thistle (*Cirsium arvense* L.)
	Yellow Nutsedge (*Cyperus esculentus* L.)
	Yellow woodsorrel (*Oxalis stricta* L.)
	Broadleaf dock (*Rumex obtusifolius* L.)
	Dandelion (*Taraxacum officinale* Weber)
FALL	
Summer annuals	Pigweeds (*Amaranthus spp.)*
	Lambsquarters (*Chenopodium album* L.)
	Goosegrass (*Eleusine indica* L.)
	Fall Panicum (*Panicum dichotomiflorum* Michx.*)*
Perennials	Canada Thistle (*Cirsium arvense* L.)
	Yellow Nutsedge (*Cyperus esculentus* L.)

LL SH

Figure 3.1 Weed emergence in NT LL and SH plots following spring broccoli planting

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4. Synthesis and Recommendations

The broad objective of this study was to optimize vegetable production during organic transition and exemplify long-term productivity and sustainability. Nitrogen management and weed suppression have been identified as the greatest difficulties for organic growers, as well as the main setbacks for growers interested in organic transition. Furthermore, organic farming is faced with other sustainability issues. In order to boost soil fertility and control weeds, organic growers often rely on an excessive use of tillage, leading to such claims that no-till systems are more environmentally benign than organic. As a result, this study shows the organic farming should be combined with no-till farming to address production challenges, improve soil quality and protect environmental quality.

A number of other studies can evolve from the work from this research. The mobility of N in agricultural systems can be further quantified. This study demonstrated the yield response to supplemental N by sampling leaf N accumulation. Without soil N measurements taken over time, N inputs and losses via leaching cannot be quantified. Furthermore, whole-plant dry weight and N samples can provide insight into the total N removal from the field. With these added measurements, a whole system N budget can be constructed to analyze N movement. Also, N labeling of inputs, such as supplemental fertilizer and cover crop residues, can further quantify their movement. In order to gain a greater understanding of N cycling in organic systems, soil N, whole-plant N and N labeling are needed.

As soil microbes play an important role in N cycling, soil microbial respiration, in the form of carbon dioxide efflux for the soil surface, can be measured to quantify microbial activity. Different qualities and quantities of cover crop residues and their management with tillage give greater insight into how these management practices affect soil microbes. Furthermore, microbial respiration can affect soil organic matter accumulation, so soil organic matter measurements may change under different cover crop and tillage treatments. As a result, a balance can be achieved between yield potential and accumulation of soil organic matter if optimum microbial activity can be harnessed.

Finally a number of steps can be taken to develop management practices to optimize weed suppression. In this study, weed biomass and flora were recorded before broccoli transplanting. In future studies, weed biomass samples can be taken over time to gain more insight into treatments effects on weed dynamics. Simpler techniques for measuring weed biomass can be used such as laying a string and counting the number of plants within that area. However, caution should be taken as weed populations can vary within a field. These and many other ideas can help further ameliorate organic production practices.

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Vitae

Daniel spent his early childhood living in many different states before moving to Bethel, Connecticut where he graduated from Bethel High School in 2000. He earned with Bachelor's of Science from the University of Maryland at College Park in 2004 after a year abroad studying horticulture in the Netherlands. After graduation in early 2005, Daniel traveled to Costa Rica and through Central America to Guatemala where he met his life partner Onna Lo on a bus. Later that year, Daniel enrolled in graduate school in Virginia Tech where he completed his Masters of Science in 18 months. In 2007, Daniel moved to Santa Rosa, California where he continues his love for growing plants.