Biol Fertil Soils (2008) 45:11–18
DOI 10.1007/s00374-008-0304-4

ORIGINAL PAPER

Orchard floor management effects on nitrogen fertility and soil biological activity in a newly established organic apple orchard

L. Hoagland · L. Carpenter-Boggs · D. Granatstein · M. Mazzola · J. Smith · F. Peryea · J. P. Reganold

Received: 1 October 2007 / Revised: 15 May 2008 / Accepted: 16 May 2008 / Published online: 11 June 2008

Abstract This study addresses the often-competing goals of organic fertility and weed control by evaluating alternative orchard floor management strategies for their impact on N cycling, tree performance, and soil biological activity in a newly established apple (*Malus domestica* Borkh.) orchard. The standard tillage weed control practice resulted in satisfactory tree growth with desirable levels of leaf N and most other nutrients; however, soil biological activity did not improve. Maintenance of a living cover understory increased soil N concentration and availability and improved soil biological activity; however, tree growth was less than in other treatments likely in response to competition with the living cover understory for space and water. Application of wood chip mulch resulted in exceptional tree growth which may have resulted from greater water availability, but available soil N was lower, and consequently, tree leaf N concentration was low; in addition, soil biological activity was not improved. Clove oil organic herbicide provided poor weed control resulting in lower leaf N and tree growth and did not improve soil biological activity. Brassicaceae seed meal applications enhanced N availability and soil nematode abundance, but leaf N and many other nutrients were below desirable levels, and additional research is needed to optimize this treatment. We conclude that meeting the multiple objectives of weed control, optimal tree health, and increased soil biological activity may require employment of different orchard floor management strategies at different times during the life of the orchard.

Keywords Living cover mulch · Wood chip mulch · Organic herbicide · Brassicaceae seed meal

L. Hoagland (✉) · J. P. Reganold
Department of Crop and Soil Sciences,
Washington State University,
385 Johnson Hall, P.O. Box 646420, Pullman,
WA 99164-6420, USA
e-mail: lori_hoagland@wsu.edu

L. Carpenter-Boggs · D. Granatstein
Center for Sustaining Agriculture and Natural Resources,
Washington State University,
Pullman, WA, USA

M. Mazzola
USDA-ARS Tree Fruit Research Laboratory,
Wenatchee, WA, USA

J. Smith
USDA-ARS Land Management and Water Conservation,
Pullman, WA, USA

F. Peryea
Tree Fruit Research and Extension Center,
Washington State University,
Wenatchee, WA, USA

Introduction

A significant impediment to establishment and maintenance of economically viable organic orchards is lack of sustainable methods for managing nitrogen (N) fertility and weeds. Organic tree fruit producers generally rely on complex organic materials such as composted animal manures to supply N. Only a fraction of the nutrients in these amendments is in readily available form with the remainder released slowly through decomposition and mineralization mediated by soil faunal communities (Laakso et al. 2000). High rates of organic N fertilizers often are applied in order to meet tree N needs, but large applications of organic fertilizers with high electrical conductivity (EC) can result in excessive levels of salts other than nitrates in soil. Soil salinization resulting from substantial and continuing compost applications can lead to N depletion, impaired nutrient cycling, and reduced crop production (Stamatiadis et al. 1999). Organic fertilizers with high N solubility and therefore more predictable behavior are available, but these are considerably more expensive. In addition, if nutrient availability and uptake are not synchronized, nitrate N is subject to leaching (Wagger et al. 1998; Stork and Jerie 2003). Organic practices are needed that will reduce N fertility inputs, synchronize mineralization and available soil N during critical tree uptake periods, and mitigate N loss.

Inability to control weeds also can be a serious impediment to organic tree fruit production. In the absence of reliable herbicides approved for use in organic systems, orchard managers often control weeds with intensive cultivation. This practice can degrade soil structure (Six et al. 1998), disrupt soil faunal communities (Fiscus and Neher 2002), and accelerate nutrient cycling and organic matter loss (Cambardella and Elliott 1993). These consequences are of particular concern as national standards dictate that production must "maintain or improve soil health" (USDA-NOP 2001) to maintain organic certification.

Weed management practices that reduce mechanical disturbance of orchard soils and groundcovers may ameliorate negative impacts on soil quality and enhance N availability. Such weed control practices include application of organically approved herbicides (Tworkoski 2002; Boyd and Brennan 2006), mulching with wood chips (Oliveira and Merwin 2001), maintenance of a vegetative cover or "living mulch" (Marsh et al. 1996; Sanchez et al. 2003; Sánchez et al. 2006), and soil amendment with Brassicaceae seed meal (BSM; Balesh et al. 2005).

To address the need for sustainable methods of N fertility and reduced-disturbance weed control in organic fruit production, we conducted studies to assess the effects of different organic amendments and weed management strategies on N cycling, apple tree nutrition, and soil biological activity. Because young trees are more sensitive to N and weed management practices, we chose to conduct the study in a newly established orchard.

Materials and methods

Study site

The study was established in spring 2005 in an orchard previously planted to sweet cherry (*Prunus avium* L.) at the Wenatchee Valley College-Auvil Teaching and Demonstration orchard in East Wenatchee, Washington. Soil at the site is Pogue sandy loam (coarse–loamy over sandy or sandy–skeletal, mixed, mesic Aridic Haploxerol), averaging 1–2% organic matter and pH 7.0. Annual rainfall averages 21.6 cm. Following stump removal and disking, apple trees (cv. Piñata on M7 rootstock) were planted at a spacing of 1.5 m within row and 4 m between rows (1,541 trees per hectare). Individual plots were arranged in a completely randomized block design with five replicates. Each plot consisted of eight trees; only the interior six trees were used for measurements.

Orchard floor treatments and N amendments

Orchard floor management treatments were applied in a 1.5-m strip centered on the tree row. Drive rows were 2.5 m wide and were planted with a perennial grass cover. Orchard floor management treatments included the following: control (CON), mechanical cultivation (CLT), living mulch legume (LML), living mulch non-legume (LMNL), sandwich legume (SWL), sandwich non-legume (SWNL), clove oil herbicide (CHE), Brassicaceae seed meal herbicide (BHE), and wood chip mulch (WC). The LMNL and CLT treatments were evaluated under low (0.5×), medium (1×), and high (1.5×) N rate, LML under low and medium N rate, WC under medium and high N rate, CHE, BHE, SWL, and SWNL under medium N rate, and CON received no nutrient inputs. In living mulch treatments, the entire 150-cm-wide tree rows were planted to a mix of broadleaf and grass species. In sandwich treatments, vegetation was limited to the central 45 cm of the tree row with flanking 52.5-cm tilled strips on each side. LML and SWL treatments included a mix of Mt. Barker subclover (*Trifolium subulata*), black medic (*Medicago lupulina), burr medic (Medicago polymorpha), birdsfoot trefoil (Lotus corniculatus), and bentgrass (Argostis tenuis). LMNL treatment contained a mix of sweet alyssum (Lobularia maritime), five spot (Nemophila maculata), mother of thyme (Thymus serpyllum), and bentgrass. SWNL was transplanted with an alternating sweet woodruff (Galium odoratum) and Corsican mint (Mentha requiennii).*

In cultivated and sandwich treatments, soil tillage was performed using a Wonder weeder implement, as needed for weed control. The Wonder Weeder is a ground-driven rolling cultivator with a spring blade that works in between trees.

A clove oil-based herbicide (Matran, Ecosmart Technologies, Franklin, TN, USA) was diluted (60 ml l^{-1}) and applied to CHE plots as needed using a backpack sprayer at a nominal rate of 230–306 l ha^{-1}. Seed meal derived from the yellow mustard *Sinapis alba* cv. Ida Gold (J. Brown, University of Idaho; 6.84% N) was broadcast over BHE plots at a rate of 1,136 kg ha^{-1}, once in May 2005 and in May, June, and July 2006. All BSM amendments were incorporated into soil at a shallow depth except the final application in 2006, which was left on the soil surface. In WC plots, a mix of conifer and deciduous wood chips (1.3 to 2.5 cm maximum dimension) was surface-applied each spring. The wood chips were applied to the tree row (1.2–1.5 m width) to a depth of 15 cm and mixed in autumn using the Wonder Weeder cultivator.

In spring 2005, pelleted chicken manure (NutriRich, Stutzman Farm, Canby, OR, USA; 4% N, pH 7.0, and 7.5 ms cm^{-1} EC) was broadcast in the tree row at a rate of 0.9 (0.5×), 1.8 (1×), or 2.7 (1.5×) kg per tree and mechanically incorporated using a rotovator prior to tree establishment. The 1× rate equaled 110.95 kg total N ha^{-1}. Because of poor initial tree growth, in mid-July, a soluble N fertilizer made from fermented plant and animal wastes (Biolink, Westbridge Ag Products, Vista, CA, USA; 14% N) was injected under each tree at a rate of 18 (0.5×), 36 (1×), or 54 (1.5×) kg total N ha^{-1}. Supplemental foliar applications of fish emulsion (Mermaids, I.F.M., Wenatchee, WA, USA) and kelp (Acadian Seaplants, Dartmouth, Nova Scotia, Canada) were applied at weekly intervals during summer to all trees at a rate of 2.75 kg total N ha^{-1}. Nitrogen fertilization rates were increased in 2006 and consisted of equal amounts of NutriRich and Nielsen's chicken manure compost (Mossyrock, WA, USA; 3.5% N, pH 8.1, and 3.7 ms cm^{-1} EC) with available N estimated at 28% and 51%, respectively. In 2006, the amendments were applied around the base of each tree in four equal split applications (April, early May, mid-May, June) for a total of 2.7 (0.5×), 5.4 (1×), and 8.1 (1.5×) kg per tree, resulting in approximately 101 kg available N ha^{-1} (1×).

Soil sampling and analyses

Composite soil samples were collected from each plot using a 2-cm diameter probe (0 to 10-cm depth) at approximately 15–30 cm from the base of each sample tree, pooled and stored at 4°C until analysis. Samples were collected annually in spring, mid-summer, and autumn. Soil was passed through a 2-mm sieve prior to analysis. Total carbon (C) and nitrogen (N) were determined for the initial spring and autumn collected samples using an automated dry combustion analyzer (LECO, St. Joseph, MI, USA). Separation of the particulate organic matter (POM) fraction was done following the method of Cambardella and Elliott (1993). Soil was shaken overnight with a solution of hexametaphosphate and passed through a 53-µm sieve. Material remaining on top of the sieve was oven dried at 50°C overnight, weighed, roller-ground, and analyzed for total C and N. To determine soluble N (ammonium +nitrate) and potentially mineralizable N (PMN), soil samples were mixed with deionized (DI) water [2.5=1 (*w/v*)] and anaerobically incubated at 40°C for 7 days (Drinkwater et al. 1996). Nitrate and ammonium concentrations in both initial and incubated samples were determined following extraction with 1 M KCl using a continuous-flow colorimetric analyzer. PMN was calculated by subtracting the initial amount of available N from that present after incubation.

Autumn soil samples were analyzed for dehydrogenase activity (Tabatabai 1994) and C mineralization (Robertson et al. 1999; Collins et al. 2000). Briefly, soil samples were incubated at 22°C in the dark and CO_2 produced was determined by gas chromatographic analysis at several time intervals. After each CO_2 measurement, soils were uncapped and flushed with humidified air and recapped.

Nematodes were extracted from 50 g subsamples of field-moist soil collected in summer, using a Baermann pan technique (7-day incubation; Ingham 1994), and counted under × 40 magnification.

Tree circumference and leaf sampling

In July 2005, each tree was permanently marked 20 cm above the graft union. Tree circumference was measured in July 2005, October 2005, and October 2006, and tree cross sectional area (TCSA) was calculated. In late July 2006, four leaves were sampled from the middle third of each of the six sample trees in each plot. The leaves were composited by plots, oven-dried at 50°C for 48 h, ground, and analyzed for N, P, K, Ca, Mg, S, Zn, B, Mn, Fe, Cu, Al, and Na concentration. Leaf N was determined by total Kjeldahl analysis and other mineral elements by dry-ashing followed by assay using inductively coupled plasma emission spectroscopy. Leaf tissue analytical data are reported on a dry-mass basis.

Release and partitioning of compost N

In 2006, compost amendments were enriched with ^{15}N (ammonium sulfate) and applied to the 1× LML, WC and CLT treatments to track N release from compost and its partitioning among orchard components. Chicken compost, pre-weighed for each sample tree, was spread on plastic and sprayed with 5.39 g of $(NH_4)_2SO4$ (~70A% ^{15}N, 0.8 g ^{15}N per tree) dissolved in 50 ml DI water 48 h prior to application. Within each plot, ^{15}N-labeled compost was applied to an individual tree during each of three compost applications (April 7, May 9, and June 7). Soil, wood chip, and plant residue samples were taken from around each sample tree at monthly intervals following application (May 9, June 7, July 13, and Sep 29). In all treatments, three soil samples were taken at approximately 15 cm from the base of each tree with a 2-cm diameter probe to a depth of 10 cm, pooled and dried at 50°C for 24 h. All dried samples were roller-ground and analyzed for ^{15}N using an isotope ratio mass spectrometer.

Statistical analyses

All statistical analyses were conducted with SAS 9.1 software (SAS Institute, Cary, NC, USA). Data generated were subjected to analysis of variance, and mean separation was based upon Fisher protected least significant difference. Fertility rates within each weed control treatment were compared for impact on soil N availability, tree growth, and leaf nutrient levels. Weed control treatments at the 1× level of fertility were evaluated in comparison to each other for impact on soil

Table 1 Effect of orchard floor management on soil inorganic N as measured throughout two growing seasons

Treatment	Sp[a] 2005 (mg kg^{-1})	Su 2005	Au 2005	Sp 2006	Su 2006	Au 2006
CON[b]	4.5 a	9.8 c	5.8 b	2.2 b	9.2 d	8.6 c
CLT	4.7 a	14.3 bc	42.9 a	2.5 b	22.9 bc	15.8 abc
LML	4.4 a	19.2 ab	33.7 ab	5.8 a	46.1 a	21.0 a
LMNL	3.9 a	12.0 bc	25.7 ab	3.0 b	28.0 bc	12.7 bc
CHE	3.9 a	14.1 bc	35.5 ab	3.0 b	31.8 b	17.9 ab
BHE	5.2 a	24.3 a	36.4 ab	3.2 b	31.9 b	22.7 a
WC	5.4 a	8.4 c	38.1 a	2.5 b	17.9 cd	12.8 bc

Means in the same column followed by the same letter are not significantly different ($P<0.05; n=5$).
[a] Sampling time designations: *Sp* spring, *Su* summer, *Au* autumn
[b] Treatment designations: *CON* control (0×), *CLT* cultivated (1×), *LML* living mulch legume (1×), *LMNL* living mulch non-legume (1×), *CHE* clove oil herbicide (1×), *BHE* Brassica herbicide (1×), *WC* wood chip mulch (1×)

biological activity. All analyses were considered significant at $P \leq 0.05$.

Results and discussion

Impact of orchard floor management on N availability and tree uptake

During orchard establishment, young trees require substantial amounts of plant available N (Ryugo 1988; Stiles 1994). Meeting this N requirement is difficult in organic systems because an unpredictable fraction of the total N in organic-based amendments is available for plant uptake during the current growing season. Cultivation of the orchard floor can help to enhance mineralization and availability of N from compost or other amendments, while simultaneously providing weed control. However, long-term soil cultivation in the tree understory can result in reduced soil N and organic matter, poor tree vigor, and reduced fruit-bearing potential (Sánchez et al. 2006). In our study, the standard weed control practice of soil cultivation successfully eliminated weed competition (Granatstein et al. 2007) and resulted in sufficient available soil N (Table 1), tree growth, and desirable levels of most leaf nutrients (Table 2) regardless of amendment rate. Despite greater soil N availability in the higher fertility rate treatments, there were no differences between tree growth or leaf N in the 0.5×, 1× or 1.5× treatments (data not shown) indicating that the trees' N needs were met at the low (0.5×) compost rate.

Maintenance of a vegetative cover, or "living mulch", can reduce nutrient loss by acting as a "catch crop," immobilizing and retaining available soil N, and/or contributing additional N via residue decomposition, if leguminous (Marsh et al. 1996; Sanchez et al. 2003; Stork and Jerie 2003; Yao et al. 2005). In addition, root exudates and decaying residues from cover crops contribute labile carbon compounds that stimulate microbial activity responsible for enhanced nutrient retention and cycling (Rovira et al. 1990; Wardle et al. 2001) and disease control (Forge et al. 2003; Gu and Mazzola 2003).

Table 2 Effect of orchard floor management treatments on the increase in Pinata/M7 trunk cross sectional area and tree leaf nutrient status in July 2006

Treatment	TCSA (%)	N (%)	P (%)	Ca (%)	Zn (mg kg^{-1})
CON[a]	142.21 e	2.08d	0.40 a	1.26 bc	9.47 a
CLT	286.28 ab	2.45 ab	0.21 b	1.27 bc	9.36 a
LML	180.84 de	2.55 a	0.24 b	1.43 a	10.37 a
LMNL	196.02 de	2.50 ab	0.24 b	1.37 ab	10.68 a
SWL	209.19 cd	2.33 abc	0.23 b	1.36 ab	10.18 a
SWNL	275.26 abc	2.29 bc	0.23 b	1.44 a	9.3 a
CHE	226.40 bcd	2.35 abc	0.26 b	1.31 abc	10.49 a
BHE	265.48 abc	2.25 cd	0.21 b	1.17 c	10.33 a
WC	298.96 a	2.05 d	0.38 a	1.30 abc	9.28 a
Desired[b]	200–300	2.4–2.6	0.11–0.3	1.5–2.0	15–200

Means in the same column followed by the same letter are not significantly different ($P<0.05$; $n=5$).
[a] Treatment designations: *CON* control (0×), *CLT* cultivated (1×), *LML* living mulch legume (1×), *LMNL* living mulch non-legume (1×), *SWL* sandwich legume (1×), *SWNL* sandwich non-legume, *CHE* clove oil herbicide (1×), *BHE* Brassica herbicide (1×), *WC* wood chip mulch (1×)
[b] Desired increase in TCSA and leaf nutrient concentration in young non-bearing apples

Table 3 Effect of orchard floor treatments on potentially mineralizable N as measured throughout two growing seasons

Treatment	Sp[a] 2005 (mg kg^{-1})	Su 2005	Au 2005	Sp 2006	Su 2006	Au 2006
CON[b]	16.7 a	8.5 ab	26.0 a	27.2 a	27.7 ab	32.8 ab
CLT	19.0 a	5.2 abc	1.5 c	15.9 b	32.5 a	19.7 b
LML	24.5 a	8.0 abc	10.6 bc	15.4 b	20.3 ab	34.5 ab
LMNL	17.2 a	5.9 abc	22.6 ab	24.6 ab	25.9 ab	38.8 a
CHE	17.0 a	1.9 c	8.9 bc	22.7 ab	12.9 b	28.0 ab
BHE	22.1 a	2.5 bc	19.6 ab	22.4 ab	33.0 a	35.4 ab
WC	23.9 a	10.2 a	8.2 bc	21.3 ab	26.6 ab	21.3 b

Means in the same column followed by the same letter are not significantly different ($P<0.05; n=5$).
[a] Sampling time designations: *Sp* spring, *Su* summer, *Au* Autumn
[b] Treatment designations: *CON* control (0×), *CLT* cultivated (1×), *LML* living mulch legume (1×), *LMNL* living mulch non-legume (1×), *CHE* clove oil herbicide (1×), *BHE* Brassica herbicide (1×), *WC* wood chip mulch (1×)

However, living cover crops often compete with trees for nutrients and water, resulting in reduced tree growth and yield, particularly in newly established orchards or when N demanding grasses predominate (Marsh et al. 1996; Sanchez et al. 2003). In this study, living mulch treatments often had greater available soil N (Table 1) and tree leaf N (Table 2) than other treatments. High levels of available soil N in spring (Table 1) indicate that this treatment may have successfully retained available N that was leached from other treatments during winter precipitation events. However, tree growth in all living mulch treatments was inferior to all other treatments with the exception of the CON and CHE (Table 2). Tree leaf N in LML treatment was greater with the higher fertility rate, but fertility rate did not have an impact on tree growth (date not shown). Sandwich treatments with reduced living cover enhanced tree growth relative to CON, but leaf N was below desirable levels (Table 2).

Isotopic labeling of nutrients is a useful tool for tracking movement through a plant system. While the behavior of N from compost amended with a ^{15}N enriched fertilizer will not be exactly the same as N derived from a compost amendment alone, we believe this strategy is a desirable way to track N movement from compost amendments. In our study, isotope analyses confirmed immobilization of compost N in living cover crops (data not shown); however, periodic mowing allowed mineralization of this N, resulting in sufficient available soil N (data not shown), overall tree leaf N (Table 3), and no significant reduction in the amount of compost N reaching tree leaves in comparison to CLT1X (Fig. 1). Given that available soil N was high under living covers and given the insignificant tree growth response to higher compost amendment rates, reduced tree growth in LML and LMNL may have resulted from competition for soil moisture, root spatial competition, or soil-borne pathogens and parasites that are effectively controlled with cultivation.

Organic herbicides such as those derived from clove oil are under study for their potential to control weeds and minimize soil disturbance (Tworkoski 2002; Boyd and Brennan 2006). Brassicaceae seed meal is another bio-herbicide with potential for multiple benefits including supplemental N (Balesh et al. 2005) as well as weed and disease control (Mazzola and Mullinix 2005). In our study, BHE enhanced tree growth 17% relative to CHE application (Table 2), likely due to competition from uncontrolled weeds in CHE-treated plots (Granatstein et al. 2007) as well as supplemental N provided by the seed meal. However, leaf N, Ca, and Zn concentrations did not reach desirable levels in these treatments (Table 2). Tree leaf chlorosis was observed following early-season Brassicaceae seed meal application in 2006 which may have been the result of reduced soil iron availability. Ionic isothiocyanate, resulting from hydrolysis of *S. alba* glucosinolates, is thought to complex the pool of plant available soil iron (M. Morra, personal communication). Delayed production of leaf chlorophyll may have reduced tree uptake and utilization of available soil N.

Application of organic mulch such as wood chips is an effective weed control strategy shown to increase tree fruit

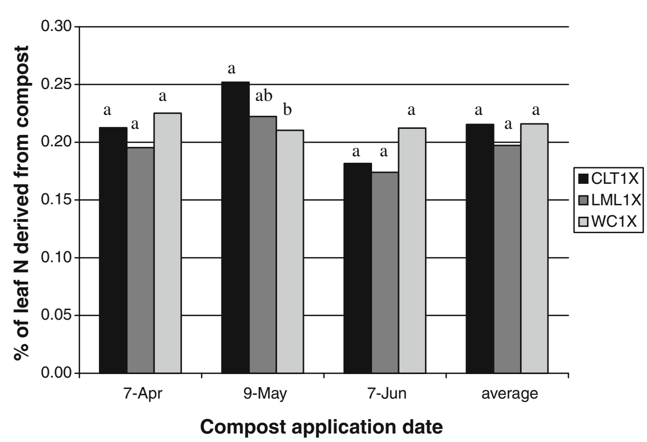

Fig. 1 Effect of orchard floor management and compost application date on percent of mid-summer tree leaf N derived from compost in 2006. Treatment designations: *CLT* cultivated (1×), *LML* living mulch legume (1×), *WC* wood chip mulch (1×). *Bars with the same letter* in different groups are not significantly different ($P<0.05$; $n=5$)

Table 4 Effect of orchard floor treatments on concentration of particulate organic matter and total carbon and nitrogen in autumn soil samples

Treatment	2006		2005		2006		2005–2006	
	POM-C (mg kg^{-1})	POM-N	C (mg kg^{-1})	N	C	N	C (% increase)	N
CON[a]	41.10 b	2.34 bc	11172 ab	911 ab	11900 cd	920 c	7	1
CLT1X	41.27 b	2.64 abc	8841 b	683 b	10500 e	800 d	19	17
LML1X	50.06 ab	3.0 ab	12255 a	939 a	14300 a	1240 a	17	32
LMNL1X	55.26 a	3.28 a	11038 ab	822 ab	14600 a	1210 ab	32	47
CHE	48.18 ab	2.94 abc	9608 ab	732 ab	12500 bc	1100 b	30	50
BHE	45.50 ab	2.92 abc	11015 ab	878 ab	13400 ab	1200 ab	22	37
WC1X	39.21 b	2.11 c	10959 ab	844 ab	11600 de	920 c	6	9

Means in the same column followed by the same letter are not significantly different ($P<0.05$; $n=5$).

[a] Treatment designations: *CON* control (0×), *CLT* cultivated (1×), *LML* living mulch legume (1×), *LMNL* living mulch non-legume (1×), *CHE* clove oil herbicide (1×), *BHE* Brassica herbicide (1×), *WC* wood chip mulch (1×)

yield and improve soil physical, chemical and biological properties (Forge et al. 2003; Neilsen et al. 2003; Oliveira and Merwin 2001; Sanchez et al. 2003; Yao et al. 2005). However, the high C/N ratio of a wood chip mulch has been associated with short-term N immobilization and reduced tree availability (Larsson et al. 1997). In our study, wood chip mulch resulted in excellent tree growth, with an increase in TCSA of close to 300% (Table 3). In contrast, tree leaf N was lower than the other treatments except for CON (Table 2). Isotopic analyses confirmed immobilization of N in wood chip residues (data not shown) and that in comparison to CLT1X and LML1X, a smaller amount of compost N reached tree leaves from the May application in WC1X (Fig. 1). Increased compost amendment rates led to higher leaf nutrient levels (data not shown) but not enough to meet levels considered desirable for young non-bearing trees (Stiles 1994), indicating that tree N needs were not met even at the high N rate. The wood chip mulch treatment resulted in abundant soil moisture, which may have contributed to the observed desirable tree growth; yet, this may also have contributed to N loss through denitrification or leaching mechanisms, as suggested by the low available soil N in summers (Table 1). In concert, these findings demonstrate that wood chip mulch is not a suitable strategy for orchard floor management during tree establishment unless additional steps are taken to manage N supply.

Impact of orchard floor management on soil biological activity

Indicators of soil biological activity were used to estimate the long-term impact of orchard floor management practices on N cycling and availability. Despite substantial compost amendments applied to the base of each tree (1×), soil biological activity in the cultivated treatment did not improve relative to the control. Potentially mineralizable N (Table 3), POM-C and -N (Table 4), C mineralization (Fig. 2), dehydrogenase activity (Fig. 2), and nematode abundance (Fig. 2) in CLT1X were not different from CON, which received no fertility additions. Total C and N in CLT1X were lower than CON by autumn 2006 (Table 4). Increasing the compost amendment rate to 1.5× in cultivated treatments did not result in soil biological activity improvement relative to the control (data not shown). These results indicate that while weed control and short-term nutrient supply in cultivated orchard floor systems can be maintained with annual compost amendment, this management strategy will not meet the goal of reducing N fertility costs or mitigating N loss in the long term.

Living mulch treatments ranked highest in all soil biological indicators. At the end of the 2005 growing season, total C and N in soil from LML1X and LMNL1X were greater than CLT1X (Table 4), 17–32% and 32–47% in C and N,

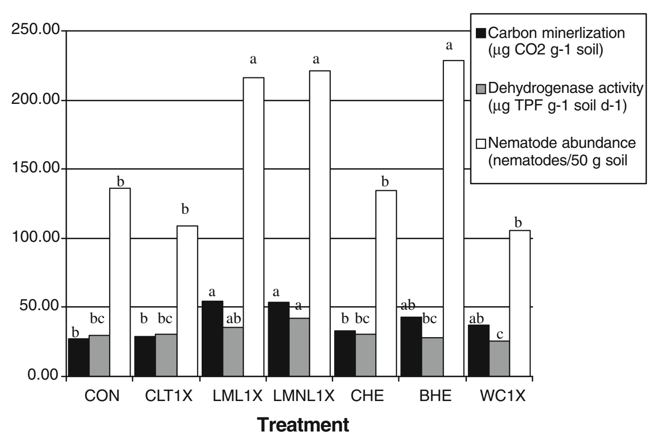

Fig. 2 Effect of orchard floor management treatment on soil carbon mineralization and dehydrogenase activity in soil collected autumn 2006 and on abundance of nematodes recovered from soils in summer 2006. Treatment designations: *CON* control (0×), *CLT* cultivated (1×), *LML* living mulch legume (1×), *LMNL* living mulch non-legume (1×), *CHE* clove oil herbicide (1×), *BHE* Brassica herbicide (1×), *WC* wood chip mulch (1×). *Bars with the same letter* are not significantly different ($P<0.05$; $n=5$)

respectively. In 2006, LML1X and LMNL1X soils possessed levels of mineralizable C that were greater than that in CLT1X, WC1X, and CHE (Fig. 2); both LML1X and LMNL1X had greater soil dehydrogenase activity than WC1X, and LMNL1X soil dehydrogenase activity was also greater than for all other treatments but LML1X (Fig. 2). By autumn 2006, LMNL1X and LML1X had greater POM-C and -N than WC1X and greater total C than all treatments except BHE (Table 4).

Living mulch treatments had greater nematode abundance than CON, CLT1X, CHE, and WC1X treatments (Fig. 2). The composition of nematode community diversity was not different, yet profiles of nematode diversity under different treatments appear to be changing and diverge over time (data not shown). Systems with reduced disturbance (Sánchez-Moreno et al. 2006) and greater inputs of organic matter (Ferris et al. 2004) may become enriched with bacterivore, fungivore, and predatory nematode species. These genera tend to be more common in mature communities and are often correlated with increased N mineralization (Neher 2001). In contrast, soil cultivation tends to result in enrichment of plant parasitic species responsible for inducing disease and lower overall tree health (Neher 2001).

Over the long term, the stimulation of biological parameters observed in the living mulch treatments may lead to increased nutrient-use efficiency and potentially healthier trees. Therefore, while not advisable during orchard establishment, living cover understories hold promise in mature orchards where they have been shown to enhance soil quality without negative impact to fruit yields (Sánchez et al. 2006). Alternatively, during tree establishment, a more desirable strategy may be application of low C/N ratio plant biomass that could improve soil biological activity without acting as a competitor to tree development (Sanchez et al. 2003).

Despite reduced disturbance, CHE, BHE, and WC1X treatments had few effects on soil biological activity. Soils for both CHE and BHE treatments ended with more total C and N than cultivated plots resulting in an increase of 22–30% and 37–50% in C and N, respectively (Table 4). However, PMN (Table 2), POM-C, and POM-N (Table 4), mineralizable C (Fig. 2), and soil dehydrogenase activity (Fig. 2) in CHE and BHE soils were all similar to the CLT treatment. Among parameters measured, only nematode abundance (Fig. 2) was greater in BHE than CON, CLT1X, CHE, and WC1X treatments. Despite substantial inputs of total C from wood chip mulch, this treatment ranked among the lowest in soil biological indicators.

Conclusions

Meeting the multiple objectives of weed control, optimal tree health, and increased soil biological activity may require employment of different orchard floor management strategies at different times during the life of the orchard. In the early years of orchard development when weed control is essential to achieve vigorous tree growth, intensive cultivation will be a desirable strategy, despite the lack of soil biological activity improvement and requirement of frequent nutrient inputs. In contrast, when orchard trees become mature, managers can begin a soil-building program and reduce fertility amendments by replacing understory cultivation with application of low C/N ratio biologically based mulch materials or through incorporation of a "living mulch." Application of Brassicaceae seed meal can provide multiple benefits to an orchard system, but additional research using different Brassicaceae species is needed to identify application rates and their timing to prevent tree injury and enhance its use as a dual-purpose organic amendment.

Acknowledgements Sincere thanks to Kent Mullinix and Amos Kukes for making available the Wenatchee Valley College Research and Demonstration Site and for their assistance with plot maintenance. We thank Michel Wiman and Kaz Lorentz for efforts in plot maintenance and data collection; Debbie Bikfasy and Antonio Izzo for their guidance; Rowena Porter and Ben Siks for assistance in laboratory analyses; and Mark Evans and Stewart Higgins for assistance in statistical analyses. This work was conducted, in part, with financial support from the Washington State University Center for Sustaining Agriculture and Natural Resources.

References

Balesh T, Zapata F, Aune JB (2005) Evaluation of mustard meal as organic fertilizer on tef (*Eragrostis tef* (Zucc) Trotter) under field and greenhouse conditions. Nutrient Cycl Agroecosyst 73:49–57

Boyd NS, Brennan EB (2006) Burning nettle, common purslane, and rye response to a clove oil herbicide. Weed Tech 20:646–650

Cambardella CA, Elliott ET (1993) Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci Soc Am J 57:1071–1076

Collins HP, Elliott ET, Paustian K, Bundy LC, Dick WA, Huggins DR, Smucker AJM, Paul EA (2000) Soil carbon pools and fluxes in long-term corn belt agroecosystems. Soil Biol Biochem 32:157–168

Drinkwater LE, Cambardella CA, Reeder JD, Rice C (1996) Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. In: Doran JW, Jones AJ (eds) Methods for assessing soil quality. Soil Sci Soc Am, Madison, pp 217–229

Ferris H, Venette RC, Scow KM (2004) Soil management to enhance bacterivore and fungivore nematode populations and their nitrogen mineralization function. Appl Soil Ecol 25:19–35

Fiscus DA, Neher DA (2002) Distinguishing sensitivity of free-living soil nematode genera to physical and chemical disturbances. Ecol Appl 12:565–575

Forge TA, Hogue E, Neilsen G, Neilsen D (2003) Effects of organic mulches on soil microfauna in the root zone of apple: implications for nutrient fluxes and functional diversity of the soil food web. Appl Soil Ecol 22:39–54

Granatstein D, Mullinix K, Wiman M, Kirby E (2007) Integrated Multiple Mulch Trial. http://organic.tfrec.wsu.edu/OrganicIFP/OrchardFloorManagement/IMM_Progress_Report_2006.pdf

Gu YH, Mazzola M (2003) Modification of fluorescent pseudomonad community and control of apple replant disease induced in a wheat cultivar-specific manner. Appl Soil Ecol 24:57–72

Ingham R (1994) Nematodes. In: Mickelson SH, Bigham JM (eds) Methods of Soil Analysis, Part 2, Microbiological and Biochemical Properties. Soil Sci Soc Am, Madison, pp 459–490

Laakso J, Setala H, Palojarvi A (2000) Influence of decomposer food web structure and nitrogen availability on plant growth. Plant Soil 225:153–165

Larsson L, Stenberg B, Torstensson L (1997) Effects of mulching and cover cropping on soil microbial parameters in the organic growing of black currant. Comm Soil Sci Plant Anal 28:913–925

Marsh KB, Daly MJ, McCarthy TP (1996) The effect of understory management on soil fertility, tree nutrition, fruit production and apple fruit quality. Biol Ag Hort 13:161–173

Mazzola M, Mullinix K (2005) Comparative field efficacy of management strategies containing *Brassica napus* seed meal or green manure for the management of apple replant disease. Plant Dis 89:1207–1213

Neher DA (2001) Role of nematodes in soil health and their use as indicators. J Nematol 33:161–168

Neilsen GH, Hogue EJ, Forge T, Neilsen D (2003) Mulches and biosolids affect vigor, yield and leaf nutrition of fertigated high density apple. Hortsci 38:41–45

Oliveira MT, Merwin IA (2001) Soil physical conditions in a New York orchard after eight years under different groundcover management systems. Plant Soil 234:233–237

Robertson GP, Wedin D, Groffman JM, Blair JM, Holland EA, Nadelhoffer KJ, Harris D (1999) Soil Carbon and Nitrogen Availability: Nitrogen Mineralization, Nitrification, and Soil Respiration Potentials. In: Robertson GP, Coleman DC, Bledsoe CS, Sollins P (eds) Standard Methods for Long-term Ecological Research. Academic, New York, pp 258–271

Rovira AD, Elliott LF, Cook RJ (1990) The Impact of Cropping Systems on Rhizosphere Organisms Affecting Plant Health. In: Lynch JM (ed) The Rhizosphere. Wiley, New York, pp 389–436

Ryugo K (1988) Fruit culture: its science and art. Wiley, New York, pp 191–201

Sanchez JE, Edson CE, Bird GW, Whalon ME, Willson TC, Harwood RR, Kizilkaya K, Nugent JE, Klein W, Middleton A, Loudon TL, Mutch DR, Scrimger J (2003) Orchard floor and nitrogen management influences soil and water quality and tart cherry yields. J Am Soc Hort Sci 128:277–284

Sánchez EE, Giayetto A, Cichon L, Fernández D, Aruani MC, Curetti M (2006) Cover crops influence soil properties and tree performance in an organic apple (*Malus domestic Borkh*) orchard in northern Patagonia. Plant Soil 292:193–203

Sánchez-Moreno S, Minoshima H, Ferris H, Jackson LE (2006) Linking soil properties and nematode community composition: Effects of soil management on soil food webs. Nematol 8:703–715

Six J, Elliott ET, Paustian K, Doran JW (1998) Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci Soc Am J 62:1367–1377

Stamatiadis S, Werner M, Buchanan M (1999) Field assessment of soil quality as affected by compost and fertilizer applied in a broccoli field (San Benito County, CA). Appl Soil Ecol 12:217–225

Stiles W (1994) Nitrogen Management in the Orchard. In: Peterson AB, Stevens RG (eds) Tree Fruit Nutrition Shortcourse Proceedings. Good Fruit Grower, Yakima, pp 41–50

Stork PR, Jerie PH (2003) Initial studies of the growth, nitrogen sequestering, and de-watering potential of perennial grass selections for use as nitrogen catch crops in orchards. Aust J Agric Res 54:27–37

Tabatabai MA (1994) Soil Enzymes. In: Mickelson SH, Bigham JM (eds) Methods of Soil Analysis, Part 2, Microbiological and Biochemical Properties. Soil Sci Soc Am, Madison, pp 775–834

Tworkoski T (2002) Herbicide effects of essential oils. Weed Science 50:425–431

USDA-NOP (2001) National Organic Program Organic certification standards http://www.ams.usda.gov/nop/NOP/standards.html Accessed 10/2006

Wagger MG, Cabrera ML, Ranells NN (1998) Nitrogen and carbon cycling in relation to cover crop residue quality. J Soil Water Cons 53:214–218

Wardle DA, Yeates GW, Bonner KI, Nicholson KS, Watson RN (2001) Impacts of ground vegetation management strategies in a kiwifruit orchard on the composition and functioning of the soil biota. Soil Biol Biochem 33:893–905

Yao S, Merwin IA, Bird GW, Abawi GS, Thies JE (2005) Orchard floor management practices that maintain vegetative or biomass groundcover stimulate soil microbial activity and alter soil microbial community composition. Plant Soil 271:377–389