Groundcover Management and Nutrient Source Effects on Soil Carbon and Nitrogen Sequestration in an Organically Managed Apple Orchard in the Ozark Highlands

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Abstract. Orchards established on weathered, acidic mineral soils in the Ozark Highlands must be managed to meet tree nutritional requirements. However, a common characteristic of Ozark Highland soils is a relatively low soil organic matter (SOM) concentration, a condition that can have detrimental effects on orchard productivity. Organic orchard management poses specific challenges to managing competitive under-tree vegetation and supplying appropriate supplemental nutrition to maintain tree growth and cropping. In Mar. 2006, an experimental apple orchard was established to evaluate the effects of under tree, in-row groundcover management system (i.e., shredded paper, wood chips, municipal green compost, and mow-blow), and nutrient source (i.e., non-fertilized control, composted poultry litter, and pelletized organic commercial fertilizer) on SOM, carbon (C), and nitrogen (N) concentration, and soil C and N sequestration over time in an organically managed orchard in the Ozark Highlands region of northwest Arkansas. Soil organic matter, total C, and total N concentrations (soil weight basis) and contents (area basis) in the top 7.5 cm increased in all groundcover management systems from 2006 to 2011. The greatest differences were observed with municipal green compost treatments. Significant interactions between groundcover management treatment and nutrient source were only observed for SOM concentration, whereas nutrient source did not affect total C and total N concentrations or contents. Soil C sequestration rates were 0.9, 1.0, and 2.8 Mg·ha⁻¹ per year under the shredded paper, wood chip, and green compost treatments, respectively, whereas total C content did not change over time under the mow-blow treatment. The green compost treatment was the only treatment that had significant total N sequestration occur (0.25 Mg nitrogen/ha/year). Results of this study indicate that organic cultural methods can significantly augment near-surface soil C and N contents, which will likely increase productivity, of apple orchards in the Ozark Highlands over a relatively short period time after establishment. This study has implications for orchards in similar soils or environmental circumstance and for both organic and conventional management systems.

and meeting the goal of the National Organic Program, soil fertility, and crop nutrient management practice standard (§205.203), which requires systems 1) to “select and implement tillage and cultivation practices that maintain or improve the physical, chemical, and biological condition of soil and minimize soil erosion”; 2) to “manage crop nutrients and soil fertility through rotations, cover crops, and the application of plant and animal materials”; and 3) to “manage plant and animal materials to maintain or improve soil organic matter content in a manner that does not contribute to contamination of crops, soil, or water by plant nutrients, pathogenic organisms, heavy metals, or residues of prohibited substances” (United States Department of Agriculture, Agricultural Marketing Service, 2012). Sustainably improving soil through organic management for fruit tree growth and cropping can be difficult in perennial cropping systems and in regions such as the Ozark Highlands with weathered and mineralized soils, which tend to be eroded and have low residual organic matter contents (Brye et al., 2013).

Returning crop residues or other plant matter to the soil, thereby increasing soil C, directly impacts SOM, humus content, and the soil C:N ratio (Himes, 1998). Previous studies have shown that increased soil C measurably affected soil physical, chemical, and biological properties such as soil aggregation and structure, soil temperature, soil aeration, cation exchange capacity, plant nutrient concentrations, and microbial activity (Merwin et al., 1994; Reganold et al., 2001; Rice et al., 2007; Sanchez et al., 2003). Soil microbial activity and soil faunal populations such as earthworms and nematodes are also likely beneficiaries of soils with increased soil C, particularly the organic fraction.

Soil organic C (SOC) is the most prevalent form present in arable land with inorganic soil C more common in semiarid climates and largely restricted to its carbonate forms (Lal et al., 1998a). Soil C, the principle component of SOM, is greatly dependent on land management practices that either serve to aggrade or degrade SOM. Research on no-tillage or reduced-tillage practices and land application of manures and mulches has shown positive impacts on soil characteristics affecting tilth and productivity and are presumably linked to increased soil C (Albrecht and Sosne, 1944; Allison, 1968; Goh et al., 2001; Hudson, 1994; Jordán et al., 2010; Merwin et al., 1994; Mulumba and Lal, 2007; Soane, 1990; Stock and Downes, 2008). Conversely, conventional tillage (Anderson and Coleman, 1985) and conventional tillage coupled with application of agricultural chemicals (Fountas et al., 2011; Merwin et al., 1994) have been linked to decreases in SOC from the rapid oxidation of the most readily decomposable pool of SOM.

Stable SOM, also known as humus, is derived in part from heterogeneous plant matter retained on the soil surface, and the soil humus concentration may be affected by intentionally placing plant residues on the soil surface for incorporation or placed adjacent

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Two important and interrelated components of orchard management are under-tree, competitive vegetation management, and supplying supplemental nutrition to the tree. This is further complicated in organic management systems where there are limited tools available

to a crop to serve as mulch. Humification of plant material, a process mediated in large part by soil microorganisms, is a sequence of steps through which plant tissues are broken down and are then reorganized through biological, microbial, and chemical soil processes into more stable compounds (Tate, 1992). Labile components of particulate organic matter (POM) containing compounds such as polysaccharides are readily used by soil microorganisms, whereas more chemically resistant plant tissues such as lignin and cellulose are decomposed more slowly (Tisdall and Oades, 1982). The products of the decomposition process are polymerized into new organic (i.e., humified) compounds, which are much more resistant to bacterial degradation than fresh organic matter (Brady, 1990).

Land use and land management practices affect SOM and, consequently, soil C and N cycling (Amuri et al., 2008; Brye and Gbur, 2010; Brye and West, 2005). In a study comparing the effects of cropping management on soil C and N, Lal et al. (1998b) reported that tall fescue (*Festuca arundinacea* Schreb.) and smooth brome grass (*Bromus inermis* Leyss.) cover crops elevated the soil C and N content by 18.5% and 12.5%, respectively, compared with a corn (*Zea mays* L.)–soybean (*Glycine max* L.) rotation, and increasing fertilizer rates enhanced total soil C sequestration by replacing nutrients removed with the harvested crop. Similarly, Nyborg et al. (1998) reported significant C increases in the light fraction of SOM, particularly when N and sulfur fertilizers were applied, whereas increases in total soil C generally had greater variability. Thus, the rate at which the soil C increases is often reduced by low soil macronutrient levels and a subsequent reduction in soil microbial activity.

Soil management effects on soil C vary geographically and climatically (Brye and Gbur, 2010). For instance, the climate of the southeastern United States does not permit large soil C increases to levels observed in more northern latitudes. This is a result of a combination of factors including warmer temperatures and more rainfall in the southeastern United States, both of which increase SOM decomposition rates. Crop and cropping system affect soil C levels as well. In perennial systems such as organic apple (*Malus × domestica* Borkh.) production, annual tillage is not required for desirable tree growth nor may it be the most viable option for controlling competitive vegetation as a result of standards set forth by the National Organic Program (United States Department of Agriculture, Agricultural Marketing Service, 2012). However, numerous studies have shown plant residues used as mulches are effective at controlling weed growth while also positively affecting soil quality indicators (Glover et al., 2000; Granatstein et al., 2010; Granatstein and Mullinix, 2008; Reganold et al., 2001), a requirement established by the National Organic Program standards. Plant residues are a source of C, and when

used long term, they may serve to increase soil C in organic production systems, particularly for apples. However, research addressing changes in C and N storage and cycling in soils used for apple production is limited.

The Ozark Highlands region of northwest Arkansas was once one of the major areas of concentrated apple production in the United States (Rom, 2007). However, the Ozark Highlands is also a region of generally low SOM as a result of the relatively old, highly weathered, and often shallow soils throughout the area (Brye et al., 2013). Furthermore, no research has been conducted regarding the potential for soil C or N sequestration in organically managed apple orchards in the Ozark Highlands, which may be representative of other areas of similar mineral soils and a warm, humid environment. Therefore, the objective of this study was to evaluate the effects of groundcover management system and nutrient source on SOM concentration and total C and N concentration, content, and change over time in the top 7.5 cm of a young, experimental, organically managed apple orchard in the Ozark Highlands region of northwest Arkansas. It was hypothesized that the addition of groundcovers and the addition of nutrients in the form of an organic amendment would increase soil C and N. It was also hypothesized that significant soil C and N sequestration could be achieved with a combination of groundwater management and nutrient source. This study has implications for organically and conventionally managed orchards in the regions with similar soils and climatic characteristics.

Materials and Methods

This study was part of a broader study examining the impacts of groundcover management systems and nutrient source on soil physical, chemical, and biological characteristics; tree health and productivity; and insect, disease, and weed management in an experimental, organically managed apple (*Malus × domestica* Borkh.) orchard that was established in 2006 at the University of Arkansas' Agricultural Research and Extension Center in Fayetteville, AR (lat. 36° N, long. 94° W). The 0.4-ha experimental orchard resides on two soil series. Two-thirds of the trees were established on a Pickwick silt loam (fine-silty, mixed semiactive, thermic Paleudults) with the remainder located on a Captina silt loam (fine-silty siliceous, active, mesic Typic Fragiudults; United States Department of Agriculture, 1969). Soil survey descriptions for both soils specify low to moderate natural fertility, low SOM, low to moderate soil pH, and moderate to high plant-available water with a fragipan commonly present in the Captina series at a depth of ≈51 cm, which limits root penetration below this depth (United States Department of Agriculture, 1969). Both soils are well suited for orchard and/or small fruit production.

Before establishment the study site had been in horticultural production for ≈75

years. In 2005, the site was leveled and cultivated to prepare for planting. Soil pH was adjusted to ≈6.5 by application of agricultural lime according to University of Arkansas Soil Testing and Research Laboratory recommendations based on preliminary soil sampling, and composted manure was applied at the rate of 5 t·ha⁻¹. The 'Enterprise'-M26 apple cultivar was planted in 2006 with 2-m tree spacing and 4-m row spacing and trained to a two-wire trellis, vertical axis system. The tree density is ≈1485 trees/ha. Orchard management followed National Organic Program regulations since establishment (United States Department of Agriculture, Agricultural Marketing Service, 2012). Drive alleys between tree rows were planted and perennially managed with planted tall fescue (*Festuca arundinacea* Schreb. 'KY 31') and other naturally occurring native, herbaceous species.

Four groundcover management system treatments (i.e., main-plot factor) and three nutrient source treatments (i.e., sub-plot factor) were arranged in randomized complete block design with six replications (i.e., blocks), where each block had all combinations of experimental factors. Treatment data trees were buffered from adjacent treatment effects by two guard trees on either side. A row of guard trees was also positioned along the outside edges of the orchard. The four groundcover management treatments studied in this field experiment included 1) urban municipal green compost (GC); 2) shredded office paper (SP); 3) waste wood chips (WC) of urban origin; and 4) a managed tall fescue mow-blow (MB) green mulch system, which served as an informal control treatment. For the MB treatment, vegetation in the row middle was cut periodically with a rotary mower and blown by the mower under the tree into an ≈2-m wide strip under the tree canopy within the tree row.

Beginning in Mar. 2006, GC, SP, and WC treatments were applied under trees annually in a 2 m wide × 4- to 10-cm deep band of each groundcover mulch extending across both sides of the tree row. Green compost, derived of urban vegetative waste (i.e., grass clippings, wood pruning, and yard waste), composted for 90 to 120 d, was obtained from the City of Fayetteville, AR, and used through the 2011 growing season. Green compost used beginning in 2012 was obtained from PC Turnkey in Springdale, AR, and consisted of grass clippings, leaves, and wood chips composted using an active-pile process. Shredded office paper was obtained from the University of Arkansas, and WC originating of primarily hardwood species was obtained from the City of Fayetteville, AR. Mow-blow green mulch was applied within the tree row by a rotary mower in late May and three to five times throughout the summer on an as-needed basis depending on interrow vegetation growth.

One of three nutrient source treatments was applied annually as 1) certified organic commercial fertilizer produced from poultry manure (pelletized poultry manure; Perdue

AgriRecycle, Seaford, DE; 4N–2P–3K nutrient analysis, CF); 2) locally available composted poultry litter; or 3) an unamended, non-fertilized control, in which all added nutrition came from the groundcover management treatments. The CF selected at the initiation of the study was used through the 2011 application, but production was subsequently discontinued. An alfalfa (*Medicago sativa*)-based commercial organic product (Bradfield Organics, Feed Solutions, St. Louis, MO; 3N–1P–5K nutrient analysis) was applied beginning in 2012. During the study, the average N–P–K content of the applied poultry litter was 1.2–1.1–0.47, respectively. Nutrient source treatments were applied in March of each year before application of groundcover management treatment at a rate of 50 g N per tree per year.

All soil sampling was conducted within 0.75 m of the tree's trunk in a treatment combination. In the event a treatment tree died, a guard tree from the original orchard planting, which had been managed in the same manner as each treatment tree, was used for subsequent sampling. Soil samples were collected from the top 10 cm in Oct. 2006 and Mar. 2012, oven-dried at 105 °C for 24 h, crushed, and sieved through a 2-mm screen for SOM concentration determination by loss-on-ignition using a muffle furnace at 500 °C for 6 h. Soil samples for bulk density (BD) determination were collected in Nov. 2006 and June 2012 from the top 6 cm. Two cores were collected from each treatment plot, dried for 3 d in a 50 °C forced-air oven, and then weighed.

Total soil C (TC) and N (TN) concentrations were not measured in 2006 at orchard establishment. However, because Pickwick and Captina soils are included in the same soil association and share similar soil-surface physical and chemical characteristics, initial TC and TN concentrations were estimated from initial SOM concentration measurements based on replicated, although unpublished, measured TC (0.53) and TN (0.056) fractions of SOM using similar sampling procedures as used in this study for an adjacent Captina soil on the same research station (K. Brye, personal communication).

In Nov. 2011, soil samples were collected from the top 7.5 cm, sieved through a 63.5-mm screen, mixed thoroughly, and allowed to air dry for 5 d. Approximately 200 g of each soil was pulverized with a mortar and pestle to a fine powder. Forty milligrams (± 0.1 mg) were analyzed for TC and TN concentrations by high-temperature combustion in an Elemental Vario EL cube (Elemental Americas, Inc., Philadelphia, PA). Soil TC and TN contents (i.e., $\text{Mg}\cdot\text{ha}^{-1}$) were calculated from 2011-measured concentrations, 2012-measured BD, and a sample depth of 7.5 cm. Soil C:N ratios were also calculated from 2011-measured TC and TN concentrations.

Adjacent (within 15 m) to the experimental, organically managed orchard, which was the focus of this study, and on the same two soil series resides a conventionally managed

orchard that was established in 1989 for apple cultivar evaluations. Orchard floor management in the conventional orchard consisted of pre-emergence and contact herbicide applications made approximately three to five times annually for competitive vegetation control. Water-soluble fertilizers, typically ammonium nitrate or urea, were applied annually at rates of 0.5 to 0.75 kg N per tree. Synthetic insecticides and fungicides were applied using integrated pest management protocols at commercially recommended application rates and timing intervals (University of Arkansas Cooperative Extension Service, 2013a, 2013b).

At the same time samples were collected from the organic orchard in 2011 and using the same sampling and processing procedures, soil samples were collected and processed from the top 6 cm of the adjacent conventionally managed orchard for SOM concentration and from the top 7.5 cm for TC and TN concentration determinations. Soil BD in the top 6 cm was also directly measured in the conventional orchard in 2012 at the same time similar measurements were made in the organic orchard. Soil TC and TN contents for the conventional orchard were calculated similar to those calculated for the organic orchard.

Analysis of variance was used to evaluate the effects of groundcover management system, nutrient source, time, and their interactions on measured and calculated soil properties (i.e., SOM, TC, and TN concentrations; TC and TN contents; C:N ratios; and BD) using the MIXED procedure in SAS (Version 9.2; SAS Institute, Inc., Cary, NC). When appropriate, means were separated by least significant difference at the 0.05 level. In the absence of interaction effects, the main effects are shown.

Because the conventionally managed orchard was not a part of the organic orchard research project, formal statistical comparisons of soil properties among groundcover management treatments in the organic orchard and the conventional orchard were not conducted. However, no organic amendments were added to the conventional orchard after its establishment; thus, qualitative conclusions were drawn regarding the effects of groundcover management on near-surface soil properties as evaluated in both orchards.

Results and Discussion

Measured SOM concentrations, estimated TC and TN concentrations and contents, and estimated C:N ratios were unaffected ($P > 0.05$) by groundcover management treatment or nutrient source based on soil samples collected in 2006 indicating homogeneous soil conditions existed at the time of organic orchard establishment (Fig. 1). Therefore, it can reasonably be assumed that any measured differences among treatments after initiating organic management were the result of the imposed treatments.

Because of its impact on a variety of soil characteristics, SOM is commonly included

as an indicator of soil quality (Fliebach et al., 2006; Granatstein and Mullinix, 2008; Gregorich et al., 1994; Karlen et al., 1992; Loveland and Webb, 2003; Merwin et al., 1994, 1995). In this study, averaged over time (i.e., 2006 and 2011), only SOM concentration differed among groundcover management treatments within nutrient sources and among nutrient sources within groundcover management treatments ($P = 0.007$; Fig. 2), whereas TC and TN concentrations (soil weight basis) and contents (area basis) and C:N ratios were unaffected by nutrient source ($P > 0.05$). Soil organic matter concentration was greatest for all three nutrient source treatments with green compost compared with the same nutrient source treatment for other groundcover management treatments (Fig. 2). When poultry litter was used as the nutrient source, the SOM concentration was greater under wood chips than under shredded paper and MB, which did not differ (Fig. 2). When the commercial fertilizer was used as the nutrient source, the SOM concentration was greater under shredded paper and wood chips, which did not differ, than under MB (Fig. 2). However, when no additional nutrient sources were added, there were no differences in SOM concentration among wood chips, shredded paper, and MB groundcover management system treatments (Fig. 2).

Within the green compost, SOM concentrations were greater for the non-fertilized control and commercial fertilizer, which did not differ, than for the poultry litter nutrient source (Fig. 2). In contrast to that in the green compost, SOM concentrations within the wood chip treatments were greater under poultry litter than under commercial fertilizer or the unfertilized control, which did not differ (Fig. 2). The inconsistent SOM concentration response to nutrient source between the wood chip and green compost treatments could be related in part to the lower C:N ratio of the commercial fertilizer compared with the poultry litter used (Choi, 2009) and may merit further evaluation. Furthermore, the addition of readily decomposable poultry litter to more readily decomposable green compost compared with poultry litter additions to more recalcitrant wood chips may have stimulated greater soil respiration, hence greater C loss as carbon dioxide to the atmosphere, from the green compost compared with the wood chip treatments.

The decomposition of groundcover management treatment mulches and nutrient-source residues may have contributed a variety of different organic compounds to the orchard soil, of which POM was probably a leading constituent, and some association of humidified residues with the mineral soil component would also have been expected (Horwath, 2007). Differences in physical and chemical compositions may have also affected the rate of groundcover management mulch decomposition. Compared with wood chips, the composting process had already decreased the particle size of the green compost and, as a result of its low C:N ratio

relative to other mulches (Mays, 2013), the best conditions for SOM aggradation were likely created under the green compost treatments. A similar observation was reported by Himes (1998) that greater SOM was associated with applications of composted cow manure as compared with ordinary crop residues having a comparatively greater C:N ratio.

As expected, SOM concentrations under shredded paper were greater with both poultry litter and commercial fertilizer, which did not differ, compared with the no-nutrient control, whereas SOM concentrations were greater from the unfertilized control and poultry litter, which did not differ, than from the commercial fertilizer in the MB treatment (Fig. 2). In contrast to the results of this study after 5 years, Choi et al. (2011) did not observe a groundcover management treatment-nutrient source treatment interaction on near-surface SOM concentration in the first 3 years after orchard establishment. However, similar to the results of Choi et al. (2011), the greatest increases in SOM concentration over time were associated with the green compost

treatments. These changes indicate that when land is converted to organic systems, there is a period of time for organic treatments to manifest themselves and stabilize.

Averaged across nutrient source, SOM, TC, and TN concentrations and soil C:N ratios increased ($P < 0.001$; Fig. 1), whereas soil BD decreased ($P < 0.001$; Fig. 3) over time in all groundcover management treatments. However, despite BD decreasing from 2006 to 2011 in all groundcover management treatments (Fig. 3), TN contents increased ($P < 0.001$) over time in the green compost but in no other groundcover management treatments, whereas TC contents increased ($P < 0.001$) over time in all groundcover management treatments except for in the MB (Fig. 1). Considering there were no differences in near-surface SOM, TC, and TN properties (Fig. 1) or BD (Fig. 3) among groundcover management treatments in 2006 when the experimental organic orchard was established, differential effects of groundcover management treatment mulches on near-surface soil properties were observed after 5 years of consistent organic management.

Soil organic matter concentration in 2011 was greater under green compost than under all other groundcover management treatments, whereas SOM concentration was greater under wood chips than under MB and shredded paper, which did not differ (Fig. 1). Total soil N concentration and TC and TN contents were greater in 2011 under green compost than under all other groundcover management treatments, which did not differ (Fig. 1). Similar to TC content, TC concentration in 2011 was greater under green compost than under all other groundcover management treatments, but TC concentration under wood chips was greater than under MB, whereas TC concentration under shredded paper was similar to both under the wood chip and MB treatment (Fig. 1). The soil C:N ratio in 2011 was greater under the wood chip treatment, which did not differ from the shredded paper, than under the green compost treatment, which was greater than that under the MB treatment (Fig. 1).

Soil BD in 2012 was greater under the shredded paper and MB, which did not differ, than under wood chip and green compost treatment, which did not differ (Fig. 3). These results indicate that that soil under the wood chip and green compost treatments was more porous and likely more well structured than under the shredded paper and MB treatments, which could have ramifications on surface water infiltration and other soil hydraulic and gas exchange properties. Nutrient source also affected ($P < 0.05$) BD over time, where the greatest decrease in BD occurred with commercial fertilizer addition, whereas the smallest decrease in BD occurred under the non-fertilized control (data not shown).

Based on significant increases in TC and TN contents, despite significant decreases in BD, over time, soil C sequestration rates were 0.9, 1.0, and 2.8 $\text{Mg} \cdot \text{ha}^{-1}$ per year within the tree row under the shredded paper, wood chip, and green compost treatments, respectively (Fig. 1). These TC sequestration rates are similar to the SOM sequestration rate of 2.2 $\text{Mg} \cdot \text{ha}^{-1}$ per year reported by Daigh et al. (2009) in the top 10 cm of a similar Captina silt-loam soil in northwest Arkansas that had been amended with poultry litter for 5 consecutive years. However, the TC sequestration rates observed under the experimental organic orchard were seven to 21 times greater than the C sequestration rates reported over a 6-year period for mature managed grasslands and a native tallgrass prairie in the Ozark Highlands (Brye and Gbur, 2011). Orchard establishment on graded, exposed soil with low initial SOM and other plant nutrients was in part responsible for the large response to groundcover management treatments in the relatively short period of time of this study. The significant observed soil C sequestration in this Ozark Highlands organic apple orchard after application of plant residue-based groundcover management treatment mulch has likely resulted in improved soil quality (Doran et al., 1996). Although the magnitude of potential future soil C sequestration with continued application of these

Fig. 1. Groundcover management system [i.e., shredded paper (SP), wood chips (WC), mow-blow (MB), and green compost (GC)] effects on soil organic matter (SOM), total soil carbon (TC), and nitrogen (TN) concentrations, TC and TN contents, and carbon-to-nitrogen (C:N) ratios over time from the top 10 cm for SOM and the top 7.5 cm for the other soil properties within 0.75 m of the tree trunk in an experimental, organically managed apple ('Enterprise'/M.26) orchard on a silt loam surface soil in the Ozark Highlands region of northwest Arkansas. Different uppercase letters atop bars indicate significant differences ($P < 0.05$) between groundcover management treatments within the same year. Different lowercase letters atop bars indicate significant differences ($P < 0.05$) over time within the same groundcover management treatments.

Fig. 2. Groundcover management system and nutrient source effects on soil organic matter (SOM) concentration measured in Mar. 2012 from the top 10 cm within 0.75 m of the tree trunk in an experimental, organically managed apple ('Enterprise'/M.26) orchard on a silt loam surface soil in the Ozark Highlands region of northwest Arkansas. Different uppercase letters atop bars indicate significant differences ($P < 0.05$) between groundcover management treatments receiving the same nutrition source. Different lowercase letters atop bars indicate significant differences ($P < 0.05$) among different nutrient sources within the same groundcover management treatment.

Fig. 3. Groundcover management system [i.e., shredded paper (SP), wood chips (WC), mow-blow (MB), and green compost (GC)] effects on soil bulk density over time from the top 6 cm within 0.75 m of the tree trunk in an experimental, organically managed apple ('Enterprise'/M.26) orchard on a silt loam surface soil in the Ozark Highlands region of northwest Arkansas. Different uppercase letters atop bars indicate significant differences ($P < 0.05$) between groundcover management treatments within the same year. Different lowercase letters atop bars indicate significant differences ($P < 0.05$) over time within the same groundcover management treatment.

treatments remains unknown, the continued application of green compost may lead to C saturation in the top few centimeters of the

mineral soil fraction (Gulde et al., 2008; Six et al., 2000). However, as a result of greater N concentrations, the amount of residue

applied, and Arkansas' climate, soil C sequestration should continue to be greater for the green compost than for the other groundcover treatments, where further increases in SOC might also be attributable to alternate soil C pools such as humus, POM, or microbial biomass in addition to C adsorbed to the mineral soil fraction.

Organic crop production systems have been shown to sequester soil N in conjunction with C (Bhogal et al., 2009; Hepperly et al., 2007) and the results of this study corroborate the assertion that sequestration of C and N are often concurrent (Himes, 1998; Stevenson, 1994), but this is among the first reports for perennial cropping systems in southern latitudes. Soil N sequestration under the green compost treatment was 0.25 Mg N/ha/year, whereas TN contents did not change over time under the other three treatments (Fig. 1). Although the volume and mass of wood chips and green compost applied to tree rows were comparable, the greater C:N ratio of the wood chips (i.e., 42:1; Mays, 2013) did not facilitate accumulation of N under wood chips as under the green treatment. Thus, greater soil TN was sequestered under the green compost, where more N was added to the system, than under the wood chip treatment.

Decomposability of the various groundcover management mulch materials, as interpreted by the C:N ratio of the added material, likely played a role in the varying magnitudes of soil property responses to groundcover management, particularly for TC and TN. By weight, wood chips in general are $\approx 50\%$ cellulose and 28% lignin (Holland et al., 1990), resulting in a greater C:N ratio and likely slower rate of decomposition than green compost material resulting from immobilization of N by soil microorganisms (Tisdale et al., 1993). In this study, the C:N ratio for the wood chips and green compost were 42:1 and 13:1, respectively (Mays, 2013). The shredded paper used in this study had the largest C:N ratio (i.e., 184:1; Mays, 2013) of all the groundcover management treatments applied and, as a result of its light weight compared with wood chips and green compost, less total residue mass was applied over the span of the study in the shredded paper compared with the wood chip and green compost treatments (Choi, 2009). The least total residue mass was applied in the MB treatment, an anticipated design issue, which was exacerbated by extreme drought in the last summer of the study when little plant material deposited into the tree row was usually visible after 3 weeks of application. However, the grass clippings of the MB treatment had the second lowest C:N ratio (i.e., 18:1; Mays, 2013) of the three other treatments, which made the MB material quite readily decomposable along with the green compost material. Therefore, based on the C:N ratios of the added materials alone (i.e., shredded paper > wood chips > green compost), it is reasonable that the largest significant soil C increase over time was achieved with the green compost, whereas

Table 1. Comparison of soil organic matter (SOM), total soil carbon (TC) and nitrogen (TN) concentration, and content among four groundcover management systems [i.e., shredded paper (SP), wood chips (WC), mow-blow (MB), and green compost (GC)] in an experimental, organically managed apple ('Enterprise'/M.26) orchard and a conventionally managed apple orchard on a silt loam surface soil in the Ozark Highlands of northwest Arkansas, Fayetteville, AR, 2012.

Soil property	Groundcover management system				Conventional orchard ^y
	SP	WC	MB	GC	
SOM (g·g ⁻¹)	0.03 (<0.01) ^z	0.03 (<0.01)	0.03 (<0.01)	0.06 (<0.01)	0.03 (<0.01)
TC (g·kg ⁻¹)	14.9 (0.9)	17.4 (1.4)	11.6 (0.4)	31.9 (2.9)	10.3 (0.6)
TN (g·kg ⁻¹)	1.2 (0.1)	1.4 (0.1)	1.1 (<0.1)	2.8 (0.2)	1.1 (0.1)
TC (Mg·ha ⁻¹)	12.4 (0.7)	13.2 (1.2)	10.2 (0.4)	24.3 (2.3)	13.1 (0.7)
TN (Mg·ha ⁻¹)	1.0 (<0.1)	1.0 (0.1)	1.0 (<0.1)	2.1 (0.2)	1.4 (0.1)

^zThe numbers in the parenthesis indicate the standard error of the sample;

^yThe conventionally managed orchard was managed as an apple cultivar trial (M.106 and M.26 rootstocks) from 1989 to 2012 and received herbicide for under-tree weed control and inorganic chemical fertilization following commercial recommendations. Data collection was conducted simultaneously in the conventional orchard and using the same sampling protocols as described for the organic orchard. Soil samples were collected from the top 7.5 cm for all soil quality indicators in Nov. 2011, except for soil organic matter, which was determined from samples collected from the top 6 cm in June 2012.

no significant increase over time was achieved with the MB as a result of the small amount of added material.

Others have shown increases in SOM when orchard floor management included the addition of mulches such as those used in this study. Peck et al. (2011) reported increases in SOM over time from both wood chip mulch and chicken manure compost. Wells (2011) reported poultry litter and crimson clover (*Trifolium incarnatum* L.) increased SOM concentration in a Georgia pecan [*Carya illinoensis* (Wangenh.) K.Koch] orchard with up to a 46% increase in SOM when litter and clover treatments were combined. Merwin et al. (1994) observed applications of straw mulch resulted in the largest increase in SOM content, whereas living mulches and chemical orchard floor management resulted in similar or decreased SOM over time. The living mulches would be comparable to the MB treatment in this study.

In a comparison among several mulches, Merwin et al. (1995) observed no significant differences between SOM accumulation after 2 years of wood chip and synthetic mulching. Although initial SOM values were not listed, Merwin et al. (1995) reported greater SOM for both orchards evaluated (4.7% to 6.3%) than that observed in this study. However, data summarized in Merwin et al. (1995) from a New York research site had previously been dedicated to apple production; thus, greater SOM would likely be expected from a perennially managed cropping system compared with that observed in a relatively young orchard system such as that investigated in this study and as a result of both climatic and soil differences. Differences in soil surface texture and seasonal environmental conditions (Stevenson, 1994) likely have large influences on soil property response to groundcover management treatments. Soil organic matter would likely be expected to be lower in the warm, moist environment of northwest Arkansas, which would favor relatively large SOM decomposition rates, compared with the cool moist environment in New York, which would favor comparatively lower SOM decomposition rates.

Considering the green compost treatment had the smallest C:N ratio and had the largest

mass of material added of all four groundcover treatments, potential concern may exist regarding the amount of N added in the green compost treatment. Choi (2009) and Rom et al. (2010) identified the possibility of nitrate leaching associated with green compost additions. Elevated nitrate levels have been detected in the 10- to 30-cm soil depth interval in this experimental, organic orchard (M. Savin, personal communication). Legitimate concerns could also exist for the potential for greater nitrous oxide emissions from the green compost compared with the other groundcover management treatments when conditions are suitable for denitrification, which could possibly offset any environmental benefits gained by the sequestration of soil C. Furthermore, overapplication of N in apple orchards has been shown to negatively affect growth and production by causing overly vigorous tree growth, poor fruit quality and color, and increased susceptibility to disease (Nielsen and Nielsen, 2003). The availability of N from the compost treatment was evident in early tree growth in this study (Rom et al., 2010).

The addition of organic compost has also been shown to facilitate soil C sequestration in apple orchards compared with conventional orchard management (Deurer et al., 2009; Glover et al., 2000). Furthermore, Amiri and Fallahi (2008) observed the greatest soil C concentration increase with applications of cow manure, whereas poultry manure applications resulted in lower soil C concentration increases. Increased microbial biomass C was observed when plant residues were applied as a groundcover management treatment (Goh et al., 2001), indicating conditions were improved for soil microbial activity when organic cultural practices were used, whereas microbial activity may have been diminished with conventional management, which often uses synthetic chemicals (Gunapala and Scow, 1998).

Although based only on an informal comparison of organic and conventional orchard soil samples, numeric differences in soil near-surface soil properties were evident between the organic and conventional orchards (Table 1). The green compost treatment had twice the SOM concentration in the organic than in the adjacent conventional

orchard; SOM concentration in the other three treatments was similar to that in the conventional orchard. Similarly, the green compost treatment had nearly twice the TN and TC concentration and content in the organic compared with that in the conventional orchard (Table 1). This observation may be related in part to reduced mobilization of N in the shredded paper, wood chip, and MB treatments than in the green compost treatment as a result of the relatively high C:N ratios of those treatments (Tisdale et al., 1993). Total soil C and N concentrations, but not TC or TN contents, under shredded paper and wood chip treatments were also numerically greater under organic compared with conventional orchard management (Table 1).

In contrast, the MB treatment under organic management had numerically similar or lower soil property magnitudes to that under conventional management (Table 1) possibly because a portion of soil N had been assimilated into vegetation growing within tree rows, whereas the conventionally managed tree rows were maintained by herbicides with a bare soil surface. In addition, the apples were not harvested from the conventional orchard and allowed to drop to the soil surface at the end of each season; thus, the fruit may have been a measurable source of recycled C and N typically unavailable in a commercial orchard in which all fruit is removed. Regardless of fruit removal, as wood chip and shredded paper mulching continues, soil TC and TN contents would be expected to increase and eventually equal or surpass TC and TN contents measured in the conventionally managed orchard. Results suggest that green compost amendments to trees in an organically managed apple orchard have the potential to sequester more soil C over time than under conventional orchard management.

Conclusions

The results of the research indicate that the use of various groundcover management systems as an orchard floor management tool can increase SOM, TC, and TN of mineral soils, thereby improving soil quality in an organically managed apple orchard on highly weathered soil of the Ozark Highlands. The

greatest increases in SOM, TC, and TN were associated with applications of green compost. Therefore, it appears that conditions required for soil C sequestration are best achieved with green compost additions as a result of accelerated formation of C and N-rich SOM. Consequently, soil conditions not initially ideal for the production of apples may be remediated over a relatively short time when amended with additions of groundcover management treatment mulches. Compared with conventional apple orchards managed with herbicides and soluble fertilizers, green compost, wood chip, and shredded paper treatment may result in improved soil quality, whereas soil properties under the MB treatment were numerically comparable to or lower than that in the conventional orchard. However, care should be taken in organic apple production to ensure nutrients are not overapplied, thereby protecting soil and water resources and maintaining the health of the orchard ecosystem. This study has implications regionally and to other similar environments, growing conditions, or soils and to both organic as well as conventional management systems.

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