ABSTRACT

GARLAND, BENJAMIN CLAYTON. Enhancing Strawberry Production in the Southeastern U.S. through Summer Cover Crops, Beneficial Mycorrhizal Fungi, and On-Farm Participatory Research. (Under the direction of Michelle Schroeder-Moreno.)

North Carolina is the 4th largest producer of strawberries, with most of its production coming from small family farms that run roadside stands and pick-your-own operations. As methyl bromide fumigation will become more restrictive to use and eventually phased out in the coming years, many growers are looking for alternative strategies to maintain productivity and reduce environmental impacts. A two-year field experiment was conducted to examine the effects of eight cover crop treatments combined with two arbuscular mycorrhizal (AM) fungal inoculants on strawberry growth and yields. Cover crop treatments included two grasses, two legumes, two grass/legume combinations, a non-mycorrhizal host, and no cover crop. Mycorrhizal treatments included a mixture of native AM fungal species found at the research site, and a single species derived from a commercially available inoculant. Cover crop treatments were assessed for their aboveground biomass and nutrient uptake, as well as their impact on weed abundance and diversity, soil nutrients, parasitic nematode populations, and subsequent strawberry growth, yields, and nutrient uptake. Mycorrhizal treatments were also assessed for their impact on strawberry

growth, yields and nutrient uptake. Strawberry plants were sampled five times throughout the growing season for dry weights of roots, crowns, leaves, flowers and fruit, leaf area, percent AM colonization of roots, total yield, cull yield, and marketable yield. Grass-based cover crop treatments, particularly pearl millet, produced much greater aboveground biomass compared to the other cover crop treatments. In both years, cover crops significantly reduced summer weed biomass compared to the no cover crop control. Cover crop treatments had no effect on the subsequent strawberry plant growth or yields in either year. Mycorrhizal inoculation treatments did not differ in their effects on overall strawberry yields nor plant growth, although scattered effects on plant growth were observed on some sample dates.

A second one-year study was conducted on three participating farms to determine the effects of summer cover crop treatments on strawberry yields, weed biomass, and cover crop biomass, and to investigate the producer-perceived benefits and barriers to the adoption of cover crops in a real-world strawberry production system. Mycorrhizal fungi populations at each farm were also assessed. Investigators maintained an ongoing discussion with producers that culminated in a formal post-season interview that gauged their concerns surrounding the adoption of cover crops, surveyed their interest in adopting organic practices, discussed their strategies for phasing out methyl bromide, and

gathered their suggestions for future research. Results showed that cover crop treatments significantly reduced weed biomass at two of the farms, but not the third. There was no significant difference between the amounts of aboveground biomass produced by the two cover crops trialed on each farm. Cover crop treatments reduced total strawberry yield compared to the bare ground control at one farm, but no difference was found at the other farm (the third farm did not participate in yield measurements). Producer interviews suggested that the most prominent barriers to adoption of cover crops are: 1) a lack of information about how to integrate cover crops into a strawberry production schedule; 2) an absence of practical guidance on how to increase cover crop biomass responses through enhanced seeding rates and other integrated organic amendment applications, 3) a need to evaluate cover crop benefits in strawberries over a longer time period, not just one season; 4) an insufficient understanding of the interactions of mycorrhizal fungi and other beneficial soil inoculants when combined together with cover crops; and 5) on-farm research should be more participatory and emphasize the producer's needs.

Enhancing Strawberry Production in the Southeastern U.S. through
Summer Cover Crops, Beneficial Mycorrhizal Fungi,
and On-Farm Participatory Research

by
Benjamin Clayton Garland

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APPROVED BY:

Dr. Michelle Schroeder-Moreno
Committee Chair

Dr. Gina Fernandez
Committee Co-Chair

Dr. Nancy Creamer
Committee Member

DEDICATION

This thesis is dedicated equally to my father, Jim Garland, my late mother, Cheral Garland, and my fiancé Laura Sue Bentz. Without my parents' support throughout my life, and Laura's support during my years in grad school, I would not have made it this far. Thanks for putting up with me.

BIOGRAPHY

Ben Garland received a Bachelor of Science in Agriculture degree in Horticulture from the University of Georgia (UGA) in 2006. During his time at UGA he became interested in sustainable and organic agriculture, venturing to Latin America to further his studies. While participating in a tropical agroecology course in Costa Rica, Ben met Michelle Schroeder-Moreno, a specialist in agroecology and mycorrhizal fungi from North Carolina State University (NCSU). Realizing their shared interests, Michelle offered him a position as her grad student where they would work on a project investigating mycorrhizal fungi and cover crops in strawberry production. He accepted and began graduate school at NCSU in the fall of 2007. Ben will receive his Master of Science in Crop Science degree in May of 2010.

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I. Introduction

North Carolina ranks 4th in strawberry production and 3rd in market value in the United States (NASS, 2008). Most of its strawberries are sold at roadside stands, farmer's markets, and pick-your-own operations (Sydorovych, 2006). Of the other leading strawberry producing states, nearly all production is destined for the wholesale fresh (California and Florida) or processing (Oregon) markets (NASS, 2008), making the preponderance of direct sales by many small strawberry farms in North Carolina a unique situation. Unfortunately, NC strawberry growers operate in a hot, humid climate that is often more favorable to diseases like anthracnose crown rot that can devastate strawberry fields if not properly managed (Smith, 2008).

Conventional strawberry growers in NC and throughout the Southeastern U.S. have traditionally dealt with the increased incidence of pests and diseases by fumigating their fields with methyl bromide (EPA, 2009) and relying on an annual production strategy (Rieger, 2007). This has worked well in the past, but the restrictions to methyl bromide fumigation are scheduled to be drastically increased beginning in 2010 (EPA, 2009). Numerous synthetic chemical replacements are becoming available but may not be as effective against some pests (Duniway, 2002). Many growers are turning to alternative strategies that could potentially reduce disease and increase yields – like adding a summer cover crop rotation (Phatak and Diaz-Perez, 2007; Sarrantonio, 2007). In addition to using a cover crop rotation, research suggests that other alternatives, such as inoculation of strawberry plants with arbuscular mycorrhizal (AM) fungi (Linderman, 1995; Norman et al., 1996; Taylor and Harrier, 2001) could also provide sustainable alternatives to methyl bromide and be of particular importance for organic growers.

The research experiments in this thesis examine the effects of cover crops and arbuscular mycorrhizal (AM) fungi on strawberries. The first chapter involves field research conducted over two years at the Center for Environmental Farming Systems (CEFS) in Goldsboro, NC. Here, we examined the effects and interactions of eight cover crop treatments paired with two AM inoculants. Cover crop treatments were assessed for their aboveground biomass, impact on weed abundance and diversity, cover crop nutrients, soil nutrients, AM populations, parasitic nematode populations, and impact on subsequent strawberry growth and yields. Strawberry plants were sampled throughout the growing season for dry weights of roots, crowns, leaves, flowers and fruit, leaf area, percent AM colonization of roots, total yield, cull yield, and marketable yield.

The second chapter presents a 1-year experiment conducted jointly with three participating strawberry producers in NC. On each farm, we assessed the impact of two producer-selected cover crops (versus a bare ground control) on strawberry yields. We also worked closely with each producer to determine the most pressing issues facing the integration of cover crops into an on-farm production system. The experiment concluded with an interview with each producer, where we asked several questions to gauge their concerns surrounding the adoption of cover crops, to survey their interest in adopting organic practices, to discuss their strategies for phasing out methyl bromide, and to gather suggestions for future on-farm research.

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II. Enhancing Strawberry Production in the Southeastern United States through Summer Cover Crop Rotation and Beneficial Mycorrhizal Fungi

Abstract

We examined the effects of eight summer cover crop treatments combined with two arbuscular mycorrhizal (AM) fungal inoculants on strawberry growth and yields in a two-year field experiment. Cover crop treatments included sudangrass [*Sorghum bicolor* (L.) Moench cv. Piper]; 2) pearl millet [*Pennisetum glaucum* (L.) R.Br. cv. 102 M Hybrid]; 3) soybean [*Glycine max* (L.) Merrill cv. Laredo]; 4) velvetbean [*Mucuna deeringiana* (Bort) Merr. cv. Georgia Bush]; 5) sudangrass / velvetbean combination; 6) pearl millet / soybean combination; 7) a non-mycorrhizal host consisting of rape [*Brassica napus* L. var. napus cv. Dwarf Essex] and buckwheat [*Fagopyrum esculentum* Moench] in year 1 and year 2, respectively; and 8) no cover crop control. Strawberry tips were inoculated with either a native mixture of several AM fungal species or a single species sold commercially, *Glomus intraradices*. Cover crop treatments were assessed for their aboveground biomass and nutrient uptake, as well as their impact on weed abundance and diversity, soil nutrients, parasitic nematode populations, and subsequent strawberry growth, yields, and nutrient uptake. Mycorrhizal treatments were also assessed for their impact on strawberry growth, yields and nutrient uptake. Strawberry plants were sampled five times throughout the growing season for dry weights of roots, crowns, leaves, flowers and fruit, leaf area, percent AM colonization of roots, total yield, cull yield, and marketable

yield. Grass-based cover crop treatments, particularly pearl millet, produced much greater aboveground biomass compared to the other cover crop treatments. In both years, cover crops significantly reduced summer weed biomass compared to the no cover crop control. Cover crop treatments had no effect on the subsequent strawberry plant growth or yields in either year. Mycorrhizal inoculation treatments did not differ in their effects on overall strawberry yields nor plant growth, although scattered effects on plant growth were observed on some sample dates.

Introduction

Strawberries are a high-value product and strawberry production has strong growth potential, especially in the Southeastern (SE) U.S. and North Carolina where most producers sell directly to consumers through pick-your-own and roadside stands (Sydorovych, 2006). At these sites, where strawberries are replanted year after year in the same location, soil borne pathogens, root rot diseases, and weeds can significantly reduce yields (Wing et al., 1995; Seigies and Pritts, 2006). Conventional producers have traditionally dealt with these pest problems by fumigating with methyl bromide, which is now under restricted use for strawberry production (United States Federal Government, 2009) with restrictions becoming significantly stronger after 2010. Many producers are considering a range of alternative synthetic chemicals and fumigants, such as Telone II, but the health risks may be significant (National Toxicology Program, 1985). There is a critical need for sustainable alternative approaches to pest and soil management for both conventional and organic strawberry production in the SE U.S. These alternatives should promote healthy plant growth and the functioning of beneficial soil organisms, while also reducing pests and diseases over the long term.

Although not a current common practice, the use of summer cover crops can be easily integrated into strawberry production in the SE U.S. and may play a critical role in sustainable soil and pest management strategies for strawberry production in this region. The incorporation of cover crops with annual crops is an important strategy that can help prevent erosion, increase soil organic matter and fertility (Sarrantonio, 2007), break up hard clay soils, interrupt pest cycles, and reduce weeds (Phatak and Diaz-Perez, 2007). Moreover, legume cover crops can fix atmospheric nitrogen, leading to increased nitrogen availability and yields of the subsequent crop. Cereal or grass cover crops can produce large amounts of biomass, increasing overall soil organic matter (Snapp et al., 2005). A few studies have documented varying benefits of cover crops particular to strawberry production. Lamondia et al. (2002) investigated sorghum-sudangrass [*Sorghum bicolor* × *S. sudanense* (Piper) Stapf] and 'Saia' oats [*Avena strigosa*

Schreb.] and found that these cover crops decreased pest populations and increased strawberry yield. Previously, Elmer and LaMondia (1999) found that these same oat cover crops combined with $(NH_4)_2SO_4$ fertilizer reduced the incidence of strawberry black root rot. More recent studies, such as Seigies and Pritts (2006), have shown similar benefits, but none have been conducted in the SE U.S. climatic and growth conditions, where higher pest pressures exist.

Selective cover crop species may also improve the arbuscular mycorrhizal (AM) fungal inoculum potential and subsequent crop benefit from AM. Arbuscular mycorrhizas are known to support healthier, higher-yielding crops through increased nutrient acquisition, specifically phosphorus (Smith and Read, 1997) but also K, S, Cu, Z, Fe (Koide, 1991) and organic N (Hodge, 2003). Extraradical AM hyphae act as extensions of plant roots, contributing an extensive absorptive surface for nutrient uptake. The benefits from AM to crops are diverse and well documented (Linderman, 1995). Plants colonized by AM have been shown to have higher shoot and root biomass, higher tissue nutrient concentrations, greater tolerance for drought conditions (Augé, 2001), and greater resistance to soil borne pathogens (Linderman, 1995; Schroeder and Janos, 2004). Mycorrhizal fungi have been demonstrated to benefit strawberry growth by increasing nutrient acquisition (Taylor and Harrier, 2001) and decreasing damage caused by *Phytophthora* root rot (Norman et al., 1996).

Commercial AM inoculants are available but they generally consist of only one or a few species that may or may not be well-adapted to the host plant on which they are applied. Locally adapted AM fungal isolates can be produced on farm (Douds et al., 2008) and may be more effective than introduced species (Bull et al., 2005). Selection of cover crops that also function as good AM hosts may increase the activity of indigenous AM fungi, leading to increased overall soil community functioning (Gosling et al., 2006). Enhancing AM host diversity through cash crop and cover crop rotations is thought to play a key role to increase AM inoculum potential and the growth of subsequent AM dependant crops (Galvez et al., 1995; Gosling et al., 2006).

There are a variety of summer cover crops species that can be grown in the SE U.S. (Creamer and Baldwin, 2000) and many of these would support AM fungi. Summer cover crops could be integrated into strawberry production in North Carolina where strawberries are harvested in May and June and the fields are replanted with new strawberry plants in October. During the months of June through August, the fields typically remain fallow. No study that we are aware of has examined the integrated approach of using summer cover crops and beneficial mycorrhizal fungi inoculants for strawberry production in field conditions. The primary objective of this study was to examine the combined effects of eight summer cover crop treatments (including a control or no cover crop) and two AM fungal inoculants on strawberry growth and yields in a two-year field experiment. Secondary objectives included assessing differences in weed abundance and diversity, soil fertility, and parasitic nematode community among the cover crop treatments.

Materials and Methods

Experimental Design

A field experiment was conducted at the Center for Environmental Farming Systems (CEFS) in Goldsboro, NC, United States (lat. 35°36' N, long. 78°04' W) between June 2007 and June 2009. The site was organically managed from 2004–2006 as part of a previous strawberry experiment and was planted in perennial rye grass during the intervening months. This field study was designed as a split plot randomized complete block design with four replications and two factors: cover crop as the main-plot factor (eight treatments) and arbuscular mycorrhizal (AM) inoculum as the sub-plot, split factor (two treatments). The eight cover crop treatments consisted of two grasses grown alone: 1) sudangrass (SG) [*Sorghum bicolor* (L.) Moench. cv. Piper; Kaufman Seed, Ashdown, AK] and 2) pearl millet (PM) [*Pennisetum glaucum* (L.) R.Br. cv. 102 M Hybrid; Albert Lea Seed House, Albert Lea, MN]; two legumes grown alone: 3) soybean (SB) [*Glycine max* (L.) Merrill cv. Laredo; Kaufman Seed, Ashdown, AK] and 4) velvetbean (VB) [*Mucuna deeringiana* (Bort) Merr. cv. Georgia Bush; Georgia Seed Development Commission, Athens, GA]; two grass/legume combinations: 5) sudangrass/velvetbean (SGVB) and 6) pearl millet/soybean (PMSB); 7) a non-mycorrhizal cover crop host (NONH) consisting of rape [*Brassica napus* L. var. napus cv. Dwarf Essex; Wyatt-Quarles Seed Co., Garner, NC] and common buckwheat [*Fagopyrum esculentum* Moench; Wyatt-Quarles Seed Co., Garner, NC] in 2007 and 2008, respectively; and 8) no cover crop control (NOCC) treatment. Mycorrhizal pre-inoculation treatments consisted of either a native AM fungal species mix (NAT) or a single AM fungal species from a commercially available inoculant (COM). Cover crop treatments were randomized into four replicated blocks each consisting of eight 6.4 m x 12 m sized plots for a total of 32 plots. Each cover crop main plot was split into two raised beds 0.91 m x 4.5 m which were spaced apart (2.44 m on center) to prevent mixing of mycorrhizal sub-plot treatments. Location of cover crop and mycorrhizal treatments were conserved from year one to year two.

Cover Crop / Field Management

Cover crops were planted mid-June each year to correspond with the end of strawberry harvest in the piedmont region of North Carolina to fit realistic conditions of cover crop adoption. Cover crops were seeded fully across each plot (see rates, Table 2.1) using a Sukup 2055 No-till Grain Drill (Sukup Manufacturing Company, Sheffield, IA), and sudangrass was additionally seeded as a 3.6 m wide buffer between blocks. Legumes were pre-inoculated with either *Bradyrhizobium japonicum* for soybean or *Bradyrhizobium sp.* for velvetbean (INTX Microbials, Kentland, IN). Cover crops were cut with a 6 ft flail mower the first week of September each year and incorporated with a 21 ft disk. OMRI-approved (Organic Materials Review Institute, Eugene, OR) fertilizers were applied each year after a second disk pass prior to bedding as follows: broadcasted limestone (Crop Production Services, Princeton, NC) at 1800 kg ha^{-1}; sodium borate spray (Crop Production Services, Princeton, NC) at 5.6 kg ha^{-1}; broadcasted potassium sulfate 0N–0P–50K (Coor Farm Supply, Smithfield, NC) at 112 kg ha^{-1}; and broadcasted soybean meal 7N–1P–1K (J. Milo Pierce Farm Center, Pikeville, NC) at 900 kg ha^{-1}.

Mycorrhizal Inoculum

The COM mycorrhizal inoculum contained a single mycorrhizal species (*Glomus intraradices*) found in commercially available mycorrhizal inoculant donated by Mycorrhizal Applications, Grants Pass, OR. The NAT mycorrhizal treatment consisted of a mixture of native AM fungal species isolated from the study site prior to the establishment of the treatments. To develop the NAT mycorrhizal inoculum, twenty random soil samples were taken at a depth of 15 cm from each main plot on April 2, 2007 and combined. This native mycorrhizal fungal species mix was developed using trap cultures. Mycorrhizal trap cultures were established in greenhouses at North Carolina State University by combining ≈300 g of each aggregate field plot soil sample at a 1:4 volume ratio with a steam-sterilized soil mix (1:1 pasteurized sand and soil) in standard 6-inch clay pots. A combination of corn [*Zea mays* L.], sudangrass [*Sorghum bicolor* (L.) Moench], and prickly sida [*Sida spinosa* L.] were used as host plants and grown for 140 days. Each pot was fertilized with 1 tsp Osmocote 19N–6P–12K fertilizer (The Scotts Company, Marysville, OH) and water was limited in the final days to induce fungal sporulation.

The following fungal species were identified from the native (NAT) mycorrhizal inoculum: *Acaulospora koskei, A. laevis, A. mellea, A. morrowiae, A. scrobiculata, Glomus clarum, Gl. etunicatum, Gl. intraradices, Gl. mosseae, Gl. tenue,* two undescribed *Glomus sp.* (small pale yellow and medium pale yellow), *Paraglomus occultum,* and *Scutellospora heterogama.* The NAT inoculant was a mix of AM fungal spores, root fragments, and the sand/soil mixture. The COM inoculant was a solution of pure spores combined with a sterilized sand/soil mix. Only the pure *Gl. intraradices* spores were used, rather than the off-the-shelf commercial inoculant, to separate the effects of only the mycorrhizal species from any additional materials commonly present in commercial inoculants (such as fertilizers and soil additives).

Strawberry Pre-inoculation and Management

Each year, new organic certified Chandler strawberry tips were purchased from Cottle Farms Nursery (Faison, NC). In 2007 Chandler tips were used, but due to severe disease problems (*Phytophthora cactorum*) observed in the 2008 Chandler tips, a new set of non-inoculated (without mycorrhizal treatments), non-organic, Camarosa plugs needed to be purchased. Due to the disease infestation in 2008, the methodology presented in the following paragraph applies to 2007 only. Since the disease took a few weeks to detect, the Camarosa plugs were field planted about one month late on November 13, 2008.

After the tips were received, they spent about one week in cold storage (1˚C) and then were transferred to 50-cell trays (cell size: 4.8 cm, 4.8 cm, 5.7 cm) and grown in the North Carolina State University greenhouses for ≈3 weeks under misting benches. Tips were planted in OMRI-approved SunGro *Natural and Organic Planting Mix* composed of 75–85% Canadian sphagnum peat, perlite, dolomite lime, and an organic wetting agent (SunGro Horticulture, Vancouver, BC, Canada) combined with either the NAT or COM mycorrhizal inoculant at a 3:1 volume ratio (≈25 g inoculant by weight) for each cell.

Subsequent analysis revealed at least 40 mycorrhizal spores per cell. Plants were misted with water 3 to 5 times per day depending on conditions and fertilized once with Organic Biolink 5N–5P–5K (Westbridge Agricultural Products, Vista, CA) foliar spray (rate: 1.5 oz per gallon of water) during the third week of greenhouse growth. Plants were placed outside under shade to acclimate one week prior to field planting.

Strawberry plasticulture beds were formed 2 weeks prior to planting using a Kennco bed shaper and mulch layer (Kennco Manufacturing, Ruskin, FL). Twenty-six strawberry plugs were planted in each mycorrhiza treatment bed in 2 rows at 12-inch (30.48 cm) spacing within each row for a total of 52 plants per cover crop main plot replicate. Only the center 12 plants in each bed were used for yield data collection. Five of the remaining plants were used for biomass collection, leaving nine additional buffer plants. From March 7 to April 7, 2008, potash 0N–0P–60K (Crop Production Services, Princeton, NC) and OMRI-approved Phytamin 800 7N–0P–0K (California Organic Fertilizers, Hanford, CA), were each applied separately via drip irrigation at a rate of 13.5 kg ha^{-1} once a week for five weeks. The same rate and time frame was used in 2009, however sodium nitrate 16N–0P–0K (Wood Creek Farm Supply, Cana, VA) supplemented the Phytamin 800 and accounted for less than 20% of the total N applied.

Data Collection

Soil fertility and nematode community structure were analyzed from composited soil samples collected in late spring 2007 and early summer 2008. Cover crop plots were evaluated in summer 2007 and 2008 for weed species richness and diversity at 4 and 8 weeks after planting using 3 randomized replications of a 0.25 m^2 quadrat within each plot. A Shannon Index (H') was used for diversity calculations (Shannon and Weaver, 1949) according to the formula:

$$H' = - \sum_{i=1}^{S} p_i \,(\ln p_i)$$

Where p_i is the proportion of the total number of individuals made up by species i and can be found by [$p_i = n_i / N$] where n_i is the number of individuals in species i and N is the total number of individuals collected in the entire sample. S is the number of samples.

At 8 weeks, the weed samples were also harvested and dried for a total aboveground biomass weight measurement. Eight weeks after planting the cover crops, a 0.5 m^2 quadrat was randomly placed in each cover crop plot and all cover crop aboveground biomass within the quadrat was cut at ground level, collected, dried at 60°C for 96 hours, and weighed. This cover crop material was sent to the North Carolina Department of Agriculture (NCDA) Agronomic

Services Lab for shoot nutrient analyses. In mixed cover crop treatments, the individual species were separated before analysis.

One representative strawberry plant per mycorrhizal treatment bed was collected at five time periods each year in 1) early January, 2) early March, 3) early April, 4) early May, and 5) late May (2008) or early June (2009). Whole strawberry plants were removed from the field, washed thoroughly, and leaves, petioles, crowns, roots and fruits/flowers (if any) were separated, dried at 60˚C for 96 hours, and weighed. Prior to drying, fresh leaf area (cm^3) was measured using a LICOR LI-3100C Area Meter (LICOR Biosciences, Lincoln, NE). Dried roots were later randomly sub-sampled for mycorrhizal colonization assessment, rehydrated, cleared, and stained (Philips and Hayman, 1970). Percent mycorrhizal colonization of strawberry roots was assessed using a grid-line intersect method (Giovanetti and Mosse, 1980). A nutrient analysis of leaf and petiole samples for the third and fifth biomass harvests was performed by the NCDA Agronomic Services Lab.

During the strawberry harvest season, marketable yield, cull yield, and average berry weight data were collected on the same twelve plants within each COM or NAT mycorrhizal treatment beds. Average berry weight was calculated based on the actual number of berries harvested from the 12 plants in each bed; if the number of berries exceeded 25, the calculation was based on a random sampling of 25 marketable berries. Culls were any berries deemed to be unmarketable due to size (<12 g), disease, or deformity.

Statistical Analyses

All data were analyzed using the PROC GLM and PROC MIXED procedures of SAS version 9.1.3 (SAS Institute, Cary, NC). Statistical significance was expressed at the $P \leq 0.05$ level. Log or square root transformations were applied to data prior to analysis if necessary to fulfill normality and homogeneity of variance assumptions. Pairwise mean comparisons were performed using Tukey's HSD. Treatments of *cover crop*, *mycorrhiza*, and their interactions were considered fixed effects while *rep*, *rep*cover crop* were considered random effects. Data collected over time considered *time* as a crossed fixed effect factor. Soil variables and cover crop biomass were analyzed following a randomized complete block design with 4 reps and 8 cover crop treatments. Strawberry biomass, yields, and plant nutrient status were analyzed following a split-plot for each time point, and as a split-split plot with *time* as a sub-subplot factor, for the combined analysis of all time points. A Multivariate Analysis of Variance (MANOVA) was used to analyze the overall treatment effects for the biomass responses (root, crown, leaves, flowers, fruit), recognizing the dependency structure of these responses.

Results

Cover Crops

Cover crop biomass differed significantly in both 2007 (P=0.0005) and 2008 (P<0.0001) with treatments that included grasses generally being higher (Figure 2.1). In both years, the fast-growing PM and SG grasses produced significantly more biomass than other cover crops in week 4 (data not shown) but this effect was reduced by week 8. Nutrient analysis of the cover crop biomass material in 2007 revealed significant differences for all macro and micronutrients (Table 2.2), while in 2008, all nutrients differed except Fe (P=0.0955), Mn (P=0.5665), and Cu (P=0.0511). Across both years, the PMSB and SGVB mixed treatments contained significantly higher concentrations of all nutrients analyzed. The average legume biomass component of the mixes was 9% for PMSB and 16% for SGVB.

After 8 weeks of cover crop growth, weed biomass differed significantly among cover crop treatments in 2007 (P<0.0001) and 2008 (P<0.0001) (Figure 2.2), with the PM and SG treatments showing the most consistent weed reduction. Contrasts of weed biomass measurements among treatments indicated that treatments containing grasses significantly reduced weed biomass compared to legume species alone (P<0.0001) and all seven cover crop treatments significantly reduced weed biomass compared to the no cover crop treatment (*P*<0.0004). Weed diversity (H') was significantly affected by cover crop treatments in 2008 (*P* =0.0191) showing reduced diversity in the PM and PMSB treatments compared to all other treatments. No difference in weed diversity was found in 2007 (*P*=0.8281) (Figure 2.3).

Soil and Nematode Analyses

In 2007 and 2008, no significant differences were found in the soil fertility analyses performed on each cover crop plot when compared to the baseline measurement and among treatments (data not shown, *P*=0.5115). Analyses of the nematode community structure in 2007 and 2008 found no elevated levels of pathogenic nematode populations in baseline and among treatments (data not shown).

Strawberry Yields, Growth, Nutrients, and Mycorrhizal Colonization

Cover crop and mycorrhizal treatments did not significantly affect average berry weight, cull yield as a percent of total harvest, marketable yield, or total yield in 2008 or 2009 (Table 2.3), nor were there any interactions among treatments. A MANOVA of the root, shoot, crown, fruit, and flower weights and leaf area per plant across all sampling dates showed no significant effects from the cover crop or mycorrhiza treatments in either 2008 or 2009 (data not shown), although some of these biomass variables varied significantly between mycorrhiza treatments on individual dates (see Table 2.4).

A MANOVA of the leaf and petiole nutrient analysis of strawberry plants showed no significant effects from cover crop treatments in either the April (Wilks' Lambda P=0.5095) or May 2008 sampling periods (Wilks' Lambda P=0.8729; data not shown). In 2009, cover crop treatment did affect Mg concentration during the April sampling period (the PMSB treatment had significantly lower Mg than all others, P=0.0205), but no differences were found in the June 2009 sample for any nutrient (Wilks' Lambda P=0.1760; data not shown). Mycorrhiza treatments did significantly differ in their effect on overall nutrient analysis in April (Wilks' lambda P=0.0199) and late May 2008 (Wilks' Lambda P<0.0001), as well as the following year in April 2009 (Wilks' lambda P=0.0035; Table 2.5). Mycorrhizal treatments did not significantly differ in their effect on the overall nutrient status of plants harvested in June 2009 (Wilks' Lambda P=0.2494; Table 2.5). When analyzed individually, in April 2008 the NAT treatment had higher levels of Ca, S, Cu, and Bo compared to the COM treatment, while in late May 2008 the NAT treatment had higher levels of N, Fe, and Cu but lower levels of P, K, Mg, S, and Na (Table 2.5). In April 2009, the NAT treatment had higher levels of Cu while in June 2009 the NAT was lower in Mn and Zn, compared to the COM treatment (Table 2.5).

In both years 2008 and 2009, cover crop treatment did not significantly affect the percent root mycorrhizal colonization in the subsequent strawberry crop (2008 P=0.4743; 2009 P=0.0816; Figure 2.4). The COM mycorrhizal treatment had a significantly higher (P<0.0001) mean percent root colonization per strawberry plant in 2008 (37.8% vs. 26.3%), but this treatment effect did not carry over into 2009 when the plants were not pre-inoculated (P=0.9936). The collection date was significant (P<0.0001) across both years, with a general trend of the percent AM colonization increasing over time (Figure 2.4).

Discussion

The ability of cover crops to reduce weeds was one of the main findings in this study. Results from our study showed a 67% reduction of weed biomass averaged over all cover crop treatments (144 kg/ha) when compared to the no cover crop (bare ground) control (440 kg/ha) averaged over both years. Not surprisingly, the high biomass producers — pearl millet and sudangrass grown alone, and the combination of pearl millet with soybean — reduced weed biomass by more than 98% compared to the no cover crop control. Cover crops are well-known as an effective weed management strategy in organic farming systems (Bond and Grundy, 2001) and similar weed reductions have been found with other cover crop species (Mennan et al., 2009).

Although cover crops greatly reduced weed biomass, this did not result in cover crops enhancing strawberry total or marketable yields in either year. The positive benefit of cover crops to soil fertility, and any resulting increase in strawberry yield, may be an effect that accumulates over a longer period beyond the timeframe of this experiment. That cover crops had no effect on the yield of a subsequent crop is in opposition to many recent studies that have found summer cover crops to increase yields of various annual crops including lettuce (Wang et al., 2008), sweet corn (Kabir and Koide, 2002), okra (Wang et al., 2006), tomato (Wang et al., 2005), and organic kale (Mennan et al., 2009). In a review of the effects of cover crops on soil health and subsequent cash crops, Fageria et al. (2005) found that when there was a crop benefit from cover crops, it came primarily from the effects of improved nutrient availability through added nitrogen from leguminous covers and/or increased soil organic matter from cover crop residues.

It is worth noting that major differences were found in the overall yield from 2008 (526 g/plant) to 2009 (166 g/plant) — a 68% reduction. We believe the most likely explanations for the lower yield in 2009 are the late planting date (November 11th 2008 vs. October 19th 2007) and weather conditions. Many growers in NC also experienced a 50% reduction in 2009 that was attributed mainly to the cold and rainy weather experienced in early spring (Poling, 2009).

We suspect we did not observe a strawberry yield benefit from cover crops in our study for two main reasons, which are not mutually exclusive:
1) nutrients, especially nitrogen, were not limiting to strawberries and 2) the 8-week window for summer cover crops may not have been of sufficient duration to maximize growth or nutrient development. In our experiment we followed the recommended rates for pre-plant and drip irrigation fertility (60 lbs N/acre) for strawberry production in the SE U.S. and thus, nutrients, especially nitrogen, were not likely to be a limiting factor. By reducing either pre-plant fertilizer or fertilizer additions through drip irrigation, it may be possible to observe the additional benefits of nutrient availability from selected cover crop species in strawberry production. This could help save producers money by reducing nitrogen fertilizer applications (Sarrantonio, 2007), which is especially important in organic production where the cost of fertilizer inputs for drip irrigation can be high. Although cover crops may be releasing nutrients slowly over the strawberry season, it is difficult to assess when these nutrient releases happen and how this coincides with specific strawberry nutrient requirements and uptake physiology. Follow-up research should examine strategies to further increase cover crop biomass production (e.g. through enhanced cover crop seeding rates or an addition of compost) compared against reduced fertilization, especially nitrogen, during the strawberry growing season.

A second challenge for maximizing cover crop benefits in strawberry production in the SE U.S. is the limited growth period of about two months. In most of the SE U.S., cover crops cannot be planted until the second half of June (after strawberry harvest) and then must be cut by the end of August to leave time to prepare the strawberry beds for an early October planting. Moreover, increases in soil organic matter from the use of cover crops is a process that takes several years (Sarrantonio, 2007) and thus full benefits may not be realized immediately. The yield increase from cover crops seen in the aforementioned studies with other horticultural crops may be due to a longer cover crop growing season; in some experiments, such as Wang et al. (2005) this was longer than four months. One way to rectify the short growth timetable for cover crops in strawberry production would be to rotate fields, but this is a challenge for many strawberry growers who run roadside pick-your-own operations and simply don't have the space available to rotate.

No significant differences were found for strawberry yields between the AM fungal inoculants, thus enhancement or pre-inoculation with the native, on-farm AM mixed species may be just as effective as purchasing a commercial AM fungal species. There was a significant difference in the percent mycorrhizal colonization of strawberry roots in 2008, but it is important to point out that no correlation has been shown between AM root colonization and host growth

(Koomen et al., 1987; Williams et al., 1992). No difference was found in the 2009 percent colonization, likely because we did not pre-inoculate the strawberry plugs and relied on background field populations of mycorrhizal fungi. The native, on-farm AM inoculant seemed to have similar effects on strawberry yields and in several cases the NAT treatment improved yields over the COM treatment. In the eight instances that the mycorrhizal treatments significantly differed, the native inoculant increased strawberry growth characteristics (root, crown, and leaf biomass and leaf area) over the commercial inoculant 75% of the time (Table 2.4). Furthermore, nutrient status of the strawberry plants between the two AM treatments showed significant variation during the 3rd and 5th biomass harvests for specific nutrients (Table 2.5), favoring the NAT treatment early in the harvest season, and the COM treatment later. Yet, neither the AM treatment differences in biomass growth, nor the differences in nutrient uptake, led to any significant difference in final strawberry yields. From a producer's perspective, it may be better to promote practices that enhance native AM diversity than to purchase an off-the-shelf inoculant based on one (or a few) species. Schreiner and Bethlenfalvay (1997) found that a mixed inoculum outperformed a single species inoculum on pea (*Pisum sativum*) plants and Klironomos (2003) found that the greatest host benefit occurs between native mycorrhizas paired with native plants. It is possible that single species AM inoculants are being outcompeted by the mixed species inoculants, or that mixed inoculants have a better chance of initiating a more favorable host–endophyte relationship and offering a variety of host benefits.

Associations with mycorrhizal fungi can enhance crops through increased nutrient uptake (especially P), disease suppression, tolerance to water stress, and improvement of the soil structure (Gosling et al., 2005). Dodd et al. (1990) found that using pre-crops (similar to cover crops) of cassava [*Manihot esculenta* Crantz], kudzu [*Pueraria phaseoloides* (Roxb.) Benth.], and sorghum [*Sorghum* sp.] significantly increased the AM colonization and subsequent yield of cowpea [*Vigna unguiculata* (L.) Walp.] and stylosanthes [*Stylosanthes capitata* Vogel]. Although we found no link between the interaction of cover crops and mycorrhizal treatments in the strawberry yield response, the possibility remains that, over time, a rotation of cover crops could influence the underlying AM fungal community to benefit strawberry yield.

The yield benefits conferred to strawberry through an association with AM fungi are well documented. Douds et al. (2008) found that AM inoculation increased strawberry yields by 17% compared to non-inoculated controls, translating to an average 3.6 additional fruit per plant. Mycorrhizal inoculation can also increase strawberry growth (Vestberg, 1992) and yields (Chávez and Ferrera-Cerrato, 1990), but only with certain combinations of fungi and strawberry cultivars, again underlining the importance of pairing hosts and endophytes appropriately. Additionally, Bull et al. (2005) found no benefit to applying commercially available inoculants in organic and non-fumigated strawberry systems when native AM are already present. Mycorrhizas have also been shown to reduce the severity of the strawberry pathogen *Phytophthora fragariae* (Norman and Hooker, 1996), although other studies looking at different AM species found no reduction (Baath and Hayman, 1984), again highlighting the importance of the host–endophyte–pathogen relationship.

Mycorrhiza functioning and the benefits realized by host plants can differ greatly between greenhouse and real-world field conditions (Fitter, 1985). Our study was the first to evaluate the integrated effects of summer cover crops and inoculation with mycorrhizal fungi on strawberry production in field conditions. The importance of investigating the effects of cover crops and mycorrhizas together in field conditions cannot be overemphasized, as soil types, climate, fertility, weed pressure, and a host of other variables could affect the outcome compared to greenhouse conditions where these factors are regulated. Hamel and Strullu (2006) believe that the complex functions of AM fungi in agricultural ecosystems and the best management practices thereof are just beginning to be understood. The task remains to determine which cover crops and mycorrhizal associations most benefit strawberries grown in the Southeastern United States, and how to package this information into systems-level practices that growers can adopt.

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Table 2.1. Cover crop seeding rates (kg ha^{-1}) for 2007 and 2008.

Cover crop [z]	2007	2008
NONH [y]	12.4	73.1
SB	96.8	148.6
VB	124.3	187.7
SG	33.9	33.9
PM	35.0	34.4
SG(VB)	4.8 (86.6)	8.1 (188.3)
PM(SB)	12.9 (66.2)	21.5 (111.9)

[z] Cover crop treatments include:
NONH = non-mycorrhizal host;
SB = soybean; VB = velvetbean;
SG = sudangrass; PM = pearl millet;
SGVB = sudangrass + velvetbean combination;
PMSB = pearl millet + soybean combination.

[y] NONH was dwarf rape in 2007
and buckwheat in 2008.

Table 2.2. Nutrient concentrations of cover crop biomass at 8 weeks after planting in 2007 and 2008.

Cover crop [z] treatment	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	Bo	Na
	Nutrient analyses in parts per million (ppm)											
2007												
NONH	15579 c [y]	4695 b	26035 a	8145 c	5248 a	1321 cd	101 c	61 b	52 bc	18 bc	20 d	187 b
SB	30179 b	2679 c	14809 b	8088 c	2820 c	1436 bc	129 bc	74 ab	35 c	15 c	37 b	110 c
VB	31931 ab	2853 c	16501 b	11661 b	2101 cd	1629 b	92 c	110 ab	42 c	23 b	30 c	124 c
SG	8626 c	2494 c	12328 b	3333 d	1713 d	921 e	115 c	50 b	33 c	14 c	5 e	112 c
PM	8057 c	3175 c	13032 b	4571 d	1694 d	1039 de	114 c	71 b	33 c	13 c	7 e	109 c
SGVB	38167 a	4851 b	30076 a	16351 a	3865 b	2851 a	200 ab	141 ab	76 a	33 a	37 b	239 ab
PMSB	37763 a	6075 a	28703 a	11499 b	5723 a	2855 a	204 a	177 a	73 ab	25 b	45 a	257 a
2008												
NONH	14181 c	3868 bc	21197 ab	9146 b	3334 b	3724 a	393 a	93 ab	59 b	47 a	27 b	236 a
SB	31539 b	2689 d	14551 bc	9350 b	3992 b	1718 cd	90 b	134 ab	50 b	9 b	35 ab	102 cd
VB	35994 ab	2655 d	9062 c	11506 ab	2072 c	1325 de	61 b	144 ab	61 b	19 b	22 b	95 cd
SG	7174 c	2774 d	12263 bc	3292 c	1876 c	741 e	53 b	78 b	42 b	9 b	5 c	58 d
PM	7189 c	3170 cd	11615 bc	3702 c	1554 c	933 e	89 b	106 ab	43 b	11 b	5 c	74 cd
SGVB	43596 a	4920 b	18773 abc	13629 a	3869 b	2100 c	108 b	227 ab	86 ab	23 ab	30 b	149 bc
PMSB	34321 b	6689 a	26708 a	13417 a	6408 a	2826 b	246 ab	247 a	124 a	24 ab	45 a	200 ab

[z] Cover crop treatments include: NONH = non-mycorrhizal host; SB = soybean; VB = velvetbean; SG = sudangrass; PM = pearl millet; SGVB = sudangrass + velvetbean combination; PMSB = pearl millet + soybean combination. NONH was dwarf rape in 2007 and buckwheat in 2008.

[y] Values with the same letter are not significantly different (P<0.05) using Tukey's HSD.

Table 2.3. Marketable and total yield, percent cull, and average berry weight for cover crop and mycorrhiza treatments in 2008 and 2009.

	Marketable yield (g/plant)		**Total yield (g/plant)**		**Percent cull (unmarketable)**		**Avg fruit wt (g/berry)**	
	2008	2009	2008	2009	2008	2009	2008	2009
Cover crop treatment [z]								
NOCC	425 [x]	113	488	173	9.5	37.6	17.7	16.0
NONH	486	92	537	143	11.4	35.2	18.8	14.8
SB	499	115	546	175	10.2	31.9	17.4	16.9
VB	521	99	576	189	8.1	34.1	18.7	17.2
SG	484	120	529	184	9.6	29.1	18.5	17.5
PM	431	133	481	163	8.5	32.7	17.5	16.9
SGVB	452	106	511	158	9.2	32.8	17.8	15.9
PMSB	489	128	540	146	12.6	32.1	18.0	16.1
P-value	0.4057	0.4536	0.6387	0.4746	0.0855	0.5552	0.5121	0.6606
Mycorrhiza treatment [y]								
COM	482	108	533	161.0	9.4	34.1	18.2	16
NAT	464	118	519	171.0	10.4	32.3	17.9	16.8
P-value	0.3314	0.2862	0.4954	0.3123	0.2802	0.3717	0.5415	0.1042
Interactions								
P-value	0.6419	0.2114	0.6422	0.1760	0.9148	0.4620	0.4807	0.4698

[z] Cover crop treatments include: NOCC = no cover crop control; NONH = non-mycorrhizal host; SB = soybean; VB = velvetbean; SG = sudangrass; PM = pearl millet; SGVB = sudangrass + velvetbean combination; PMSB = pearl millet + soybean combination. NONH was dwarf rape in 2008 and buckwheat in 2009 harvest season.

[y] COM = commercial mycorrhiza; NAT = native mycorrhiza.

[x] Tukey's HSD showed no significant differences ($P<0.05$) between treatments for the yield data presented here.

Table 2.4. Mean per-plant leaf area and dry weights of strawberry roots, crowns, leaves, and fruiting structures (flowers + fruit) throughout the growing season in 2008 and 2009 for the cover crop and mycorrhiza treatments.

	2008					2009				
	Jan 11	Mar 3	Apr 4	May 12	May 27	Jan 11	Mar 5	Apr 5	May 11	June 1
Treatment	***Roots (g)***									
NOCC [z]	1.26	2.19	2.50	2.28	2.04	**0.92** ab	0.86	0.80	1.30	3.14
NONH	1.00	2.67	2.65	1.93	2.09	**0.91** ab	1.09	1.11	1.60	2.71
SB	1.59	2.27	2.88	2.25	2.19	**0.56** b	0.83	0.91	1.75	3.13
VB	1.40	2.30	2.68	2.21	1.89	**0.78** ab	1.22	0.86	1.49	3.17
SG	1.50	1.86	2.33	2.12	2.43	**0.85** ab	0.81	1.13	1.53	2.25
PM	1.51	1.90	2.39	1.82	2.23	**1.35** a	0.97	1.20	1.71	2.68
SBVB	1.66	1.78	2.71	2.07	2.34	**0.88** ab	1.02	1.06	1.44	2.03
PMSB	1.72	2.50	2.59	2.53	2.07	**1.08** ab	1.21	1.00	1.92	2.23
P-value [y]	0.3126	0.0851	0.8479	0.5621	0.7399	0.0404	0.1951	0.4971	0.3500	0.2419
COM [x]	1.41	2.12	2.46	2.07	2.10	**0.79** b	1.00	1.07	1.48	2.69
NAT	1.50	2.25	2.72	2.23	2.21	**1.04** a	1.00	0.95	1.71	2.64
P-value	0.4785	0.4149	0.1729	0.2638	0.4914	0.0060	0.9606	0.2051	0.0829	0.8542
	Crowns (g)									
NOCC	0.61	1.67	3.95	3.88	3.78	0.46	0.51	1.04	1.51	5.73
NONH	0.58	2.00	4.27	3.90	4.20	0.47	0.56	1.09	1.89	3.77
SB	0.79	1.90	3.62	4.36	4.97	0.29	0.45	1.02	2.47	4.34
VB	0.71	2.01	3.71	5.09	4.11	0.43	0.70	0.95	1.78	4.39
SG	0.85	1.65	3.43	4.30	4.57	0.43	0.52	1.20	2.25	3.73
PM	0.80	1.57	3.55	4.01	4.43	0.65	0.62	1.15	2.01	4.78
SBVB	0.81	1.42	3.03	3.99	4.49	0.46	0.63	1.20	1.71	3.46
PMSB	1.00	1.96	3.28	4.92	5.44	0.56	0.64	1.06	2.11	4.37
P-value	0.1197	0.6566	0.4168	0.4138	0.5903	0.1427	0.5008	0.8721	0.1431	0.1830
COM	0.74	1.71	**3.91** a	4.06	4.23	**0.41** b	0.57	1.10	**1.67** b	4.27
NAT	0.79	1.83	**3.30** b	4.55	4.76	**0.53** a	0.58	1.07	**2.26** a	4.37
P-value	0.4809	0.3949	0.0196	0.1245	0.2013	0.0084	0.8919	0.7689	0.0013	0.7488

Continued next page...

Table 2.4. Continued

	2008					2009				
	Jan 11	Mar 3	Apr 4	May 12	May 27	Jan 11	Mar 5	Apr 5	May 11	June 1
Treatment	***Leaves (g)***									
NOCC	1.29	3.71	9.43	10.75	14.23	0.29	0.69	2.82	8.45	22.11
NONH	1.13	4.12	9.20	13.25	18.38	0.36	0.84	3.18	10.39	17.88
SB	1.58	3.95	8.99	13.45	19.86	0.20	0.63	2.56	12.77	18.89
VB	1.41	3.81	9.75	13.91	16.70	0.29	0.78	2.98	10.88	17.64
SG	1.39	3.30	7.78	13.09	17.18	0.34	0.67	2.90	11.63	14.81
PM	1.44	3.29	8.40	12.16	17.10	0.38	0.75	2.70	10.92	17.72
SBVB	1.53	3.04	8.11	11.75	18.31	0.40	0.81	3.19	9.02	12.74
PMSB	1.70	3.93	9.24	15.57	16.21	0.39	0.95	2.84	10.83	17.40
P-value	0.4386	0.6998	0.8065	0.2704	0.8255	0.4658	0.2523	0.9061	0.5435	0.4870
COM	1.48	3.60	8.59	12.49	18.61	**0.27** b	0.77	3.02	**9.45** b	17.35
NAT	1.39	3.69	9.13	13.49	15.89	**0.40** a	0.76	2.78	**11.77** a	17.45
P-value	0.3865	0.7197	0.3840	0.2806	0.1105	0.0009	0.7944	0.3443	0.0335	0.9505
	Fruiting structures (g)									
NOCC		0.61	5.66	35.67	43.63		0.12	1.28	9.41	13.47
NONH		0.72	5.31	35.38	39.14		0.21	1.32	8.73	10.28
SB		0.63	5.72	38.64	50.23		0.14	0.88	10.50	12.84
VB		0.80	5.60	32.24	43.49		0.14	1.04	8.33	16.02
SG		0.76	5.05	37.03	48.76		0.14	1.26	9.18	12.19
PM		0.56	4.29	36.93	56.04		0.15	1.15	7.75	11.16
SBVB		0.54	5.06	39.98	44.56		0.16	1.42	7.53	10.86
PMSB		0.69	5.91	42.01	48.88		0.20	0.95	6.51	12.66
P-value		0.6056	0.8220	0.6469	0.3363		0.4664	0.6301	0.7169	0.7872
COM		0.67	5.16	38.69	47.61		0.16	1.15	8.34	12.45
NAT		0.66	5.49	35.78	46.08		0.15	1.17	8.65	12.42
P-value		0.8834	0.4346	0.1363	0.5991		0.6802	0.8872	0.7414	0.9866

Continued next page...

Table 2.4. Continued

	2008					2009				
	Jan 11	Mar 3	Apr 4	May 12	May 27	Jan 11	Mar 5	Apr 5	May 11	June 1
Treatment	***Leaf area (cm³)***									
NOCC	158	399	1150	1622	1711	30	72	374	736	1922
NONH	160	461	1218	1977	2357	39	81	427	886	1548
SB	192	439	1100	1911	2469	23	77	355	1087	1525
VB	176	424	1250	2042	2133	34	96	394	1004	1701
SG	190	364	1076	1945	2182	38	64	347	1268	1682
PM	174	372	1174	1742	2111	39	63	398	1062	1321
SBVB	182	344	1156	1645	3168	43	86	430	809	1159
PMSB	205	448	1177	2260	2044	42	75	401	915	1572
P-value	0.9025	0.7123	0.9857	0.2975	0.2429	0.5185	0.1294	0.8506	0.2324	0.5190
COM	186	391	1112	1841	**2565** a	**30** b	77	407	899	1532
NAT	174	421	1214	1945	**1979** b	**42** a	76	375	1043	1576
P-value	0.3636	0.3269	0.2578	0.4111	0.0277	0.0026	0.8197	0.3192	0.1578	0.7822

[z] Cover crop treatments include: NOCC = no cover crop control; NONH = non-mycorrhizal host; SB = soybean; VB = velvetbean; SG = sudangrass; PM = pearl millet; SGVB = sudangrass + velvetbean combination; PMSB = pearl millet + soybean combination. NONH was dwarf rape in 2008 and buckwheat in 2009 harvest season.

[y] Letters shown and values bolded where differences exist. Values with same letter are not significantly different (P<0.05) using Tukey's HSD.

[x] COM = commercial mycorrhiza; NAT = native mycorrhiza.

Table 2.5. Strawberry leaf and petiole nutrient analyses over two sampling periods during the growing season in 2008 and 2009 for the two mycorrhiza treatments.

		2008		2009	
Nutrient [z]	**Treatment** [y]	Apr 4	May 27	Apr 5	June 1
N	COM	35304 [x]	**24426** b	39066	23983
	NAT	35340	**25718** a	39151	23759
	P-value	0.9320	0.0445	0.8498	0.6363
P	COM	4162	**3185** a	3973	3212
	NAT	4147	**2777** b	3902	3080
	P-value	0.8896	0.0003	0.5163	0.2351
K	COM	16469	**19024** a	22244	16311
	NAT	17000	**14618** b	22022	16218
	P-value	0.0667	<.0001	0.4840	0.8165
Ca	COM	**10747** b	17514	11774	17062
	NAT	**11572** a	18448	11932	16800
	P-value	0.0009	0.0575	0.6228	0.7965
Mg	COM	3628	**3495** a	4887	4115
	NAT	3717	**3031** b	5024	4144
	P-value	0.2086	0.0002	0.1705	0.8569
S	COM	**1884** b	**1580** a	2259	1485
	NAT	**1960** a	**1402** b	2263	1419
	P-value	0.0012	<.0001	0.9161	0.0596
Fe	COM	134	**102** b	110	93
	NAT	142	**157** a	108	95
	P-value	0.3198	<.0001	0.4602	0.6484
Mn	COM	103	74	105	**115** a
	NAT	100	79	91	**86** b
	P-value	0.6814	0.4924	0.1820	0.0306
Zn	COM	45	36	40	**38** a
	NAT	45	31	37	**33** b
	P-value	0.7796	0.2573	0.1547	0.0165
Cu	COM	**11.1** b	**7.5** b	**9.9** b	11.9
	NAT	**12.0** a	**9.2** a	**11.4** a	10.6
	P-value	0.0155	<.0001	0.0222	0.1543
Bo	COM	**60** b	57	56	88
	NAT	**68** a	59	58	90
	P-value	0.0020	0.3638	0.2492	0.6325
Na	COM	196	**183** a	253	150
	NAT	207	**152** b	236	153
	P-value	0.1944	0.0002	0.0627	0.7059

[z] Nutrients reported in parts per million (ppm).

[y] COM = Commercial mycorrhiza treatment;
NAT = Native mycorrhiza treatment.

[x] Letters shown and values bolded where differences exist (P<0.05) using Tukey's HSD.

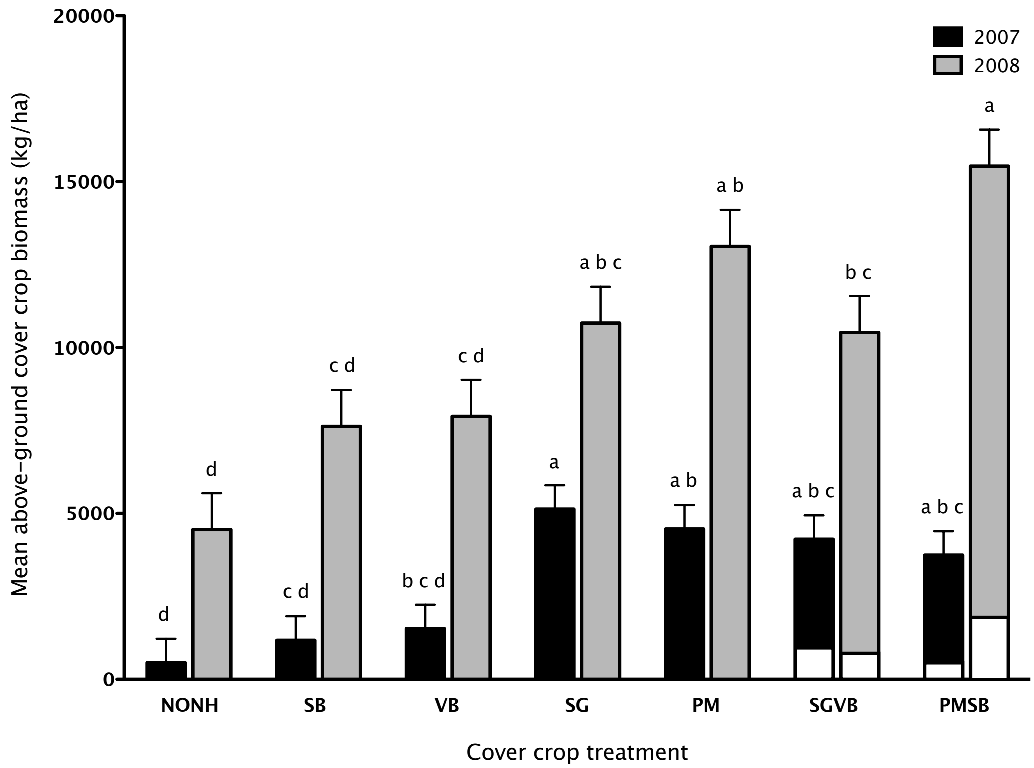

Figure 2.1. Mean aboveground cover crop biomass (kg ha^{-1}) sampled 8 weeks after planting in 2007 and 2008. Cover crop treatments include NONH = non-host, dwarf rape in 2007 and buckwheat in 2008; SB = soybean; VB = velvetbean; SG = sudangrass; PM = pearl millet; SGVB = sudangrass + velvetbean combination; PMSB = pearl millet + soybean combination. White areas in the combination treatments represent the legume fraction. Error bars represent SE, and bars with the same letter are not significantly different according to Tukey's HSD ($\alpha = 0.05$). Each year was analyzed separately as a 1-way ANOVA.

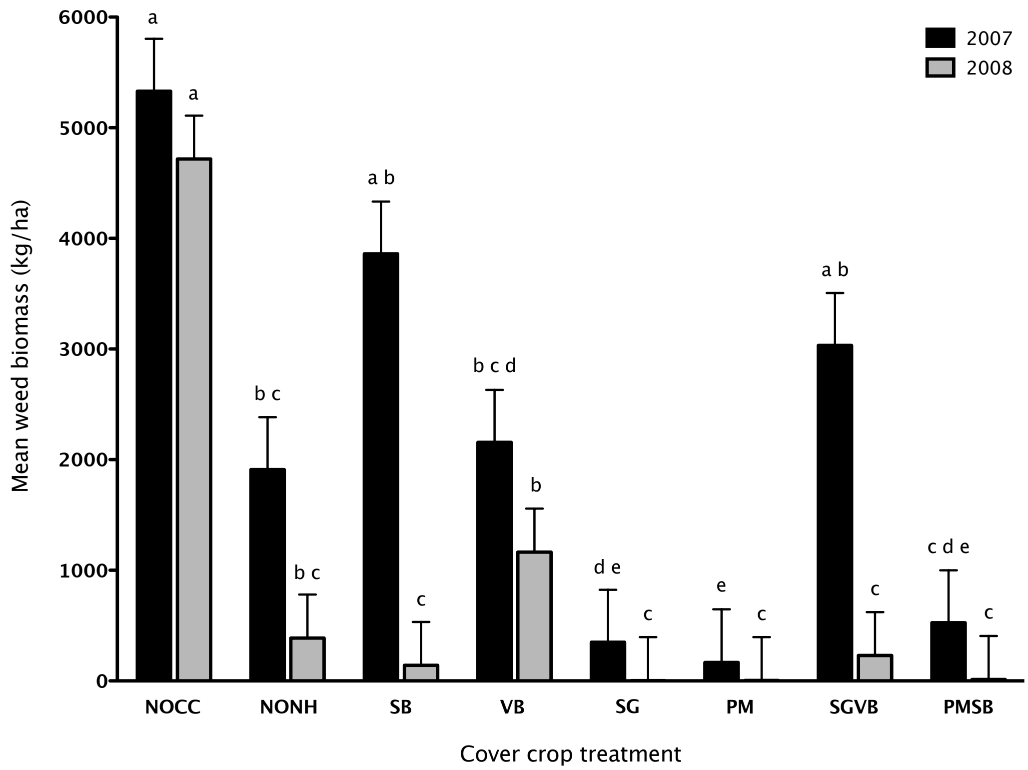

Figure 2.2. Mean weed biomass (kg ha^{-1}) sampled 8 weeks after planting in 2007 and 2008. Cover crop treatments include: NOCC = no cover crop control; NONH = non-host, dwarf rape in 2007 and buckwheat in 2008; SB = soybean; VB = velvetbean; SG = sudangrass; PM = pearl millet; SGVB = sudangrass + velvetbean combination; PMSB = pearl millet + soybean combination. Error bars represent SE, and bars with the same letter are not significantly different according to Tukey's HSD ($\alpha = 0.05$). Each year was analyzed separately as a 1-way ANOVA.

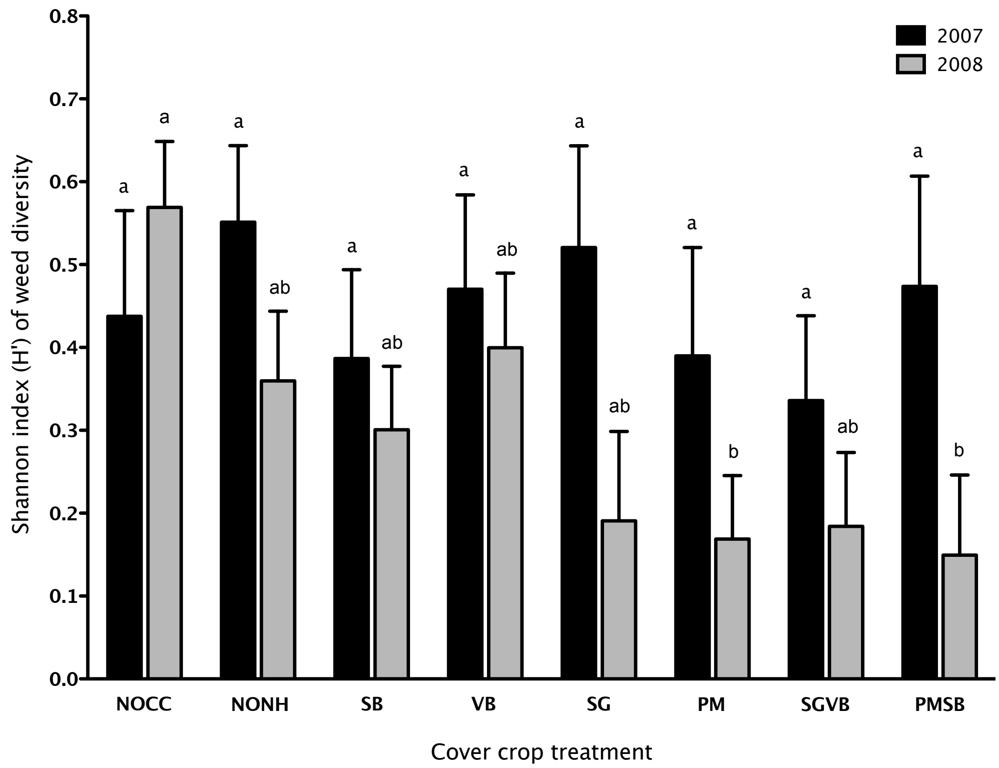

Figure 2.3. Shannon index (H') of weed diversity in 2007 and 2008. Cover crop treatments include: NOCC = no cover crop control; NONH = non-host, dwarf rape in 2007 and buckwheat in 2008; SB = soybean; VB = velvetbean; SG = sudangrass; PM = pearl millet; SGVB = sudangrass + velvetbean combination; PMSB = pearl millet + soybean combination. Error bars represent SE, and bars with the same letter are not significantly different according to Tukey's HSD ($\alpha = 0.05$). Each year was analyzed separately as a 1-way ANOVA.

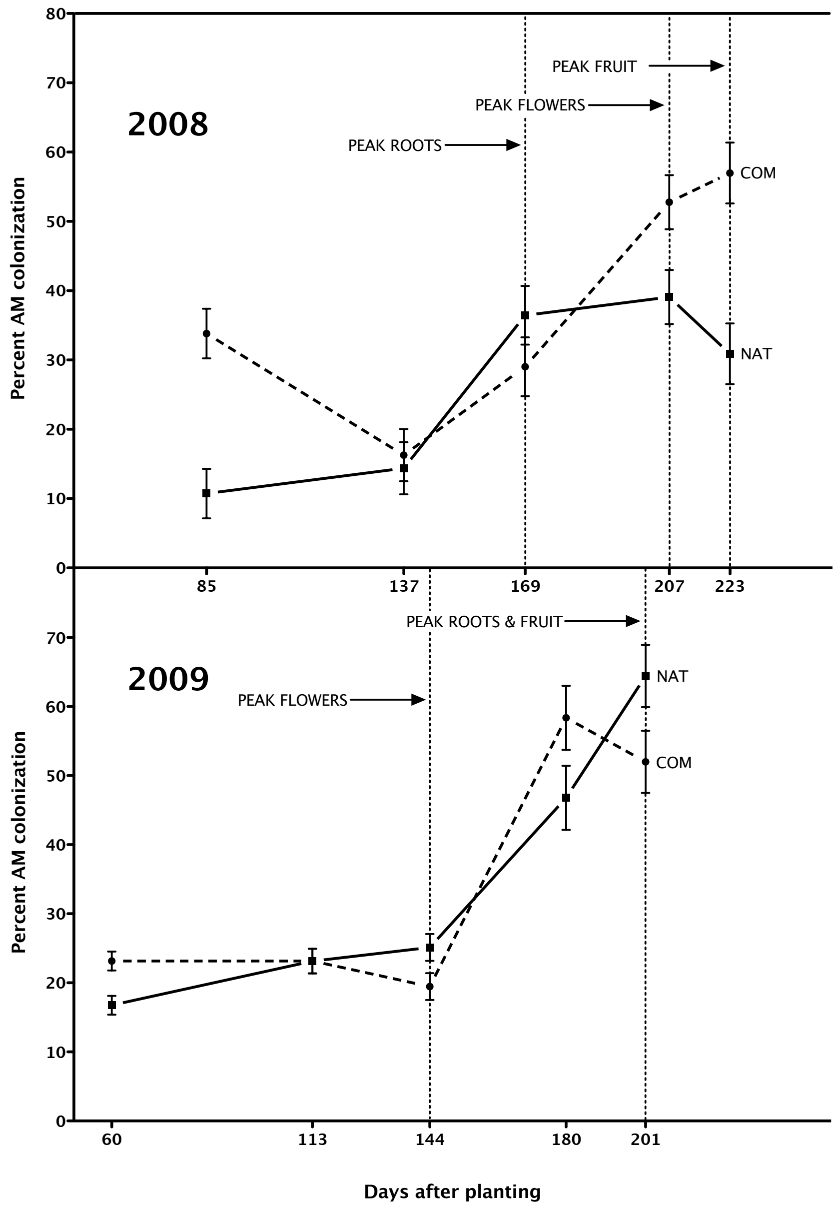

Figure 2.4. Percent arbuscular mycorrhizal (AM) colonization of strawberry roots from whole plants sampled at different days after planting for commercial (COM) and native (NAT) AM inoculants in 2008 and 2009. Vertical dashed lines represent peak stages of strawberry growth (as labeled). No significant difference was found among cover crop treatments in either year and therefore the data are not presented here. Values are mean percentages (±1 SE; n=4).

III. Evaluating the On-Farm Benefits and Performance of Summer Cover Crops for Strawberry Production in North Carolina

Abstract

As fumigation with methyl bromide is phased out, the integration of summer cover crops into Southeastern U.S. strawberry production offers an alternative management practice that could reduce weeds and pathogen incidence while increasing strawberry yields. To investigate the farm-level benefits and challenges of this practice, we partnered with three conventional strawberry producers in North Carolina who each had different prior experience using cover crops. Our primary goal was to evaluate the management hurdles in adoption of cover crops, and the effects of cover crop treatments on strawberry yield, weed biomass, and cover crop biomass, over one season. We also quantified the arbuscular mycorrhizal (AM) fungi population at each site since AM are known to confer numerous benefits to strawberries, but can be negatively impacted by methyl bromide fumigation. On each farm, investigators and producers jointly selected two cover crops, one grass and one legume, to compare against a bare ground control. Cover crop treatments included cowpea [*Vigna unguiculata* (L.) Walp. var. Iron Clay], foxtail millet [*Setaria italica* (L.) Beauv.], pearl millet [*Pennisetum glaucum* (L.) R.Br. cv. 102 M Hybrid], and soybean [*Glycine max* (L.) Merrill cv. Laredo] on the different farms. Investigators maintained an ongoing discussion with producers that culminated in a formal post-season interview to gauge concerns surrounding the adoption of cover crops

into their production systems. Cover crop treatments significantly reduced weed biomass at two of the farms, but not the third, compared to the bare ground control. There was no significant difference between the amounts of aboveground biomass produced by the two cover crops on any farm. Cover crop treatments reduced total strawberry yield compared to the bare ground control at one farm, but no difference was found at the other farm (the third farm did not participate in yield measurements). Producer interviews suggested that the most prominent barriers to adoption of cover crops are: 1) a lack of information about how to integrate cover crops into a strawberry production schedule; 2) an absence of practical guidance on how to increase cover crop biomass responses through enhanced seeding rates and other integrated organic amendment applications, 3) a need to evaluate cover crop benefits in strawberries over a longer time period, not just one season; 4) an insufficient understanding of the interactions of mycorrhizal fungi and other beneficial soil inoculants when combined together with cover crops; and 5) on-farm research should be more participatory and emphasize the producer's needs.

Introduction

Strawberry production practices in the Southeastern United States (SE U.S.) make long-term sustainable management particularly difficult. It is common for producers to grow strawberries as their primary (or only) crop and/or to run a roadside pick-your-own operation, resulting in fields that are replanted in strawberries year after year (Sydorovych et al., 2006). Failing to rotate crops can and often leads to increased incidence of insect pests, diseases, and weeds (Altieri, 1995). To combat this pest pressure, growers have traditionally fumigated their fields with methyl bromide. At present, methyl bromide is under limited use restriction for strawberry growers, but this exception is currently set to become much more restrictive in 2010, after which it may not be economically feasible to use (United States Federal Government, 2009). Other chemicals, such as chloropicrin, methyl iodide, and 1,3-dichloropropene (Telone) are available as replacements, but these substitutes may increase the cost of current management practices and may not be as effective as methyl bromide against some pests (Duniway, 2002). As the EPA limits the allowed exemptions and market supply for methyl bromide it is critical to investigate alternative pest and soil management strategies that are environmentally friendly and cost effective for both organic and conventional strawberry producers in the SE.

The use of summer cover crops can be integrated into strawberry production in the SE U.S, although this practice has been understudied and underutilized in strawberry production in this region. Cover crops can play a critical role in sustainable soil and pest management strategies in the SE, where growers have to contend with generally poor soils and chronic pest problems (Jacobsen, 2009). The incorporation of cover crops with annual crops can help prevent erosion, increase soil organic matter and fertility (Sarrantonio, 2007), break up hard clay soils, interrupt pest cycles, and reduce weeds (Phatak and Diaz-Perez, 2007). Moreover, legume cover crops can fix atmospheric nitrogen, leading to increased soil fertility and yields of the subsequent crop. Cereal or grass cover crops can produce large amounts of biomass, improving overall soil organic matter and nitrogen availability (Snapp et al., 2005). A few studies have documented varying benefits of cover crops particular to strawberry production, such as increased yield and reduced pest populations (Lamondia et al., 2002), increased yield from adding a cover crop rotation compared to continuous strawberries (Siegies and Pritts, 2006), and reduced incidence of strawberry black root rot (Elmer and Lamondia, 1999). All of these studies, however, have been conducted outside the climate conditions, poor soils, and high pest pressures of the SE U.S., where cover crops may have the greatest benefit.

Despite these benefits from cover crops, their adoption in strawberry production systems in the SE U.S. is not widespread. Using cover crops is a management practice that accrues benefits over the long term, requiring continual investments in time, material, management, and persistence from the grower. Integrating cover crops into strawberry production may be particularly demanding on producers' schedules in the SE, since cover crops must be planted immediately after strawberry harvest ends, and must be incorporated a short 2 months later to allow ample time for field management activities at the beginning of the next strawberry season. Additionally, thicker or more lignified cover crops may not adequately break down prior to forming the strawberry beds and may interfere with equipment or tear the plastic, which producers simply cannot afford to risk in lost time and money. Perhaps the largest barrier to cover crop adoption by strawberry producers in the SE U.S. is a lack of specific cover crop information and characteristics for the growing conditions in this region. To successfully integrate cover crops into strawberry production, producers need to know which cover crops to select (and why), how to grow them, the costs and management practices required, and the expected short- and long-term benefits.

With this in mind, we set out to examine how cover crops performed on three working strawberry farms in North Carolina. Each farm differed in strawberry production experience, prior experience with cover crops (with strawberries and other crops), and geographical location. Additionally, two of the producers were identified as innovators that other SE strawberry producers might emulate, thus increasing the likelihood of cover crop adoption. This project had three main objectives: 1) to evaluate summer cover crop performance and effect on strawberry yields in realistic farm production situations in NC, 2) to describe the participating producers' perceived benefits and challenges of using cover crops in strawberry production, and 3) to determine how future research can address the producers' desire to convert to more sustainable management practices.

Materials and Methods

Three strawberry growers in North Carolina agreed to participate in this on-farm research study from June 2008 through August 2009 to examine the effects of using selected summer cover crop species on their strawberry yields and perceived benefits and management challenges of rotating cover crops with strawberries. We chose growers that represented diverse locations, soil conditions, management practices, and differing experiences with strawberry production and the use of cover crops. The three farms consisted of: Indigo Farms (IND) in Calabash, NC (lat. 33°55´ N, long. 78°37´ W), Buckwheat Farm (BWT) in Apex, NC (lat. 35°42´ N, long. 78°53´ W), and Iseley Farms (ISY) in

Burlington, NC (lat. 36°8´ N, long. 79°28´ W). Indigo Farms and Iseley Farms grow a large variety of crops, operate diverse roadside stands and pick-your-own operations, and have been in operation for over 100 years. Buckwheat Farm, in contrast, grows just three acres of strawberries for pick-your-own and farm stand sales and has been in operation for 13 years. Soil conditions are as follows: BWT, severely eroded sandy loam with clay; IND, fine sandy loam; ISY, sandy loam, partly eroded. All farms represent the diversity of typical strawberry growers and conditions in NC and the SE (Sydorovych et al., 2006) and produce strawberries using conventional practices including raised beds under black plastic and methyl bromide fumigation. Indigo Farms was the only producer that rotated the research field with a crop other than strawberry (the field was planted with oats in the preceding year).

Project investigators met with each producer the year prior to beginning the on-farm research to understand the production and site challenges, to collectively select specific cover crop species to examine for the conditions on each farm, and to develop an agreement of shared responsibilities for managing the cover crops, strawberries, and data collection. Investigators also offered to examine the effects of AM fungi in on-farm strawberry production, but all producers declined. The producers were compensated to cover any additional costs incurred as a result of participation in this project. Producers helped select an appropriate site (average size: 1380 m^2) for the on-farm research within the strawberry production area. On each farm two single cover crop treatments were compared to a control (no cover crop; NOCC) and each on-farm experimental site was set up as a randomized complete block design with three treatments and three replicates for nine total plots (Figures 3.1–3.3; Table 3.1). Cover crops included cowpea (CP) [*Vigna unguiculata* (L.) Walp. var. Iron Clay; Wyatt-Quarles Seed Co., Garner, NC], foxtail millet (FM) [*Setaria italica* (L.) Beauv.; Wyatt-Quarles Seed Co., Garner, NC], pearl millet (PM) [*Pennisetum glaucum* (L.) R.Br. cv. 102 M Hybrid; Albert Lea Seed House, Albert Lea, MN], and soybean (SB) [*Glycine max* (L.) Merrill cv. Laredo; Kaufman Seed, Ashdown, AK]. Experimental sites on each farm were not included in the producer's pick-your-own operation to reduce customer interference with data collection.

Randomized soil samples (20 per plot) for soil nutrient analyses, nematode community evaluation, and mycorrhizal fungi assessment were taken from each treatment plot in early June 2008 when plots were established but before cover crops were planted. The soil and nematode samples were analyzed at the North Carolina Department of Agriculture (NCDA) Agronomic Services Lab in Raleigh, NC. Mycorrhizal trap cultures were established in greenhouses at North Carolina State University by combining ≈300 g of each aggregate field plot soil sample at a 1:4 volume ratio with a steam-sterilized soil mix (1:1 pasteurized sand and soil) in standard 6-inch clay pots. A combination of corn [*Zea mays* L.], sudangrass [*Sorghum bicolor* (L.) Moench], and prickly sida [*Sida spinosa* L.] were used as host plants and grown for 140 days. Each pot was fertilized with 1 tsp Osmocote 19N–6P–12K fertilizer (The Scotts Company, Marysville, OH) and water was limited in the final days to induce fungal sporulation.

Cover crops were seeded at IND on June 19, BWT on June 23, and ISY on June 25, 2008 via hand-held broadcast spreaders (see Table 3.1 for rates). Cover crop biomass and weed diversity were assessed ≈8 weeks after planting in all treatment plots on each farm. Cover crop biomass was assessed by harvesting aboveground biomass from one randomly placed 0.5 m^2 quadrat per plot. The cover crop biomass samples were then dried at 60°C for 96 hours and weighed.

Weed species and abundance were measured by harvesting aboveground biomass from three randomly placed 0.25 m^2 quadrats per plot and these data were later used to calculate a Shannon Index of diversity (Shannon and Weaver, 1949) with the formula:

$$H' = -\sum_{i=1}^{S} p_i \,(\ln p_i)$$

Where p_i is the proportion of the total number of individuals made up by species i and can be found by [$p_i = n_i / N$] where n_i is the number of individuals in species i and N is the total number of individuals collected in the entire sample. S is the number of samples.

Cover crops were cut in late August at each farm and then incorporated after an additional two-week period needed for the cover crops to dry and decompose. The fields were then disked and pre-plant fertilizers were applied following typical practices on each farm (≈60 lbs N/acre and ≈50 lbs K/acre depending on site needs). In mid-September, drip irrigation and plastic beds were formed and fumigated with methyl bromide on all farms. Deer fencing was installed after the bedding process was completed. Strawberry plugs were then planted 2–3 weeks later in early October. Strawberry harvest season typically begins mid-April and goes until early June, but this varied slightly between sites due to climactic conditions (Table 3.1). Berries were harvested by the growers according to their own timetable, usually 2–3 times per week. Yield data were taken only from strawberry plants in a delineated center section (2 beds) of each plot to minimize any edge effects (BWT: 80 plants per plot; IND: 68 plants per plot; ISY: 80 plants per plot). Outlying strawberry plants were used as buffers and harvested by the growers but not counted as data. Only the total end-of-season harvest, calculated on a per-plant average basis, was used for comparison among cover crop treatments. BWT measured only strawberry marketable yield. IND measured both marketable and cull (unmarketable) yield. Culls were any berries deemed to be unmarketable due to size (<12 g), disease, or deformity. The research plot at ISY was destroyed by deer mid-season and therefore not included in the strawberry yield analysis.

At the conclusion of the study, the project investigators met individually with each producer to evaluate their experiences with cover crops and the on-farm study, describe the perceived benefits and challenges of using cover crops in strawberry production on their farm, and determine what other sustainable or organic management practices interest them. A series of open-ended and Likert scale-based questions were asked of each producer to assess these objectives (Appendix A).

Results

Cover crop aboveground dry weights did not significantly differ among cover crop treatments at any of the on-farm research sites (BWT: P=0.4056; IND: P=0.0714; ISY: P=0.0725; Table 3.2). Cover crop treatments did significantly reduce weed biomass compared to the control (NOCC) at IND (P<0.0001) and ISY (P=0.0162). No significant reduction was found at BWT (P=0.3883) where weeds were generally sparse even in the NOCC control plots (Table 3.2). Total season strawberry yield was not significantly different among cover crop treatments at BWT (P=0.9985) but was at IND (P=0.0322) where the FM and NOCC control plot had higher yield than the SB. IND was the only participator to collect cull (unmarketable) data, and here the cover crop treatments did not significantly affect the amount of cull strawberries produced (P=0.4040). As stated previously, ISY did not participate in yield measurements because deer destroyed all the plants and beds. An analysis of the pre-experiment mycorrhizal populations on each farm revealed 7 species at IND (*Acaulospora morrowiae, Gigaspora margarita, G. rosea, Glomus etunicatum, Gl. intraradices, Gl. mosseae, Scutellospora pellucid*), 5 species at BWT (*Acaulospora mellea, Gl. intraradices, Gl. mosseae, Glomus sp., Scutellospora pellucid*), and 2 species at ISY (*Gl. mosseae, Glomus sp.*).

Selected questions from the following producer interviews were scored using the Likert scale; results are shown in Table 3.3. Below are summaries of the individual producer interviews that were conducted at the conclusion of the project.

Buckwheat Farm Post-study Interview

Karma Lee has been growing strawberries for 13 years and has used pearl millet as a cover crop sporadically since 2000. She likes this cover crop because it is consistent, inexpensive, easy to obtain, and adds a manageable amount of biomass to her field. Her primary reason for incorporating cover crops is to prevent erosion on her sloped fields, but she also hopes that cover crops will help break up the hard clay soil and suppress summertime weeds. She wants to explore adding a legume, such as cowpea, as a cover crop for its nitrogen-fixing ability. Her main challenges with adopting cover crops are the short growth window and other scheduling difficulties, plus the hard, clayey soil on her farm makes it problematic to plant and till cover crops. One interesting perception is that she believes that some cover crops may impact the flavor of the subsequent strawberry crops. She is very cautious about changing her regime because she says her customers return based on her strawberry flavor.

In response to the results from the study, Karma was somewhat disappointed with cowpea. She expected a nitrogen boost that would directly increase yields, but no yield difference was found among the cowpea, pearl millet, or no cover crop treatments. Despite no impact on yield, she ultimately felt that the cover crops were beneficial. From future research she would like to know what types of summer and inter-row cover crops best control weeds in the planting holes and between strawberry rows during the growing season.

Karma is interested in converting to more sustainable production practices but says there are too many unanswered questions surrounding pest and disease management without using synthetic inputs. In the meantime she is concerned with the upcoming fumigant alternatives to methyl bromide. Since she pays a custom fumigator to lay her plastic, shape her beds, and fumigate the soil, she feels that she has little say in which new chemicals are used. She is also worried about some of the new EPA restrictions on soil fumigation since her farm is located near a housing community. She would like more research and information on how a strawberry grower like her could be more sustainable without greatly increased financial or managerial burdens.

When asked what types of improvements could be made to the participatory on-farm research model, she thought it was important to increase customer visibility and signage of the study. She wants her customers to know that she is working with researchers to discover improved and sustainable production strategies. Overall, however, she said the process was painless and she would do it again.

Indigo Farms Post-study Interview

Sam Bellamy has been growing conventional strawberries for 28 years and using cover crops in his organic vegetables for several years. He has just begun to experiment with cover crops in his organic strawberries and integrates the cover crops in alternating strips during the growing season. This way he can grow cover crops for a longer period and potentially realize greater benefits. With his conventional strawberries he doesn't use alternating rows of cover crops (for economic reasons) so a cover crop rotation must fit into the between-season growth window. He perceives the greatest value of cover crops to be weed management, natural soil tillage, and the enhancement of soil biology. His biggest challenge with cover crops is time management and preparing for cover crop planting after he is finished with the strawberry harvest and other farm responsibilities. In his coastal location he can grow strawberries nearly all year so finding the time for cover crops is particularly difficult.

Overall, Sam was pleased with the yield results. While the *no* cover crop treatment curiously showed the greatest strawberry marketable yields over the season, he knows that this isn't likely over the long term and he values cover crops as an integral part of his sustainable management strategy. In the future, he wants to increase cover crop seeding rates and amend the plots with compost to see if there is any positive effect. He believes that fostering healthy soil and plants goes a long way towards preventing diseases, weeds, and other pests. He would like to gradually expand his organic strawberry production but his primary concerns are how to control pests and diseases in strawberries in an organic system. He is wary that once a disease strikes there is no immediate treatment such as the synthetic pesticides used in conventional production. In general he wants to see research that combines several sustainable tactics such as cover crops, vermicompost, and crop rotation into a defined program that a farmer can implement.

When asked about this study, Sam said he was very happy to participate in a small farmer-oriented program. Since he runs his own market, he feels it is important to have in-store signage on display so that customers are aware of the farm's participation in research. He also wants to know what he can do to be a better farmer without introducing added stress or complexity. Unfortunately, he feels that most research does not consider what one small farmer can do on his own. He suggests that researchers take into account the efficiency and economics of their recommendations and determine how it applies to a small family farm.

Iseley Farms Post-study Interview

Jane Iseley has been growing strawberries since 1997 and using cover crops since 2000. During this time she has used pearl millet, sudangrass, cowpea, and buckwheat. She experimented with sunflower a few times for its visual appeal, but found that the tough stalks later interfered with laying down strawberry beds. Her primary reason for planting cover crops was to control erosion, but she now recognizes improved soil productivity as an overall benefit. Her biggest challenge in adopting cover crops is scheduling, particularly the need to remove the strawberry plants and plastic from the field in time to plant the cover crops. For the last few years she has used mainly cowpea and pearl millet but always tries to include some areas in buckwheat since it is quick to flower and good for bee populations. The pearl millet provides an additional benefit in that she can feed it to her cows during dry years when pasture is scarce. Her goal with cover crops is to make sure that the soil in all parts of her farm is never bare.

Jane already grows organic tobacco on her farm and her customers are always asking about organic strawberries and vegetables. Just this past year she acquired a new 60-acre field and hopes to be able to begin a more diversified strawberry rotation strategy. She describes herself as "scared of methyl bromide" and wants to convert her strawberries (and vegetables) to organic but is hesitant due to the increased cost of organic fertilizers used in drip irrigation and the more complex management practices involved. She also didn't feel that the market in her area would bear any organic premium price.

From future research, she hopes to learn the best way to manage a crop rotation, which cover crops to plant based on the cash crops that she grows, and if (and how) cover crops could be used to manage strawberry clipper (*Anthonomus signatus*, an insect pest). When asked if she had any advice for the researchers, she said she wanted bigger and more signage to let her customers know about the study.

Discussion

The participating strawberry producers are encouraged by the long-term benefits of cover crops and plan to continue using them on their farms even though no strawberry yield benefits were demonstrated in this study. It is important to note, however, that several hurdles must be overcome before a more widespread adoption of cover crop practices can occur. Some of the main challenges to increased cover crop adoption in SE strawberry production include the following: 1) a lack of information about how to integrate cover crops into a strawberry production schedule; 2) an absence of practical guidance on how to increase cover crop biomass responses through enhanced seeding rates and other integrated organic amendment applications, 3) a need to evaluate cover crop benefits in strawberries over a longer time period, not just one season; 4) an insufficient understanding of the interactions of mycorrhizal fungi and other beneficial soil inoculants when combined together with cover crops; and 5) on-farm research should be more participatory and emphasize the producer's needs.

The greatest challenge to cover crop adoption by strawberry growers in the SE U.S. is a lack of information describing how to integrate a cover crop rotation. While we can't speak for all strawberry growers, our producers all knew why cover crops are beneficial, but were generally unsure about the management specifics. They wanted to know how each particular cover crop could be tailored to a specific benefit (e.g. legumes for nitrogen), what seeding rates should be used for the most uniform establishment, how and when cover crops should be cut and tilled, and what cover crops would cost in time and labor. The producers in our study had all used cover crops with their strawberries multiple times in the past, yet these fundamental questions still remained, underlining the importance of developing additional research that addresses these concerns.

Although the strawberry yield results showed no apparent benefit from cover crops after one year, this is unlikely to hold true over the long term as cover crops increase soil organic matter and nutrient availability (Sarrantonio, 2007). In a 2-year study, Seigies and Pritts (2006) found that cover crops markedly improved yield in a field that had been planted in continuous strawberries for 7 years. Wang et al. (2008) tested cowpea and sudangrass in a 4-year cantaloupe production system and found that both cover crops significantly increased yields compared to a bare-ground control. Given time, it is likely that incorporation of cover crops into a conventional strawberry management system can lead to healthier strawberry plants and increased yields when compared to simply leaving the fields bare during the summer months.

Analysis of the mycorrhizal community on the three farms revealed a surprising diversity given that all fields had been fumigated with methyl bromide in previous years. As An et al. (1990) discovered in a soybean system, methyl bromide–chloropicrin fumigation had little effect on spores 30–45 cm deep in the soil. They showed that although fumigation killed all spores in the first 15 cm of soil, a subsequent analysis after the crop production season revealed that some mycorrhizas in this top layer had recovered to pre-fumigation levels and were in fact higher in number than a non-fumigated control plot. Previously, Menge (1982) had similarly found that these fumigants had little effect on mycorrhizas deep in the soil, but attributed recolonization primarily to mycorrhizas in the top layers that had survived fumigation (largely due to poor fumigation technique).

Further research of this type is needed to determine which specific cover crops are best suited to strawberry production in the SE U.S., especially since many producers grow strawberries in the same field year after year. Working with producers via participatory research proves useful to understanding the issues they face and developing solutions that address the challenges directly (Lawrence et al, 2007). Guerin and Guerin (1994) identified four major constraints to the adoption of new agricultural innovations: the complexity and difficulty of the technology; how readily observable the outcomes are; the financial cost; and the farmer's beliefs and opinions of the technology. The producers in this study made a number of other important recommendations that are relevant to developing successful on-farm research and implementing new practices. They include: consider the appropriate scale and economics of the technology (small family farms); remain clear about the division of tasks between farmer and researcher; and use high-quality signage so the producer's customers are aware of the farm's participation in cutting-edge research. The task remains to overcome these obstacles by synthesizing the information provided by this study and others into a cover crop management plan that strawberry producers in the SE U.S. can successfully implement.

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Table 3.1. Overview information for the three participating farms and associated cover crop treatments.

Farm name	Location	Farm age	Farm size	Strawberry size	Cultivar	Plot size	Cover crops [z]	Harvest dates
Buckwheat Farm	Apex, NC	13 years	1.25 ha	1.25 ha	Camarosa	1672 m^2	CP, PM, NOCC	4/23 - 6/09/2009
Indigo Farms	Calabash, NC	100+ years	81 ha	3 ha	Camarosa	1462 m^2	FM, SB, NOCC	4/16 - 6/15/2009
Iseley Farms	Burlington, NC	100+ years	100 ha	1.21 ha	Chandler	1003 m^2	CP, PM, NOCC	NA

[z] Treatments include:
CP = cowpea (*Vigna unguiculata* var. Iron Clay, rate: 99 kg ha^{-1}, source: Wyatt-Quarles Seed Company, Garner, NC);
FM = foxtail millet (*Seteria italica*, rate: 28 kg ha^{-1}, source: Wyatt-Quarles Seed Company, Garner, NC);
PM = pearl millet (*Pennisetum glaucum* cv. 102M Hybrid, rate: 38 kg ha^{-1}, source: Albert Lea Seed House, Albert Lea, MN);
SB = soybean (*Glycine max* cv. Laredo, rate: 106 kg ha^{-1}, source: Kaufman Seed, Ashdown, AK);
NOCC = no cover crop.

Table 3.2. Cover crop biomass, weed biomass, strawberry yield, and strawberry cull measurements for each cover crop treatment by farm.

	Cover crop treatments [z]								
	Buckwheat Farm			**Indigo Farm**			**Iseley Farm**		
Measurement	CP	PM	NOCC	SB	FM	NOCC	CP	PM	NOCC
Above-ground cover crop biomass (kg/ha)	1800 a [y]	2180 a	NA	1360 a	3160 a	NA	3760 a	8260 a	NA
Above-ground weed biomass (kg/ha)	0 a	0 a	140 a	200 c	720 b	1680 a	440 b	0 b	2880 a
Total season strawberry yield (g/plant)	202 a	201 a	202 a	305 b	341 ab	455 a	NA	NA	NA
Total season strawberry cull (g/plant)	NA	NA	NA	23 a	21 a	25 a	NA	NA	NA

[z] Cover crop treatments include: CP = cowpea; FM = foxtail millet; PM = pearl millet; SB = soybean; NOCC = no cover crop.

[y] Letters are read across rows and within-farm only. Different letters indicate significance (P<0.05) according to Tukey's HSD.

Table 3.3. Likert-scored questions from farmer interviews conducted at the end of the study.

	Farm		
Question	**Buckwheat**	**Indigo**	**Iseley**
How satisfied were you with the cover crop species chosen on your farm?	Satisfied	Satisfied	Very satisfied
I plan on using cover crops in strawberry production again.	Strongly agree	Strongly agree	Strongly agree
I am interested in knowing more about organic strawberry production on my farm.	Unsure	Strongly agree	Strongly agree
I was satisfied with this on-farm research project.	Strongly agree	Strongly agree	Strongly agree

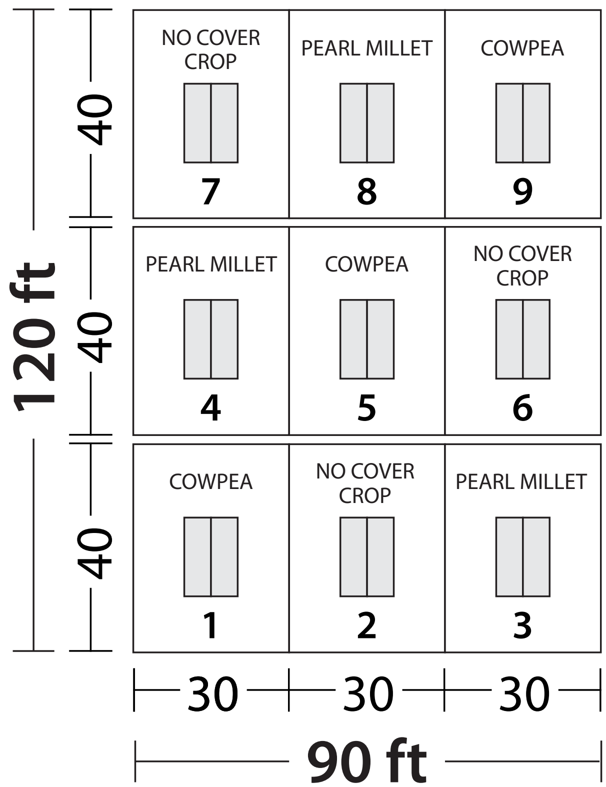

Figure 3.1. Plot layout at Buckwheat Farm (BWT) in a 3x3 randomized complete block design. Each individual treatment area was 1200 ft^2 (111.5 m^2) and contained 80 plants from which strawberries were harvested.

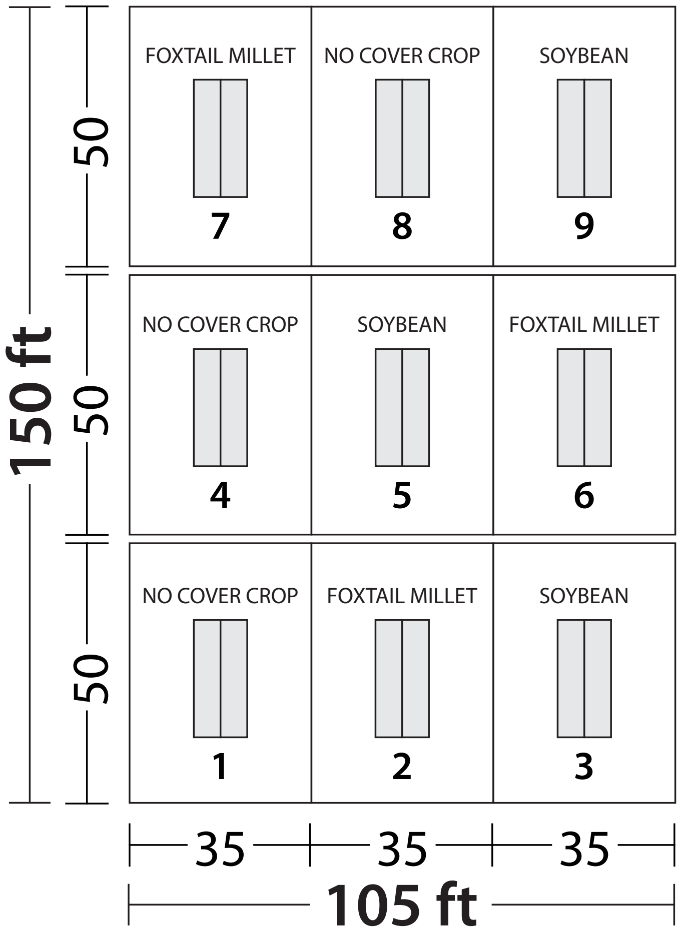

Figure 3.2. Plot layout at Indigo Farms (IND) in a 3x3 randomized complete block design. Each individual treatment area was 1750 ft^2 (162.5 m^2) and contained 68 plants from which strawberries were harvested.

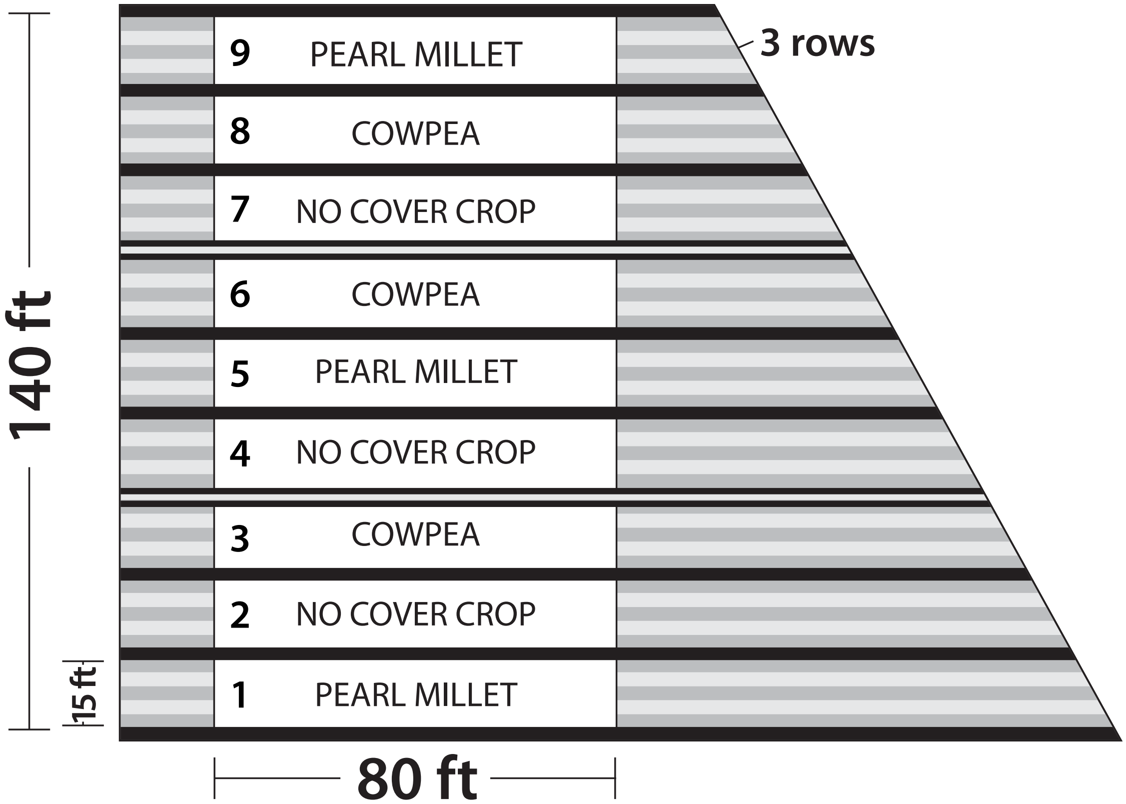

Figure 3.3. Plot layout at Iseley Farms (ISY) in a 3x3 randomized complete block design by rows. Each treatment area was 1200 ft^2 (111.5 m^2) and contained 80 plants from which strawberries were to be harvested (but were not, as noted in the text).

APPENDIX A

ON-FARM INTERVIEW QUESTIONS

1. Have you ever used cover crops before this project on your farm? If so, why and for what crop? If not, why not?

2. How satisfied were you with the cover crop species chosen on your farm? (choose one: 1=very dissatisfied, 2=dissatisfied, 3=no opinion, 4=satisfied, 5=very satisfied)

3. Why or why not satisfied? (Question 2) Please elaborate.

4. Which cover crops were you most satisfied with? Least satisfied with? Please elaborate.

5. What do you think are the biggest challenges to using cover crop with strawberries in rotation? How would you approach solving this challenge?

6. What are all the benefits you perceived in using cover crops in strawberry production? (e.g. soil erosion control, enhancement of soil organic matter, breaking pest cycles etc)

7. Please rate this sentence – I plan on using cover crops in strawberry production again. (choose one: 1=strongly disagree, 2=disagree, 3=no opinion, 4=agree, 5=strongly agree)
Why or why not? Which cover crops species do you prefer for strawberry production on your farm and why? It may or may not be one of the cover crops used in this project.

8. What type of research do you think needs to be done with cover crop production to be used in strawberries? What type of other research do you think needs to be done with other sustainable soil pest management practices?

9. What other type of sustainable soil and pest management alternatives to methyl bromide are you interested in knowing more about (e.g. vermicompost, composted manures applications, strawberry field rotations, etc)? Please identify the specific practices.

10. Please rate this sentence – I am interested in knowing more organic strawberry production on my farm. (choose one: 1=strongly disagree, 2=disagree, 3=no opinion, 4=agree, 5=strongly agree)

11. What do you think the biggest challenge for organic strawberry production in North Carolina? More information, access to specialized equipment, etc? What type of research or training do you think needs to be done to improve this?

12. Methyl bromide is planned to phase out in 2010 and there are many alternatives that are being researched and promoted. What methyl bromide alternatives are you interested in knowing more about? What methyl bromide alternatives do you think you will implement on your farm? What are your concerns with the methyl bromide alternatives?

13. Have you participated in on-farm research before?

14. Please rate this sentence – I was satisfied with this on-farm research project. (choose one: 1=strongly disagree, 2=disagree, 3=no opinion, 4=agree, 5=strongly agree) Why or why not?

15. What types of improvements could be made for future participation in on-farm research?

IV. Conclusions

Summary of Conclusions

Our major finding in both studies was that summer cover crops significantly reduced weeds compared to a bare ground control, and we remain optimistic that future research will reveal other important interactions among cover crops, mycorrhizal fungi, and strawberries that can help producers as they transition to more sustainable management practices. The continued use of summer cover crops by strawberry producers can only have positive benefits over the long term, and growers should not be dismayed by the length of this process nor any year-to-year fluctuations that may occur. A cost and benefit analysis of long-term cover crop use in strawberry production in the SE U.S. may be useful to producers and should be investigated.

In both experiments, the recommended rates of fertilization were used and this could be one reason why we did not see any benefits from cover crops, or any differences between the two mycorrhizal treatments. It is likely that any increase in nutrient availability (from cover crops) or an improved ability to uptake nutrients (from mycorrhizal fungi) would not become apparent in a production system where nutrients were not limited. Future research that investigates the nutrient uptake dynamics of strawberries with cover crop and AM inoculation treatments could prove very useful in determining how to reduce applications of off-farm nutrients while still maintaining strawberry productivity.

Strawberry producers are still faced with the challenge of a short summertime growth window for cover crops. One way to ameliorate this issue would be to rotate fields, but this is a challenge for many small-farm growers in the SE, especially if strawberries are their only crop. Follow-up research should examine the ways that cover crop biomass production could be improved within the 2-month growth window, such as through enhanced seeding rates and cover crop combinations (e.g. grass/legume). Investigating inter-row cover crops during the growing season also offers a possibility for increasing soil organic matter over time.

We found no direct correlation between strawberry yield and the interactions of the cover crop and AM treatments, however, previous research suggests that both cover crops and AM fungi can directly affect strawberry yield so the possibility remains for beneficial interactions to occur. Future research should focus on the interactions of specific cover crops with specific mycorrhiza species to determine if some cover crops are generally more beneficial than others in improving the AM community. Furthermore, growers need to know precisely which species of AM are most beneficial so that strawberry fields can be amended with these AM fungi if they are not present.

Our second major finding regarding AM fungi was that the single species (*Glomus intraradices*) commercial (COM) mycorrhizal inoculant overall proved no better at increasing strawberry yield than the mixed species native (NAT) inoculant. This may have been due to the abundance of native inoculant present in the organic field in which our experiments were conducted (thus possibly having multiple species of AM fungi colonize the "single species" plants in the field), but other experiments have also shown no benefit from commercial inoculants. Growers may find that maintaining a mixed diversity of AM fungi confers several benefits to crop plants that cannot be obtained from a single species alone. Until more research of this type can be conducted, perhaps the most prudent action for growers is to implement practices — such as cover crops and crop rotation — that conserve and promote the diversity of native AM fungi in their own fields (which we found in the three on-farm studies, despite a historical annual regimen of methyl bromide applications).

Lastly, working with three strawberry producers in North Carolina gave us great insight into the challenges they face in adopting cover crops and implementing sustainable practices in general. If we learned only one thing from them, it is that they don't lack the desire to change – they simply need information about how to apply alternative, sustainable practices into their management plans. The great challenge here, for researchers, extension agents, and farmers alike, is to work together to develop the knowledge base that clearly explains why new practices should be adopted, what costs are involved, and how to implement them.