TREE AND SOIL NITROGEN RESPONSES TO ALTERNATIVE GROUND COVER MANAGEMENT STRATEGIES IN ORGANIC APPLE PRODUCTION

By

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A thesis submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE IN SOIL SCIENCE

WASHINGTON STATE UNIVERSITY
Department of Crop and Soil Science

AUGUST 2009

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ACKNOWLEDGMENTS

I would like to thank my committee members for their excellent guidance and support in this process. I would also like to thank the BioAg Program of the Center for Sustaining Agriculture and Natural Resources' Center at Washington State University and the USDA Federal Special Grant for Organic Research for their funding contributions.

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Abstract

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Organic mulches and cover crops are options for weed control, nutrient supply and soil quality management in organic orchards. This study examines the effects of ground cover management and compost rate on 1) tree performance, 2) internal cycling and partitioning of apple tree N, 3) N-use efficiency, 4) soil N supply and 5) soil biological activity. Wood chip mulch, cultivation, brassica seed meal and bare ground treatments resulted in higher fruit yields and tree growth, regardless of compost rate, than legume and non-legume cover crop treatments. Trees with wood chip mulch had greater dry weight and N accumulation in vegetative tree components than cultivated or legume cover cropped trees. Fruit yield in the cultivated treatment was similar to the wood chip treatment, despite reduced vegetative growth, as the cultivated treatment partitioned more dry weight into fruit (44%) than the wood chip treatment (31%). In the legume cover crop treatment, 20-100% of cover crop biomass N was derived from compost in the legume cover treatment, reducing compost N-use efficiency by trees compared to wood chip and cultivation treatments. Tree reserves were an important source of N for fruit and leaf growth in all treatments, but more so for trees under cultivation. Trees allocated 72% of spring N uptake into leaves and fruit and 71% of summer N uptake into woody tissues, bolstering N reserves. Compost rate influenced total soil N, while ground cover management affected the soil microbial community, but not total soil N. From September 2005 to September 2007, the high compost rate increased total soil N in the non-legume cover crop, wood chip mulch and cultivation treatments. Wood chips and brassica seed meal increased earthworm densities compared to other ground covers. Root colonization by mycorrhzal fungi was greatest in non-legume cover and unfertilized control treatments and cover-cropping increased soil microbial activity. In this experiment, improvements in soil N supply and microbial activity did not always translate into better tree performance. Wood chip mulch offered the best balance between improving soil quality and enhancing tree performance in a young organic apple orchard.

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CHAPTER 1

GENERAL INTRODUCTION

Organic apple production is becoming increasingly popular as it is not as reliant on inorganic fertilizers and synthetic pesticides and can bring price premiums for growers. Instead, organic apple production uses compost and other organic fertilizers to supply nutrients to trees. These organic sources are often more expensive (Granatstein and Mullinix, 2008), and release nitrogen (N) slowly, which can result in poor yields and low leaf and fruit tissue N levels (Delate *et al.*, 2008). Improving organic fertilizer-use efficiency is critical to increasing cost efficiency in organic apple production. Integrating organic mulches and cover crops into apple production systems has been proposed as a means to improve yields, nutrient availability and long-term sustainability.

Organic mulches, cover crops and organic fertilizers such as compost, add large amounts of organic carbon (OC) to the soil. Decomposition and nutrient release from these additions can increase soil N, C, and microbial biomass and change the composition of the soil microbial community (Laakso *et al.*, 2000; Wardle *et al.*, 2001). However, studies of organic mulches and cover crops in fruit production have returned both positive and negative results. Sanchez *et al.* (2003) and Hoagland *et al.* (2008a) reported increased soil N availability and a more active soil microbial community using both legume and non-legume cover crops. However, Marsh *et al.* (1996) observed that non-legume cover crops reduced fruit yield and tree growth compared to leguminous cover crops. In these and other studies improved soil quality did not translate into increased tree growth or yield, likely because of competition between trees and cover crops (Neilsen and Hogue, 1985; Sanchez *et al.*, 2003; Hoagland *et al.*, 2008a). Forge *et al.* (2003) and

Yao *et al.* (2005) reported that organic mulches such as wood chips, shredded paper and alfalfa increased soil microbial activity and N turnover, increasing N availability and fertilizer-use efficiency. Conversely, Larsson *et al.* (1997) reported that N was immobilized in wood chip mulch resulting in N deficiency, despite high levels of N fertilization. Brassica seed meals are another possible soil amendment which may serve as an organic source of N (Balesh et al., 2005), a biological control for pathogens (Cohen and Mazzola, 2006) and a biological control of weeds (Hoagland *et al.*, 2008b)

Using herbicides to maintain bare ground in tree rows is the most common practice in conventional apple production; however lower soil N and C content have been reported in these conventional systems compared to systems using organic mulches and cover crops (Sanchez *et al.*, 2003). Likewise, cultivation, the most common practice in organic production, can have detrimental effects on soil N, C and the soil microbial community, reducing soil quality and nutrient availability (Cambardella and Elliot, 1992; Sanchez *et al.*, 2007; Van Den Bossche *et al.*, 2009).

It is critical to ensure N is supplied at the appropriate times to achieve adequate tree growth and yield. In-season N uptake and reserve N stored in perennial tissues (i.e., branches, trunk and roots) from previous growth cycles are both vital to apple tree nutrition. In late summer and autumn, absorbed N is stored in perennial tissues and can constitute a significant portion of reserve N (Millard and Thomson, 1989; Neilsen *et al.*, 2001b; Sanchez *et al.*, 1992; Toselli *et al.*, 2000). Also, before leaf abscission, 35-70% of leaf N is relocated into perennial tissues as reserve N (Blasing *et al.*, 1990; Munoz et al., 1993). Remobilization of these reserves from woody tissues is the main driver of early season fruit and leaf growth and has been correlated with leaf canopy development (Cheng and Fuchigami, 2002; Khemira *et al.*, 1998; Millard and Neilsen, 1989, Neilsen *et al.*, 2001a; Titus and Kang, 1980).

Partitioning of in-season N uptake is affected by fertilizer timing. Early season fertilizer N is heavily partitioned into fruit and leaves (Cheng and Fuchigami, 2002; Khemira *et al.*, 1998). Munoz *et al.* (1993) reported N uptake in April was preferentially partitioned into fruit, whereas May N uptake was allocated into leaves of peach trees (*Prunus persica*), with vegetative growth being greatest from May to August. Fertilizer N application during this period of vegetative growth can result in higher fruit N concentrations, having possible detrimental affects on fruit quality and storage (Sanchez et al., 1992; Toselli *et al.*, 2000).

The objectives of this thesis are twofold. Chapter 2 examines the effects of cultivation, wood chip mulch and a legume cover crop on tree growth, partitioning of compost N and fertilizer-use efficiency in young apple trees (*Malus domestica* Borkh) at different compost application dates across two growing seasons. Chapter 3 measures the impact of different ground cover management strategies and compost rates on soil N supply, total N and C, soil biological activity and fruit yield and tree growth in the same apple orchard during three growing seasons.

CHAPTER 2

INFLUENCE OF GROUND COVER MANAGEMENT AND COMPOST APPLICATION TIMING ON N PARTITIONING IN ORGANIC APPLE TREES

Abstract:

Synchronizing apple tree needs with N release from compost is essential to cost-effective organic apple production. This study examines the effects of three ground covers: cultivation, wood chip mulch and a legume cover crop, on partitioning of compost N in young apple (*Malus domestica* Borkh.) trees at different compost application dates across two growing seasons. Compost enriched with ^{15}N was applied to apple trees in April, May and June of 2006 and 2007, and trees were excavated in September 2007 to determine the fate of labeled compost N. Trees with wood chip mulch had significantly greater dry weight and N accumulation in vegetative tree components than trees with cultivation or legume cover. Fruit yields were similar between cultivation and wood chip treatments despite less vegetative growth under cultivation as these trees partitioned more dry weight into fruit (44%) than wood chip mulch trees (31%). Nitrogen-use efficiency by trees was lower with a living legume cover crop than in other treatments due to competition for resources. Of the total N in the cover crop above-ground biomass, 20-100% was derived from compost. In comparison, only 5-40% of wood chip mulch N was from compost. Tree reserves were an important source of N for spring fruit and leaf growth in all treatments, but significantly more so for trees under cultivation. Fruit and leaves were strong sinks for compost N early in the season, with trees allocating 72% of spring N uptake into leaves and fruit. In the summer, N uptake increased improving compost N-use efficiency. Summer N was preferentially allocated to perennial tissues (71%) bolstering N reserves. Trees with wood chip mulch

performed well and had greater capacity to build N reserves, making wood chips ideal for establishing young organic apple orchards. However, as the orchard matures, it may be beneficial to switch to a ground cover that reduces tree vegetative growth.

1. Introduction

Organic apple production has experienced significant growth in the past 20 years, largely due to food and environmental safety concerns regarding synthetic pesticides and fertilizers. Increased organic fruit production can also be attributed to advancements in organic production practices, such as pheromone mating disruption for codling moth (*Cydia pomonella*), and yet significant challenges remain (Delate *et al.*, 2008). Among the most significant challenges is N supply: organic fertilizers are often bulky and expensive, and release of N can be unpredictable. Improving N cycling and organic fertilizer-use efficiency are critical to cost effective organic fruit production.

Cultivation in the tree row is currently the most common understory management practice in organic apple production despite its high cost and detrimental effects on soil quality and N availability (Cambardella and Elliot, 1992; Granatstein, 2004; Sanchez *et al.*, 2007). Alternative ground cover strategies that reduce costs and improve N mineralization of organic fertilizers are needed. Possible ground covers include organic mulches and leguminous cover crops.

Increased soil N availability and mineralizable forms of N with use of organic mulches such as wood chips, shredded paper or alfalfa have been reported in multiple studies (Forge *et al.*, 2002; Marsh *et al.*, 1996; Sanchez *et al.*, 2003; Yao *et al.*, 2005). Elevated soil N availability may result from increased microbial activity and N turnover (Forge *et al.*, 2002; Yao *et al.*, 2005). Forge *et al.* (2002) reported that use of high C:N ratio mulch in the tree row of an apple orchard did not result in net N immobilization or lower N supply and, to the contrary, increased N fertilizer-use efficiency. Neilson *et al.* (2003) observed increased apple tree vigor and yield with organic mulches. In a comparison study of different ground cover systems, Shribbs and Skroch (1986) observed that apple trees under organic mulches had larger trunk diameter after four years, compared to bare ground, cultivation and a legume cover crop.

Sanchez *et al.* (2003) and Hoagland *et al.* (2008a) reported that leguminous cover crops resulted in greater soil N availability and microbial activity than alternative ground covers. Numerous studies, however, have reported reduced tree growth and yield due to increased competition between trees and cover crops (Hoagland *et al.*, 2008a; Larsson *et al.*, 1997; Sanchez *et al.*, 2003;).

It is critical to ensure N is supplied at the appropriate times to achieve adequate tree growth and yield. In-season N uptake and reserve N stored in perennial tissues (i.e., branches, trunk and roots) from previous growth cycles are both vital to apple tree nutrition. In late summer and autumn, absorbed N is stored in perennial tissues and can constitute a significant portion of reserve N (Millard and Thomson, 1989; Neilsen *et al.*, 2001b; Sanchez *et al.*, 1992; Toselli *et al.*, 2000). Also, before leaf abscission, 35-70% of leaf N is relocated into perennial tissues as reserve N (Blasing *et al.*, 1990; Munoz et al., 1993). Remobilization of these reserves from woody tissues is the main driver of early season fruit and leaf growth and has been correlated with leaf canopy development (Cheng and Fuchigami, 2002; Khemira *et al.*, 1998; Millard and Neilsen, 1989, Neilsen *et al.*, 2001a; Titus and Kang, 1980).

Partitioning of in-season N uptake is affected by fertilizer timing. Early season N uptake is heavily partitioned into fruit and leaves (Cheng and Fuchigami, 2002; Khemira *et al.*, 1998). Munoz *et al.* (1993) reported N uptake in April was preferentially partitioned into fruit, whereas May N uptake was allocated into leaves of peach trees with vegetative growth being greatest from May to August. Fertilizer N application during this period of vegetative growth can result in higher fruit N concentrations, having possible detrimental affects on fruit quality and storage (Sanchez et al., 1992; Toselli *et al.*, 2000).

Previous mulching and cover cropping studies have focused on tree and soil responses, but have not examined their affects on internal N cycling. Conversely, N partitioning and uptake studies have centered on inorganic fertilizer use and application timing. Interactions between N partitioning, organic fertilizers and ground cover management are not well understood. The objectives of this study were to determine the effects of cultivation, wood chip mulch and a legume cover crop on tree growth, partitioning of compost N at different application timings and fertilizer-use efficiency.

2. Materials and Methods

2.1 Study Site

This study was established in spring 2005 at the Wenatchee Valley College-Auvil Teaching and Demonstration Orchard in East Wenatchee, Washington, USA. Soil at the study site is a Pogue sandy loam (coarse-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Aridic Haploxerol), averaging 1-2% organic matter and a pH of 7.0. Annual rainfall at the orchard site averages 21.6 cm. The study site was previously planted to sweet cherry; after stump removal and disking, apple trees (cv. Pinata on EMLA 7 rootstock) were planted at a spacing of 1.5 x 4 m (1541 trees per hectare). This study is part of a larger experiment in which plots were arranged in a completely randomized block design, and had 3 replicates. Each plot consisted of a row of 8 trees; 6 study trees with a guard tree on each end. Trees were irrigated as needed throughout the growing season with undertree microsprinklers (R-10 rotators, Nelson Irrigation, Walla Walla, WA)

2.2 Orchard floor treatments and N amendments

Three ground cover management systems were selected for this study: mechanical cultivation, wood chip mulch, and legume cover crop. Ground cover treatments were applied to a 1.5 m strip centered on the tree row. A 2.5 m drive alley planted to perennial grass was established between tree rows. Mechanical cultivation (CLT) using a Wonder Weeder (Harris Manufacturing, Burbank WA) was done four times per season on the sides of the tree and rototilling between the trunks was done as needed, disturbing only the upper 8-10 cm of soil. Wood chip mulch (WC) plots had a 15 cm layer of mixed conifer and deciduous wood chips (1.3 to 2.5 cm maximum dimension) applied every spring. In 2005 and 2006 weeds were hand pulled and in 2007 glyphosate (1% solution) was spot sprayed as needed to control weeds. Legume cover crop (LC) plots were established in May 2005 using a mix of Mt. Barker subterranean clover (*Trifolium subterraneum*), black medic (*Medicago lupulina*), burr medic (*Medicago polymorpha*), birdsfoot trefoil (*Lotus corniculatus*), and Colonial bentgrass (*Argostis tenuis*). The drive alley and legume cover crop were mowed as needed with clippings left on the ground.

In spring 2005, pelleted chicken manure (NutriRich, Stutzman Farm, Canby, OR, USA; 4% N) was broadcast in the tree rows at a rate of 111 kg total N ha^{-1} and incorporated prior to tree planting. Due to poor initial tree growth, a soluble N fertilizer of fermented plant and animal waste (Biolink, Westbridge Ag Products, Vista, CA, USA; 14% N) was injected below each tree at 36 kg total N ha^{-1} in mid-July. An additional 2.75 kg total N ha^{-1} was applied at weekly intervals throughout the summer as a foliar application of fish emulsion and kelp (Mermaids, I.F.M., Wenatchee, WA, USA; Acadian Seaplants, Dartmouth, Nova Scotia, Canada).

In 2006 and 2007, 101 kg available N ha^{-1} $year^{-1}$ was applied in three split applications (April 7, May 9 and June 7, 2006 and April 24, May 25 and June 21, 2007) of Nielsen's chicken manure compost (Mossyrock, WA, USA; 3.5% N, 51% available in a 14-day anaerobic incubation). Compost was spread around the base of each tree 15 to 30 cm from the trunk.

At each compost N application date in 2006 and 2007, a separate tree from each plot was treated with ^{15}N (ammonium sulfate) enriched compost. Forty-eight hours prior to application, compost for each tree was spread on a plastic sheet, sprayed with 5 g $(NH_4)_2SO_4$ (~70A% ^{15}N, 0.8 g ^{15}N per tree) dissolved in 50 ml distilled water, and allowed to incubate at room temperature until application.

2.3 Soil and ground cover sampling and analysis

One month after application of ^{15}N enriched compost, samples of soil, wood chip duff and cover crop residue were taken approximately 15 cm from the base of each tree. Sample dates were May 9, June 7, July 13 and September 29 in 2006 and May 23, June 19, July 19 and

September 23 in 2007. Soil samples were composites of three cores taken with a 2-cm diameter probe to a depth of 10 cm. Cover crop residue samples were composites of all above ground biomass from three 7.4 x 10 cm areas. Wood chip duff samples were taken by clearing away intact wood chips and taking three samples of approximately 20 g of decomposed wood chip litter. Soil and wood chip samples were sieved to pass through a 2 mm sieve. All samples were oven dried, roller-ground and analyzed for ^{15}N and total N and C using an isotope ratio mass spectrometer (Thermo Finnigan, Germany) and a dry combustion analyzer (Costech, CA, USA).

2.4 Fruit Harvest and Tree Excavation

In 2006, blossoms were removed to prevent fruiting. In 2007, fruit were hand thinned to five fruit per cm^2 trunk cross sectional area (TCSA). Fruit were harvested on September 15, 2007 from the center 6 trees of each plot. Thirty fruit per tree were randomly selected and sliced radially into eight sections. Two opposing eighths per apple were ground into slurry using a food processor, oven-dried at 105 °C for 72 hours, roller-ground and analyzed for ^{15}N and total N and C.

Sample trees were excavated on September 24, 2007. Trees were stripped of leaves by hand and pulled out with an excavator; soil in the root zone was sifted using pitchforks to recover remaining roots. Each tree was separated into roots (below the graft union), new growth (2007 shoots) and frame (trunk + previous season branches). Frame fresh weight was measured in the field, after which tree frames were ground in a wood chipper and approximately 500 g of wood chips were sub-sampled, oven-dried, and weighed to determine percent moisture. Frame subsamples, new growth, roots and leaves were oven-dried, weighed, ground with a Wiley mill, roller-ground and analyzed for ^{15}N and total N and C.

2.5 Calculations and statistical analysis

Nitrogen accumulation was calculated as dry weight x N concentration. Nitrogen derived from compost (NDFC), was calculated using the equation:

$$\text{NDFC} = \frac{\text{tissue atom \% } ^{15}\text{N excess}}{\text{compost atom \% } ^{15}\text{N excess}}$$

Nitrogen utilization, the proportion of available applied compost N present in the tree at excavation, was calculated as follows:

$$\text{N utilization} = \frac{\text{\% NDFC x total tree N}}{\text{Rate of N application (g)}}$$

Statistical analyses were conducted using SAS 9.1 software (SAS Institute, Cary, NC, USA). Differences in accumulation and partitioning of dry weight and N in tree components between ground cover treatments were analyzed using one-factor ANOVA. Differences in NDFC in trees and soils and N utilization were analyzed were analyzed using two-factor ANOVA, separately for each year, with ground cover treatment and month as factors. Nitrogen derived from compost in cover crop residue and wood chip mulch was analyzed using two-factor ANOVA with year and month as factors. Simple effect comparisons were used when an interaction was present. Mean separation was considered significant at $P \leq 0.05$ using a Protected LSD.

Table 1. Dry weight, N accumulation and N concentration in tree components of 'Pinata'/M7 apple trees at excavation. Numbers within the same column followed by the same letter are not significantly different (P≤0.05)

Treatment	Roots	Frame	New Growth	Leaves	Fruit	Total
	Dry weight (g/tree)					
Cultivation	304 a	1495 b	90 b	310 b	1717 a	3917 b
Wood chip mulch	371 a	2964 a	496 a	874 a	1930 a	6648 a
Legume cover	230 b	1178 b	107 b	256 b	883 b	2654 c
	Nitrogen (g/tree)					
Cultivation	3.07 b	7.25 b	1.15 b	7.33 b	15.25 a	34.1 b
Wood chip mulch	5.19 a	13.83 a	5.83 a	20.86 a	14.67 a	59.8 a
Legume cover	2.71 b	5.95 b	1.29 b	6.25 b	5.57 b	21.8 c
	Nitrogen concentration (%)					
Cultivation	1.03 b	0.49 a	1.30 a	2.35 a	0.90 a	
Wood chip mulch	1.35 a	0.48 a	1.15 b	2.40 a	0.78 a	
Legume cover	1.15 b	0.51 a	1.30 a	2.45 a	0.73 a	

3. Results

At excavation, tree dry weight and N accumulation were significantly different among ground cover treatments (Table 1). Trees with WC had the most dry weight and N accumulation followed by CLT then LC. Tree component dry weight was greater in WC than in CLT or LC for frame, new growth, and leaves. The root:shoot ratio (root dry weight: frame + new growth dry weight) was significantly greater in CLT (1:6.3) and LC (1:6) trees than WC (1:9.6). Total N was greater in WC than in CLT or LC for roots, frame, new growth and leaves. Fruit dry weight for CLT was similar to that of WC, these treatments producing over twice as much fruit dry weight as LC. Nitrogen concentration was greater in WC in roots but lower in new growth compared to CLT and LC (Table 1). There were no significant treatment differences in the N

Table 2. Percentage of total tree dry weight and N partitioned into tree components at tree excavation. Numbers within the same column followed by the same letter are not significantly different (P≤0.05)

Treatment	Roots	Frame	New Growth	Leaves	Fruit
	------------------------- Dry matter partitioning (%) -------------------------				
Cultivation	7.8 a	37.8 b	2.2 c	8.0 c	44.2 a
Wood chip mulch	5.6 b	43.7 a	7.2 a	12.9 a	30.6 b
Legume cover	8.8 a	45.8 a	4.1 b	9.7 b	31.6 b
	--------------------------- Nitrogen partitioning (%) --------------------------				
Cultivation	9.1 b	21.7 b	3.1 c	21.8 c	44.4 a
Wood chip mulch	8.3 b	22.8 b	9.0 a	35.2 a	25.9 b
Legume cover	11.6 a	27.1 a	5.3 b	28.6 b	24.8 b

concentration of frame, leaves or fruit, and leaf N concentrations were adequate for young fruit bearing apple trees, greater than 2.2%, in all treatments (Stiles, 1994).

Trees under CLT partitioned a larger proportion of dry weight and N into fruit than either WC or LC trees (Table 2). More than 44% of both dry weight and N was allocated to fruit under CLT, whereas only 32% and 30% of dry weight and 25% and 26% of N was allocated to fruit under LC and WC, respectively. Trees in LC partitioned more N into roots and frame while WC trees had a significantly larger proportion of dry weight and N in new growth and leaves.

Tree N derived from compost applied in 2006, regardless of date, was significantly lower than N originating from 2007 compost applications (Figure 1). Averaged across all three application dates each year a larger percentage of tree N was derived from compost in CLT trees than either WC or LC trees in 2006 and CLT and LC were greater than WC in 2007. There were no significant differences among application dates in 2006, whereas in 2007 tree N originating from the April compost application was significantly lower than from the May and June applications.

There was interaction between ground cover treatment and application date for compost N utilization of 2006 compost. Significantly greater compost N was recovered in wood chip trees than other ground cover treatments in April, whereas in May and June more compost N was recovered under cultivation than legume cover (Figure 2). In 2007, compost N recovered in WC and CLT trees was greater than LC trees when averaged across all application dates, and N utilization was notably lower (P $\leq$ 0.1) for April applied compost compared to the June application.

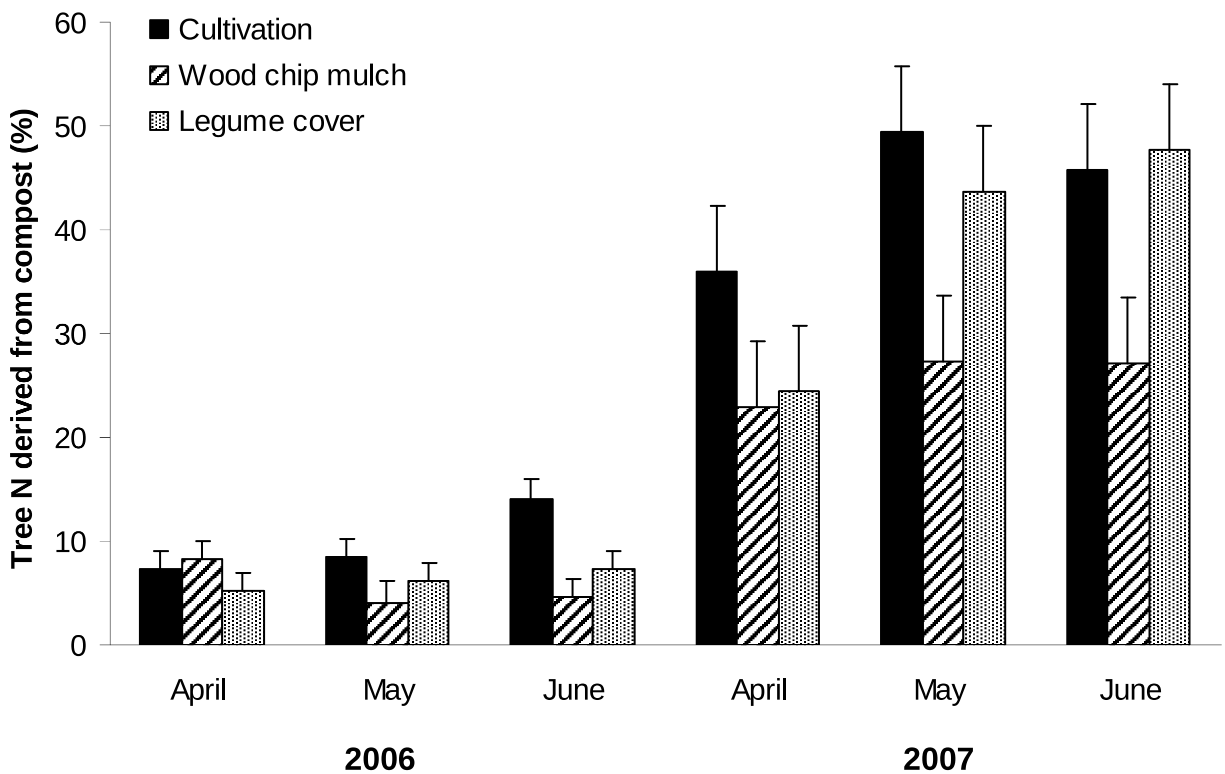

Figure 1. Percent of total tree N derived from compost from six application dates in 2006 and 2007 at excavation in September 2007. Mean $\pm$ SE (n=3)

Compost N was partitioned to tree components much the same as total N (Table 3). Compost N was preferentially allocated into fruit (44%) under CLT, whereas WC partitioned more compost N to leaves and new growth (together 44%) and LC partitioned more compost N into roots and frame (together 39%).

Allocation of compost N to tree components was influenced by application timing as well as ground cover treatment. In 2007, trees received compost N from four sources: April, May and June compost applications as well as reserve N (Table 3). Reserve N encompasses all labeled N from the April, May and June 2006 compost applications, combined. This N may have been taken up and remained in storage organs over winter, becoming available for remobilization in early spring 2007, or may have remained in compost or soil over winter then was taken up in

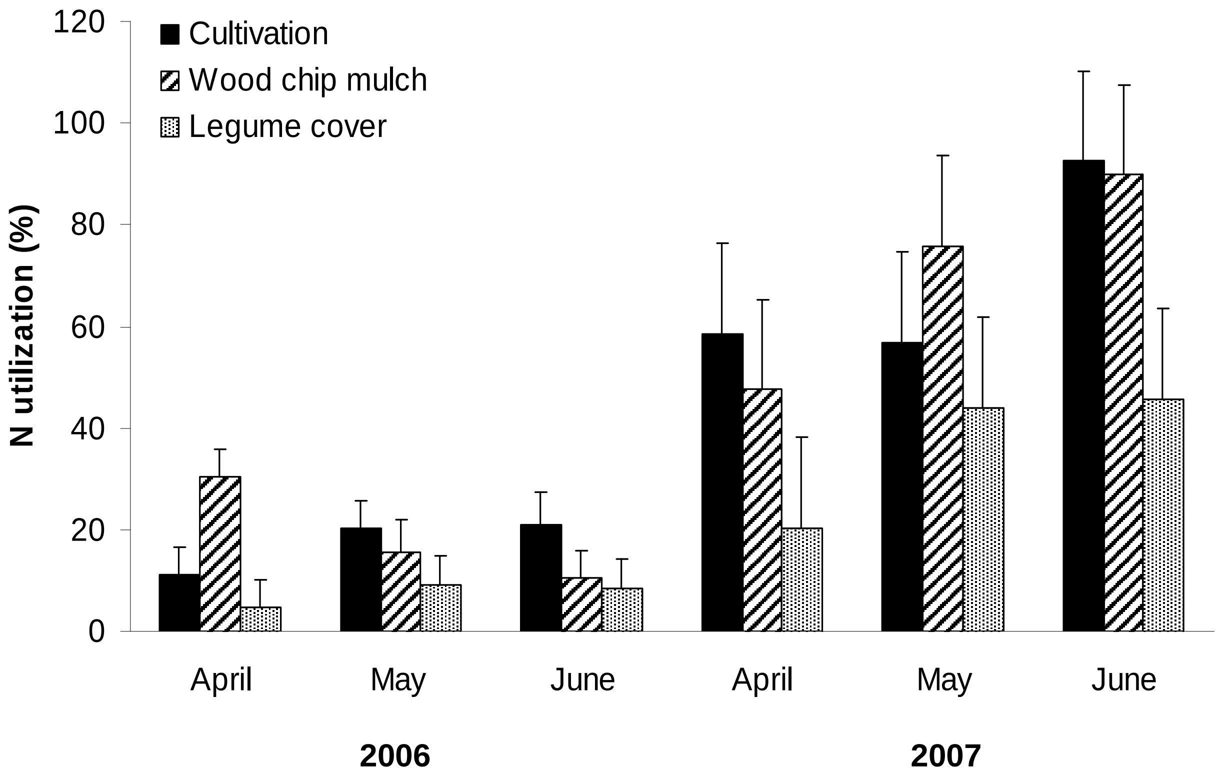

Figure 2. Percent of compost N applied on six dates in 2006 and 2007 present in trees at excavation in September 2007. Mean ± SE (n=3)

Table 3. Partitioning of compost N (%) recovered at tree excavation into tree components; by application time and ground cover treatment. Reserve N represents labeled N recovered from the April, May and June 2006 compost applications, combined. Numbers within the same column followed by the same letter are not significantly different ($P \leq 0.05$)

Time	Roots	Frame	New Growth	Leaves	Fruit
Reserve N	10.6 a	24.9 b	5.7 ab	26.6 b	32.1 b
April 2007	6.2 b	16.3 c	4.7 b	31.4 a	41.3 a
May 2007	10.4 a	31.5 b	5.6 b	21.9 c	30.6 b
June 2007	11.4 a	51.8 a	7.8 a	12.7 d	16.1 c
Treatment					
Cultivation	8.4 b	28.0 a	3.2 b	18.5 c	41.9 a
Wood chip mulch	7.9 b	32.0 a	9.8 a	28.0 a	22.4 b
Legume cover	12.6 a	33.5 a	5.0 b	23.1 b	25.8 b

2007. Trees mobilized nearly equal portions of reserve N into fruit (32%), leaves + new growth (32%) and roots + frame (36%). Of the April compost application, 73% of N was allocated to leaves and fruit, and 27% into woody tissues. Conversely, only 29% of June compost N was allocated to leaves and fruit, with 71% being partitioned into woody tissues.

Both the legume cover crop and decomposing wood chip layer represented alternative sinks for compost N. In May 2007 almost 100% of N in the cover crop was derived from compost (Figure 3A). Compost N constituted a significantly larger portion of legume cover crop N in 2007 than 2006 at similar dates. In both years NDFC of the cover crop decreased over the course of the growing season. Similarly, the NDFC of the wood chip layer was greatest both years at the May sampling (Figure 3B), but was less than the legume cover crop, ranging from 5-40%. The total N content of the decomposing wood chip layer was 1.6-1.8% and C:N ratio was 8.3 to 9.5 on all sampling dates (data not shown).

There was significant interaction between ground cover treatment and application date in the percentage of soil NDFC in both 2006 and 2007. In 2006, NDFC in CLT soil was significantly higher than in soil under WC and LC in May, and higher than WC soils in July, while WC soil had the highest proportion of N derived from compost in June (Figure 4A). In May, NDFC represented a significantly greater proportion of soil N than July, followed by September. In 2007, soil N derived from compost did not change significantly throughout the season, and compost N made up a more significant portion of soil N in CLT soil than WC and LC plots in May, July, and September (Figure 4B). Ground cover treatment did not significantly affect soil N content, but there was a significant increase in soil N in September 2007 compared to other sample dates (Figure 5).

4. Discussion

The use of WC increased vegetative growth in apple trees considerably over CLT and LC trees. Despite less vegetative growth in CLT trees, fruit yield was similar to WC suggesting an increased fruit:vegetative growth efficiency in CLT. However, increased root:shoot ratio in CLT and LC indicate that trees were under moisture or nutrient stress (Forshey and Elving, 1989) compared to WC trees. Preferential partitioning of dry weight and N into fruit in CLT may have been caused by reduced N uptake due to root damage or decreased N supply (Marsh *et al.*, 2003; Sanchez *et al.*, 2007; Yao *et al.*, 2005). In low N conditions trees may reduce the number of competing sinks for N; i.e., reduce vegetative growth (Neilsen *et al.*, 2006). Conversely, partitioning of dry weight and N into the fruit of WC and LC trees was similar, suggesting that N availability was not the main cause of growth and yield differences between these treatments.

Instead, lower root growth as seen in the LC trees can signify moisture stress (Forshey and Elving, 1989). If moisture is insufficient, the photosynthetic capacity of trees is reduced and trees are unable to build the carbon skeleton needed for growth.

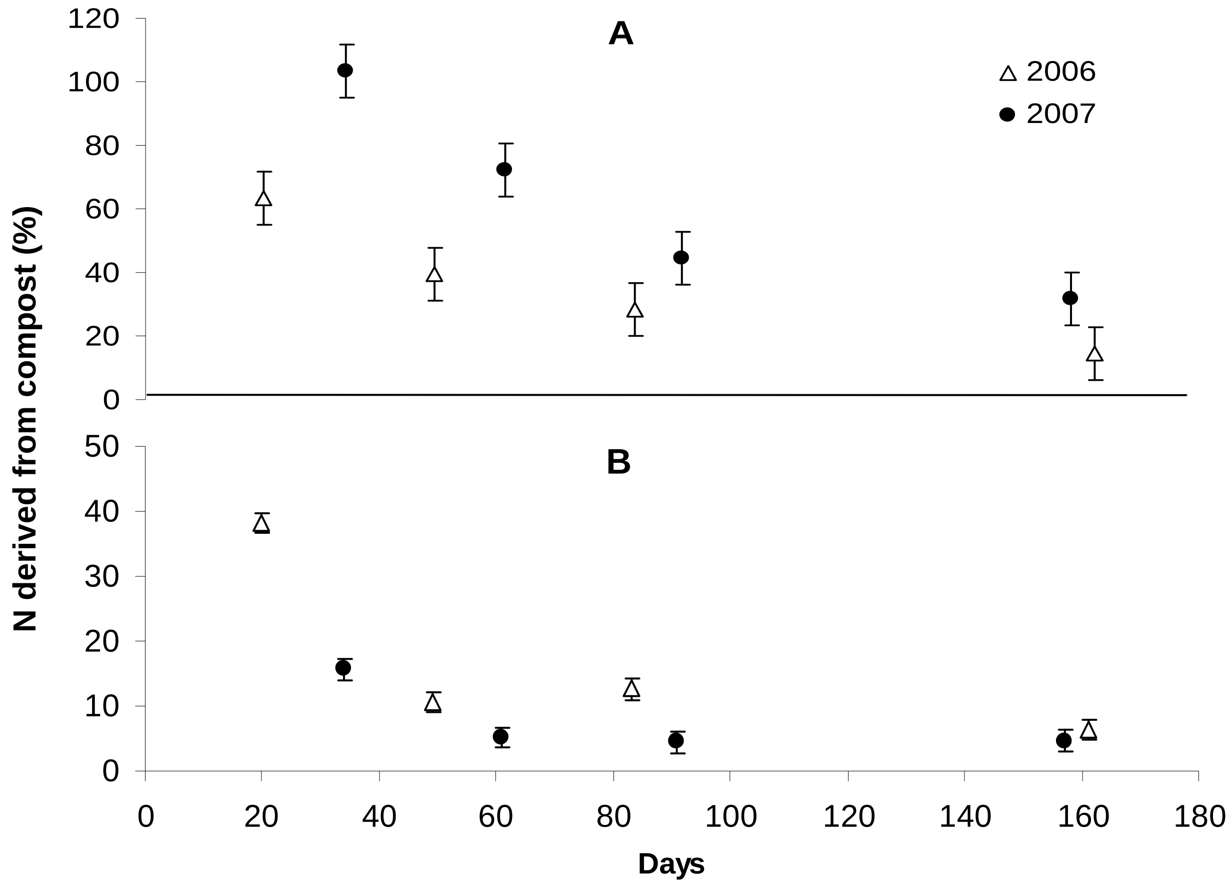

Figure 3. N derived from compost (%) in 2006 and 2007 in A) legume cover crop cuttings and B) decomposing wood chip layer, starting from April 20 (Day 0). Samples taken May 9, June 7, July 13 and September 29 in 2006 and May 23, June 19, July 19 and September 23 in 2007. Mean ± SE (n=3)

Increased mass of perennial tissues (roots, frame and new growth) in WC trees increased their capacity to store N in autumn for the subsequent growing season. Also, superior leaf growth increased the pool of N available for relocation into N reserves prior to leaf senescence.

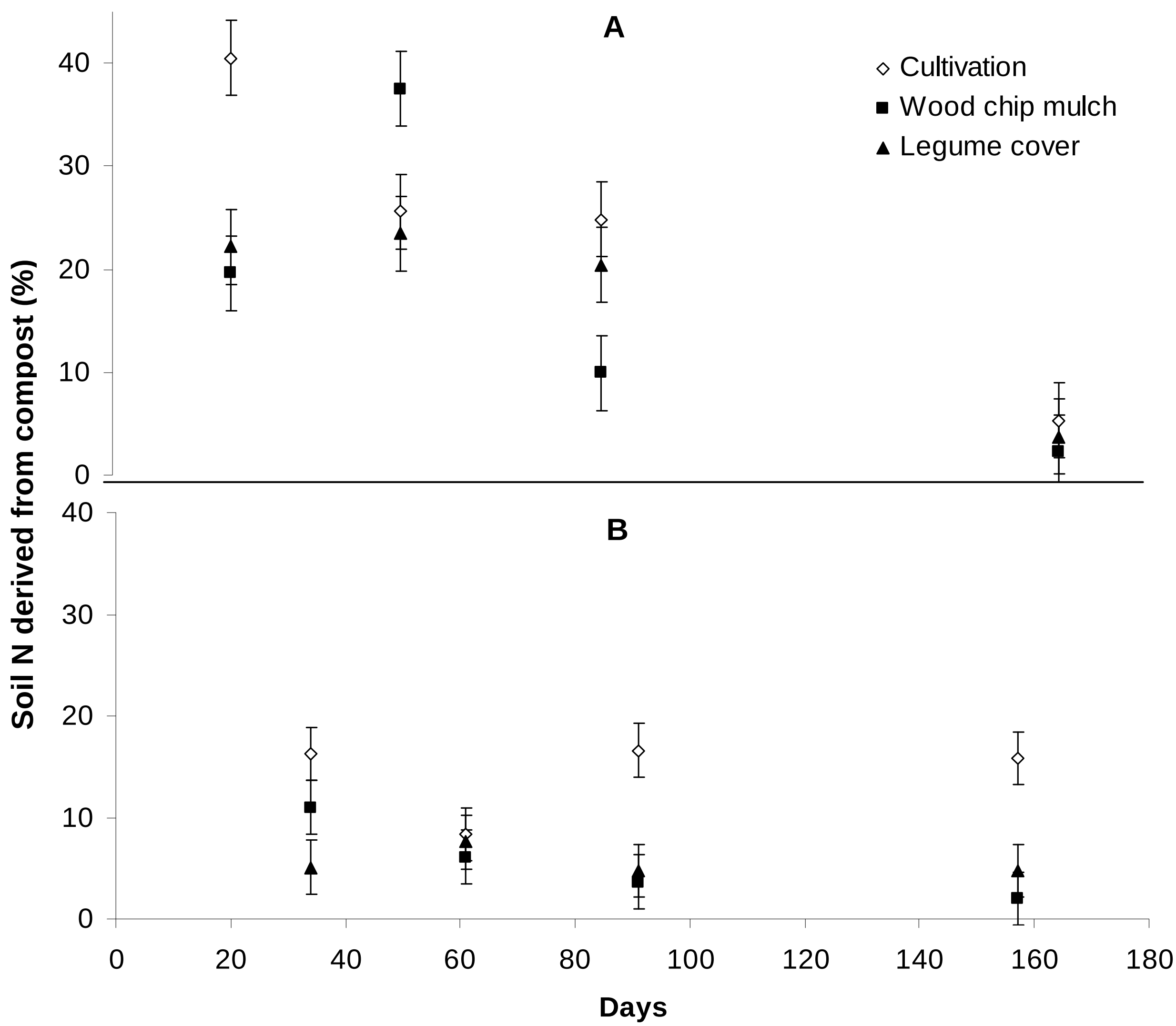

Figure 4. Soil N derived from compost (%) in ground cover treatments in A) 2006 and B) 2007, starting from April 20 (Day 0). Samples taken May 9, June 7, July 13 and September 29 in 2006 and May 23, June 19, July 19 and September 23 in 2007. Mean ± SE (n=3)

In this experiment, trees were excavated just after harvest, therefore partitioning to N reserves at excavation was the result of N uptake and not backflow of N from leaves. Therefore, the greater N concentration in WC roots suggests that trees may store a larger percentage of late season N uptake in the roots than in CLT or LC trees.

Fruit and leaves acted as strong sinks for compost N early in the season, for both reserve and April applied compost N. As the season progressed a larger percentage of N was allocated into perennial tissues, either as vegetative growth or reserve N. These results are consistent with studies conducted using inorganic N sources (Munoz *et al.* 1993; Khemira *et al.*, 1998; Cheng and Fuchigami, 2002).

By the time of tree excavation in September 2007, NDFC and utilization of compost N applied in 2006 were low. This could be the result of lower N uptake and/or substantial loss of 2006 compost N. Modes of loss of 2006 compost N from trees include leaf abscission in the autumn of 2006, fruit thinning in 2007 and natural root turnover. Compost N-use efficiency was

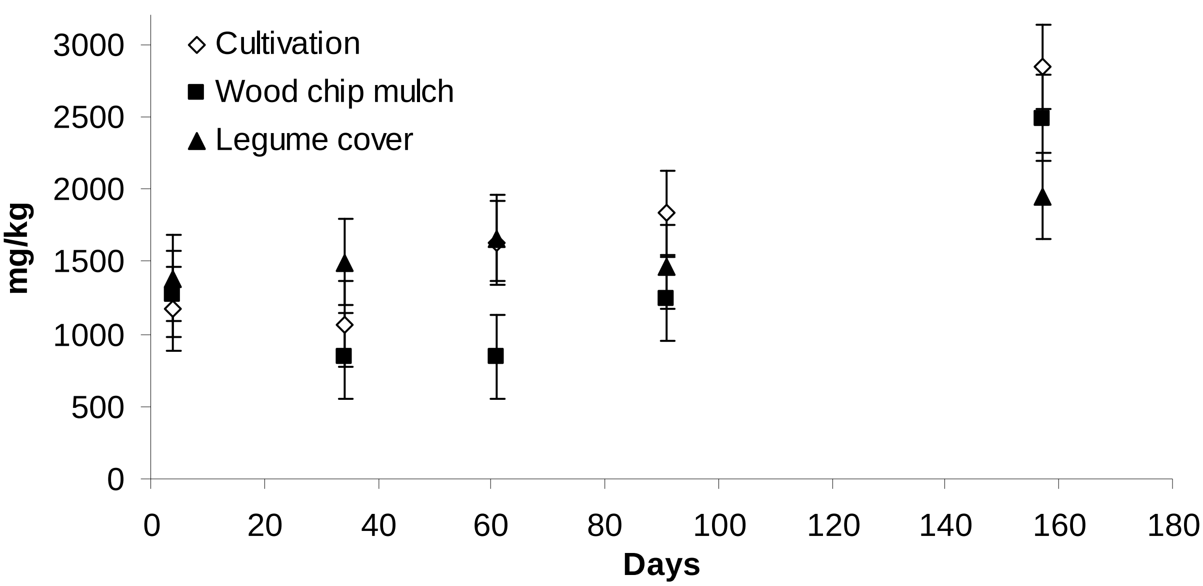

Figure 5. Total soil N concentration by ground cover treatment over the course of the 2007 growing season, starting from April 20 (Day 0). Samples taken April 23, May 23, June 19, July 19 and September 23 in 2007. Mean ± SE (n=3)

greatest in the WC and CLT treatments, but increased N accumulation and lower tree NDFC indicate that trees in WC received a significant amount of N from non-compost sources. In contrast, trees under CLT and LC were more reliant on compost as a N source. Dependence on compost N in the LC, combined with low total tree N, suggests that N fixation in the legume cover crop did not supply significant N to the apple trees. Nitrogen uptake, as represented by amount of tree N derived from compost and N utilization, was lower in April than May and June, consistent with Munoz *et al.*, (1993) who observed peak N uptake from June to August in peach trees. This is due, in part, to strong competition between apple trees and legume cover crops or the decomposing wood chip layer, which was greatest in the spring. In the legume cover crop treatment, bentgrass re-establishing quicker than the legume (data not shown) and cool spring temperatures depressing N fixation combined to increase cover crop competition for N. Cultivation incorporated N into the soil, increasing soil NDFC compared to soils under WC and LC. In the WC treatment, addition of high C:N ratio mulch in April resulted in compost N immobilization early in the season. We observed roots growing into the wood chip layer and believe that as the season progressed the decomposing wood chip layer shifted from a sink to source of N, resulting in lower N concentration and higher C:N ratio later in the season. Also, irrigation and soil organisms helped move N out of the wood chip layer and compost and into the soil, increasing soil N in all treatments over the course of the growing season.

Fertilizers labeled with ^{15}N are frequently used to track N uptake and movement in fruit trees but have only used inorganic fertilizers (Cheng and Fuchigami, 2002; Khemira *et al.*, 1998; Millard and Neilsen, 1989; Millard and Thompson, 1989; Munoz et al., 1993; Neilsen *et al.*, 2001b; Neilsen *et al.*, 2001b; Toselli *et al.*, 2000). The addition of ^{15}N enriched fertilizer increases the amount of available N in compost compared to non-enriched compost. This may alter the pattern of compost N uptake and utilization by trees. We believe, however, that ^{15}N compost enrichment is a useful method to track N movement from compost. Further study is needed to establish how ^{15}N enrichment affects N release and uptake from compost or other organic sources of N.

Vigorous tree growth in the wood chip treatment allowed young apple trees to establish quickly. As the orchard matures, however, overly vigorous tree growth could increase orchard management costs through increased pruning and added difficulty in training limbs to leaders. It may be necessary then, to compliment wood chip mulch with other management strategies to reduce vegetative growth, such as deficit irrigation, reduced N applications or changing the timing of compost application. Otherwise, after orchard establishment, switching to a ground cover strategy that reduces tree vigor may be needed to reduce vegetative growth.

In the short term, cultivation resulted in high fruit yields despite reduced vegetative growth. Trees under cultivation were more dependent on compost for N than trees under wood chips, and had high fertilizer-use efficiency. However, due to the negative long-term soil impacts of cultivation and the need for an active soil microbial community to mineralize organic N, the long-term effectiveness of this system needs to be studied.

The grass-legume mixture used in this study competed for moisture, reduced tree growth, fruit yield, and fertilizer-use efficiency and absorbed significant amounts of compost N. A legume that can out-compete grasses and re-establish early in the spring may reduce competition for compost N and increase N transfer to apple trees. Legume covers have been found to improve soil microbial activity, and may be useful in established orchards (Hoagland *et al.*, 2008a). We conclude, however, that legume cover is unsuitable ground cover for orchard establishment.

CHAPTER 3

GROUND COVER MANAGEMENT AND COMPOST RATE INFLUENCE N SUPPLY, SOIL BIOLOGY AND FRUIT YIELD IN ORGANIC APPLE PRODUCTION

Abstract:

Organic mulches and cover crops add organic carbon (OC) to soils, potentially increasing mineralization and supply of N through enhanced soil biological activity. In this study, bare ground, brassica seed meal, cultivation, wood chip mulch, legume cover crop and non-legume cover crop ground cover treatments and three compost rates were evaluated for effects on soil N supply, biological activity and tree performance in a newly planted apple (*Malus domestica* Borkh.) orchard during the first three growing seasons. Ground cover management and compost rate influenced soil N supply in years two and three of the study. Wood chip mulch around trees increased total soil N, C and labile C, but decreased soil N supply due to immobilization. Wood chip mulch and brassica seed meal increased earthworm population compared to other ground covers. Brassica seed meal consistently increased soil N supply compared to other treatments, but did not change total soil N or C. In cultivation and non-legume cover crop treatments N supply increased as compost rate increased and at the highest compost rate total soil N and C was greater than either the low of medium rate. Fruit yields in cultivation, wood chip mulch, bare ground, and brassica seed meal treatments were greater than with legume and non-legume cover crops, regardless of compost rate. Using a legume cover crop did not increase soil N supply compared to a non-legume cover crop but competition between apple trees and cover crops reduced tree growth and yield. Microbial biomass was greatest in these treatments. Both ground cover management and compost rate significantly impact soil quality and tree performance.

1. Introduction

Organic apple production is becoming increasingly popular as it is not as reliant on inorganic fertilizers and synthetic pesticides and can bring price premiums for growers. Instead, organic apple production uses compost and other organic fertilizers to supply nutrients to trees. These organic sources are often more expensive (Granatstein and Mullinix, 2008), and release nitrogen (N) slowly, which can result in poor yields and low leaf and fruit tissue N levels (Delate *et al.*, 2008). Improving organic fertilizer-use efficiency is critical to increasing cost efficiency in organic apple production. Integrating organic mulches and cover crops into apple production systems has been proposed as a means to improve yields, nutrient availability and long-term sustainability.

Organic mulches, cover crops and organic fertilizers such as compost, add large amounts of organic carbon (OC) to the soil. Decomposition and nutrient release from these additions can increase soil N, C, and microbial biomass and change the composition of the soil microbial community (Laakso *et al.*, 2000; Wardle *et al.*, 2001). However, studies of organic mulches and cover crops in fruit production have returned both positive and negative results. Sanchez *et al.* (2003) and Hoagland *et al.* (2008a) reported increased soil N availability and a more active soil microbial community using both legume and non-legume cover crops. However, Marsh *et al.* (1996) observed that non-legume cover crops reduced fruit yield and tree growth compared to leguminous cover crops. In these and other studies improved soil quality did not translate into increased tree growth or yield, likely because of competition between trees and cover crops (Neilsen and Hogue, 1985; Sanchez *et al.*, 2003; Hoagland *et al.*, 2008a). Forge *et al.* (2003) and Yao *et al.* (2005) reported that organic mulches such as wood chips, shredded paper and alfalfa increased soil microbial activity and N turnover, increasing N availability and fertilizer-use efficiency. Conversely, Larsson *et al.* (1997) reported that N was immobilized in wood chip mulch resulting in N deficiency, despite high levels of N fertilization. Brassica seed meals are another possible soil amendment which may serve as an organic source of N (Balesh et al., 2005), a biological control for pathogens (Cohen and Mazzola, 2006) and a biological control of weeds (Hoagland *et al.*, 2008b)

Using herbicides to maintain bare ground in tree rows is the most common practice in conventional apple production; however lower soil N and C content have been reported in these conventional systems compared to systems using organic mulches and cover crops (Sanchez *et al.*, 2003). Likewise, cultivation, the most common practice in organic production, can have detrimental effects on soil N, C and the soil microbial community, reducing soil quality and nutrient availability (Cambardella and Elliot, 1992; Sanchez *et al.*, 2007; Van Den Bossche *et al.*, 2009). Soil disturbance also reduces earthworm populations and root colonization by arbuscular-mycorrhizal (AM) fungi (Bohlen *et al.*, 1999; Boddington and Dodd, 2000). Both earthworms and AM fungi have been shown to improve soil quality and nutrient cycling. Earthworms improve incorporation of surface litter, increase soil organic N levels and N mineralization and can alter the soil microbial community structure (Aira *et al.*, 2008; Beare, 1997). Arbuscular-mycorrhiz fungi play a critical role in nutrient cycling in the soil, assist in nutrient uptake, aid in decomposition of recalcitrant organic residues and improve soil structure through increased aggregate stability (Barea *et al.*, 2005).

In cultivation and herbicide strip systems, often the only additions of OC are senescent leaves and organic fertilizers such as compost, and larger applications of these fertilizers may be needed to achieve soil quality benefits. Bhogal *et al.* (2009) and Gopinath *et al.* (2008) observed increased crop yields and soil quality improvements as manure and compost additions increased. Whalen *et al.* (2008) reported that soil microbial biomass C, organic C, total N and NO_3^- in soil did not increase compared to soils fertilized with inorganic fertilizer at 5 or 10 Mg ha^{-1} of compost, but did increase with 15 Mg ha^{-1} of compost. Reganold *et al.* (2001) showed higher soil quality ratings and similar yields in organic compared to conventional apple production systems, largely owing to the addition of compost and mulch in the organic system.

In this study we wanted to examine how several ground cover management strategies and compost rates interact to supply N to apple trees. However, accurately estimating soil N supply is difficult, and many methods have been proposed (Jalil et al., 1996; Sharifi et al., 2007a; Sharifi et al., 2007b). In this study, measuring only soluble N (NO_3^- + NH_4^+) would not accurately reflect soil N supply because release of compost N is driven by soil microbial processes, and N is mineralized and immobilized by microorganisms simultaneously (Haynes, 2005). Long-term laboratory incubations measuring mineralized N could over-estimate N mineralization because ideal soil conditions are used and would at best represent the maximum potential N mineralization (Haynes, 2005; Robertson *et al.*, 1999). Nitrogen mineralized from a 14-day anaerobic incubation represents a readily available labile N pool that has been strongly correlated with soluble N (Sharifi et al., 2007a). The combination of soluble N and N mineralized from a short-term anaerobic incubation has been proposed as a good predictor of N supply (Sharifi et al., 2007b). In this study we used a modification (7-day incubation) of this latter method to estimate soil N supply. The objectives of this study are to examine the impact of ground cover management and compost rate on soil N supply, total N and C, soil biological activity and fruit yield and tree growth.

2. Materials and Methods

2.1 Study Site

This study was established in spring 2005 at the Wenatchee Valley College-Auvil Teaching and Demonstration Orchard in East Wenatchee, Washington, USA. Soil at the study site is a Pogue sandy loam (coarse-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Aridic Haploxerol), averaging 1-2% organic matter and a pH of 7.0. Annual rainfall at the orchard site averages 21.6 cm. The study site was previously planted to sweet cherry. After stump removal and disking, apple trees (cv. Pinata on EMLA 7 rootstock) were planted at a spacing of 1.5 m x 4 m (1541 trees per hectare). Plots were arranged in a completely randomized block design with 5 replicates of 13 treatments. Each plot consisted of a row of eight trees: six study trees with a guard tree at each end. Unfertilized control plots consisted of only 3 trees due to space constraints. Trees were irrigated as needed throughout the growing season with undertree microsprinklers (R-10 rotators, Nelson Irrigation, Walla Walla, WA)

2.2 Ground cover treatments

Ground cover treatments were established in a 1.5 m wide strip within the tree row, with a 2.5 m drive alley between rows planted to perennial grasses in 2005. Seven ground cover treatments were used (Table 4): 1) unfertilized control (CON), 2) bare ground (BG), 3) bare ground + brassica seed meal amendment (BSM), 4) mechanical cultivation (CLT), 5) wood chip mulch (WC), 6) legume cover crop (LC), and 7) non-legume cover crop (NLC). Bare ground was maintained in the CON, BG and BSM treatments with the combination of cutting weeds at ground level with a string trimmer (6-7 times), shallow hoeing (2-3 times), and Matran organic herbicide (20% solution, sprayed to wet leaves, 3 times) in 2005 and 2006. Due to difficulty controlling weeds with these methods, economic purposes and the planned removal of the orchard, weeds were controlled in 2007 by spot spraying with post-emergent glyphosate (1% solution). In all years, mechanical cultivation consisted of using a Wonder Weeder (Harris Manufacturing, Burbank WA) four times per season on the sides of the tree and rototilling between the trunks as needed, disturbing the upper 8-10 cm of soil. Wood chip mulch plots had a 15 cm layer of mixed conifer and deciduous wood chips (1.3 to 2.5 cm maximum dimension) applied in the spring of all years. In 2005 and 2006 weed escapes were hand pulled, and in 2007 glyphosate (1% solution) was spot sprayed as needed. Legume cover crop was established using a mix of Mt. Barker subterranean clover (*Trifolium subterranean*), black medic (*Medicago lupulina*), burr medic (*Medicago polymorpha*), birdsfoot trefoil (*Lotus corniculatus*), and Colonial bentgrass (*Argostis tenuis*). Non-legume cover crop was established using a mix of sweet alyssum (*Lobularia maritime*), five spot (*Nemophilia maculate*), mother of thyme (*Thymus serpyllum*), and Colonial bentgrass (*Argostis tenius*). The drive-alley, legume cover crop and non-legume cover crop were mowed as needed with clippings left on the ground.

2.3 Compost N amendments

Compost N was applied at low ($_L$), medium ($_M$) and high ($_H$) rates. The M rate was based on the optimum rate of N to meet tree needs of approximately 60 g N tree^{-1} (Fallahi and Mohan, 2000; Fallahi *et al.*, 2001), and was applied to the BG, CLT, WC, LC and NLC cover treatments.

Table 4. Ground cover management and compost rate

Treatment	Compost rate	Ground cover management
Control (CON)	None	Undisturbed bare ground, hand weeding and glyphosate
Bare ground (BG)	Medium	Undisturbed bare ground, hand weeding and glyphosate
Brassica seed meal (BSM)	Low	Undisturbed bare ground, hand weeding and glyphosate + 1,136 kg ha^{-1} *Sinapsis alba* seed meal each year
Cultivation (CLT)	Low, medium and high	Tilled bare ground, tilled 4x per season
Wood chip mulch (WC)	Medium and high	15 cm layer of mixed deciduous and coniferous wood chips applied each April
Legume cover crop (LC)	Low and medium	Mix of birdsfoot trefoil, Colonial bentgrass, Mt. Barker subterranean clover, black medic and burr medic
Non-legume cover crop (NLC)	Low, medium and high	Mix of sweet alyssum, five spot, mother of thyme and Colonial bentgrass

Due to space constraints the L rate was applied only to CLT, LC and NLC cover treatments, but not to WC because reduced N additions would likely result in N immobilization in the WC mulch (Larsson *et al.*, 1997). The H rate was applied to CLT, WC and NLC, but not to LC because increased N additions were presumed to have less influence on tree responses in the presence of a legume.

In spring 2005, pelleted chicken manure (NutriRich, Stutzman Farm, Canby, OR, USA; 4% N, 28% available in a 14-day anaerobic incubation) was broadcast in tree rows at 56, 111 and 166 kg total N ha^{-1} for the L, M and H rates, respectively, and incorporated prior to tree planting. Due to poor initial tree growth an additional 2.75 kg N ha^{-1} was applied equally to all treatments at weekly intervals starting in June and continuing throughout the summer as a foliar application of fish emulsion and kelp (Mermaids, I.F.M., Wenatchee, WA, USA; Acadian Seaplants, Dartmouth, Nova Scotia, Canada). A soluble N fertilizer of fermented plant and animal waste (Biolink, Westbridge Ag Products, Vista, CA, USA; 14% N) was also injected below each tree at 18, 36 or 54 kg N ha^{-1} in mid-July for the L, M and H rates, respectively.

In 2006, compost was applied in four split applications (April 7, May 9, May 25 and June 7); and in 2007 in three split applications (April 25, May 25 and June 21). Nielsen's chicken manure compost (Mossyrock, WA, USA; 3.5% N, 51% available in a 14-day anaerobic incubation) was spread around the base of each tree 15 to 30 cm from the trunk, at 48, 101 and 152 kg available N ha^{-1} $year^{-1}$ for the L, M and H rates, respectively. In 2006 and 2007 the BSM treatment was given a reduced rate of compost to allow for N release from seed meal, 62 kg available N ha^{-1} $year^{-1}$ compost. Seed meal derived from the yellow mustard *Sinapsis alba* cv. Ida Gold (J. Brown, University of Idaho; 7% N) was broadcast over BSM plots at a rate of 1,136 kg ha^{-1}, once in May 2005, three times in 2006 (May, June and July) and three times in 2007 (April, May and June). BSM was incorporated into the shallow at a shallow depth in May 2005, May 2006 and June 2006. In July 2006 and all 2007 applications, BSM was left on the surface.

2.4 Sampling and analysis

Each year soil samples were collected in April (prior to compost application), July and September by taking one core per tree with a 2 cm diameter probe (0-10 cm depth), 15-30 cm from the base of each tree and composited into one sample per plot. Additional soil cores (15 cm diameter, 0-10 cm depth), specifically for earthworm population density and AM fungi root colonization were taken from 3 trees per plot in September 2007. April and July soil samples were oven dried at 105°C for 24 hours and then passed through a 2 mm sieve. September samples were passed through a 2 mm sieve and stored at 4°C until analysis. Soils from all sampling dates were analyzed for soluble N (ammonium + nitrate) and readily mineralizable N (RMN). Soil samples were mixed with deionized water at 1:2.5 (w/v) and incubated at 40°C for 7 days (Schmidt and Belser, 1994). Nitrate and ammonium concentrations in both initial and incubated samples were determined following extraction with 1 M KCl using a continuous-flow colorimetric analyzer (Alpkem, OR, USA). Readily mineralizable N was calculated by subtracting the initial amount of available N from that present after incubation.

September soil samples were analyzed for total N and C using a dry combustion analyzer (Costech, CA, USA) in 2005 and 2007. September samples in 2007 were also analyzed for dehydrogenase activity (Tabatabai 1994), C mineralization (Robertson *et al*., 1999; Collins *et al.*, 2000), and microbial biomass measured by substrate induced respiration (SIR) (Anderson and Domsch, 1978). The 15 cm soil core samples were hand sorted to determine earthworm population density. Apple tree roots recovered from soil cores were cleared, dyed (0.4% Trypan blue solution) and AM fungi root colonization was quantified using the grid-line intersect method (Reich and Barnard, 1984).

In 2007, fruit were thinned to 5 fruit per cm^2 trunk cross sectional area (TCSA) in June. In July, four leaves were sampled from the middle third of each sample tree, composited by plot, oven-dried at 50 °C for 48 hours, ground and analyzed for N concentration using a dry combustion analyzer. In September, TCSA was calculated from tree circumference measurements taken 20 cm above the graft union, and fruit were harvested.

2.5 Statistical analysis

Statistical analyses were conducted using SAS 9.1 software (SAS Institute, Cary, NC, USA). Ground cover management and compost rate effects on soil N supply, total N and C, soil biology and tree performance were analyzed with one-factor analysis of variance of a completely randomized block design. Mean separation was based upon Fisher Protected LSD and differences were considered significant at $P \leq 0.05$.

3. Results and Discussion

3.1 N Supply

In this study the majority of soluble N was NO_3^- (data not shown). Total soil N supply was primarily in readily mineralizable forms in April of all years (Figure 8). The proportion of N supply as soluble N increased in July and September of every year as temperatures increased, adequate soil moisture content was maintained through irrigation (Zhang et al., 2008) and compost N was applied, increasing N mineralization.

In 2005, neither ground cover treatment nor compost rate significantly affected N supply (Figure 8A). Nitrogen supply decreased in most treatments from April to July, and increased in all treatments from July to September. It appears that tree N uptake and slow release of N from pelleted chicken manure compost reduced N supply in mid-summer. An organic soluble N product was injected into the root zone during the summer and increased September soil N supply. The bulk of September N supply was soluble N, and because the majority of soluble N was NO_3^- and not NH_4^+, was therefore susceptible to leaching and denitrification over the winter, reducing N supply the following spring.

In 2006, N supply increased in all treatments from April to July, then decreased in most treatments in September (Figure 8B). Improved microbial activity has been shown to increase N retention in apple orchards (Sanchez *et al.*, 2003; Yao *et al.*, 2005), and the increased soil C at this site (Hoagland *et al.*, 2008a) may have improved N retention over the winter, resulting in greater N supply in April 2007 (Figure 8C). Neilsens chicken manure compost was used in 2006 and 2007 and was more available (51%) than the Stutzman pelleted chicken manure compost used in 2005 (28%); Neilsens compost may have released N into soil more quickly, causing the larger fluctuations in N supply observed in 2006 and 2007. Also, N release from compost is long-term. In years two and three N was released not only from that year's compost, but from previous year's compost as well. We only sampled to a depth of 10 cm in this study; therefore the decreased soil N supply in September 2006 and July and September 2007 may reflect N leaching below our sampling depth, but this N may have remained available to apple trees. Otherwise, different climatic conditions across years may have affected N mineralization rates at the orchard site.

Soil N supply was influenced by both ground cover management and compost rate in 2006 and 2007. In July and September 2006, BSM and LC_M had significantly greater N supply than CON, WC_H and WC_M. In April 2007, N supply was elevated in NLC_H, BSM, CLT_H, NLC_M and LC_M compared to BG_M, CLT_L, CLT_M, WC_H and LC_L. In September 2007, N supply was greater in NLC_H, CLT_H and WC_H, than CON, CLT_L, BSM, CLT_M and NLC_L.

Total N and C content in soils were affected more by the compost rate than by ground cover management (Table 4). Total 2007 N and C content was greatest in NLC_H, CLT_H, WC_H

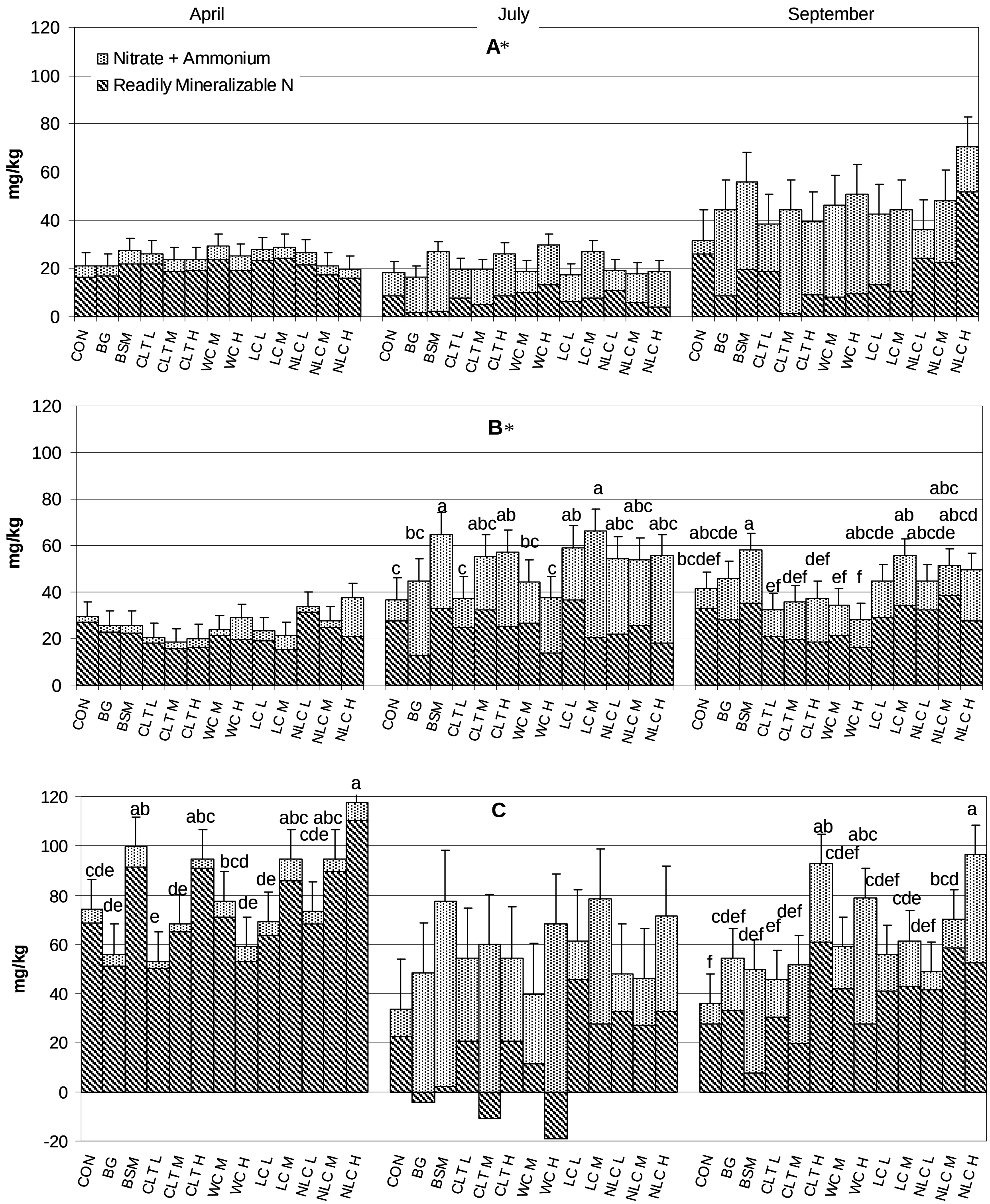

Figure 6. Soil N supply, mineral N + readily mineralizable N, in April, July and September of A) 2005 B) 2006 and C) 2007. Mean ± SE (n=5). Means within each year and month with the same letter or no letter are not significantly different (P ≤ 0.05).
*Soil N supply data from 2005 and 2006 courtesy of Hoagland (2007).

and WC_M, and corresponded with large increases in total N and C from 2005 to 2007. In this study, compost N was applied near tree trunks and soil samples were taken beneath the compost, therefore N and C increases are localized to the site of compost application.

Brassica seed meals have been reported as a readily mineralizable N amendment (Balesh *et al.*, 2005) that increases the nitrifying bacterial population in soils (Cohen and Mazzola, 2006). In this study, N supply in BSM was consistently elevated, except in September 2007, but did not increase total N or C compared to CON or BG_M (Figure 6, Table 4). Consequently, differences in N supply reflect an increase in the proportion of total N that was readily available. The additional compost applied to BG_M compared to BSM did not increase N supply; to the contrary, N immobilization was observed in BG_M in July 2007.

We expected incorporation of compost into the soil with cultivation to stimulate N mineralization, increasing N supply. At the low and medium compost rates, however, N supply and total N and C generally did not increase over CON. However, at the high compost rate total N and C increased significantly, and N supply was elevated in April and September 2007. Microbial turnover of N is often C-limited (Sanchez *et al.*, 2003), and lower compost rates may not have supplied enough C to the soil to stimulate N mineralization; evidence of this is the N immobilization observed in July 2007. These results are consistent with Whalen *et al*. (2008), who found that large amounts of compost were needed to increase soil NO_3^- and total N.

Organic mulches and cover crops add large amounts of OC to soils, stimulating soil microbial processes (Wardle *et al.*, 2001). In this experiment OC additions were wood chip mulch once per year, compost three times per year, periodic mowed plant litter and constant root turnover and exudates. Addition of wood chips increased total soil N and C, with larger increases at the high compost rate (Table 4). However, WC treatments also had the largest soil

Table 5. Soil total N and C, C/N ratio in 2007 and percent N and C increase from September 2005 to September 2007. Values within a column followed by the same letter are not significantly different ($P \leq 0.05$).

Treatment	Rate	N (mg/kg^{-1})	C (mg/kg^{-1})	C:N	N inc. (%)	C inc. (%)
Control (CON)	N	1021 d	9808 d	9.6 def	20 d	-7 c
Bare ground (BG)	M	1289 cd	11879 d	9.2 defg	77 bc	24 ab
Brassica (BSM)	M	1375 cd	12132 d	8.9 efg	54 cd	10 ab
Cultivation (CLT)	L	1068 d	9956 d	9.4 def	55 cd	11 b
	M	1481 cd	12642 d	8.6 g	115 abc	42 ab
	H	2137 ab	18593 bd	8.8 fg	180 ab	80 ab
Wood chips (WC)	M	1674 bc	20058 ab	10.8 b	125 abc	104 ab
	H	2294 ab	25489 a	11.2 a	131 abc	99 ab
Legume Cover (LC)	L	1198 cd	11935 d	9.6 cd	97 bc	46 ab
	M	1382 cd	13166 cd	9.5 def	51 cd	8 b
Non-legume Cover (NLC)	L	1182 cd	12418 d	10.5 bc	54 cd	17 b
	M	1417 cd	13535 cd	9.6 de	79 bcd	30 ab
	H	2415 a	22080 ab	9.2 efg	225 a	123 a

C:N ratio and soil N supply was generally low, suggesting that a significant portion of soil N may have been immobilized. Compost N may also have been retained in the wood chip layer before N could leach into the soil or was transported from soil to the wood chip layer via fungal hyphae (Larsson *et al.*, 1997). Additional N may have been lost as organic mulches create favorable conditions for N leaching and denitrifcation by increasing soil water content (Hoagland *et al.*, 2008a; Larsson *et al.*, 1997; Sanchez *et al.*, 2003). Nitrogen supply between LC and NLC treatments did not differ significantly, but increased with compost rate in 2007. Total N and C in the treatments receiving the low and medium compost rates did not differ, and were significantly lower than NLC_H, which had increases in total N and C of 225% and 123%, respectively. LC_M increased N supply over CON and both WC treatments in 2006, but not in 2007. It appears that in 2006 N fixation by the legume species may have increased N supply, but may have been out-competed by grasses in 2007, reducing its impact on soil N supply.

3.2 Soil Biological Responses

Wood chip mulch and brassica seed meal were favorable substrates for earthworms, yielding the highest earthworm densities of 430 and 355 m^{-2}, respectively, compared to the other ground cover treatments (Table 5). Cultivation had a relatively low earthworm density, consistent with other studies (Beare, 1997; Parmelee *et al.*, 1990) both cultivation and herbicide use reduced surface residue, reducing substrate for earthworms in CLT, BG and CON. However, earthworm densities in CLT and BG treatments were significantly greater than NLC, despite a layer of thatch in cover crop treatments. Moisture competition between apple trees and cover crops may have created drier soil conditions reducing earthworm activity. This is supported by Parmalee *et al.* (1990), who observed reduced earthworm populations under drought conditions. Differences in litter quality may have also affected earthworm populations. In a study examining earthworm responses to different surface litters, Bohlen *et al.* (1999), reported that earthworm activity decreased when using rye litter compared to cow manure. Earthworm activity can enhance incorporation of surface litter and may have played a role in increasing total N and C in WC treatments (Beare, 1997).

The NLC treatment had the highest AM fungal root colonization, 36%, significantly higher than all other treatments. Control also had high AM fungi colonization, 21.9%, significantly greater then both the CLT (7.2%) and BSM (5.6%) treatments. Soil disturbance has been reported to negatively affect root colonization by AM fungi (Boddington and Dodd, 2000).

Table 6. Soil biological responses to ground cover management, only the M rates of CLT, WC, LC and NLC were evaluated. Values within a column followed by the same letter are not significantly different ($P \leq 0.05$).

Treatment	Earthworms (#/m^2)	AM fungi root infection (%)	SIR (μg C g $soil^{-1}$)	Dehydrogenase μg TPF/hour
Control (CON)	26 cd	21.9 b	1936 b	2.63 a
Bare ground (BG)	102 bc	14.2 bc	1962 b	4.43 a
Brassica (BSM)	355 a	5.6 c	1947 b	2.37 a
Cultivation (CLT)	143 b	7.2 c	1999 b	2.29 a
Wood chip (WC)	430 a	13.4 bc	1945 b	5.84 a
Legume cover (LC)	45 bcd	11.5 bc	2089 a	5.02 a
Non-legume cover (NLC)	11 d	36.0 a	2123 a	5.72 a

Modifications to the soil microbial community by brassica seed meal (Cohen and Mazzola, 2005) may have inhibited AM fungi root colonization. Arbuscular-mycorrhizal fungi can aid the decomposition of organic matter (Atul-Nayyer *et al.*, 2009) and transfer of N from legume to non-legume species (Frey and Schuepp, 1993), but in this study low root colonization in LC makes it difficult to determine if root infection by AM fungi had any effect on plant growth.

Microbial biomass, as measured by SIR, was greatest in the LC and NLC treatments compared to all other treatments, which were similar, but there were no significant differences in dehydrogenase activity among treatments (data not shown). WC had significantly greater cumulative CO_2 respiration than BSM and CON, and CLT had greater cumulative respiration than CON (Figure 9), suggesting that the labile C pool was largest in WC and CLT treatments (Collins et al., 2000). Although there were not elevated levels of microbial biomass in WC there was an increase in labile C. Wood chip mulch may favor specific species of fungi that break down lignin and other polyphenols (Yao *et al.*, 2005), which may not be responsive to glucose. Otherwise, low N supply observed in the WC treatments may have reduced potential microbial activity. Increased microbial biomass in LC and NLC may have increased N mineralization and was likely caused by constant inputs of plant litter and root turnover and exudates as sources of C (Wardle *et al.*, 2001). Reduced OC inputs in the CON, BG, BSM and CLT treatments reduced microbial biomass and labile C. Soil biological responses reported here reflect the addition of the medium compost rate and may have been changed with different compost rate.

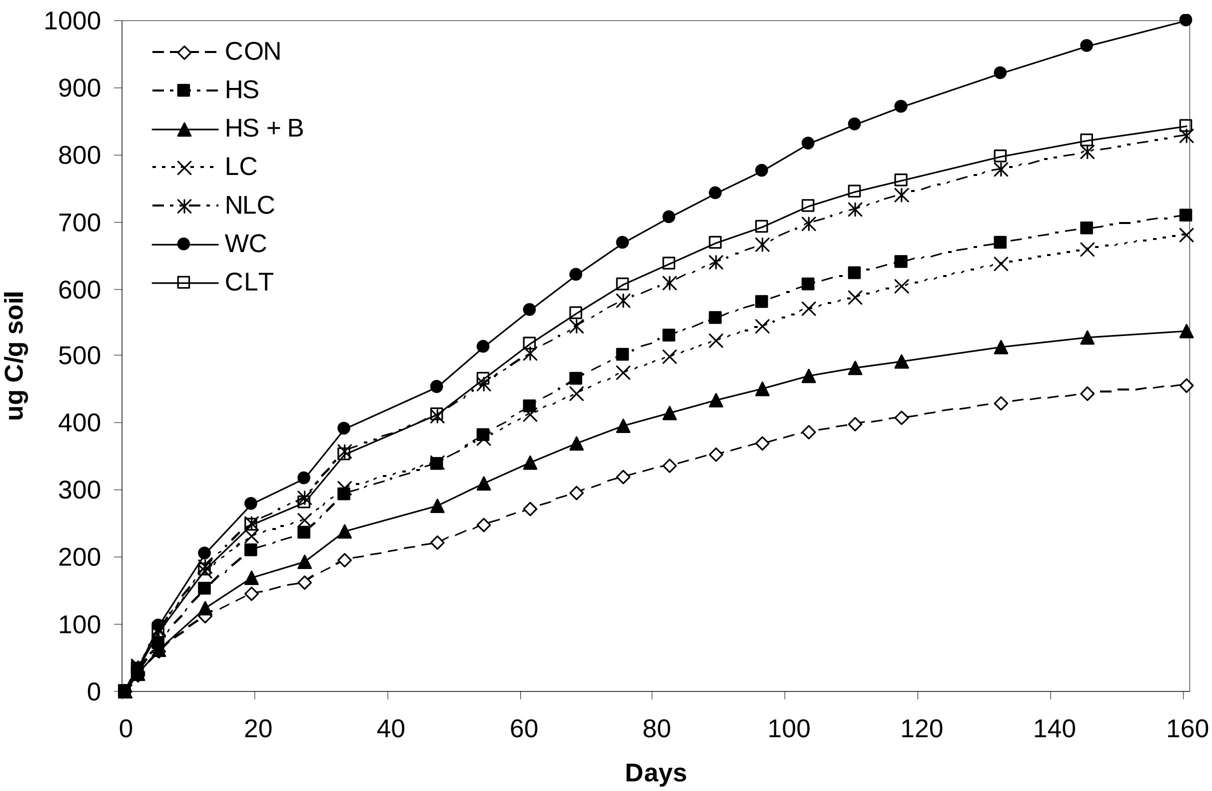

Figure 7. Cumulative CO_2 evolution during laboratory incubation

3.3 Tree Responses

Fruit yields were greatest in CLT_H and WC_H among all treatments (Table 6), significantly greater than CLT_M, BG_M and BSM, which in turn were significantly greater than CON and LC and NLC treatments, regardless of compost rate. WC_M, WC_H, CLT_H, and CLT_L treatments had larger TCSA than CON and all LC and NLC treatments, and BG_M and CON had significantly larger TCSA than LC_M and NLC_L. BG_M, BSM, and all CLT and WC treatments had significantly better yield efficiencies than LC and NLC treatments, which had better yield efficiencies than CON. Leaf N was adequate for young fruit bearing apple trees regardless of treatment (Stiles, 1994), but was lowest in CON, NLC_L and NLC_M treatments.

Elevated N supply in BSM did not translate into improved yield or tree growth compared to BG, CLT or WC treatments. Lack of alternative sinks for N in CLT treatments may have increased tree N uptake, significantly increasing yields and tree growth at all compost rates compared to cover crop treatments, despite reduced N supply in CLT_L and CLT_M. Increased N supply in CLT_H significantly increased fruit yields over CLT_L and CLT_M treatments, but increased risk of N leaching losses. Immobilization of N in the wood chip layer and consequently low soil N supply did not negatively affect tree growth, yield or leaf N. Decomposing wood chips may have acted as both a sink and a source of N, as tree roots were observed growing into the wood chip layer. Both LC and NLC trees yielded lower than other ground cover treatments, regardless of compost rate. Tree growth and yield between LC and NLC treatments were not significantly affected at the low or medium compost rate, but LC_M had significantly greater leaf N concentration. NLC responded to the improved soil N supply and total N and C that was observed at the H compost rate with significantly greater leaf N than at L

Table 7. Apple tree performance in 2007. Values within a column followed by the same letter are not significantly different (P ≤ 0.05).

Treatment	Rate	Fruit yield (kg/tree)	TCSA (cm^2)	Yield efficiency (kg/cm^2)	Leaf N (%)
Control (CON)	N	2.6 e	16.6 cde	0.14 h	2.87 cde
Bare ground (BG)	M	13.1 c	16.6 cde	0.80 abc	3.00 abc
Brassica (BSM)	M	12.4 c	17.7 bcd	0.73 abcd	3.13 a
Cultivation (CLT)	L	13.8 bc	20.3 ab	0.69 cde	2.98 abc
	M	13.3 c	15.8 def	0.87 a	3.07 ab
	H	17.6 a	21.5 a	0.84 abc	3.10 a
Wood chip (WC)	M	14.1 bc	20.6 ab	0.69 bcd	3.09 a
	H	16.5 ab	20.0 abc	0.85 ab	3.04 abc
Legume cover (LC)	L	5.7 d	13.6 efg	0.43 fg	2.91 bcd
	M	6.7 d	12.7 fg	0.52 ef	3.08 ab
Non-legume cover (NLC)	L	2.9 de	11.5 g	0.27 gh	2.77 de
	M	6.0 d	14.0 efg	0.41 fg	2.73 e
	H	8.0 d	14.9 defg	0.60 de	3.01 abc

or M rates. It appears that NLC_L and NLC_M treatments were N deficient, affecting not only the apple trees, but also the cover crops. N deficiency can reduce cover crop growth, reducing the supply of plant litter, root turnover and exudates to the soil, further limiting N mineralization. Moisture and root spatial competition between cover crops and fruit trees likely decreased tree growth and fruit yield in LC and NLC treatments, which has also been reported in other studies (Hoagland et al., 2008a; Sanchez et al., 2003).

Table 8. Summary of soil and tree performance. L = low, M = medium, and H = high.

Treatment	Rate	Soil N supply	Total N & C	Soil Biology	Tree growth	Fruit Yield	Overall Performance
Control (CON)	N	L	L	L	M	L	L
Bare ground (BG)	M	L	L	M	M	M	M
Brassica (BSM)	L	H	L	M	M	M	M
Cultivation	L	L	L		H	M	M/L
(CLT)	M	M	L	L	M	M	M
	H	H	H		H	H	H
Wood chip mulch	M	L	M	H	H	M	H/M
(WC)	H	L	H		H	H	H
Legume cover	L	M	L		L	L	L
(LC)	M	H	L	M	L	L	L
Non-legume	L	L	L		L	L	L
cover (NLC)	M	M	L	H	L	L	L
	H	H	H		L	L	M

3.4 Overall tree and soil performance

The high compost rate increased overall tree and soil performance in CLT, WC and NLC treatments (Table 8), with CLT_H and WC_H having the best over all performance. Maintaining bare ground or bare ground + BSM increased performance over CON, but these treatments did not perform as well as WC_M, WC_H or CLT_H. The CLT treatments were affected by compost rate with soil N supply and overall performance increasing with compost rate. Compost rate did not affect the performance of LC treatments, whereas there was an increase in NLC performance at the high compost rate. WC treatments performed better than other treatments despite reduced soil N supply.

In this study increasing the compost rate often increased soil N supply and total soil N and C. However, both economical and environmental impacts need to be considered when examining the long-term sustainability of each management system. Increasing the rate of compost application increases fertilizer costs and more soluble soil N may have negative environmental consequences if N leaching increases. It might be more sustainable if the objectives of ground cover management were as follows: to reduce compost applications, decreasing costs; to avoid environmental degradation; and to improve soil quality while enhancing tree performance. Using these criteria the WC_M treatment appears to be the best strategy of those we examined.

4. Conclusions

Ground cover management had significant impacts on soil N supply, total N and C, soil biology, tree growth and fruit yield. However, soil N supply was not significantly affected by ground cover treatment or compost rate until the second and third years of the study. Large compost additions significantly increased N supply in cultivation and non-legume cover treatments, but did not affect wood chip mulch. Brassica seed meal increased soil N supply and earthworm density, but did not affect tree growth or yield compared to BG_M. Cultivation with large compost additions resulted in the greatest fruit yield and elevated soil N. However, cultivation reduced earthworm population, AM fungi root colonization and soil biological activity, negatively impacting the long-term sustainability of this system. The use of cover crops improved soil N supply and biological activity but competition between apple trees and cover crops severely reduced tree growth and yield. Wood chip mulch improved total soil N, C, labile C and earthworm density, increasing tree performance despite lower soil N supply, and appears to be the best system overall, of those studied.

CHAPTER 4

CONCLUSIONS

Ground cover management and compost rate influenced soil biology and soil N and C pools, affecting tree performance. Ground cover management had significant impact on soil N supply, total N and C, soil biology, tree growth and fruit yield. However, soil N supply was not significantly affected by ground cover treatment or compost rate until the second and third years of the study.

Nitrogen reserves and compost application timing played important roles in fruit and vegetative growth and partitioning of compost N to tree components. Fruit and leaves were strong sinks for N early in the summer, but as the season progresses N was preferentially allocated in woody tissues, roots, frame and new growth, bolstering N reserves.

Brassica seed meal increased soil N supply and earthworm density, but did not affect total soil N and C or tree performance compared to BG_M. However BSM and BG_M trees performed better than LC and NLC trees, despite BG_M having low soil biological activity and N supply. Legume cover crop and non-legume cover crop treatments increased soil N supply and microbial activity, but had poor tree growth and fruit yield. In the LC treatment compost N accounted for 20-100% of cover crop biomass N and competition between trees and cover crops reduced N accumulation and compost N-use efficiency.

Greater vegetative growth in WC increased the N storage capacity of WC trees compared to CLT and LC trees, allowing for larger N reserves with the potential to increase spring leaf and fruit growth. Wood chip mulch, regardless of compost rate, also increased fruit yield compared to LC, NLC and CON. Nitrogen immobilization in WC appears to have reduced soil N supply, but did not reduce compost N-use efficiency in WC, which was greater than LC. Wood chip mulch also positively impacted soil quality by improving total soil N, C, labile C and earthworm activity. As the orchard matures, however, overly vigorous tree growth could increase orchard management costs through increased pruning and added difficulty in training limbs to leaders. At which point it may be necessary to compliment WC with other management strategies such as deficit irrigation, reduced N applications, altering compost application timing or switching to a ground cover strategy to reduce vegetative growth.

Cultivation trees partitioned a larger percentage of dry weight and N into fruit compared to other treatments, resulting in high fruit yields despite reduced vegetative growth. Trees under CLT also had high compost N-use efficiency, largely due to increased dependence on compost for N compared to WC trees. Cultivation reduced earthworm populations, AM fungi root colonization and soil biological activity, negatively impacting the long-term sustainability of this system. However, at the high compost rate CLT had the greatest fruit yield and elevated soil N.

Increasing the rate of compost application increases fertilizer costs and more soluble soil N may have negative environmental consequences if N leaching increases, reducing the long-term sustainability at the high compost. It might be more sustainable if the objectives of ground cover management were as follows: to reduce compost applications, decreasing costs; to avoid environmental degradation; and to improve soil quality while enhancing tree performance. Using these criteria the WC_M treatment appears to be the best strategy of those we examined.

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