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Groundcover Management System and Nutrient Source Impact Physical Soil Quality Indicators in an Organically Managed Apple Orchard

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By

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ABSTRACT

In March 2006, four groundcover management systems (GMS) and two nutrient sources (NS) were implemented for their ability to alter the soil physical condition of a newly established, organically managed apple (*Malus* x *domestica* Borkh.) orchard. Annual applications of municipal green compost (GC), shredded office paper (SP), wood chips (WC), and mow-blow (MB) grass mulch were utilized as GMS, and NS supplied to trees were from composted poultry litter (PL), a commercial organic fertilizer (CF), or an untreated control (NF) in a 4x3 factorial study. An established, conventionally-managed orchard was located adjacent to the organic research orchard on the same silt loam soil. Physical soil characteristics were measured from the conventional orchard providing a qualitative comparison of orchard management systems. Soil organic matter (SOM) concentration averaged 1.5% from 0 – 10 cm depth across all treatments at orchard establishment (2006). By 2012, SOM increased to 5.6% in GC, and SOM in MB, SP, and WC increased to 2.6%, 3.0%, and 3.2%, respectively. Commercial organic fertilizer and NF treatments with GC resulted in greatest SOM increases. The change in SOM impacted physical soil characteristics. Mow-blow treatments provided the least measured change in soil quality and served as a comparator to other GMS not measured in 2006. Significant increases in estimated plant available water, water stable aggregate formation, water infiltration rate, and saturated hydraulic conductivity were observed in GC. No differences were found in bulk density (BD) in 2006 from 0 – 6 cm, but BD decreased in following years for all GMS. All GMS treatments increased TC and TN concentrations from 2006 to 2011 in the top 7.5 cm soil layer, most significantly in GC. The greatest increases in TC and TN contents from 2006 were also observed in the GC treatments. Compared to the conventional orchard, GC most improved soil quality. Collectively, the soil quality indicators measured in this study show the addition of GMS and organic NS has improved soil quality since organic orchard establishment, and are a tangible means of meeting NOP requirements for improving soil quality in Ozark Highlands apple orchards, concurrent with production of certified organic crops.

This thesis is approved for recommendation
to the Graduate Council.

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TABLE OF CONTENTS

LIST OF FIGURES
CHAPTER 2

APPENDIX I

LIST OF FIGURES, CONTINUED
CHAPTER 3

LIST OF TABLES
CHAPTER 2

APPENDIX 1

LIST OF TABLES, CONTINUED
CHAPTER 3

APPENDIX 2

Chapter 1: Introduction and Literature Review

Agricultural scientists are becoming increasingly aware of production methods which degrade soils, and much has been written on the topics of soil quality and health. The terms soil quality and soil health are often defined similarly in scientific literature (Arshad and Martin, 2002; Doran et al., 1996; Doran, 2002; Hussain et al., 1999; Liebig, undated). In an agricultural context, soil heath refers to a soil's ability to function as a living system capable of sustaining crop productivity while promoting plant, animal, and human health (Doran et al., 1996). Soil quality refers to a soil's ability to function correctly in the capacity for which it is being used as well as sustaining ecosystem health (Karlen et al., 1997). Discussions of soil quality may include concepts of soils being dynamic and responsive to changes in management, and include an emphasis on building or improving the condition of the soil. Additionally the concept of soil quality has been aligned with the function of quantifiable physical and chemical soil characteristics which support biological soil activity and plant physiological growth requirements (Dexter, 2004; Doran et al., 1996).

An "unhealthy" soil may be capable of supplying a crop's physiological needs. Coupled with fertilization, irrigation, and pesticide inputs, satisfactory yields are realized on soils which would otherwise support limited crop growth. Depending, therefore, on one's perspective, a given agricultural soil might be classified both as unhealthy and of suitable quality, if specified crop yields are the measure by which quality is determined. However, the long-term sustainability of high input production systems remains questionable at best.

Seybold et al. (1998) assign a number of basic environmental functions performed by quality soils, including maintenance of physical soil properties, cycling of nutrients between the soil and environmental sources, filtering and buffering chemical and biological inputs, ensuring adequate water and solute flow throughout the solum, and maintenance of organism biodiversity and soil productivity. Doran et al. (1996) suggest that poor soil quality can be correlated with poor human health. Aerosol sediment inhaled by humans may lead to respiratory disorders, and nitrate-contaminated surface or groundwater is associated with serious health disorders including blue baby syndrome. Agricultural chemicals such as pesticides may be assimilated by plants during growth and then be consumed when the crop is eaten (Doran et al., 1996). Additionally, crops grown on soils with inadequate mineral nutrient levels, or on soils with an unsuitable pH, may not receive adequate amounts of nutrients, thereby decreasing yields and the total nutritive value of the crop (Hornick, 1992).

Quantification of soil characteristics makes evaluation of soil quality an objective exercise. Arshad and Martin (2002) define soil quality indicators as *"measurable soil attributes that influence the capacity of soil to perform crop production or environmental functions"*. Measurable soil quality indicators include physical, chemical, and biological variables such as bulk density, water infiltration rate, water holding capacity, internal drainage, percent organic matter, soil aggregation, penetration resistance, and the ability of the soil to store and release nutrients as needed by crops. Similar lists of assessable soil quality indicators have been proposed by Arshad and Coen (1992), Doran and Parkin (1994) and Larson and Pierce (1994). These soil properties alone do not indicate the soil's capacity to perform a desired function. Rather, by measuring a selection of specific soil quality indicators, inferences may be made regarding a soil's ability to serve a given set of functions over time (Seybold et al., 1998).

In orchards, soil management strategies may be quite diverse depending on the location of the orchard. Obviously, the soil is the medium in which the tree is anchored. However, soils within the tree row must also receive and exchange nutrients between roots and the soil matrix, receive water from precipitation or irrigation, and act as a buffer between environmental conditions and the root system. In conventionally managed orchards, soil in the tree row may receive agricultural chemicals intended to kill a variety of organisms competing with the tree. Between rows, soils are subject to traffic by mowing, spraying, and harvesting equipment. These soils may be plowed to address weed control, pest management concerns, or perhaps to improve physical condition.

An unintended effect of conventional orchard management practices on soil quality may include a decrease in soil organic matter because of limited plant biomass returns to the soil (Sanchez et al., 2003). Additionally, soil fauna such as earthworms are susceptible to high levels of copper, and elevated soil copper concentrations associated with repeated application of fungicide sprays can have a detrimental impact on earthworm numbers (van Rhee, 1976). Thus, orchard soils must be resilient enough to withstand production-induced stresses and remain capable of serving host of functions which are challenged by orchard management.

An important consideration in organic orchards pertains to management of competitive vegetation and supplying needed tree nutrition. These objectives are sometimes met using groundcover management systems (GMS) including living mulches and mulches derived of plant residues. Assorted mulches and cover crops have been the subject of previous research (Deurer et al., 2009; Granatstein and Mullinix, 2008; Rom et al., 2010), and groundcovers may impact orchard soil quality over time. Generally, decomposition of mulches increases soil organic matter (Merwin et al., 1995), a soil constituent which impacts water infiltration, aggregation, penetration resistance, and nutrient retention (Anderson and Coleman, 1985; Carter, 2002; Lado et al., 2004; Tisdall and Oades, 1982). Strategies which enhance soil humification may result in increased yields and profitability. Indeed, organic production methods have shown to be superior to conventionally managed orchards in these respects (Reganold et al., 2001).

Management options available for organic production systems are constrained compared to those used in conventional orchards. United States National Organic Program (NOP) standards prescribe allowable treatments for procedures including fertilization and pest management. National Organic Program standards require growers to develop and implement an Organic Management Plan demonstrating tangible soil improvement strategies. Growers must attend to the "*physical, chemical, and biological condition of soil*" and "*manage crop nutrients and soil fertility through rotations, cover* *crops, and the application of plant and animal materials*" (USDA NOP §205.203). In perennial crops such as apples, the application of mulches to suppress growth of competitive vegetation and supply nutrients needed by trees for appropriate growth is a practical means of meeting both NOP requirements listed above. Therefore, determining the most appropriate indicators of soil quality and health, and how various groundcover management systems impact these indicators, would be useful for scientists and organic producers alike. Management goals may be set based on continual evaluation of quantifiable soil quality characteristics which result in healthier, higher quality soil as time passes.

Apple production has a long history in the Ozarks Highlands of northwest Arkansas. Washington and Benton Counties were among the foremost apple-producing counties in the United States in the 1890's (Strausberg, 1989). By the mid-twentieth century, apple production had declined in Arkansas due to challenges in apple culture. Production in Benton, Boone, Carroll, Cross, and Washington Counties totaled 706,000 bushels, and Arkansas ranked 25th in apple production in 1949 (McPeek et al., 1951). As the U.S. apple industry continued to shift production to the Pacific Northwest, apple orchard numbers in northwest Arkansas also continued their descent. However, there has recently been a revival of interest in orchard establishment in this region, much of which is managed organically and on a small scale, and caters to local markets. Further, the public is becoming more aware of the fundamental role soil quality plays in the production of quality crops, and local apple producers could benefit from data showing the impacts of GMS and organic nutrient sources (NS) on orchard soil quality.

Soil quality indicators for apple orchards have been studied in the northwestern United States (Glover et al., 2000; Reganold et al., 2001). Further, universities in the mid-western and eastern United States have developed general scoring metrics useful for managing soil quality, thereby enabling growers to make educated decisions regarding soil management (University of Wisconsin, undated; Evanylo and McGuinn, 2009; Gugino et al., 2009). In the southeastern US, no research has shown the impact of organic GMS and NS on soil quality in apple orchards. A high percentage of southeastern US soils, including the Ozarks Highlands of northwest Arkansas, are highly mineralized with low soil organic matter, acidic, and have lower natural fertility than other productive United States soil orders (Brady, 1990). Consequently, research on soil quality indicators pertinent to efficient, prolific organic apple production in other US geographies may not apply to soil conditions confronted by growers in the northwest Arkansas.

Soil Quality Indicators

Geography, climate and topography, and past and present land use may influence soil quality indicators. For Arkansas organic apple production systems utilizing mulches as a GMS and organic NS, a range of soil quality indicators are possible, but a list of pertinent physical and chemical characteristics may be reduced to the following:

1. soil organic matter concentration, due to its impact on other soil properties
2. formation of water stable soil aggregates
3. water infiltration rate
4. plant available water capacity
5. bulk density
6. soil C and N quantities

Quantification of these properties provides researchers the ability to analyze soil conditions and make recommendations toward management of GMS and NS which serve to improve orchard soil quality.

Soil Organic Matter

When evaluating the sustainability of organic orchard floor management practices, the addition of organic matter to the soil, particularly in the form of mulches, is a suitable practice. Hot summer temperatures and dry soil conditions create high evapo-transpiration rates which can lower rhizosphere water reserves (Taiz and Zeiger, 2010). Such conditions are typical of summers in northwest Arkansas, and mulches provide efficient conservation of irrigation and rainwater, thereby reducing future irrigation requirements in some situations and making the best use of applied irrigation water (Granatstein and Mullinix, 2008).

Returning crop residues or other plant matter to the soil directly impacts the SOM fraction and soil C:N ratio (Himes, 1998). Studies show positive impacts on measurable chemical and physical soil properties such as cation exchange capacity, plant nutrient concentrations and exchange, microbial activity, soil aggregation and structure, soil temperature, and soil aeration (Merwin et al., 1994; Reganold et al., 2001; Rice et al., 2007; Sanchez et al., 2003). Soil microbial activity and larger soil fauna populations such as earthworms and nematodes are also likely beneficiaries of and contributors to soils with increased C content.

Soil organic matter (SOM) reduces soil compaction, bulk density, and penetration resistance in a number of ways. Humic materials and polysaccharides generated from bacteria and fungi, in addition to the presence of fine roots and hyphae, stimulate the creation of stable soil aggregates (Tisdall and Oades, 1982) and thus increase soil porosity (Deuer et al., 2009). Organic materials are elastic as well, stretching and bending in response to internal soil forces, and their presence in the soil absorbs forces which might otherwise compact soil (Soane, 1990). Further, the bulk density of SOM is lower than the bulk density of mineral soil particles (Scott, 2000). Increasing SOM lowers soil bulk density and penetration resistance through a dilution of denser mineral soil particles.

Many southeastern US soil orders have high clay content and may be prone to compaction. Increasing SOM may help offset challenging conditions inherent to mineral orchard soils, or created by orchard management practices. Orchard soils are susceptible to compaction due to the nature of the production system and the weight of spraying, mowing, and harvesting equipment utilized therein. Soil texture also influences the probability of soil compaction, leaving finer texture soils at greater risk of succumbing to a loss of macropores (Dexter, 2004). A consequent decline in root growth and exploration, tree growth, and fruit development has been noted in compacted soils (Arshad and Coen, 1992; Stevens, 1994). Hence, the introduction of organic matter to orchard soils is likely to benefit tree growth and fruit yield by improving physical soil quality (Glover et al., 2000; Reganold et al., 2001)

Water-Stable Soil Aggregates

Soil aggregates may be defined as a "group of primary particles that cohere to each other more strongly than to surrounding soil particles (Kemper and Rosenau, 1986). Good aggregation in agricultural soil is commonly associated with higher rates of water infiltration, greater tilth, decreased incidence of crust formation at the soil surface after heavy rainfall or irrigation, decreased bulk density, and decreased soil erosion. Well-structured soils with a variety of stable aggregate sizes are favored by apple trees, and tree performance will likely be retarded if the soil is compacted and has a high bulk density (Barden and Neilsen, 2003).

The addition of organic matter to soils is important to achieve a well-aggregated soil. Inert groundcovers appropriate for organic apple production include woodchips, municipal compost, paper products, mow-blow grass clippings (Rom et al., 2010). Other researchers have utilized hay-straw and living ground covers (Granatstein and Mullinix, 2008; Merwin et al., 1994, 1995, 1999; Sanchez et al., 2003).

Groundcover C/N ratios vary, but all sources listed provide some level of C to the soil and may increase total soil C over time. Sanchez et al., (2003) reported over 20% greater total C in a cherry orchard managed with compost. Deurer et al. (2008) documented approximately two times greater microbial biomass C and 27% lower soil aggregate stability in organically-managed apple rows as compared to that observed in integrated apple orchard rows. Further, a study on wheat straw mulching rates in southwestern Spain demonstrated that aggregate stability increased linearly with increasing application rates (Jordán et al., 2010). Similar results are noted by Mulumba and Lal (2007) whose work revealed increased porosity and aggregate stability as mulch application rates increased from 0 – 16 $Mg \cdot ha^{-1} \cdot yr^{-1}$.

Factors influencing aggregate formation in most soils include microorganisms, environmental variables, inorganic binding agents, soil fauna, and roots (Six et al., 2004). In order for soil aggregates to remain intact once formed, external forces applied to the aggregate must be lower than the internal forces binding the individual aggregate particles (Allison, 1968). Such forces include abrasive activity exerted by physical manipulation of soil during tillage or erosive activities and entry of water into the aggregate (Kemper and Rosenau, 1986). Carter (2002) proposed that soil aggregates store and protect organic soil constituents and also serve as a reservoir of nutrients and energy available to crops during their growth.

At the most basic level, soil aggregation involves the flocculation of clay particles around particulate organic matter (Jastrow and Miller, 1998) and is a function of hydrogen and van der Waals bonding between mineral soil particles and organic gums exuded by a host of soil organisms (Tisdall and Oades, 1982). Surface and cohesive tensions in the air and liquid phases of the soil matrix also serve a role in the formation of soil aggregates (Kemper and Rosenau, 1986). Larger associations of very small aggregates may be assimilated by physical restraint of plant roots and fungal hyphae as well as the exudates of these organs which glue microaggregates into larger, more cohesive macroaggreagates (Tisdall and Oades, 1982; Thomas et al., 1993; Tisdall, 1991). Earthworm activity is instrumental in creating stable soil aggregates (Barois et al., 1993; Lee and Foster, 1991; Stork and Eggleton, 1992; Winsome and McColl, 1998), and aggregate stability is associated with the stability of their casts and tunnels (Ehlers, 1975).

Tisdall and Oades (1982) categorize soil aggregates as either microaggregates (less than 0.25 mm) or macroaggregates (greater than 0.25 mm). Both are formed by three classes of binding agents: i) transient, consisting of polysaccharide compounds subject to rapid bacterial decomposition; ii) temporary, consisting of small roots and fungal hyphae that last a few weeks or months and form macroaggregates; and iii) persistent, containing complexes of aromatic compounds and polyvalent cations which primarily function as mineral soil particle cementing agents. Microaggregates are fixed by polysaccharides and organo-mineral complexes to form relatively stable structures largely unaffected by soil management practices (Tisdall and Oades, 1982; Six et al., 2004). Macroaggregates are usually bound by plant roots and fungal hyphae and tend to decline in number as soil organic matter content declines (Tisdall and Oades, 1982; Jastrow and Miller, 1991; Karlen et al., 1992).

Oades (1984) proposed that microaggregates may be formed within macroaggregates. As roots and hyphae which penetrate and surround macroaggregates decompose, clay minerals adhere to fragments of particulate organic matter and form the core of a new microaggregate. Using $^{13}C^{15}N$ labeled wheat straw, Angers et al. (1997) corroborated Oades' hypothesis by demonstrating that ^{13}C first accumulated in macroaggregates as the straw decayed. However, as time passed and macroaggregates decomposed, ^{13}C was readily detected among microaggregates, indicating that microaggregates were formed from within macroaggregates upon macroaggregate decomposition.

For optimum plant growth, soils should consist primarily of relatively stable macroaggregates (Nichols and Toro, 2011). Macroaggregates create larger pores which facilitate increased air and water movement through the soil profile (Deurer et al., 2009), thereby affecting the time required for a soil to attain and remain at field capacity after wetting, as well as providing adequate gas exchange between roots and the soil matrix. Deurer et al. (2009) noted that stable macropores created in soils with a high percentage of stable macroaggregates produce less N_2O, a product of denitrification and a greenhouse gas, due to enhanced drainage and adequate soil O_2. Other beneficial aspects of well-aggregated soils include protection of soil organic matter within the aggregate (Tisdall and Oades, 1982), increased richness and diversity of the soil microbial community (Flieβbach et al., 2006), potential for increased availability of plant nutrients (Linquist et al., 1997), habitat for soil organisms (Franzluebbers, 2002), and a reduction of surface crusting, runoff, and soil erosion (Carter, 2002; Karlen et al., 1992; Kemper and Rosenau, 1986).

Water Infiltration Rate

Two terms are commonly used to describe water movement through soils. Infiltration refers to the entry of water through the soil surface and into the soil profile, while internal drainage encompasses the redistribution of soil water within a soil column (Scott, 2000). From a soil quality standpoint, rate of water infiltration is important. The extent to which water can enter a soil largely determines the amount of water left over as runoff, and greater runoff increases soil erosion (Le Bissonnais, 1996; Lado et al., 2004; Stern et al., 1991; Wakindiki and Ben-Hur, 2002). Stable aggregates at the soil surface improve infiltration by slowing crust formation during a rain or irrigation event, and the link between soil aggregation and increased infiltration is well documented (Albrecht and Sosne, 1944; Le Bissonnais, 1996; Le Bissonnais and Arrouays, 1997; Boyle et al., 1989; Freebairn et al., 1991; Lal, 1993). The arrangement of macroaggregates with respect to one another creates macropores (Deurer et al., 2009), and pore size and porosity of soil largely dictate the rate of water drainage down the soil profile (Arshad and Coen, 1992; Scott, 2000). Other factors impacting infiltration of water include initial soil water content, soil texture, clay type, vegetative cover, rainfall intensity, slope, and air entrapment (Scott, 2000).

In perennial tree crops such as apples, control of competitive vegetation may be achieved by application of herbicides and/or soil tillage, and orchard soils may be subject to soil erosion. However, orchards may also be managed with plant residue-based groundcovers. Mulches used to control competitive plant species in orchards may have the potential of increasing soil aggregation due to their high OM content and in turn increase macroaggregate and macropore formation by increasing earthworm activity (Ehlers, 1975). Using a blue dye to trace infiltration through earthworm channels in a loess soil, Ehlers (1975) documented significant channel formation to depths of 60 cm, and as deep as 180 cm on untilled soils, whereas the dye showed no channel formation on tilled soil. Collectively, Ehlers calculated all earthworm channels contributed to infiltration of more than 1 $mm \cdot min^{-1}$ in untilled soils. Merwin et al. (1999) found vole activity to be greatest in association with crownvetch and hay-straw mulch. The burrowing activity of these rodents can significantly affect infiltration rate by creating large macropores, and rodent burrows may contribute to differences in water infiltration rates between organic and conventionally managed orchards.

Lado et al. (2004) found that infiltration rate increased and dispersivity of clay decreased with increasing SOM. In a comparison of organic, conventional, and integrated orchards, Goh et al. (2001) showed higher infiltration rates in the organic production system and attributed this to organic mulches in the tree rows. Similarly, Granatstein and Mullinix (2008) observed highest infiltration rates under shredded paper mulch, wood chip mulch, and chopped alfalfa hay, all of which reduced irrigation requirements. Mulches likely provide a double benefit of allowing greater water infiltration into the soil and then retaining water under the mulch layer for an extended period of time. After six years of orchard research, Merwin et al. (1994) documented decreased SOM and water infiltration in plots treated with pre-emergence herbicides and tillage as compared to those managed with living and residual mulches. Thus, utilization of GMS and NS which increase SOM, and the ensuing processes of soil aggregation and macropore formation, may lead to an overall increase in water infiltration rates.

Plant-Available Water

The addition of organic matter to mineral soil is recognized as a beneficial practice to plant-available soil water (Bhogal et al., 2009; Hudson, 1994; Jordán et al., 2010; Mulumba and Lal, 2007). For much of the 20th century this was not understood, and Hudson (1994) provides a thorough review of the misconceptions surrounding the view that increases in SOM decrease plant-available water. Plant-available water capacity is defined as the amount of water held in soil between field capacity and the permanent wilting point (Soil Science Society of America, 2012). In addition to SOM concentration, a soil's water holding capacity is determined by soil texture, with finer texture soils capable of storing more water than coarser textured soil (Brady, 1990; Scott, 2000). However, as organic matter is added to soil, available water increases across a variety of textures, and plant-available water has been shown to approximately double as SOM increased from 1.0% to 3.0% (Hudson, 1994).

Organic matter from crop residues, manures, composts, etc., acts much like a sponge, by absorbing water draining through a soil column. Studies have shown that addition of SOM is beneficial toward improving physical soil properties, including plant-available water capacity. In a study of the effects wheat-straw mulch on soil physical properties, Jordán et al. (2010) determined mulch applied at rates between 5 and 15 Mg/ha increased available water, by as much as 18%, while mulches applied at rates below 5 Mg/ha resulted in little difference from the control. Mulumba and Lal (2008) obtained similar results with wheat-straw mulch, and they concluded plant-available water increased as mulch application rates increased. However, their data showed greater benefit at lower application rates, such that even at low rates, mulching significantly increased plant-available water

The form of organic matter applied may also impact the extent to which soil hydraulic properties are affected. Bhogal et al. (2009) found manure applications increased plant-available water and pore space while decreasing soil bulk densities, but crop residues had little effect on these soil variables. Hati et al. (2007) established a positive correlation between plant-available water and the application of manure applied in conjunction with 100% of the N, P, and K requirements, applied as inorganic fertilizers, of a soybean-wheat-maize rotation, indicating the combination of manure and inorganic fertilizers increase plant-available water.

Bulk Density

Bulk density (BD) has been listed in scientific literature as an indicator of soil and environmental quality (Arshad and Coen, 1992; Doran et al., 1996; Lal and Kimble, 2001), and BD measurements were included in studies examining root penetration (Grossman and Reisch, 2002) and soil water movement (Lal and Kimble, 2001; Saxton and Rawls, 2006). Bulk density is defined as the mass per unit volume of soil. Bulk density is calculated after the sample has been oven dried and includes both solid mineral components and pore space (Grossman and Reinsch, 2002). As a soil becomes more porous, BD decreases, and lower BD is commonly observed in soils with high clay or organic matter contents (Scott, 2000). Compacted soils with lower porosity, such as is common with tillage pans, fragipans, and in soil found at greater depths in the profile, commonly has greater BD (Scott, 2000).

Applications of organic matter including land-applied mulches, incorporation of green-manure crops, livestock manure, and composted plant residues increase pore space and as a consequence reduce soil BD (Celik et al., 2010; Jordán et al., 2010; Soane, 1990; Stock and Downes, 2008). In no-tillage or reduced-tillage cropping systems, soil C levels are often elevated as compared to conventional tillage (Franzluebbers, 2002) while porosity increases and BD decreases (Fountas et al., 2011).

It should be noted that following tillage, soil BD and porosity values may be comparable to or even more favorable than those observed in no-tillage or heavy-mulch production systems, but compaction and crusting of surface soil layers occurs following rain events, reducing porosity and increasing surface runoff in tilled areas (Merwin et al., 1994). Thus, additions of organic residue amendments likely benefit cropping systems by increasing soil water retention (Emerson, 1995), plant available water (Jordán et al., 2010), and improve water infiltration rate (Lado et al., 2004), all of which are related to long-term increases in porosity and reduction of BD (Kay, 1998).

A significant amount of orchard GMS research has occurred within the last two decades, and soil quality indicators measured therein have generally shown the quality of orchard soils to improve as a result of utilizing living or plant residue-based mulches. Specifically, Goh et al. (2001) noted organically-managed apple orchards in New Zealand which implement grassed allies and tree rows have lower soil BD than conventionally-managed orchards whose tree rows routinely receive herbicide applications. Glover et al. (2000) observed lower soil BD and higher porosity values in organic apple production systems than in conventional and integrated orchards. Conversely, Granatstein and Mullinix (2008) found no significant differences in BD between living and residue-based groundcovers and a bare ground control.

S**oil C and N**

Soils serve as significant reservoirs of C and contain well over two times the amount stored in atmospheric and biotic pools (Lal et al. 1998c). Carbon dioxide (CO_2), a greenhouse gas, is released in large quantities from anthropogenic sources such as manufacturing and industrial centers, machinery and vehicles, and power plants utilizing fossil fuels, all of which are commonly attributed to an apparent increase in global temperatures. Agricultural land management practices, primarily soil tillage, may be overlooked as a contributor to elevated atmospheric levels of CO_2, but the degradation of SOM associated with land cultivation, and the subsequent mineralization and release of carbon, has probably contributed to the warming phenomenon currently documented by climatologists. Utilizing agricultural land management strategies to sequester atmospheric C into stable forms of SOM, thereby potentially reducing the net contribution of CO_2 from agricultural production systems, is a tangible means of combating global warming (Lal, 2004).

Sequestration of C into soil is also valued as a means of increasing soil quality (Doran et al., 1996; Evanylo and McGuinn, 2009; Gugino et al., 2009) due to enhancement of physical and chemical soil characteristics such as available water capacity, aggregation, porosity, bulk density, and cation exchange capacity. Using these and other soil characteristics as indicators of soil quality, numerous studies spanning approximately two decades document the positive effects of increased SOM on soil productivity and suitability for crop production.

The positive effects of SOM on soil productivity and tilth have been long recognized by soil scientists and crop producers alike. Farmers' utilizing no-tillage cultural methods note field-observable changes in soil characteristics, compared to conventional tillage, including reduced soil erosion, increased stability of long-term fertility programs, increased water infiltration, increased water availability, decreased BD, and decreased soil crusting, all of which are attributed at least in part to increased soil C levels (Bhogal et al., 2009; Kimble, 2007). Conversely, conventional tillage and management practices tend to decrease soil C content and reverse the benefits associated with higher soil C levels.

Carbon is found in soils in organic and inorganic forms. Soil organic carbon is most prevalent in arable land, with soil inorganic C largely restricted to its carbonate forms and more common in semi-arid climates (Lal et al., 1998c). Soil organic C content, the principle component of SOM, is dependent on agricultural land management strategies which either serve to aggrade or degrade SOM. Aggrading processes are those which permit a long-term buildup of soil C and include use of cover crops or living mulches, plant residue-based mulches, additions of manure, and reduction or elimination of soil tillage, while processes which degrade soil carbon include intensive tillage and soil erosion (Lal et al. 1998b). Research on no-tillage or reduced-tillage cultivation and land application of manures/mulches has shown positive impacts on soil characteristics affecting tilth and productivity and is 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) as compared to conventional tillage (Anderson and Coleman, 1985), or conventional tillage coupled with application of agricultural chemicals (Fountas et al. 2011; Merwin et al. 1994) which do not favor accumulation of soil C. Further, testimonials from growers indicate field-observable improvements in soil quality when intentional efforts were made to increase soil C content (Kimble, 2007).

Stable, decomposed SOM, also known as humus, is derived of heterogenous plant matter retained on the soil surface, and soil humus content may be affected by intentionally placing plant residues on the soil for incorporation or placed adjacent to a crop, serving as mulch. Humification of plant debris, a process mediated in large part by soil microorganisms, is a sequence of steps through which plant tissue degrades and is then reorganized into more stable compounds (Brady 1990). Labile components of particulate organic matter, such as polysaccharides, are readily utilized by soil microorganisms, while more resistant plant tissues such as lignin and cellulose are decomposed relatively slowly (Tisdall and Oades, 1982). The products of this decomposition process are polymerized into new organic (humified) compounds which are more resistant to bacterial degradation than fresh organic matter (Brady, 1990).

Humus is approximately 58% organic C by weight, with an organic C to humus ratio of about 1:1.7 (Brady, 1990; Stevenson, 1994). Significant amounts of C may comprise a hectare furrow slice of soil whose management has provided for aggradation of soil C. The average proportion of C/N/P/S in soils is approximately 140:10:1.3:1.3, and these elements are predominantly held in the soil in their organic forms in more humid geographies (Stevenson, 1994). Since the humification of plant residues is mediated by microbial activity, increases in soil C are associated with notable increases in soil N (Himes, 1998).

During decomposition of organic matter, bacterial production of extracellular polysaccharides and an assortment of other mucilages associated with microbial and fungal activity cause clay and silt-size soil particles to adhere to plant residue (Jastrow and Miller, 1998). Fine plant roots and fungal hyphae further enmesh the decomposing residue to form soil macroaggregates (Tisdall and Oades, 1982; Tisdall, 1991) approximately as stable as the plant residue at their cores (Golchin et al., 1998). As the residue within macroaggregates decomposes, they are reduced to smaller and smaller microaggregates whose stability increases with decreasing aggregate size (Golchin et al., 1998) and whose recalcitrance is largely due to physical entrapment of soil C within the clay and silt encrusted microaggregates (Jastrow and Miller, 1998; Kay, 1998; Lal, 2004). Microaggreagates are then formed within macroaggregates (Tisdall and Oades, 1982; Denef et al., 2007; Six et al., 2012), and disturbances such as tillage which fragment and accelerate the degradation of macroaggregates may reduce the formation of stable microaggregates, thereby decreasing soil C content over time (Six et al., 2012). Thus, an understanding of soil aggregation is helpful when evaluating soil C mineralization and sequestration, and soil management practices which sequester more C than is lost to mineralization should favor aggregation of soil.

Macroaggregates are primarily comprised of particulate organic matter, also designated as the light fraction of SOM (Wander et al., 1994), and are an important reservoir of soil C. Macroaggreagtes have little if any association with mineral soil particles (Kay, 1998) and may contain particulate organic matter. Particulate organic matter is an important contributor to soil fertility due to its cation exchange capacity and inherent concentration of plant nutrients (Tisdale et al., 1993). However, the light fraction does not greatly contribute to stable soil C pools because of its labile nature and susceptibility to microbial degradation. Thus, elevated levels of soil C held in macroaggregates may benefit seasonal crop production, but a large portion of this C may be mineralized quickly and not contribute greatly to the formation of water-stable soil aggregates and sequestration of soil C in the short term.

The most stable forms of soil C are stored in 2 - 50 µm particles, including the smallest microaggregates and the silt-plus-clay fraction of soil (Six et al., 2012), and have developed over a period of years. Stable forms of soil C are commonly occluded within microaggregates, as a result of production of microbial mucilages associated with decomposing plant or microbial residues and subsequent encrustation of these residues with clay particles (Hassink, 1997; Six et al., 2000; Balabane & Plante, 2004; Denef et al., 2007; Virto et al., 2010).

In a study comparing the effects of cropping management on soil C and N contents, Lal et al. (1998a) determined tall fescue and smooth bromegrass cover crops elevated soil C content by 18.5% and N content by 12.5% compared to a corn-soybean rotation, and increased fertilizer rates enhanced total soil C sequestration by replacing nutrients removed with the harvested crop. In another study evaluating the effects of fertilization on grassland ecosystems, Nyborg et al. (1998) found C increased significantly in the light SOM fraction of grassland soil, particularly when N and S fertilizers were applied, while there was greater variability in total soil C content. Further they determined that when N and S were applied at a 10:1 ratio, 65 kg of C was sequestered, while no C sequestration occurred when N and S were applied alone. Thus, the rate at which soil C content increases may be reduced by low soil macronutrient levels, particularly when soil N is lacking.

Research has shown soil C saturation eventually occurs with heavy applications of organic matter. Gulde et al. (2008) determined stable soil C sequestration plateaued in all aggregate sizes <2000 µm when manure applications reached 120 Mg ha^{-1} yr^{-1}, and only the largest water-stable macroaggregates (>2000 µm) increased in soil C when application rates were increased to 180 Mg ha^{-1} yr^{-1}. They attributed this increase to elevated levels of particulate organic matter within the larger macroaggregates. These results support Hassink's (1997) determination that silt and clay fractions of sandy, grassland soils eventually reached a maximum level of C saturation. In a corn (*Zea mays*) and annual winter cereal rotation, Chung et al. (2008) reported greater C saturation in small macroaggregates (2.0 to 0.25 mm) than in the microaggregate size fractions (<0.25 mm) and silt-plus-clay fraction (<0.053 mm) under both no-tillage and moldboard plow cultivation systems. They attributed this observation to lower total C saturation potential of microaggregates and the silt-plus-clay fraction, with saturation of the smaller soil units achieved with lower C inputs. The same study reported that tillage systems affected C saturation potential per unit of soil C input. Moldboard plowing promoted decomposition of SOM and suppressed the soil's ability to sequester C. As a result soil C levels increased per unit of C input under no-tillage management.

Effects of soil management on soil C levels may be further pronounced relative to site geography. The climate of the southeastern United States does not permit soil C to attain the contents typically observed in northern latitudes, due to hot summer temperatures, higher rainfall, and consequent increases in SOM decomposition rates. Soil test results commonly reveal low SOM content, and accordingly, soil quality indicators such as BD, water infiltration rate, and soil fertility may be negatively affected for cropping. Increasing soil C content of such soils is possible when utilizing production methods which introduce large amounts of C into the soil, and followed by managing the soil in such a way that C is not lost or degraded, as in organic production systems (Deurer et al, 2008).

In perennial cropping systems, such as organic apple production, annual tillage is not required for desirable growth and may not be the most viable option for controlling competitive vegetation due to standards set forth by the NOP (USDA-AMS, NOP § 205.203). However, numerous studies have shown that plant residue-based mulches are effective at controlling weed growth while also benefitting soil quality (Glover et al., 2000; Granatstein and Mullinix, 2008; Granatstein et al., 2010 Reganold et al., 2001), a requirement established by NOP standards. Some mulch types may also effectively eliminate the need for fertilizer additions and are therefore a satisfactory means of providing nutrients to the tree (Merwin et al., 1995; Rom et al., 2010; Sanchez et al., 2003) while meeting NOP requirements for improving soil quality. Residual mulches are a source of C, and utilized long-term, they may serve to sequester C and increase soil C content in organic production systems.

Such aggradation of soil C has been noted in forest soils (Johnston et al., 1996) where mulching occurs naturally as litter accumulates on the soil surface. Similar C accumulation has been observed in agroforestry systems utilizing trees and alley cropping (Lulu and Insam, 2000). Orchard systems, including apples, are effectively managed as an alley crop, and it is reasonable to suggest significant amounts of C may accumulate in orchard soils.

In two New Zealand apple orchards, Deurer et al. (2008) found that organic management with green waste compost led to conservation of total soil C and an increase of labile soil C in the tree row. Goh et al. (2001) determined significantly greater microbial biomass C in organically-managed orchards than in conventionally-managed orchards and greater microbial biomass C and N concentrations in the top 50 cm of soil than in the 50 – 150 cm portion of the soil profile. Likewise, Glover et al. (2000) measured greater microbial biomass C and N and significant increases in soil organic C in organic and integrated apple orchards as compared to conventionally-managed orchards over a four year time period.

In organic orchards, heavy in-row plant-residue based mulch applications may increase soil C content and further enhance C sequestration (Deurer et al., 2008). Additional research addressing changes in the soil C balance in orchard soils is limited, and no research has been located indicating the potential for C sequestration in organically managed southeastern US orchards.

Objectives

The primary objective of this experiment was to determine the impact of four GMS and two NS on the previously discussed soil quality indicators in an organic apple orchard in northwest Arkansas. It was hypothesized that GMS and NS would impact soil properties within the tree row. To ascertain the impact of GMS and NS on orchard soil quality, the goals of the project were pursued as follows:

- To determine the effects of GMS and NS treatments on formation of water stable soil aggregates.
- To calculate water infiltration rate as affected by GMS treatments.
- To estimate plant available water capacity as affected by GMS and NS treatments.
- To determine changes in soil BD after six years of GMS and NS treatments.
- To determine changes in SOM and total soil C and N content in the first six years following orchard establishment as affected by GMS and NS treatments.

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Chapter 2: Groundcover management and nutrient source impacts soil quality indicators in an organically managed apple orchard

[z]This paper is formatted for submission to HortScience.

Abstract

In March 2006, four groundcover management systems (GMS) and two nutrient sources (NS) were implemented for their ability to alter the physical condition of newly established, organically managed apple (*Malus* x *domestica* Borkh.) orchard. Annual applications of municipal green compost (GC), shredded office paper (SP), wood chips (WC), and mow-blow (MB) grass mulch were utilized as GMS, and NS supplied to trees were from composted poultry litter (PL), a commercial organic fertilizer (CF), or an untreated control (NF) in a 4x3 factorial study. An established, conventionally-managed orchard was located adjacent to the organic research orchard on the same silt loam soil. Physical soil characteristics were measured from the conventional orchard providing a qualitative comparison of orchard management systems. The soil organic matter (SOM) fraction averaged 1.5% from 0 – 10 cm depth across all treatments at orchard establishment in 2006. By 2012, SOM increased to 5.6% in GC, and SOM in MB, SP, and WC increased to 2.6%, 3.0%, and 3.2%, respectively. The change in soil organic matter impacted physical soil characteristics. Mow-blow treatments provided the least measured change in soil quality and served as a comparator to other GMS not measured in 2006. Significant increases in estimated plant available water was noted in treatments receiving GC applied alone (18.1%) or in combination with commercial fertilizer (17.7%). No differences were found in bulk density (BD) in 2006 (1.34 $g{\cdot}cm^{3}$) from 0 – 6 cm, but BD decreased in following years for all GMS. Most significant reductions occurred in WC (1.01 $g{\cdot}cm^{-3}$) and GC (1.02 $g{\cdot}cm^{-3}$) treatments. Green compost treatments resulted in a 285% increase in 2.0 to 4.0 mm water stable aggregate content in the upper 7.5 cm of soil. Infiltration rate was calculated for all treatments based on time required for complete drainage and over the total 18 minute drainage time. The greatest infiltration rate was associated with SP (10.1 mm/min) and was slowest in WC (3.2 mm/min. Compared to the organic orchard, only MB had a lower SOM content (2.6%). With the exception of GC applied alone (18.1%) or in combination with commercial organic fertilizer (17.7%), estimated plant available water was lower in the organic orchard than the

conventional orchard (17.2%). Soil bulk density was 1.3 g·cm^{-3} in 2012 and higher than that in all GMS treatments. All GMS treatments resulted in greater water stable aggregate formation than the conventional orchard. Compared to the conventional orchard, GMS enhanced infiltration rate in all tests except WC. Collectively, the soil quality indicators measured in this study show the addition of GMS has improved soil quality since orchard establishment. Implementation of these or similar groundcover management systems are a tangible means of meeting NOP requirements for improving soil quality concurrent with production of certified organic crops.

The United States Department of Agriculture National Organic Program (USDA-NOP) standards specify a necessary increase in soil quality concomitant with the production of certified organic crops (USDA-AMS, NOP § 205.203). A host of scientific studies conducted across several decades support opinions held by many farmers that increases in soil humus enhance physical and chemical soil properties, and management practices which favor the aggradation of soil organic matter reveal field-observable benefits related to plant growth and crop productivity (Kimble, 2007). Moreover, comparisons between organic or integrated orchard management systems and conventional orchard management practices may reveal measurable differences in SOM levels (Merwin et al., 1994). Qualitative characterizations of conventionally-managed orchard soils reflect lower soil quality ratings for the soil ecosystem than for organic or integrated systems (Reganold et al., 2001), while greater soil quality in organic and integrated systems is attributed to additions of organic residues to the soil surface. Such groundcover management systems (GMS) provide continuous additions of SOM to the soil and may affect soil quality.

The addition of SOM to mineral soil is recognized as a beneficial practice from the standpoint of increasing the capacity to store plant-available water (Bhogal et al., 2009; Hudson, 1994; Jordán et al., 2010; Mulumba and Lal, 2007). Plant-available water is defined as water held in soil between field capacity and the permanent wilting point (Soil Science Society of America, 2012). In addition to SOM, a soil's water holding capacity is determined by soil texture, with fine-textured soils capable of storing more water for plant use than those of coarser textures (Brady, 1990; Scott, 2000). Organic constituents from crop residues, manures, and composts absorb water as it moves downward through a soil column.

Likewise, applications of organic matter, including land-applied mulches, incorporation of green manure crops, livestock manure, and garden compost increase pore space and as a consequence reduce bulk density (Celik et al., 2010; Jordán et al., 2010; Soane, 1990; Stock and Downes, 2008). Bulk density (BD) is related to other physical soil properties and has been described in scientific literature as an indicator of soil and environmental quality (Arshad and Coen, 1992; Doran et al., 1996; Lal and Kimble, 2001). Decreases in BD may be achieved as soil aggregation improves, and beneficial aspects of well-aggregated soils include protection of SOM within the aggregate (Tisdall and Oades, 1982), increased diversity of the soil microbial community (Flieβbach et al., 2006), enhanced soil, air, and water movement (Deurer et al., 2009), and a reduction of surface crusting, runoff, and soil erosion (Carter, 2002; Karlen et al., 1992; Kemper and Rosenau, 1986).

Surface crusting and erosion may be reduced or eliminated in orchards with application of non-living groundcover mulches. Appropriate mulches for organic apple production include woodchips, municipal green compost, shredded paper, and mow-blow green mulch (Rom et al., 2010). Other researchers have utilized hay-straw and living ground covers, including white clover (*Trifolium repens* L.) and red clover (*Trifolium pratense* L.), all of which contribute to SOM reserves (Granatstein and Mullinix, 2008; Merwin et al., 1994, 1995, 1999; Sanchez et al., 2003) and favor formation of water stable soil aggregates.

An important constituent for binding aggregates into water-stable forms and supporting maintenance and growth of a healthy soil food web is carbon (C). Soil aggregates are instrumental in storing and protecting a portion of C mineralized from decomposed residues. Carbon in soil aggregates exists in a variety of forms, from decomposing, labile particulate organic matter (POM) bound into aggregates by fine roots and hyphae to stable, humified plant residues occluded within small microaggregates and unavailable to the soil microbial community (Kay, 1998; Tisdall and Oades, 1982). Further, polysaccharides and mucilages exuded from soil microorganisms may also be tightly adsorbed onto the mineral soil particles, thereby strengthening aggregate fracture zones and decreasing the potential for slaking (Kay, 1998).

Tisdall and Oades (1982) categorized soil aggregates as either macroaggregates (greater than 0.25 mm diameter) or microaggregates (less than 0.25 mm diameter). Macroaggregates are usually bound by plant roots and fungal hyphae and tend to decline in number as SOM declines (Tisdall and Oades, 1982;

Jastrow and Miller, 1991; Karlen et al., 1992). Microaggregates are fixed by polysaccharides and organo-mineral complexes to form relatively stable structures largely unaffected by soil management practices (Tisdall and Oades, 1982; Six et al., 2004).

The porous nature of well-aggregated soils also affects the rate at which water enters the soil profile. Infiltration refers to the entry of water through the soil surface (Scott, 2000), and the extent to which water can enter a soil impacts the amount of water left to runoff. Greater runoff increases soil erosion (Le Bissonnais, 1996; Lado et al., 2004; Stern et al., 1991; Wakindiki and Ben-Hur, 2002) and decreases plant available water retained in the soil profile (Merwin et al., 1994).

To reduce water droplet impact and promote the formation of stable aggregates, land management strategies which conserve residues at the soil surface are often recommended, and greater water-stable aggregate content can improve infiltration by slowing crust formation during a rain or irrigation event (Albrecht and Sosne, 1944; Boyle et al., 1989; Freebairn et al., 1991; Lal, 1993; Le Bissonnais, 1996; Le Bissonnais and Arrouays, 1997). The arrangement of macroaggregates with respect to one another creates macropores (Deurer et al., 2009), and pore size and pore volume per volume of soil dictate rate of water infiltration into the soil profile (Arshad and Coen, 1992; Scott, 2000). Other factors affecting water infiltration include initial soil water content, soil texture, clay type, vegetative cover, rainfall intensity, slope, and air entrapment (Scott, 2000).

Studies have shown application of mulches in apple orchards increased infiltration rates (Goh et al., 2001; Granatstein and Mullinix, 2008) and soil aggregate stability (Deurer et al., 2008). Mulches likely provide a double benefit of permitting greater water infiltration into the soil and greater water retention for an extended period of time due to reductions in evaporation, thereby reducing irrigation requirements (Granatstein and Mullinix, 2008). After six years of orchard research, Merwin et al. (1994) documented decreased SOM and water infiltration in plots treated with pre-emergence herbicides and tillage as compared to those managed with living and inert mulches. Thus, utilization of groundcover management systems (GMS) which increase SOM and the ensuing processes of soil aggregation and macropore formation should lead to an overall increase in water infiltration rates.

The southeastern United States has experienced a revival of interest in orchard establishment and fruit production, much of which is managed organically and on a small scale. A considerable amount of information is available on the efficacy and suitability of using GMS systems as an orchard floor management tool in other regions of the US, but no research exists that shows their effects on physical properties of weathered Ozarks Highlands soils. Further, the impact of organic nutrient sources (NS) on orchard soils in this geography is not documented. Therefore the objectives of this study were to evaluate the impact of GMS and two NS on SOM content, plant available water, BD, formation of water stable aggregates, saturated hydraulic conductivity, and water infiltration rate in an organic apple orchard on a mineral soil in northwest Arkansas.

Materials and Methods

This experiment was part of a broader study examining the impacts of GMS and NS on physical, chemical, and biological soil characteristics, tree health and productivity, and insect, disease, and weed management in an organically-managed apple (*Malus* x domestica Borkh.) orchard. The research orchard is located at the University of Arkansas Main Agricultural Experiment and Extension Center, Fayetteville, Arkansas (36^{o}N, 94^{o}W) and is situated on two soil series. Two-thirds of the trees are established on a Pickwick silt loam (fine-silty, mixed semi-active, thermic Paleudults), with the remainder located on a Captina silt loam (fine-silty siliceous, active, mesic Typic Fragiudults) (Figure 1, Appendix 1). Soil survey descriptions for both soils specify low to moderate natural fertility, low SOM content, low to moderate soil pH, and moderate to high plant available water, and fragipans are commonly present in Captina soils at approximately 51 cm, limiting root penetration below this depth (USDA – SCS, 1969). Both are well suited for orchard and/or small fruit production.

The site selected for the organic orchard had been in horticultural production for approximately 75 years. Prior to orchard establishment, the site was planed and leveled in 2005. Soil pH was adjusted by application of agricultural lime according to University of Arkansas Soil Testing and Research Laboratory recommendations, and composted manure was applied at the rate of 5 $MT \cdot ha^{-1}$. 'Enterprise'/M26 apple trees were planted in 2006 in a trained two-wire trellis system with vertical tree supports in 2006, and orchard management has followed NOP regulations since establishment. The orchard covers 0.40 ha with 2 m tree spacing and 4 m row spacing. Tree density is approximately 1485 trees/ha. Treatment trees are buffered from adjacent treatment effects by two guard trees on either side. A row of guard trees is also positioned along the outside edges of the orchard (Appendix 1, Figure 2). Drive alleys are perennially managed with established tall fescue (*Festuca arundinacea* Schreb. 'Kentucky-31') with other native herbaceous plants occurring.

The experimental design was a 4 X 3 factorial of four GMS treatments by three NS treatments. The orchard is divided into six blocks with groundcover as the main-plot effect and nutrient source as the sub-plot effect resulting in 12 possible treatment combinations and a total of 72 treatment plots (Appendix 1, Figure 3). Groundcover management systems selected for this experiment included 1) urban municipal green compost (GC), 2) shredded office paper (SP), 3) waste wood chips of urban origin (WC), and 4) a managed tall fescue mow-blow (MB) green mulch system which serves as an informal control treatment.

Beginning in spring of 2006, GC, SP, and WC treatments were applied under trees annually in March in a 2 m wide by 10 to 12 cm deep band extending across both sides of the tree row (Appendix 1, Figure 4). Green compost, derived of urban vegetative waste (i.e. grass clippings, wood prunings, and yard waste) and composted 90-120 days 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, 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 rotary mower in late May and three to five times throughout the summer depending on its growth.

Nutrient sources were provided annually and included A) certified organic commercial fertilizer (CF) produced from poultry manure (Perdue AgriRecycle, pelletized poultry manure, Seaford DE; 4-2-3 analysis), B) locally available composted poultry litter (PL), or C) an un-amended control treatment (NF) in which all added nutrition came from the GMS (Appendix 1, Figure 5). The CF selected at the initiation of the study was used through the 2010 application, but production was subsequently discontinued. An alfalfa-based commercial organic product (Bradfield Organics, Feed Solutions, St. Louis, MO, 3-1-5 analysis) was applied beginning in 2012. Nutrient source treatments were applied in March of each year prior to application of GMS treatments at 50g of actual N per tree per year. All sampling was conducted with 0.75 m of the treatment tree trunk. In the event a treatment tree had died, a guard tree from the original orchard planting was selected for sampling.

Soil organic matter content from the upper 10 cm of soil was determined by loss on ignition using a muffle furnace at 500^{o}C for 6 hours, after oven-drying soil at 105^{o}C for 24 hours. Soil organic matter content was determined in October 2006 and March 2012 and calculated on a dry weight basis. Soil BD was determined in November 2006 and June 2012 from cores obtained using a 5.4 cm wide by 6 cm depth ring. Mulches were raked away to expose the mineral soil surface and rings were driven into the soil until the top edge of the ring was flush with the soil surface (Appendix 1, Figure 8). Two cores were collected from each treatment plot in this manner and dried for 3 days in a 50^{o}C forced-air oven. Samples were then weighed and bulk density calculated for each sample as specified by Hillel (1980).

Particle size fractions for sand, silt, and clay were determined for all treatments in the organic orchard following methods of Arshad et al. (1996). Two 5.4 cm wide by 6 cm depth soil cores were collected in June 2012, dried at 50^{o} C for three days, ground, and passed through a 2 mm screen. Fifty grams (+/- 0.1g) of each soil sample were weighed into individual containers to which 50 ml of a 100 g·L^{-1} sodium hexametaphosphate solution were added. The contents were mixed and rinsed into a 1 L sedimentation cylinder and brought to volume with deionized water. The cylinder contents were allowed to come to room temperature overnight. Samples were mixed, and using a standard hydrometer with a Bouyoucos scale, a solution density measurement was recorded after 40 seconds. This process was repeated three times and the density readings averaged to ascertain the sand content of the sample. The contents of the sedimentation cylinder were allowed to settle for two hours. The hydrometer was then placed back into the solution and the silt-plus-clay fraction measured.

The hydrometer was calibrated using a 1 L blank solution containing 50 ml sodium hexametaphosphate and 950 mL deionized water. The solution was thoroughly mixed and a blank reading obtained with the hydrometer. A thermometer was placed in the calibration cylinder, and the temperature was recorded. A calibration reading and temperature reading were recorded again after approximately four hours and the values were averaged. For each degree C above 20^{o}C, 0.40 g· L^{-1} was added to the blank hydrometer reading to correct for temperature differences above 20^{o}C. Sand, silt and clay were calculated using the following equations:

Plant available water was estimated using the SPAW (Soil-Plant-Air-Water) model (USDA-NRCS). The SPAW model estimates plant-available water based on the relationship between soil texture, soil bulk density, and percent soil organic matter (Saxton and Rawls, 2005). Given the input of these variables, the model predicts percent volumetric water content at field moisture capacity and permanent wilting point (Appendix 1, Figure 9). Estimated plant-available water was calculated as the difference between estimates of field moisture capacity and permanent wilting point as described by Hudson (1994). Bulk density, sand, silt, and clay concentration, and organic matter concentrations were entered into the SPAW model, yielding estimates of field moisture capacity and permanent wilting point. Estimates of plant-available water were then derived for each replicate treatment plot. Likewise, saturated hydraulic conductivity was predicted by the SPAW model based on input of the aforementioned soil properties.

To determine percent water-stable soil aggregates, soil samples were collected in November 2011 using a 7.3 cm diameter core chamber and sliding hammer. Soil from beneath all replications of GMS and NS treatments on the Pickwick soil were sampled (4 of 6 blocks); replications on the Captina series were not evaluated for this portion of the study due to the close similarities between Captina and Pickwick soils. Groundcovers were raked away to expose the mineral soil, and two cores 15 cm in length were extracted from beneath each treatment tree. Cores were collected from within a 0.75 m radius of the tree trunk. Each core was divided in half resulting in a 0 to 7.5 cm surface layer and 7.5 to 15 cm sub-surface layer. The respective layers from both replicate cores were mixed, constituting an upper depth and lower depth sample for each plot, and passed through a 63.5 mm screen. Samples were air dried for 5 days on paper plates in a ventilated greenhouse and stored in unsealed plastic bags until wetsieving was conducted. Moisture content was not determined prior to wet sieving.

Wet sieving followed the technique utilized by Yoder (1936) and Brye and Riley (2009). The wet-sieving apparatus consisted of a 31 cm wide by 76 cm tall PVC water-filled column and an electric motor which powered the plunge arm. A set of nested sieves with mesh openings measuring 4 mm, 2 mm, 1 mm, 0.5 mm and 0.25 mm was attached to the plunge arm and adjusted to its bottom reach inside the cylinder. Water was added to the cylinder to the depth of the upper rim of the top sieve. The wet-sieve apparatus was adjusted to deliver 130 cycles/minute (Appendix 1, Figure 7).

Subsamples (300 g) were weighed from air-dried soil samples and placed in the top sieve. Wet sieving was allowed to proceed for 5 minutes. While wet sieving occurred, successively smaller mineral soil particles and water-stable soil aggregates passed through the screens until aggregate or mineral soil particle size exceeded the screen size. Water-stable aggregates and mineral soil particles less than 0.25 mm collected at the bottom of the water cylinder. After five minutes, the wet-sieve apparatus was stopped and the sieves were removed from the water column. The contents of each sieve were rinsed individually into small, aluminum loaf pans. Because each GMS was replicated in triplicate blocks, samples were sieved in triplicate according to GMS and soil depth, and the water column was drained and refilled between samples from different groundcovers.

All loaf pans and their contents were placed into an 80^{o} C forced-air oven for 24 hours. Upon removal from the oven, coarse fragments were removed by hand from the loaf pans containing the contents of the 4mm and 2mm mesh screens, and the tins and contents were weighed. Because the mineral soil particles retained on the remaining screens were too small to remove by hand, the weights of the 1 mm, 0.5 mm, and 0.25 mm mesh screens reflect the weight of mineral soil and water-stable aggregates.

Infiltration rates were measured in May 2012. On 18 May, tree rows were irrigated for eight hours at the rate of 45 $L \cdot hr^{-1}$ to achieve uniform soil moisture contents. Infiltration measurements were collected on 21 May 2012 from replications on the Pickwick soil and on 22 May 2012 from replications on the Captina soil. Replications selected for this measurement consisted only of control (NF) plots and had received only the GMS treatments. Infiltration data were collected using a double-ring infiltrometer with an inner ring diameter of 16 cm. Mulches were removed within 0.50 to 1.0 m from the trunk of treatment trees to expose the mineral soil surface. Vegetation growing in the MB treatment was removed with a string trimmer to expose the mineral soil surface. Due to the presence of significant rodent burrowing under SP treatments, an area void of burrows at the soil surface was selected as the representative portion of the tree row for infiltration measurements.

Infiltration measurements were performed using the technique outlined by Reynolds et al. (2002). Initial soil volumetric water contents were determined immediately after mulch removal by the average of three measurements using a Field Scout TDR300 soil moisture meter (Spectrum Technologies, Inc., Plainfield, IL) equipped with 6 cm long probes. The outer ring was filled to within approximately 1 cm of the top of the ring. The inner ring was then filled, and the water height was immediately measured (Time 0). Height measurements were subsequently recorded at 1, 3, 6, 9, 12, 15, and up to 18 minutes if complete infiltration did not occur first (Figure 6, Appendix 1). The mid-point of each time interval served as the explanatory variable rather than the original time points and was plotted against the infiltration time at each location. The change in water column height at each time interval was natural log transformed to linearize the data, and infiltration rates were compared as follows: 1) the average infiltration rate over 18 minutes, 2) the specific infiltration rate, as determined by the time required for all water to drain from the infiltrometer, and 3) as regression equations in which time and soil volumetric water contents were analyzed as co-variates of GMS.

A conventionally-managed orchard established in 1989 and used for cultivar trials (M106 and M26 rootstocks) through 2012 was located on the same Pickwick and Captina soils approximately 20 m from the organic orchard. Because the conventionally-managed orchard was not included as a part of the organic orchard research project, a formal statistical comparison was not made between data collected from each site. However, no organic amendments were added to the conventional orchard after its establishment, and qualitative conclusions were drawn regarding the effects of GMS and NS treatments on soil quality indicators as evaluated in both orchards. Orchard floor management in the conventional orchard consisted of pre-emergence and contact herbicide applications made three to five times yearly for control of competitive vegetation. Water soluble fertilizers were applied annually at rates of 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, MP 144 and MP 154, 2013). Trees were not irrigated in 2012.

Plant available water, bulk density, and water-stable soil aggregation were determined in the conventional orchard on the same dates and using the same methods already described for the organic orchard. Because the conventionally managed orchard was not irrigated in 2012, infiltration measurements were delayed until after rainfall occurred to approximate conditions created in the organic orchard after irrigation. Infiltration was measured on 6 June 2012, two days following a 4.8 cm rain event. All data analyses from the conventional orchard were limited to descriptive statistics, including means and standard errors of the mean.

Statistical analyses were performed on data from the organic orchard using the MIXED procedure (SAS Institute Inc., Cary, NC). Analysis of variance was used to evaluate treatment main effects of GMS and NS on the variables of SOM concentration, plant available water, bulk density, saturated hydraulic conductivity (N = 6), and water-stable aggregation, in which the main effect measured was GMS, and NS was the split-plot effect. Where differences by year were evaluated, year was treated as a split-split plot effect. Means were separated by least significant difference at the 0.05 level. Total water stable aggregate concentrations were analyzed as a split-split plot design, where the whole-plot factor was GMS in a randomized complete block (N = 4), the split-plot factor was NS, and the split-split-plot factors were the two sampling depths. A split-split-split plot analysis was added to evaluate differences between concentrations of four aggregate size classes, differentiated by sample weight, at both depths. Analysis of variance was used to evaluate treatment main effects of GMS on specific and average water infiltration rates using the GLM procedure. Analysis of co-variance was used to test the interaction of groundcover by time and groundcover by volumetric soil water content on infiltration rates. Due to the inherent variability associated with soil hydraulic properties, significance was judged at the 0.1 level for all infiltration data analyses.

Results and Discussion

At the time of orchard establishment uniform soil conditions across the experimental plot area were created by land grading and cultivation. Over the following six years, it was hypothesized that annual applications of GMS treatments affected physical soil properties, and GC treatments significantly affected each soil quality indicator measured. Humified residue from annual applications of GC over the span of the study was typically observed in the top 2 cm of soil, and in some cases it was challenging to determine the interface between the mineral soil surface and GC mulch. Less decomposed residue was observed beneath WC and SP treatments, and decomposing plant litter was only detectable in MB treatments for approximately three weeks following each application.

Due to its impact on soil characteristics, SOM content was determined for all treatment replications. Soil organic matter did not vary among GMS treatments at the initiation of the study (Figure 1). Application of each GMS yielded increases in SOM after 6 seasons. However, the greatest increas in SOM from the 2006 (orchard establishment) observations was observed in the blocks receiving GC alone or GC plus commercial organic fertilizer treatments (Figure 2). Green compost and CF contained the greatest N concentration and lowest C:N of all GMS and NS evaluated (Choi, 2009), and conditions required for aggradation of SOM were met with these treatments. The disparity between the effects of PL in GC and WC treatments is interesting and is likely related to the differences between C:N ratios of the GMS and NS combinations (Table 2, Appendix 2), and to understand these interactions, future work may be warranted. Choi (2009) observed seasonal variations in SOM for all GMS studied, in which the SOM fraction increased during early spring, plateaued through early summer, then decreased during fall and winter months. As in the present study, Choi (2009) determined greatest increases in SOM in the GC treatments.

Increases in SOM were expected to increase soil C content (Stevenson, 1994), and soil C increased with GC treatments since establishment of the organic orchard in 2006 (Mays, Chapter 3 of this thesis). The chemical composition of residues may have affected the rate of humification and C mineralization (Tate, 1992), and differences in the chemical and physical nature of GMS treatments may have also affected changes in soil C and N content, due to differences in soil food web structures, with WC largely regulated by fungal biomass and GC, SP, and MB mediated by soil bacteria (Thorn and Lynch, 2007).

Studies have shown that integrated or organic orchard floor management practices using living and plant residue-based groundcovers increased SOM and soil C. Wells (2011) determined the combination of poultry litter and crimson clover (*Trifolium incarnatum* L.) increased SOM compared to an untreated control in pecan [*Carya illinoeninsis* (Wangenh.) K. Koch] production. Deurer et al. (2009) determined the top 10 cm of an organically managed apple orchard receiving annual applications of compost contained 32% greater soil organic C than an integrated orchard in which herbicides were used to control competitive vegetation. Peck et al. (2011) documented greater accumulation of SOM in an integrated apple orchard receiving bark mulch applications and occasional herbicide applications than in an organically-managed apple orchard treated with tillage and composted poultry litter. Conversely, Merwin et al. (1995) observed no differences in SOM concentrations between plant-based mulches and rows receiving plastic mulches and herbicides.

Plant Available Water Capacity. Because soil texture is closely linked to plant-available water, particle size analyses were conducted for each treatment plot. No differences were observed in soil clay content among GMS treatments (data not presented). Differences in particle size fractions were detected between GMS and the sand and silt fractions. However, the disparity in their concentrations were small and agronomically insignificant, with 13% and 11% differences, respectively, between the largest and smallest sand and silt fractions among GMS treatments. It was, therefore, concluded that sand and silt fractions did not vary appreciably between GMS and NS, and differences in plant-available water were attributed to effects of GMS and NS treatments. Differences in estimated plant-available water varied by GMS and NS and generally mimicked differences in SOM among GMS and NS (Table 1).

Similar plant-available water levels were observed in GC treatments receiving NF and CF, while GC amended with PL yielded among the smallest estimates of plant available water (Table 1). Otherwise, plant available water did not vary among SP, WC, and MB receiving NF or CF, and differences in field moisture capacity and permanent wilting point were only observed in GC receiving NF or CF.

These results corroborate Hudson's (1994) assertion that increased SOM content may correspond to increased plant-available water. Although large increases in estimated plant available water were not observed, greater SOM content was observed with GC or GC plus CF (Figure 2) and resulted in increased plant-available water compared to other GMS treatments. As suggested by Hudson, these treatment combinations resulted in sufficient increases in field moisture capacity to offset the corresponding increases observed in permanent wilting point, yielding a net increase in plant-available water capacity. Deurer et al. (2008) determined that with organic orchard management, plant-available water was slightly higher deeper in the soil profile than in the surface layer (0 – 10 cm). Merwin et al. (1995) documented greatest water availability associated with wood chip applications, or under straw mulch (Merwin et al., 1994). Emerson (1995) concluded that increases in soil water content are correlated to the magnitude of change soil C levels, due to storage of water in polysaccharide gels, and the findings of this study support this previous work, suggesting water availability is positively affected by organic production methods and subsequent increases in soil C levels.

Bulk Density. Soil BD measured at orchard establishment (2006) revealed no differences prior to initiation of GMS treatments, but BD decreased in all GMS treatments over time in the first 6 years of the study (Figure 3). In 2012, BD was 25% lower in the GC treatment and 27% lower for WC than in 2006. Nutrient sources also impacted BD over time. Commercial organic fertilizer applications resulted in the lightest bulk density (1.03 $g \cdot cm^{-3}$), and different from treatments receiving NF (1.12 $g \cdot cm^{-3}$). Poultry litter was intermediate and did not differ from commercial fertilizer or control treatments (1.09 $g \cdot cm^{-3}$). However, GMS and NS did not collectively affect BD. The lack of a BD interaction between GMS and NS is likely due to the greater amount of organic material added with each GMS, and the effects of NS were overshadowed by the effects of GMS applications. Nevertheless, the placement of organic residues at the soil surface added SOM to the upper 6 cm of soil measured in this study, thereby impacting soil BD to varying degrees across GMS and NS treatments. The pronounced BD decrease in GC and WC applications over SP and MB are best explained by the differences in amount of residue applied across the treatments. Greater total residue mass was added with GC and WC, than with the lighter SP mulch or occasional deposition of MB green mulch, suggesting the quantity of residue applied with each GMS impacted the magnitude of change in BD.

Although Granatstein and Mullinix (2008) did not observe differences in BD between organic and conventionally-managed orchards, other studies have shown organic orchard floor management decreased soil BD. Goh et al. (2001) and Glover et al. (2000) reported diminishing BD in organic apple orchards implementing mulches as an orchard floor management tool. Deurer et al. (2009) observed greater macroporosity in an organic apple orchard receiving compost and maintained under grass cover, than in an integrated system utilizing herbicidal orchard floor management. They attributed this to the activity of roots and soil fauna, as well as increases in soil aggregate stability, microbial biomass, and subsequent increases in macropore stability. In the present study, decreases in BD since 2006 were most attributable to a dilution of the mineral soil component with organic residues and aggregation of soil within the top 6 cm of soil, although burrowing animals and soil macrofauna may have also contributed.

Water-Stable Soil Aggregates. The formation of water-stable soil aggregates was impacted by GMS and was most pronounced in the upper 7.5 cm of soil. Significant differences were observed in water-stable soil aggregate formation among groundcovers, sat two soil depths, and among sieve mesh size, but there was no NS or GMS X NS interaction that affected water-stable soil aggregate formation (Table 2, Appendix 1). Total water-stable soil aggregate formation was greatest in association with GC at both depths evaluated, compared to MB (Table 2), and differences in water stable aggregate formation were only observed between GC and MB. It is also noteworthy that the concentration of water-stable soil aggregates in the lower 7.5 - 15 cm depth in GC treatments was numerically equal to that in the top 7.5 cm in the MB treatment, highlighting the influence GC had on the formation of water-stable soil aggregates.

Among GMS treatments, aggregates larger than 4.0 mm rarely withstood the wet-sieving process, and those that were retained on the 4.0 mm screen were almost exclusively from soils amended with GC. For this reason, water-stable aggregates in the >4.0 mm size class were ignored and statistical analysis was not performed. A large macroaggregate fraction was observed in the GC 2.0 to 4.0 mm size class at a depth of 0 - 7.5 cm. Compared to MB, GC applications resulted in a 4200% increase in 2.0 to 4.0 mm macroaggregate weight, and aggregate masses from all size classes in GC were greater than the comparable size classes retained from SP, WC, and MB treatments (Table 3, Appendix 1). The greatest total mass of water stable aggregates was also observed in GC (Table 4, Appendix 1). Shredded paper yielded equal gains to GC in the formation of water-stable aggregates between 0.25

mm to 0.50 mm, but aggregate retention decreased quickly for SP as sieve mesh size increased (Table 3). No differences were observed in water stable aggregation among size classes in WC and MB treatments.

Water-stable aggregate formation was greater in the top 7.5 cm than in the 7.5 - 15 cm depth for all GMS treatments, with greatest aggregate masses occurring in the 0.25 to 0.50 mm size class among all GMS. With the exception of GC, aggregate retention tended to decrease with increasing aggregate size (Table 3). The water stable-aggregate fraction was smallest in the 2.0 – 4.0 mm size class within all GMS treatments, but this is due in part to the removal of stone fragments after wet sieving occurred. Consequently, aggregate fractions recorded for the 2.0 to 4.0 mm size class reveal the truest measure of water-stable soil aggregates, because weights of all other screen sizes also included the weight of the mineral soil. However, changes in the mineral soil fraction were not expected in response to the addition of GMS treatments, and any variation in water-stable aggregates among GMS was attributed to treatment effects.

Tisdall and Oades (1982) suggested that aggregates larger than 2 mm are held together primarily by fine roots and hyphae in soils with more than 2% organic matter. Green compost treatments contained greatest SOM (5.6%) of all GMS, a condition which was directly correlated to greater aggregate stability (Lado et al., 2004). Due to prior composting activity and its low C:N ratio, GC may have been humified and incorporated into the rhizosphere more quickly than in other GMS treatments included in this study, thereby stimulating enough growth of fine roots and fungi whose hyphae readily enmesh the smaller aggregates (Jastrow and Miller, 1998). Because of its composted nature, chemical and physical characteristics of the GC should allow greater soil microorganism activity, thereby increasing production of polysaccharide gels important to the formation of water-stable aggregates (Kay, 1998). On the contrary, WC have a larger C:N ratio, and when applied at high rates, as with mulching, soil microbial activity may be reduced due to N immobilization, thereby limiting bacterial-induced water-stable aggregate formation in this treatment.

Although less total residue was applied, aggregation was higher in soil under SP treatments than in than WC in the upper 7.5 cm. This observation could be due to the rate at which SP mulch decomposed, with a greater portion of SP mulch visibly decaying by the end of each growing season, compared to WC, thereby contributing more C to the soil food web and inducing aggregate formation. It was thought MB ranked lowest in total water-stable aggregate formation due to the small total amount of residue applied over the span of each growing season. While total weight of the MB green mulch was not measured per unit area for this study, compared to other treatments, much less discernible residue layered the ground surface after each mowing, compared to other GMS applications, and most of the grass had decomposed within three weeks of MB applications.

Other studies have shown applications of plant-based residues increase aggregate stability in orchard soils. Peck et al. (2011) observed greater aggregate stability in association with the use of bark mulches, and Deurer et al. (2008) showed greater aggregate stability was associated with the organic production system and compost applications than in an integrated orchard floor managed by herbicide applications. Glover et al. (2000) observed increases in aggregation in an integrated apple production system which utilized bark mulch and limited herbicide application over conventional management implementing herbicide applications. As in the present study, the findings of Glover et al. (2000) suggested GMS systems that protect the soil surface with relatively large amounts of organic residues lead to increased formation of water-stable aggregates. Orchard floor management systems such as cultivation, which disturb the soil, or herbicide applications which leave the soil surface bare, appear less conducive to soil aggregation and maintenance of soil structure. Similarly, this study demonstrates the use of plant-residue based GMS favors soil aggregation in weathered Ozark Highlands soils, and soil structure may be improved relatively quickly as GMS materials decompose.

Infiltration Rate. The effects of GMS on water infiltration were assessed after 6 years of annual organic orchard floor management. Analysis of soil volumetric water content showed no correlation between soil moisture at the time of measurement and infiltration rate, nor was there a NS effect associated with infiltration rates. Additionally, average infiltration rates did not vary among GMS treatments. Shredded paper resulted in the greatest specific infiltration rate (10.1 $mm \cdot min^{-1}$) while the slowest specific infiltration rate (3.2 $mm \cdot min^{-1}$) was observed in WC treatments (Figure 4). Blocks receiving WC had the least incidence of complete infiltration, as water did not completely drain from the infiltrometer after the full 18 minutes had elapsed in many of the WC plots. Granatstein and Mullinix (2008) also found greatest infiltration rates occurred after shredded paper treatments. However, in their study, infiltration rates after wood chip treatments did not significantly vary from shredded paper. Specific infiltration rates of WC and MB did not differ, and although not statistically different from GC, the numerical infiltration rate for SP was nearly two times faster than that of GC. In a related study, Choi (2009) reported differences in soil moisture between SP and WC and a mowing/cultivation treatment, with greatest soil moisture and infiltration in SP treatments.

Analysis of covariance revealed that neither initial volumetric soil water content nor GMS affected the slope (-0.11) of the relationship between infiltration rate and time. The relationship between the intercepts differed by GMS, indicating the initial infiltration rate varied among GMS treatments immediately after infiltration began. As with specific infiltration rates, WC applications resulted in the slowest initial infiltration while initial infiltration was fastest with SP, according to the differences in y-intercepts among GMS treatments (Fig. 5-b).

When conducting the infiltration experiment, the infiltrometer was placed in an area which, at the surface, appeared to be representative of average soil conditions. However, due to the greater infiltration rates observed, it is thought that, as water drained from the infiltrometer, it entered macropores not visible from the soil surface, thereby increasing initial infiltration compared to other treatments. However, as the soil became wetter, less variation was observed among GMS (Figure 5a).

Observable differences were noted in the greater number of SP plots which had complete infiltration, compared to other GMS treatments. Perceptible differences in soil structure were noted under SP and GC, with both having a more granular appearance than observed in WC and MB treatments. Further, burrowing activity by rodents was visibly most common in SP treatments. Shredded paper appeared to provide habitat preferred by rodents, as evidenced by the greater number of burrows observed in these treatments, and macropores approximately 2.5 cm in diameter provided a conduit for quick infiltration of water in SP treatments. Merwin et al. (1999) observed significant meadow vole (*Microtus pennsylvanicus* Ord.) activity when straw mulch and crownvetch (*Coronilla varia* L.) were used as a GMS compared to orchard floor management including herbicide applications, managed sod production, and tillage, indicating rodents may prefer burrowing beneath lighter weight groundcovers.

At the time of infiltration testing, more earthworms were observed under the SP and GC mulches than in WC and MB treatments (unreported data). Deurer et al. (2009) attributed increased incidence of stable macropore formation in part to greater earthworm tunneling in an organically managed orchard, compared to an integrated system using herbicides for management of weed growth. Similarly, Van Rhee (1977) and Jamar et al. (2010) documented increased earthworm abundance when application of agricultural chemicals were minimized, as in organic production, and greater earthworm tunneling likely contributed to increased infiltration in the present study (Lee and Foster, 1991).

Increased infiltration rate may benefit orchard production during hot, dry summer months in the Ozarks Highlands. Increasing the amount of water entering the soil profile decreases the likelihood of runoff during heavy rain events, and greater utilization of rainfall is advantageous toward reducing or delaying irrigation. Groundcovers increase the roughness of the soil surface, slowing the movement of water, and permitting more water to enter the soil. Additionally, as previously discussed, GMS and NS treatments have caused reductions in soil bulk density, and GMS have benefitted water-stable aggregate formation, thereby increasing porosity and improving structure at the soil surface. Groundcover management systems may also increase infiltration rate by creating conditions promoting macrofaunal colonization of the rhizosphere and as a result create greater observable macropore formation. Thus, GMS slightly to significantly affected infiltration, and more efficient use of rainfall and irrigation is expected when using organic orchard floor management (Goh et al., 2001; Merwin et al., 1994; Reganold et al., 2001).

Saturated hydraulic conductivity (K_{sat}) was estimated using the SPAW model (Table 4). Interactions were detected between GMS and NS, with the greatest estimated conductivities in GC treatments receiving NF or CF. K_{sat} values for SP and MB did not differ among NS, but greater conductivities were correlated to greater SOM concentrations among GC treatments. Although saturated conditions are unlikely to exist for any length of time in an orchard, knowledge of water movement during saturated soil conditions may be helpful in evaluating and monitoring soil quality. Soil organic matter concentrations were greatest in GC applied with NF or with CF, while soil texture and bulk density remained relatively constant. Thus, these results suggest greater saturated hydraulic conductivity may be associated with GC over other GMS treatments

Conditions in an Adjacent Conventional Orchard. Soil organic matter content in the conventional orchard was higher than observed in MB treatments in the organic orchard. Otherwise remaining GMS treatments had higher SOM than was measured in the conventional orchard, a finding which has been documented in other studies examining the effects of GMS on SOM (Amiri and Fallahi, 2008; Glover et al., 2000; Reganold et al., 2001)

Estimated plant available water across all GC treatments was almost equal to that in the conventional orchard (Table 5). However, GC receiving NF and CF were both greater than the values estimated for the conventional orchard (5% and 3% respectively). Although these are modest increases, they show the beneficial effects of additional OM on plant available water. Otherwise, plant available water was estimated to be slightly higher in the conventional orchard than for SP, WC, and MB.

Bulk density was greater in the conventional orchard than in all GMS treatments, and the lower BD in the organic orchard was attributed to increased SOM (Deurer et al., 2009). This soil quality indicator, however, revealed changes across all GMS treatments, with 21% lower BD in WC applications compared to the BD measurement in the conventional orchard. Green compost additions yielded a similar 20% reduction while SP and MB reduced BD by 11% and 8% respectively.

Total water-stable soil aggregate formation within the upper 7.5 cm of the soil profile was numerically greater for all GMS treatments in the organic orchard than in the conventional orchard. Large differences were noted between total aggregation in GC and SP treatments (Table 2) and the total aggregate fraction in the conventional orchard (Table 5). In the 7.5 - 15 cm depth, differences in the total aggregate fraction between the conventional and organic orchards were greatest with GC (Table 2). However, when compared by sieve size, aggregate formation was greater for both SP and GC treatments than with each corresponding sieve size from the conventional orchard. Little difference was noted between any of the aggregate fractions in the 7.5-15 cm depth for both orchards.
Thus, it is probable aggregation in the conventional orchard was reduced due to the absence of plant residues at the soil surface, which in turn reduced microorganism and macrofaunal activity in the rhizosphere (Tisdall, 1991), and reduced aggregation in the conventional orchard may also be related to lower SOM (Carter, 2002). Based on the results of this study, the addition of organic residues to an orchard floor benefits water stable aggregate formation, and mulches with a low C:N ratio show potential to benefit the orchard soil structure.

Volumetric water content determined in the conventional orchard prior to conducting infiltration measurements was comparable to values obtained in the organic orchard after an eight hour irrigation cycle, and it was assumed there was no interaction between volumetric water content and infiltration rate in the conventional orchard. Specific and average infiltration rates associated with SP, MB, and GC treatments in the organic orchard were numerically greater than those measured in the conventional orchard. However, WC treatments displayed numerically slower specific and average infiltration rates than measured in the conventional orchard. These data indicated that with the exception of WC applications, water infiltration in the organic orchard tends to be faster than observed in the conventional orchard.

Conclusions

The soil quality indicators evaluated collectively portray the effects and benefits of organic orchard floor management, using GMS and organic NS, on apple orchard soil quality in the Ozarks Highlands of Arkansas. Significant changes in SOM content were achieved in only six years due to application of GMS and NS treatments, increasing SOM over establishment levels across all treatments, and consequently impacting all other soil quality indicators in the study. Nutrient source treatments also positively affected some soil quality indicators, but their impact on soil quality was not consistent across all measured soil properties. Green compost had the greatest positive impact on soil quality of all GMS and NS treatments, because of its greater apparent ability to increase SOM than other GMS assessed. Soil structure at the GC-soil interface appeared consistently more granular in the field and probably contributed to infiltration rates numerically higher than for MB and WC, and to greater water-stable aggregate formation, particularly in the 2.0 – 4.0 mm size class, than the other GMS. Decreases in soil BD from establishment levels were associated with all GMS, but were most pronounced with GC and WC. Compared to soil properties observed in the conventionally-managed orchard, GC most improved soil quality among all indicators evaluated, while the other GMS evaluated also positively impacted soil quality, although to a lesser extent. Thus, the GMS and NS evaluated in this study provide a viable management option for Arkansas apple producers wishing to improve orchard soil quality, while also satisfying the USDA-NOP requirement to improve soil quality simultaneously with crop production.

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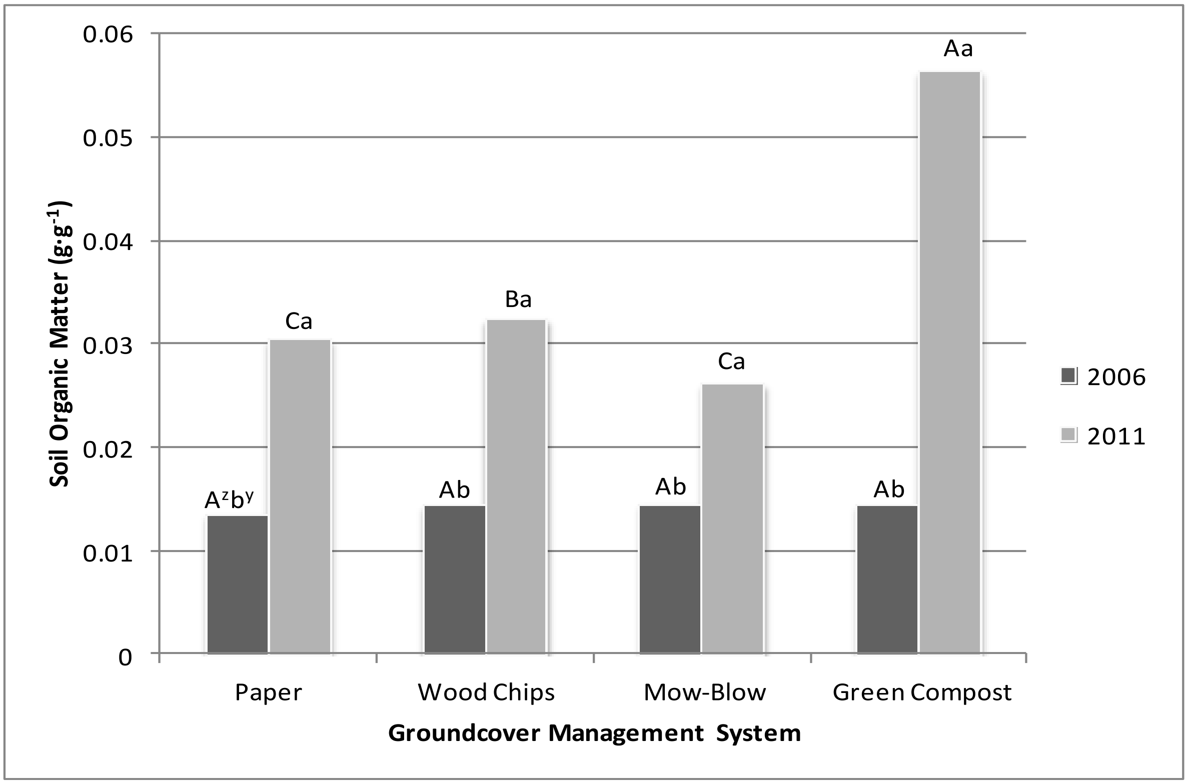


Figure 1. Change in soil organic matter content in an organically-managed apple ('Enterprise'/M.26) orchard, as affected by groundcover management system treatments, since orchard establishment (2006), Fayetteville, AR. Samples collected within 0.75 m of tree trunk October 2006 and March 2012 from a silt loam soil, 0 - 10 cm soil depth.

^{z}Means comparisons between groundcover management treatments within year by LSD; treatment values within a year with different upper case letters atop their bar are significantly different, 0.05 level, N=6.

^{y}Means comparisons within groundcover management treatments between years by LSD; treatment values with different lower case letters atop their bar are significantly different, 0.05 level, N=6.

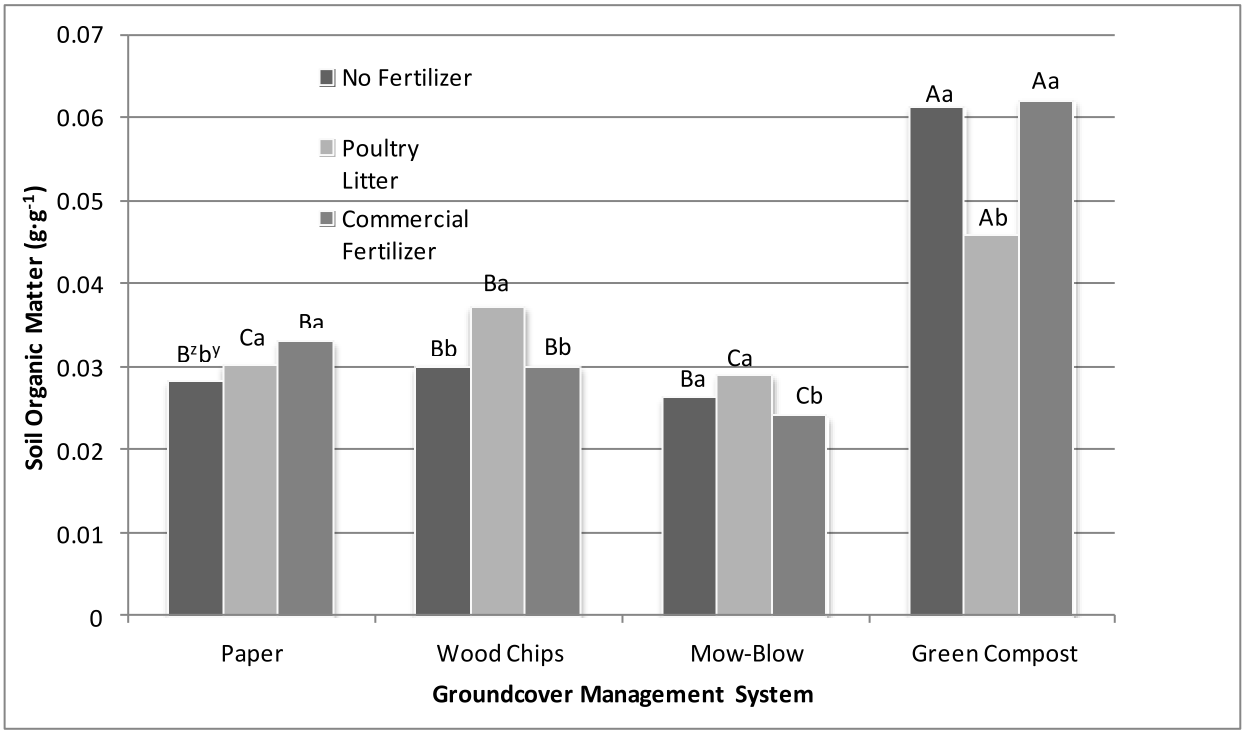


Figure 2. Interaction between groundcover management system and nutrient source treatments on soil organic matter content in an organically-managed apple ('Enterprise'/M.26) orchard, Fayetteville, AR. Samples collected within 0.75 m of tree trunk from a silt loam soil, 0 - 10 cm depth, March 2012.

[z]Means comparisons among treatments by LSD; different uppercase letters atop bars indicate significant differences between GMS treatments receiving same nutrition source, 0.05 level, N=6.

[y]Means comparisons among treatments by LSD; different lowercase letters atop bars indicate significant differences within GMS treatments receiving different nutrition sources, 0.05 level, N=6.

Table 1. The interaction between groundcover management system (GMS) and nutrient source treatments on estimated plant available water, field moisture capacity, and permanent wilting point in an organically managed apple ('Enterprise'/M.26) orchard, in the 0 - 10 cm soil depth; silt loam soil; conducted in June 2012, Fayetteville, AR[z].

Plant Available Water ($v \cdot v^{-1}$)

	Nutrient Source			
GMS	No Fertilizer	Poultry Litter	Commercial Fertilizer	Groundcover Average
Shredded Paper	16.4 B[y]a[x]	16.7 ABa	16.7 Ba	16.6
Wood Chips	16.5 Ba	16.6 ABa	15.9 Ba	16.3
Mow-Blow	16.7 Ba	17.0 Aa	16.5 Ba	16.7
Green Compost	18.1 Aa	16.0 Bb	17.7 Aa	17.9
Nutrient Source Average	16.5	16.8	16.7	

Field Moisture Capacity ($v \cdot v^{-1}$)

	Nutrient Source			
GMS	No Fertilizer	Poultry Litter	Commercial Fertilizer	Groundcover Average
Shredded Paper	21.6 Ba	21.8 ABa	21.8 Ba	21.7
Wood Chips	22.0 Bab	22.8 Aa	21.1 Bb	22.0
Mow-Blow	21.8 Ba	21.4 Ba	21.4 Ba	21.5
Green Compost	26.3 Aa	22.6 ABb	26.2 Aa	25.0
Nutrient Source Average	22.9	22.2	22.6	

Permanent Wilting Point ($v \cdot v^{-1}$)

	Nutrient Source			
GMS	No Fertilizer	Poultry Litter	Commercial Fertilizer	Groundcover Average
Shredded Paper	5.2 Ba	5.2 Ba	5.1Ba	5.2
Wood Chips	5.5 Bab	6.2 Aa	5.1 Bb	5.6
Mow-Blow	4.7 Ba	4.8 Ba	4.9 Ba	4.8
Green Compost	8.3 Aa	6.7 Ab	8.5 Aa	7.8
Nutrient Source Average	5.9	5.7	5.9	

[z]Means shown are estimates of soil water characteristics derived from SPAW model.

[y]Means comparisons among treatments within a column by LSD; means followed by different upper case letters within a column are significantly different, 0.05 level, N=6.

[x]Means comparisons among nutrient sources between columns across rows by LSD; means followed by different lower case letters between columns are significantly different, 0.05 level, N=6.

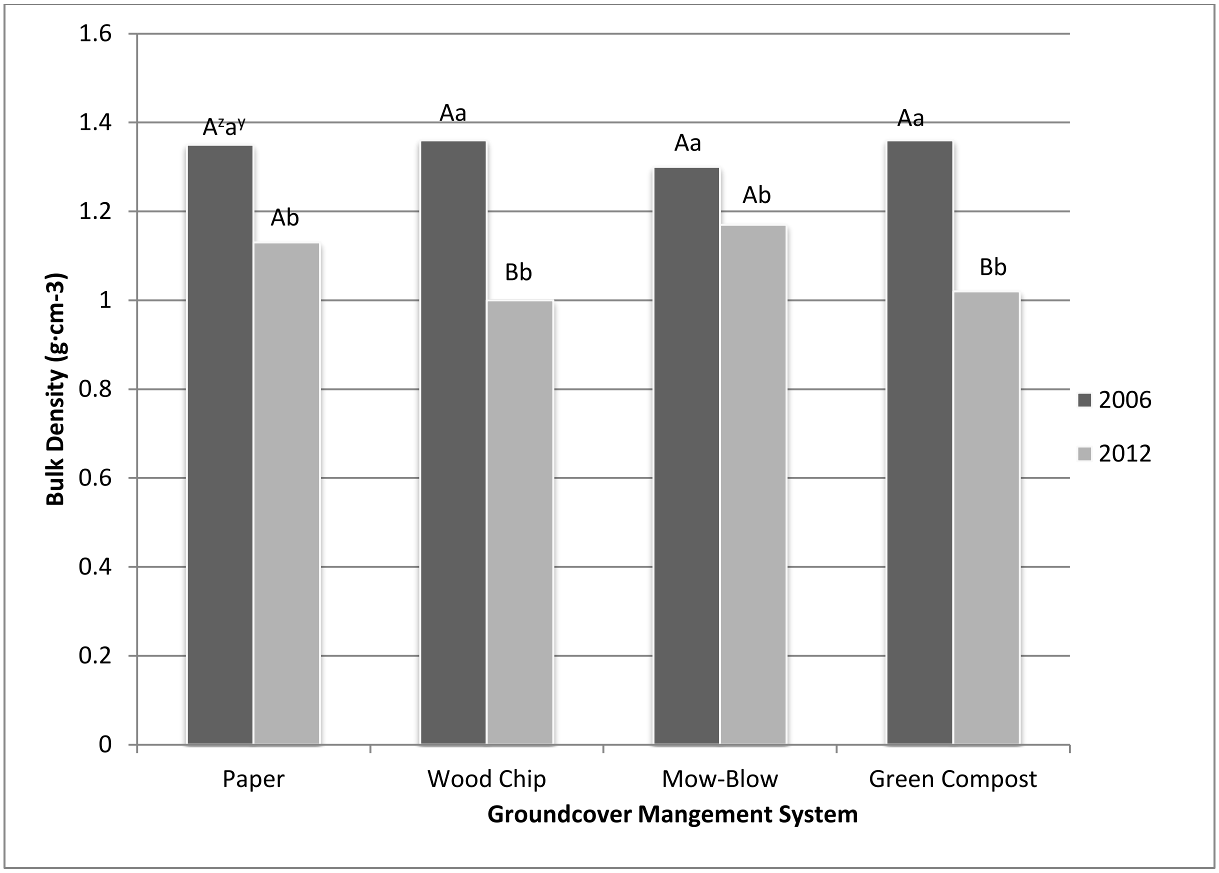


Figure 3. Effects of groundcover management system on soil bulk density since establishment (2006) in an organically-managed apple ('Enterprise'/M.26) orchard. Samples collected within 0.75 m of tree trunk from a silt loam soil, 0 - 6 cm soil depth, November 2006 and June 2012, Fayetteville, AR.

[z]Means comparisons between GMS treatments within year by LSD; treatment values within a year with different upper case letters atop their bar are significantly different, 0.05 level, N=6.

[y]Means comparisons within GMS treatments between years by LSD; treatment values with different lower case letters atop their bar are significantly different, 0.05 level, N=6.

Table 2. The influence of four groundcover management system (GMS) treatments on the total water-stable soil aggregate fraction at two depths in an organically-managed apple ('Enterprise'/M.26) orchard, Fayetteville, AR. Samples collected from a silt loam soil 0.75 m from tree trunk, November 2011.

	Total Water Stable Aggregate Fraction (g/g)	
	Depth	
GMS	0 - 7.5 cm	7.5 - 15 cm
Shredded Paper	0.12 AB[z]a[y]	0.07 Aa
Wood Chips	0.08 ABa	0.05 Aa
Mow-Blow	0.07 Ba	0.06 Aa
Green Compost	0.2 Aa	0.07 Ab

[z]Means comparisons among treatments within a column by LSD; means followed by different upper case letters among treatments are significantly different, 0.05 level, N=4.

[y]Means comparisons between depths between columns by LSD; means followed by different lower case letters between depths are significantly different, 0.05 level, N=4.

Table 3. The influence of four groundcover management system (GMS) treatments on water stable soil aggregate fractions at four sieve sizes and two depths in an organically-managed apple ('Enterprise'/M.26) orchard, Fayetteville, AR, 2012. Samples collected from a silt loam soil 0.75 m from tree trunk, November 2011.

		Water Stable Aggregate Fraction (g/g)			
		Sieve Size			
GMS	Depth	0.25 mm	0.50 mm	1.0 mm	2.0 mm
Shredded Paper	0-7.5 cm	0.06 A[z]a[y]α[x]	0.04 Baβ	0.02 Baγ	0.001 Baδ
	7.5-15 cm	0.03 Abα	0.02 Abβ	0.01 Aaβ	<0.001 Aaγ
Wood Chip	0-7.5 cm	0.04 Baα	0.02 Bcaβ	0.02 Baβ	0.002 Baγ
	7.5-15 cm	0.03 Abα	0.02 Aaβ	0.01 Aaβ	<0.001 Aaγ
Mow-Blow	0-7.5 cm	0.04 Baα	0.02 Caβ	0.02 Baβ	<0.001 Baγ
	7.5-15 cm	0.03 Abα	0.02 Aaβ	0.01 Aaβ	<0.001 Aaγ
Green Compost	0-7.5 cm	0.06 Aaα	0.05 Aaβ	0.06 Aaαβ	0.03 Aaγ
	7.5-15 cm	0.03 Abα	0.02 Abβ	0.02 Abβ	0.001 Abγ

[z]Means comparisons among treatments within a column by LSD; means followed by different upper case letters within a column and at the same depth are significantly different , 0.05 level, N=4.

[y]Means comparisons among depths by LSD; means followed by different lower case letters between depths and within the same GMS are significantly different, 0.05 level, N=4.

[x]Means comparisons among sieve sizes across rows by LSD; means followed by different Greek letters between sieve sizes, within the same GMS, and at the same depth are significantly different, 0.05 level, N=4.

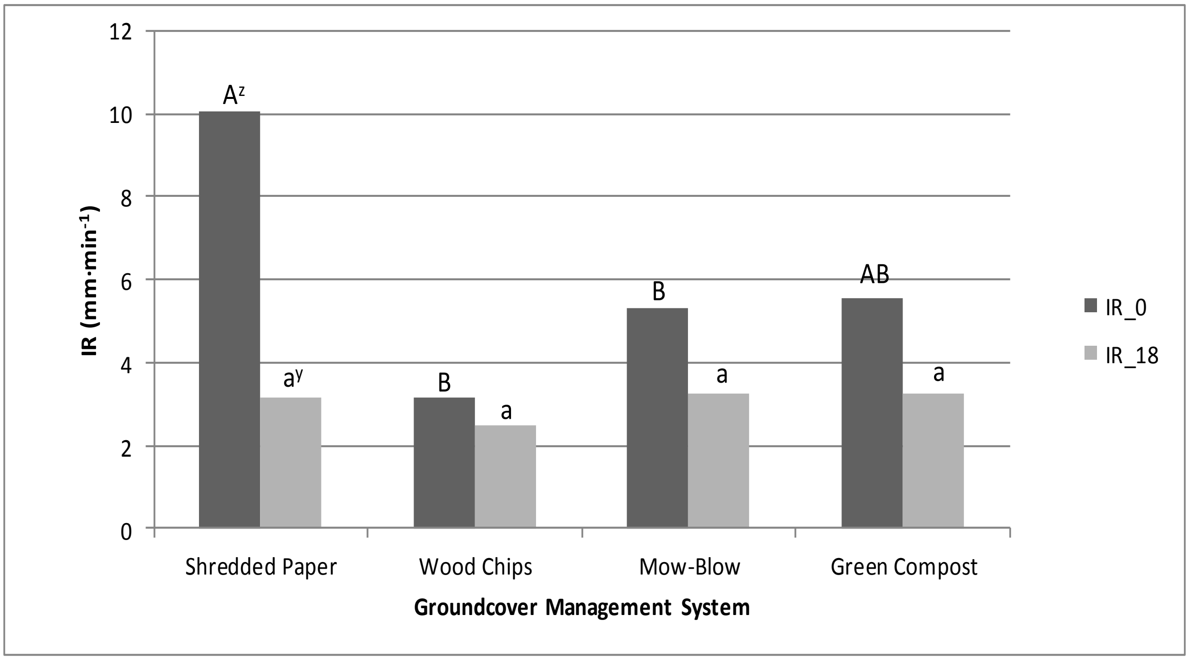


Figure 4. The influence of four groundcover management system (GMS) treatments on average infiltration rate (IR_18) and specific infiltration rate (IR_0) in an organically-managed apple ('Enterprise'/M.26) orchard. Sampling conducted within 0.75 m of tree trunk on a silt loam soil, May 2012, Fayetteville, AR, 2012.

[z]Means comparisons with different uppercase letters atop their bars are significantly different, 0.1 level, N=6.

[y]Means comparisons with different lowercase letters atop their bars are significantly different, 0.1 level, N=6.

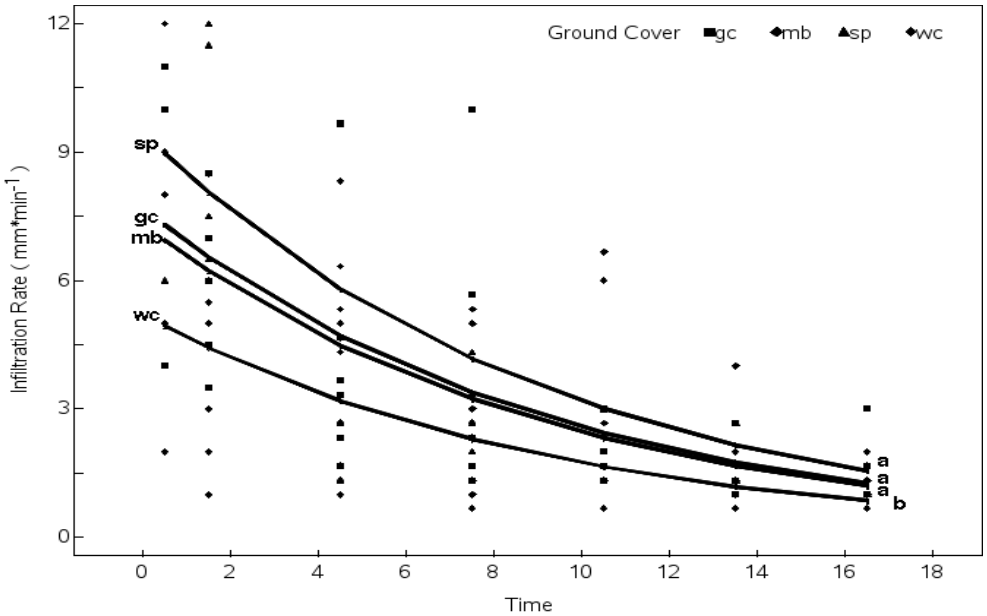


Figure 5a. Best fit linear model for infiltration rate as affected by groundcover management system treatments in an organically managed apple ('Enterprise'/M.26) orchard[z].

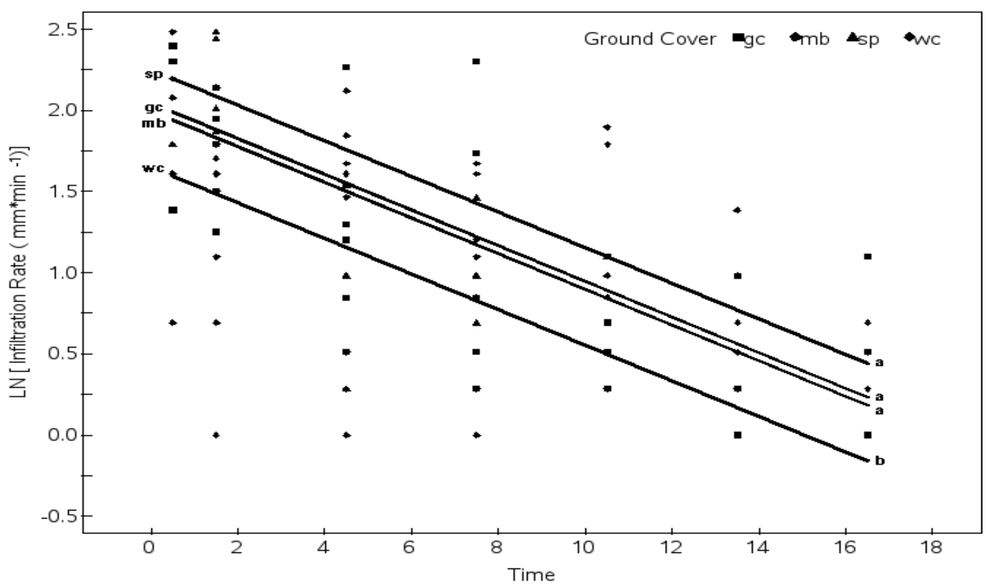


Figure 5b. Interaction of the co-variates groundcover and time on infiltration rate expressed as the natural log of infiltration rate (slope -0.11). Groundcover and soil volumetric water content were also measured as co-variates and generated an identical graph[z].

[z]Sampling conducted on a silt loam soil within 0.75 m of tree trunk, Fayetteville, AR, May 2012. Different letters at lower end of graphs represent significant differences between infiltration rates (5a) and intercepts of regression equations (5b), 0.1 level, N=6. Calculated intercepts: SP=2.25 (se ± 0.18); WC = 1.65 (se ± 0.17); MB = 1.99 (se ± 0.17); GC = 2.04 (se ± 0.17)

Table 4. The influence of groundcover management system (GMS) treatments on estimated saturated soil hydraulic conductivity (Ksat) in an organically managed apple ('Enterprise'/M.26) orchard. Sampling conducted at 0-6 cm soil depth and 0.75 m from tree trunk on a silt loam soil. Fayetteville, AR, June 2012[z].

	Estimated Ksat ($mm \cdot hr^{-1}$)		
	Nutrient Source		
GMS	No Fertilizer	Poultry Litter	Commercial Fertilizer
Shredded Paper	57.7 Ba	60.6 Ba	67.0 Ba
Wood Chips	57.8 Bb	68.2 Ba	64.6 Bab
Mow-Blow	57.1 Ba	60.4 Ba	51.7 Ca
Green Compost	100.0 Aa	86.1 Ab	102.6 Aa

[z]Estimates generated from SPAW model, USDA-NRCS.

[y]Means comparisons among treatments by LSD; different uppercase letters indicate significant differences between GMS treatments receiving same nutrition source, 0.05 level, N=6.

[x]Means comparisons among treatments by LSD; different lowercase letters indicate significant differences within GMS treatments receiving different nutrition sources, 0.05 level, N=6.

Table 5. Informal comparison of soil quality indicators in a conventionally (CONV) managed apple orchard with those from an organically-managed apple ('Enterprise'/M.26) orchard utilizing groundcover management systems [shredded paper (SP); wood chips (WC); mow-blow (MB); green compost (GC)]. Water stable soil aggregate (WSA) concentrations from two depths were determined November 2011. Soil organic matter (SOM) concentration, bulk density (BD), field moisture capacity (FMC), permanent wilting point (PWP), plant available water capacity (PAW), saturated hydraulic conductivity (K_{sat}), specific infiltration rate (IR_0), and average infiltration rate (IR_18) determined June 2012. Data shown include mean and standard mean error. All sampling conducted on a silt loam soil and 0.75 m from tree trunk, Fayetteville, AR[z].

	Groundcover Management System									
Soil Quality Indicator	**CONV**	std error	**SP**	std error	**WC**	std error	**MB**	std error	**GC**	std error
SOM ($g \cdot g^{-1}$)	0.03	0.001	0.03	0.001	0.03	0.002	0.03	0.001	0.06	0.004
BD ($g \cdot cm^{-3}$)	1.3	0.03	1.13	0.03	1.01	0.04	1.17	0.02	1.02	0.02
PAW (%)	17.2	0.3	16.6	0.1	16.4	0.2	16.7	0.1	17.3	0.4
FMC (%)	22.3	0.4	21.7	0.3	22.0	0.4	21.5	0.2	25.1	0.6
PWP (%)	5.1	0.4	5.1	0.2	5.6	0.4	4.8	0.3	7.8	0.4
IR_0 ($mm \cdot min^{-1}$)	3.5	1.1	10.1	3.0	3.2	0.9	5.3	1.2	5.6	1.6
IR_18 ($mm \cdot min^{-1}$)	2.8	0.4	3.2	0.3	2.5	0.4	3.3	0.5	3.2	0.8
K_{sat} ($mm \cdot hr^{-1}$)	53.1	2.9	61.8	2.3	63.5	3.5	56.4	2.4	96.2	3.4
WSA, 0 - 7.5 cm ($g \cdot g^{-1}$)	0.06	0.003	0.12	0.01	0.08	0.007	0.07	0.01	0.2	0.03
WSA, 7.5 - 15 cm ($g \cdot g^{-1}$)	0.06	0.003	0.07	0.002	0.05	0.009	0.005	0.002	0.07	0.006

[z]Conventionally managed orchard managed as an apple cultivar trial (M.106 and M.26 rootstocks), 1989 - 2012. Conventional orchard received herbicides for under-tree weed control and inorganic chemical fertilization following commercial recommendations. Data collection was conducted simultaneously in the conventional orchard and using same sampling protocols as described for the organic orchard, with a total of 12 soil cores collected in the conventional orchard. Soil organic matter concentration, bulk density, plant available water, field moisture capacity, permanent wilting point, K_{sat} measurements conducted in June 2012, N=6. Infiltration rates were determined May 2012, N=6. Water stable aggregate concentrations determined November 2011, N=4.

Appendix 1: Supplemental Tables and Photographs Explaining Interaction between Physical Soil Quality Indicators, Groundcover Management Systems, and Nutrient Sources[z]

[z]Material in Appendix 1 supports Chapter 2.

Table 1. ANOVA table for effects of groundcover management system (GMS) and nutrient source (NS) treatments on soil hydraulic properties and bulk density in an organic apple ('Enterprise'/M.26) orchard, June 2012, Fayetteville, AR. $P \leq 0.05$.

	Treatment Effect, N = 6 (P < F)		
Soil Quality Indicator	GMS	NS	GMS X NS
Plant Available Water	0.010	0.294	0.002
Field Moisture Capacity	<0.001	0.277	<0.001
Permanent Wilting Point	<0.001	0.583	<0.001
Saturated Hydraulic Conductivity	<0.001	0.347	0.0036
Bulk Density	0.016	0.022	0.127

Table 2. ANOVA table for interaction between groundcover management system (GMS), nutrient source (NS), and soil depth (DEP) on water stable soil aggregate (WSA) separated by sieve mesh opening in mm (Size) on the WSA fraction (g/g) in an organic apple ('Enterprise'/M.26) orchard, Fayetteville, AR, November 2011. Samples collected 0.75 m from tree trunk on a silt loam soil[z]. (N=4, P<0.05)

	Soil Quality Indicator (P < F)	
Treatment	Total WSA Fraction	WSA Fraction X Sieve Size
GMS	0.029	0.022
NS	0.7	0.668
Dep	<0.001	<0.001
GMS X NS	0.811	0.707
GMS X Dep	**<0.001**	**<0.001**
NS X Dep	0.914	0.919
GMS X NS X Dep	0.999	0.999
Size		<0.001
GMS X Size		<0.001
NS X Size		0.595
GMS X NS X Size		0.978
Dep X Size		<0.001
GMS X Dep X Size		**0.001**
NS X Dep X Size		0.779
GMS X NS X Dep X Size		0.841

[z]Sample weight was 300 g air dried soil.

Table 3. Weight of water-stable soil aggregates categorized by groundcover management system, sieve mesh size, and depth from an organic apple ('Enterprise'/M.26) orchard, Fayetteville, AR. Samples collected 0.75 m from tree trunk on a silt loam soil, November 2011. Sample size for WSA analysis was 300 g.

		Water Stable Aggregate Weight (g)			
		Sieve Size			
Groundcover	Depth	0.25 mm	0.50 mm	1.0 mm	2.0 mm
Shredded Paper	0-7.5 cm	18.42 A[z]a[y]α[x]	10.89 Baβ	6.95 Baγ	0.52 Baδ
	7.5-15 cm	9.78 Abα	5.28 Abβ	4.40 Aaβ	0.15 Aaγ
Wood Chip	0-7.5 cm	11.17 Baα	7.31 Baβ	5.71 Baβ	0.61 Baγ
	7.5-15 cm	7.70 Abα	4.70 Aaβ	4.21 Aaβ	<0.001 Aaγ
Mow-Blow	0-7.5 cm	10.58 Baα	6.09 Caβ	4.82 Baβ	0.21 Baγ
	7.5-15 cm	7.70 Abα	4.70 Aaβ	4.23 Aaβ	0.12 Aaγ
Green Compost	0-7.5 cm	18.59 Aaα	15.34 Aaβ	17.46 Aaαβ	8.82 Aaγ
	7.5-15 cm	9.75 Abα	6.27 Abβ	5.44 Abβ	0.39 Abγ

[z]Means comparisons among treatments within a column by LSD; means followed by different upper case letters within a column and at the same depth are significantly different , 0.05 level, N=4.

[y]Means comparisons among depths by LSD; means followed by different lower case letters between depths and within the same GMS are significantly different, 0.05 level, N=4.

[x]Means comparisons among sieve sizes across rows by LSD; means followed by different Greek letters between sieve sizes, within the same GMS, and at the same depth are significantly different, 0.05 level, N=4.

Table 4. Total weight of water-stable soil aggregates categorized by groundcover management system and soil depth from an organic apple ('Enterprise'/M.26) orchard, Fayetteville, AR. Samples collected 0.75 m from tree trunk on a silt loam soil, November 2011. Sample size for WSA analysis was 300 g.

	Total Water Stable Aggregate Weight (g)	
	Depth	
Groundcover	0-7.5 cm	7.5-15 cm
Shredded Paper	36.8 AB[z]a[y]	19.6 Aa
Wood Chips	24.9 ABa	16.0 Aa
Mow-Blow	21.7 Ba	16.8 Aa
Green Compost	59.6 Aa	21.9 Aa

[z]Means comparisons among treatments within a column by LSD; means followed by different upper case letters among treatments are significantly different, 0.05 level, N=4.

[y]Means comparisons between depths between columns by LSD; means followed by different lower case letters between depths are significantly different, 0.05 level, N=4.

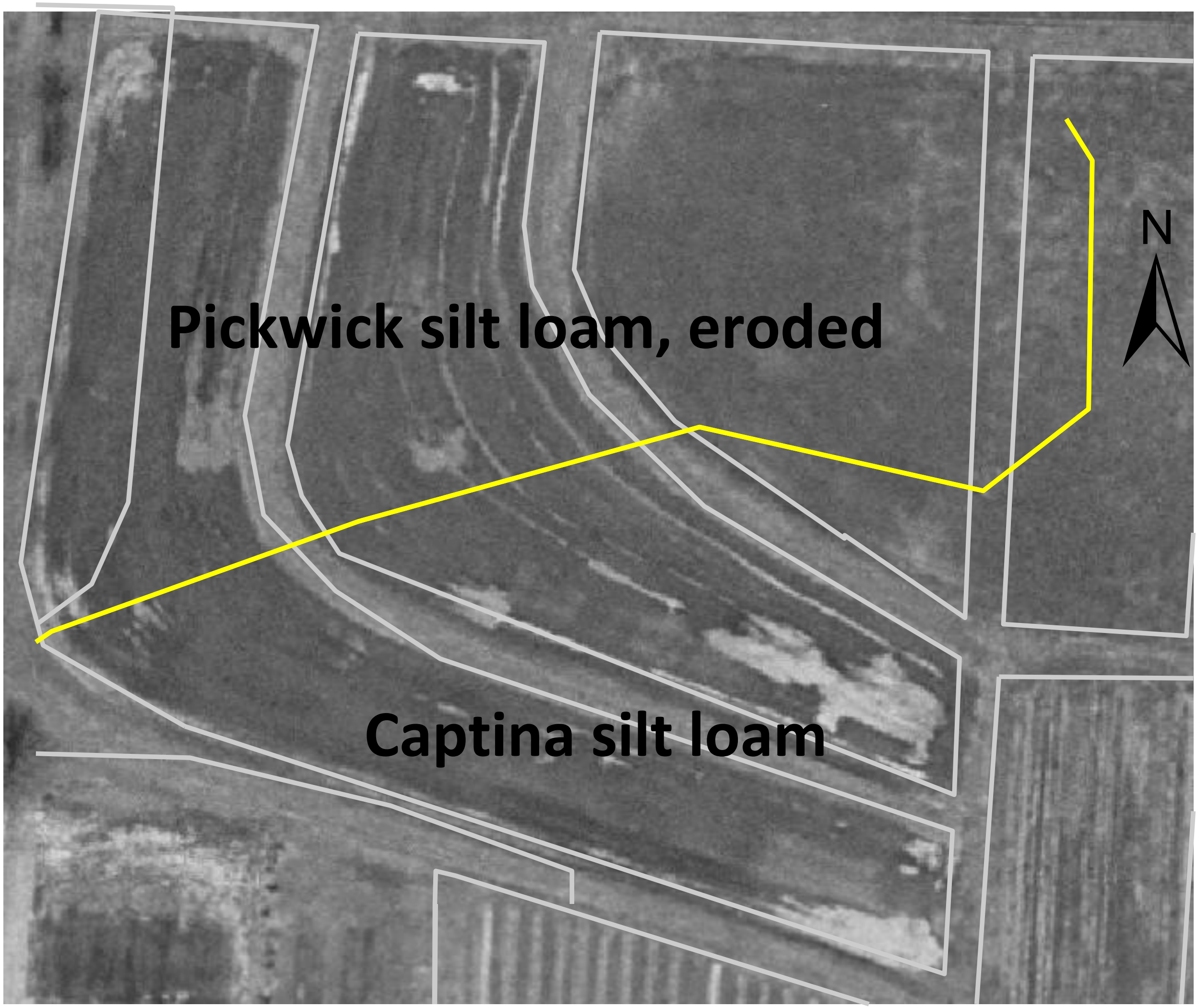


Figure 1. Aerial photograph of site prior to organic apple ('Enterprise'/M.26) orchard establishment in 2006, Fayetteville,AR. Boundary between Pickwick and Captina soil is shown approximately across center of photo.

Figure 2. Current photo of organic apple (‘Enterprise’/M.26) orchard (2012), Fayetteville, AR.

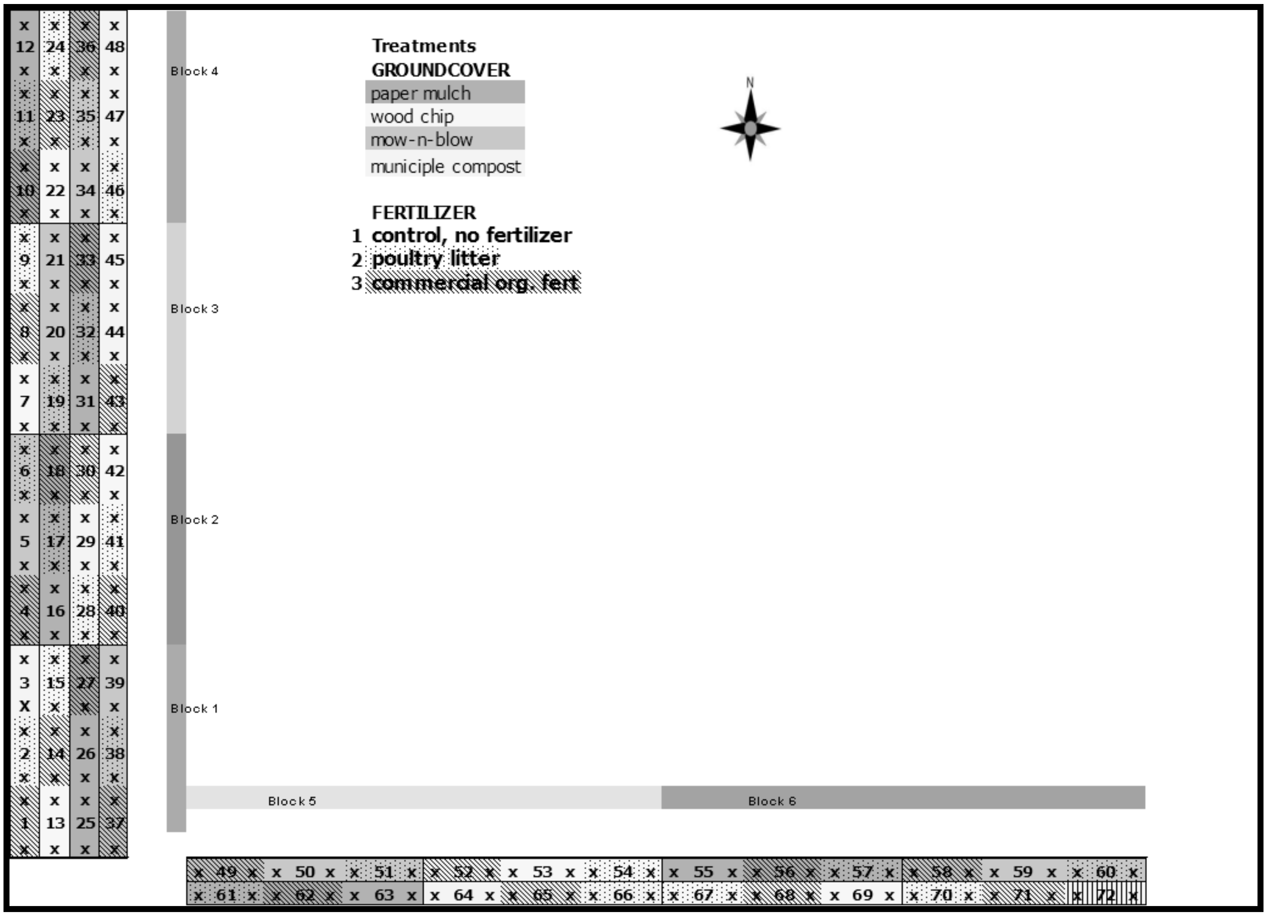


Figure 3. Organic apple ('Enterprise'/M.26) orchard layout, Fayetteville, AR.

4a.

4b.

4c.

4d.

Figure 4. Groundcover treatments evaluated in organic apple (‘Enterprise’/M.26) orchard, Fayetteville, AR. 4a) wood chips, 4b) green compost, 4c) mow-blow, and 4d) shredded paper. Groundcovers applied annually in March.

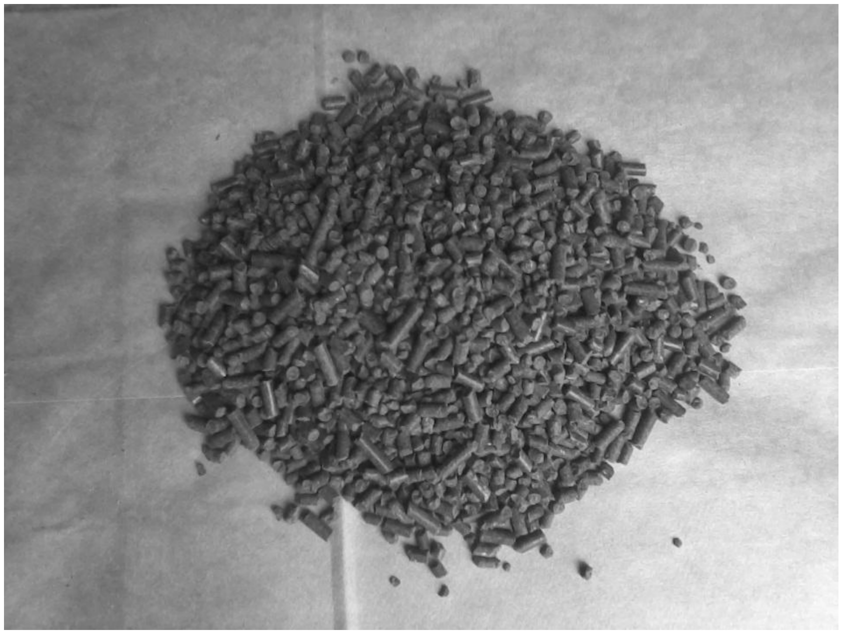
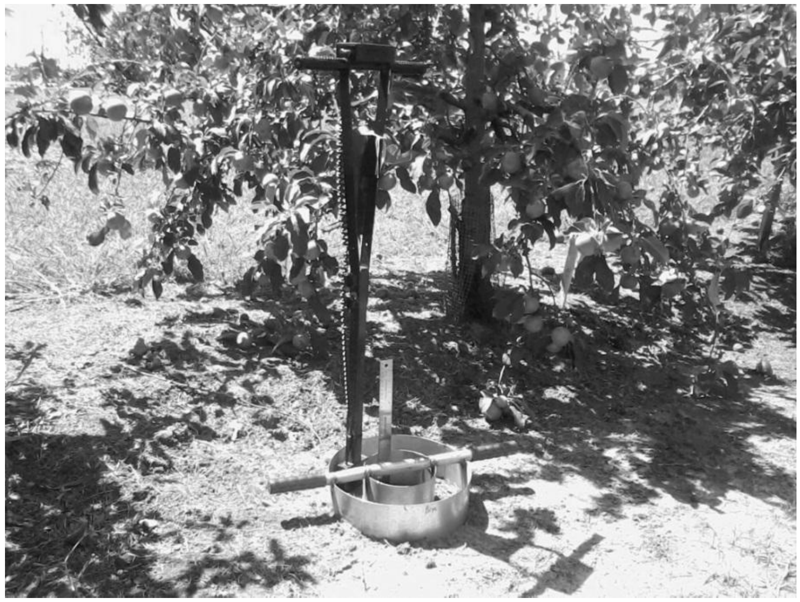


Figure 5. Nutrient sources evaluated in organic apple (‘Enterprise’/M.26) orchard, Fayetteville, AR. Top: commercial organic fertilizer. Bottom: composted poultry litter. Nutrient sources applied annually in March.



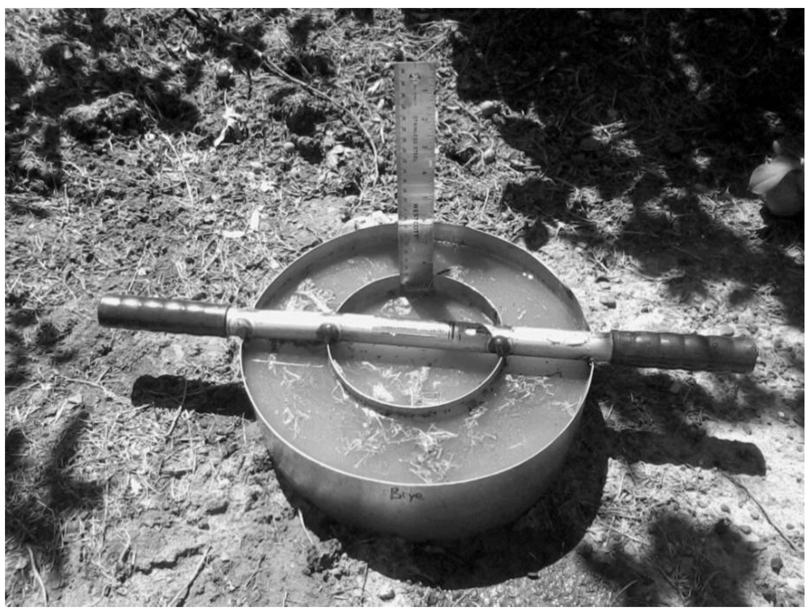
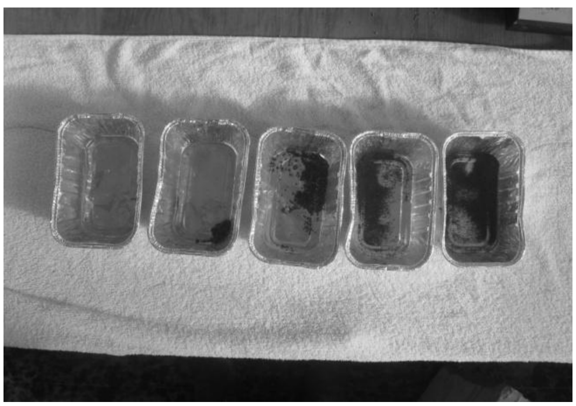


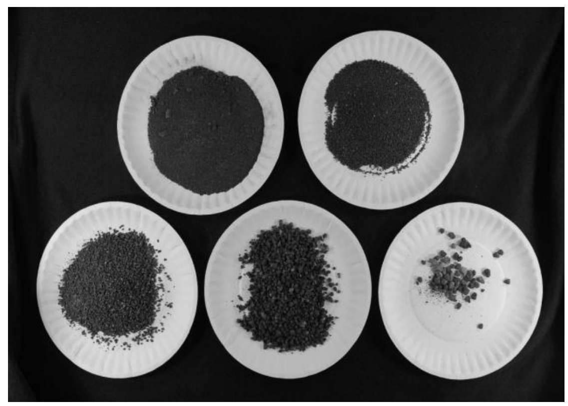
Figure 6. Water infiltration evaluation in organic apple (‘Enterprise’/M.26) orchard, Fayetteville, AR, May 2012. Top: Placement of double ring infiltrometer in tree row and measurement of soil volumetric water content. Bottom: Initiation of infiltration measurement with outer and inner rings full of water.

7a.

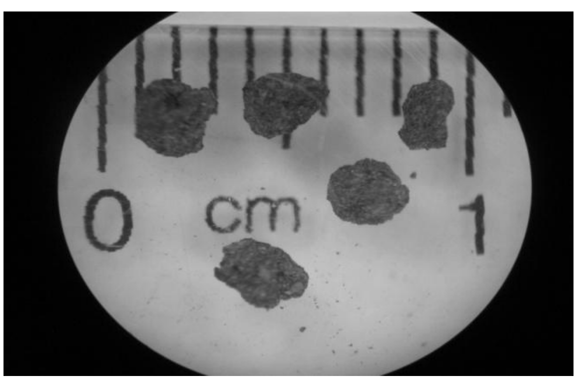
7b.



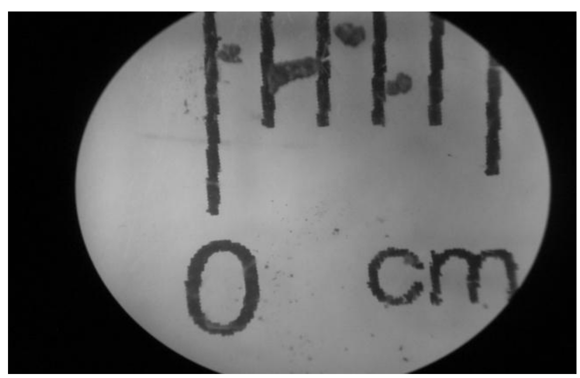
7c.



7d.



7e.



7f.

Figure 7. Water stable soil aggregates collected from organic apple ('Enterprise'/M.26) orchard, Fayetteville, AR, 2011. 7a) Wet sieving apparatus, 7b) Aggregates collected after sieving, 7c) Aggregates prepared for drying, 7d) Dried aggregates, 7e) Aggregates retained on 2mm sieve, and 7f) Aggregates retained on 0.25mm sieve.

Figure 8. Sampling for soil bulk density in the organic apple ('Enterprise'/M.26) orchard, Fayetteville, AR, June 2012.

Chapter 3: Soil Carbon and Nitrogen Sequestration Potential in an Organically Managed Ozark Highlands Apple Orchard[z]

[z]This paper is formatted for submission to HortScience

Abstract

New orchards established on weathered, acidic Ozark Highlands mineral soils must be managed to meet tree nutritional requirements. A common characteristic of these soils is low organic matter concentration, a condition which can have detrimental effects on orchard productivity. In March 2006, an experimental apple orchard was established to evaluate the effect and interactions of four groundcover management systems (GMS), shredded paper (SP), wood chips (WC), municipal green compost (GC), and mow-blow (MB) and three organic nutrient source (NS) amendments [control (NF), composted poultry litter (PL), pelletized organic fertilizer (CF)] on tree growth and productivity and soil quality indicators. As a study of the potential environmental impacts of organic orchard management, changes in soil carbon and nitrogen over time were monitored as affected by the GMS and NS treatments. Soil samples (0 - 10 cm depth) were analyzed for soil organic matter (SOM) content by loss on ignition in October 2006 and in March 2012. In November 2011, 7.3 cm wide by 7.5 cm depth soil cores were collected from beneath each tree canopy. Total soil carbon (TC) and total soil nitrogen (TN) concentrations were determined by high temperature combustion. Total C contents and TN contents ($Mg \cdot ha^{-1}$) were calculated according to measured TC and TN concentrations and bulk densities. All GMS treatments increased SOM, increased TC concentrations and contents, and increased TN concentrations and contents from 2006 to 2011 in the top 7.5 cm soil layer. The greatest differences were observed with GC treatments. Interactions between GMS and NF, PL, and CF were only observed in SOM content; NS did not affect TC and TN levels. These results indicate that, using organic cultural methods, soil C and N content can be significantly augmented in Ozark Highlands apple orchards over a relatively short time.

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

Soil organic C is the most prevalent form present in arable land, with inorganic soil C more common in semi-arid 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 have 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 declines in soil organic C.

Stable SOM, also known as humus, is derived in part from heterogeneous plant matter retained on the soil surface, and soil humus content may be affected by intentionally placing plant residues on the soil surface for incorporation or placed adjacent to a crop and serve as a mulch. Humification of plant debris, a process mediated in large part by soil microorganisms, is a sequence of steps through which plant tissues degrade and are then reorganized through biological, microbial, or chemical soil processes into more stable compounds (Tate, 1992). Labile components of particulate organic matter (POM) containing compounds such as polysaccharides are readily utilized by soil microorganisms while more chemically resistant plant tissues, such as lignin and cellulose, are decomposed relatively slowly (Tisdall and Oades, 1982). The products of the decomposition process are polymerized into new organic (humified) compounds which are much more resistant to bacterial degradation than fresh organic matter (Brady, 1990).

In a study comparing the effects of cropping management on soil C and N levels, Lal et al. (1998b) determined tall fescue (*Festuca arundinacea* Schreb.) and smooth bromegrass (*Bromus inermis* Leyss.) cover crops elevated the soil C content by 18.5% and N content by 12.5% compared to a corn-soybean rotation, and increasing fertilizer rates enhanced total soil C sequestration by replacing nutrients removed with the harvested crop. Nyborg et al. (1998) reported significant C increases in the light fraction of SOM, particularly when N and S fertilizers were applied, while increases in total soil C content generally had greater variability. Thus, the rate at which soil C content increases is usually reduced by low soil macronutrient levels and a subsequent reduction in soil microbial activity.

The most stable forms of soil C are stored in 2 - 50 µm diameter particles including small microaggregates (<0.25 mm) and the silt-plus-clay fraction of soil (Six et al., 2012) and have developed over a period of years. Stable soil C is routinely occluded within microaggregates due to continual production of microbial mucilages, which are associated with decomposing plant or microbial residues, and subsequent encrustation of these residues with clay particles (Hassink, 1997; Six et al., 2000; Balabane and Plante, 2004; Denef et al., 2007; Virto et al., 2010). Macroaggregates (> 0.25 mm diameter) are largely comprised of POM, also designated as the light fraction of SOM (Wander et al., 1994), and are an important reservoir of soil C. Macroaggreagtes have little, if any, association with mineral soil particles (Kay, 1998). Particulate organic matter is a contributor to soil fertility due to its cation exchange capacity and inherent content of plant nutrients (Tisdale et al., 1993). However, the light fraction does not contribute greatly to stable soil C pools because of its lability and susceptibility to microbial degradation.

Effects of soil management on soil C content may vary according to site geography. For instance, the climate of the southeastern U.S. does not permit soil C increases to levels observed in northern latitudes. This is a result of a combination of factors including warmer summer temperatures and more rainfall in the southeastern U.S., 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* X *domestica* Borkh.) production, annual tillage is not required for desirable tree growth, nor may it be the most viable option for controlling competitive vegetation due to standards set forth by the National Organic Program (USDA-AMS, NOP § 205.203). 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; Reganold et al., 2001; Granatstein and Mullinix, 2008; Granatstein et al., 2010), a requirement established by the NOP standards. Plant residues are a source of C, and utilized long-term, they may serve to sequester C and increase soil C levels in organic production systems.

Additional research addressing changes in the soil C balance in orchard soils is limited, and no research has been located regarding the potential for C sequestration in organically-managed Ozark Highlands apple orchards. Therefore the objectives of this study were to a) evaluate the effects of GMS and NS on SOM content, TC concentrations and contents, and TN concentrations and contents over time in the upper/shallow soil layers and b) informally compare SOM content, TC concentrations and contents, and TN concentrations and contents under various GMS to a conventionally-managed apple orchard.

Materials and Methods

This experiment was part of a broader study examining the impacts of GMS and NS on physical, chemical, and biological soil characteristics, tree health and productivity, and insect, disease, and weed management in an organically-managed apple (*Malus* x domestica Borkh.) orchard. The research orchard is located at the University of Arkansas Main Agricultural Experiment and Extension Center, Fayetteville, Arkansas (36^{o}N, 94^{o}W) and is situated on two soil series. Two-thirds of the trees are established on a Pickwick silt loam (fine-silty, mixed semi-active, thermic Paleudults), with the remainder located on a Captina silt loam (fine-silty siliceous, active, mesic Typic Fragiudults) (Figure 1, Appendix 1). 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, and fragipans are commonly present in Captina soils at approximately 51 cm, limiting root penetration below this depth (USDA – SCS, 1969). Both are well suited for orchard and/or small fruit production.

The site of the study orchard had been in horticultural production for approximately 75 years. Prior to orchard establishment, the site was planed and leveled in 2005. Soil pH was adjusted by application of agricultural lime according to University of Arkansas Soil Testing and Research Laboratory recommendations, and composted horse manure was applied at the rate of 5 $MT \cdot ha^{-1}$. Enterprise/M26 apple cultivars were planted 2006 and trained to a two-wire trellis vertical axis system. The orchard covers 0.40 ha with 2 m tree spacing and 4 m row spacing. Tree density is approximately 1485 trees/ha. Orchard management followed NOP regulations since establishment. Drive alleys are perennially managed with tall fescue (*Festuca arundinacea* Schreb. 'KY 31') with other native herbaceous plants occurring.

The experimental design was a 4 X 3 factorial of four GMS treatments by three NS treatments. The orchard was divided into six blocks with GMS as the main-plot effect and NS as the sub-plot effect, resulting in 12 possible treatment combinations and a total of 72 treatment plots (Figure 3, Appendix 1). Treatment 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 (Figure 2, Appendix 1). Groundcover management systems studied in this experiment included 1) urban municipal green compost (GC), 2) shredded office paper (SP), 3) waste wood chips of urban origin (WC), and 4) a managed tall fescue mow-blow (MB) green mulch system which served as an informal control treatment.

Beginning in 2006, GC, SP, and WC treatments were applied under trees annually in March in a 2 m wide by 10 to 12 cm deep band extending across both sides of the tree row (Figure 4, Appendix 1). Green compost, derived of urban vegetative waste (i.e. grass clippings, wood prunings, and yard waste) and composted 90-120 days 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, 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 rotary mower in late May and three to five times throughout the summer depending on its growth.

Tree nutrient sources were provided annually and included A) certified organic commercial fertilizer (CF) produced from poultry manure (Perdue AgriRecycle, pelletized poultry manure, Seaford DE; 4-2-3 analysis), B) locally available composted poultry litter (PL), or C) an un-amended control (NF) treatment in which all added nutrition came from the GMS (Figure 5, Appendix 1). The CF selected at the initiation of the study was used through the 2010 application, but production was subsequently discontinued. An alfalfa-based commercial organic product (Bradfield Organics, Feed Solutions, St. Louis, MO, 3-1-5 analysis) was applied beginning in 2012. Nutrient source treatments were applied in March of each year prior to application of GMS treatments at 50g of actual N per tree per year. All sampling was conducted with 0.75 m of the treatment tree trunk. In the event a treatment tree had died, a guard tree plot from the original orchard planting was selected for sampling.

Soil organic matter content from the upper 10 cm of soil was determined by loss on ignition using a muffle furnace at 500°C for 6 hours, after oven-drying soil at 105°C for 24 hours. Soil organic matter was determined in October 2006 and March 2012 and calculated on a dry weight basis. Soil bulk density (BD) was determined in November 2006 and June 2012 from 5.4 cm wide by 6 cm depth cores. Mulches were removed to expose the mineral soil surface, and rings were driven into the soil until the top edge of the ring was flush with the soil surface (Appendix 1, Figure 8). Two cores were collected from each treatment plot in this manner and dried for 3 days in a 50°C forced-air oven. Samples were then weighed and bulk density calculated for each sample as specified by Hillel (1980).

Soil C and N levels were not measured at orchard establishment (2006), but initial SOM content was determined. Because Pickwick and Captina soils are included in the same soil association and share similar physical and chemical characteristics, estimates of original Pickwick C and N concentration were estimated as a percentage of the total SOM concentration (C = 0.53 and N = 0.056). These percentages originate from unpublished research documenting typical SOM C and N concentrations, using the same techniques as described above, for an adjacent Captina soil on the University of Arkansas- Fayetteville Experiment Station (K. Brye, personal communication).

Current soil C and N concentrations and contents were determined from soil samples collected in November 2011. Mulches were raked away to expose the mineral soil surface 0.75 m from the tree trunk, and soil cores 7.5 cm long by 7.3 cm in diameter were collected. Samples were sieved through a 63.5 mm screen, mixed thoroughly, and allowed to air dry for 5 days. Approximately 200g of each soil was pulverized with a mortar and pestle to a fine powder. Forty milligrams (+/- 0.1 mg) subsamples were placed into aluminum boats and for high temperature combustion in an Elementar vario EL cube (Elementar Americas, Inc., Philadelphia, PA) for analysis of total C and N concentration (mg/kg) by high temperature combustion, and C/N ratios were calculated from these concentrations. Soil C and N contents were calculated as shown below:

A conventionally managed orchard was established in 1989 for apple cultivar evaluations (M106 and M26 rootstocks). It was located on the same Pickwick and Captina soils approximately 20 m away from and adjacent to the study orchard. Because the conventionally managed orchard was not part of the organic orchard research project, a formal statistical comparison was not made between data collected from each site. However, no organic amendments were added to the conventional orchard after its establishment, and qualitative conclusions were drawn regarding the effects of groundcover treatments on soil quality indicators as evaluated in both orchards. 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 were applied annually at rates of 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, MP 144 and MP 154, 2013).

Soil samples were not obtained from the conventional orchard in 2006. However, because there have been no organic residue additions, it was conservatively hypothesized that current SOM in the conventional orchard are largely unchanged since 2006. Samples were analyzed for SOM content, total C and N concentration, and BD and were collected at the same time and using the same methods described for the organic orchard.

Analysis of variance was used to evaluate GMS and NS effects on measured and calculated soil properties (i.e. SOM concentration, TC concentration, TC content, TN concentration, TN content, C:N ratio, and BD) using the MIXED procedure in SAS (SAS institute, Inc., Cary, NC). Significance was judged at the 0.05 level.

Results and Discussion

Soil samples collected in 2006 indicated homogeneous soil conditions existed at the time of orchard establishment, and no pre-existing effects were observed on SOM content, TC concentrations and content, TN concentrations and content, or C:N ratio (Table 1). It could be assumed, then, that any differences among treatments after five seasons of organic management could be due to treatment effects. Soil organic matter differed among GMS and NS after five seasons (Figure 1), but interactions between GMS and NS were not observed for TC concentration or content, TN concentration or content, or C/N ratio (Table 1, Appendix 2).

Because of its impact on a variety of soil characteristics, measurements reflecting SOM were commonly included as an indicator of soil quality (Fließbach et al., 2006; Granatstein and Mullinix, 2008; Gregorich et al., 1994; Karlen et al., 1992; Loveland and Webb, 2003; Merwin et al., 1994, 1995). This study revealed substantial changes in SOM were possible over a relatively short period of time (6 years) with all GMS systems evaluated. Soil organic matter was greatest in treatments receiving GC alone or in conjunction with CF (Figure 1). Although GC applied with PL yielded greater SOM than all other GMS and NS, it was significantly less than that of treatments receiving GC alone or GC and CF. Conversely, WC treatments receiving PL were greater than WC alone or WC and CF. The explanation for the wider disparity in SOM content between WC and GC receiving CF, PL, and NF could be related in part to the lower C/N ratio of CF, compared to PL (Choi, 2009) and may merit further evaluation. Choi et al. (2011) did not observe GMS X NS interactions in SOM in the first three years following orchard establishment, but they reported greatest increases in SOM were associated with GC treatments. In the present study, all GMS treatments resulted in increased SOM over the six year study period (Figure 2). Of these, the greatest increases were observed in GC treatments, which had an approximate four-fold increase since 2006. Otherwise SOM content approximately doubled since 2006.

The decomposition of GMS and NS 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 humified residues with the mineral soil component would also be expected (Horwath, 2007). Differences in physical and chemical compositions may have also affected the rate of GMS decomposition. Compared to WC, the composting process had already decreased GC particle size, and due to its low C/N ratio, relative to other mulches (Table 2, Appendix 2), the best conditions for SOM aggradation were likely created under GC. A similar observation was made by Himes (1998), that greater SOM was associated with applications of composted cow manure, as compared to ordinary crop residues having a greater C/N ratio.

By weight, WC were approximately 50% cellulose and 28% lignin (Holland et al., 1990) resulting in a greater C/N ratio and slower rate of decomposition than GC, due to immobilization of N by soil microorganisms (Tisdale et al., 1993). Shredded paper also had a high C/N ratio, and due to its light weight, compared to WC and GC, less was total residue mass was applied over the span of the study (Choi, 2009). Similarly, the least total residue mass was applied in MB treatments, an anticipated design issue which was exacerbated by extreme drought in the last summer of the study, and little plant material deposited into the tree row was usually visible following three weeks of MB applications. Consequently, SOM increased the least with WC and SP treatments.

Others have shown increases in SOM when orchard floor management included the addition of mulches. Peck et al. (2011) associated increases in SOM over time with 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* illinoinensis (Wangenh.)K.Koch] orchard, with up to a 46% increase in SOM when litter and clover treatments were combined. Merwin et al. (1994) found applications of straw mulch caused the greatest increase in SOM content, while living mulches and chemical orchard floor management maintained or led to decreases in SOM.

In a comparison of several mulches, Merwin et al. (1995) observed no significant differences between SOM accumulation after two years of wood chip and synthetic mulching. Although initial SOM values were not listed, they reported greater SOM for both orchards evaluated (4.7% to 6.3%) than observed in this study. However, the New York research site established by Merwin et al. (1995) was previously dedicated for apple production, and as a perennially managed cropping system, greater SOM would be expected compared to that observed in northwest Arkansas. Additionally, the difference in soil types and seasonal environmental conditions may have effects. Latitude differences impact SOM content (Stevenson, 1994), and lower SOM would be expected in Arkansas compared to New York. Finally, land grading and site preparation contributed to mixing of the topsoil and subsoil in the Arkansas orchard, a condition which also likely decreased initial soil organic matter concentrations.

Increases in SOM resulted in increased total C concentrations and contents and TN concentrations and contents, and C/N ratios differed among GMS treatments ($P < 0.001$; Table 1). Because total C and N concentrations and contents were not directly measured in 2006, changes in their values are derived from direct observations of 2006 SOM content, which did not differ among GMS treatments at the time of orchard establishment. It was, therefore, assumed TC and TN concentrations were also uniform among GMS treatments in 2006. After five years of GMS applications, total soil C concentration had increased four-fold by 2011 in GC treatments, and smaller increases were observed among the other treatments, with MB providing the smallest increase (146%) in total soil C concentration since 2006. The extent of these differences may be explained by the presence of more abundant macroaggregates in larger size classes (> 0.50 mm) (Six et al., 2004) in GC than in other GMS treatments (Mays 2013, chapter 2 of this thesis).

Total soil N concentration ($g \cdot kg^{-1}$) across GC treatments increased by 327% from 2006 to 2011 while smaller gains in WC (161%), SP (148%), and MB (133%) were observed. Soil C/N ratios also increased over 2006 levels, with the greatest increase in WC and least change observed in MB. A calculated estimate of total C and N applied by GMS and NS treatment, based on Choi's (2009) accounting of C and N applied (g nutrient·tree^{-1}·year^{-1}), is shown for six years of organic management in Appendix 2, Table 3. Carbon and N additions of approximately 14 and 5 Mg, respectively, were added since 2006.

To determine changes in TC and TN content, soil BD determined for all GMS treatments at the initiation of the study and in June 2012. No differences were observed in 2006. However, BD decreased across all GMS treatments over time from 2006 (Figure 3). Bulk density was 25% lower in the GC treatment and 27% lower for WC by 2012. Nutrient source also decreased bulk density. The greatest reduction was associated with CF, while NF reduced bulk density the least. However, GMS and NS did not collectively affect BD.

Green compost, SP, and WC increased TC content over that measured in 2006, and by 2011, TC content in GC treatments were well over twice the establishment levels (Table 1). The difference in the amount of C sequestered between GC (2.9 Mg C·ha^{-1}·yr^{-1}) and all other GMS evaluated may be attributed to its low C/N ratio (Table 2, Appendix 2) relative to WC (1.0 Mg C·ha^{-1}·yr^{-1}) and SP (0.9 Mg C·ha^{-1} ·yr^{-1}). Although MB treatments had a similar C/N ratio, less total MB residue was applied over the span of the study, and less C was applied in the MB treatment. Thus, significant C sequestration was not observed in MB (0.5 Mg C·ha^{-1}·yr^{-1}). Although C concentrations in MB increased relative to 2006, C contents did not increase, presumably due to the added variability in bulk densities across treatments. Shredded paper was applied within the tree rows at the same depth and width as green compost and wood chips but with less volume due to density differences in the GMS treatments. Because SP does not compact into a dense layer during its application, as with GC and WC, less total SP residue was applied than in WC and GC treatments (Choi, 2009). Despite the greater residue mass added in WC treatments, compared to SP, decomposition of SP was almost complete each year while WC decomposition was visually slower, and the difference in the rates of decomposition between WC and SP may help explain the similar rates of C sequestration observed between WC and SP treatments.

The addition of organic residues has been shown to facilitate the sequestration of C in apple orchards receiving compost additions compared to conventional management (Deurer et al., 2009, Glover et al., 2000). Further, Amiri and Fallahi (2008) observed greatest C accumulation with applications of cow manure, while poultry manure afforded lower soil C concentrations. Increased microbial biomass C was observed when plant residues were applied as GMS (Goh et al., 2001), indicating conditions were improved for soil microbial activity when organic cultural practices were employed, while microbial activity may have been diminished with conventional management (Gunapala and Scow, 1998). However, the magnitude of future C sequestration possible with continued application of these GMS remains unknown.

Due to the humid climate in the southeastern U.S., greater N concentration, and the amount at which it is applied, C sequestration should be greater for GC than for the other GMS treatments, and continued application of GC may lead to C saturation in the top few centimeters of the mineral soil fraction (Gulde et al., 2008; Six et al., 2002). Further increases in SOC might be attributable to alternate soil C pools, such as humus, POM, or microbial biomass, rather than 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 Himes (1998) and Stevenson's (1994) assertion that sequestration of C and N are concurrent. Increased total N content in GC treatments were 2.5 times greater by 2011 than at orchard establishment, but total soil N content did not vary among WC, MB, and SP due to the variability in soil bulk density across treatments (Table 1). Nitrogen concentrations in GC were approximately twice as high as that of WC and 30% lower than the N concentration of MB (Table 2, Appendix 2). Although the volume and mass of WC and GC applied to tree rows was comparable, the greater C/N ratio of WC did not facilitate such accumulation of soil N as in GC. Thus, greater TN was sequestered in GC treatments (0.25 Mg N·ha^{-1}·yr^{-1}), where more N was added to the system, and was attributed to the presence of greater N in the GC and its application rate, which was numerically the greatest of all GMS (Choi, 2009).

Concern exists, however, about the amount of N added with GC treatments. Rom et al. (2011) raised concerns about the possibility of nitrate leaching associated with GC, and elevated nitrate levels have been detected in the 10 – 30 cm profile depth in this orchard (M. Savin, personal communication). Legitimate concerns could also be raised about the potential for greater nitrous oxide volatilization in GC treatments when conditions are suitable for denitrification, possibly offsetting any environmental benefits gained by the sequestration of soil C. Further, over-application of N in apple orchards has been shown to cause overly vigorous tree growth, poor fruit quality and color, and increased susceptibility to disease (Neilsen and Neilsen, 2003).

Although based only on an informal comparison of organic and conventional orchard soil samples, all GMS resulted in numerically greater SOM, TC and TN concentrations and contents and C/N ratios (Table 2) than observed in the conventional orchard. Green compost had 207% greater SOM than that observed in the conventional orchard, while WC and SP showed intermediate increases in SOM compared to the conventional orchard. Total C content was larger for the GC treatment than observed in all other organic treatments compared to the conventional orchard, and TC content means for SP, WC, and MB were roughly equal to or less than conventional orchard TC content.

Similarly, increases in TN concentration and content were most pronounced with GC. This observation may be related in part to immobilization and plant uptake of N in SP, WC, and MB treatments. Wood chips and SP have large C:N ratios (Table 2, Appendix 2) which normally facilitate immobilization of mineral N constituents (Tisdale et al., 1993). However, conversion of mineral N to organic forms should not yield a decline in TN as measured by high-temperature combustion because both organic and inorganic forms of N are captured. Rather, the lower TN content of GMS with greater C:N ratios likely reflected lower total N inputs, and as time passes TN measurements may increase and ultimately reach an equilibrium.

Estimated total soil N content at the time of organic orchard establishment was approximately 0.8 $Mg \cdot ha^{-1}$, and 2011 soil N levels in the conventional orchard were comparable to that observed in the SP, WC, and MB treatments. In the conventional tree rows managed with herbicides, soil N concentrations were probably largely related to fertilizer applications. Mow blow treatments resulted in lower TN levels than observed in the conventional orchard, possibly because a portion of soil N had been assimilated into grasses and was not detectable in conventional orchard soil samples. Likewise soil C accumulation was reduced with conventional management because organic residues were limited on the soil surface and in the rhizosphere. In this case, all fruit was not harvested from the conventional orchard and was allowed to drop at the end of the season, and it may have been a measurable source of recycled C and N typically unavailable in a commercial orchard, which would have all fruit harvested. As WC and SP mulching continues, soil TC and TN contents are expected to increase and eventually equal or surpass TC and TN contents measured in the conventionally managed orchard. However, GC applications consistently provided greater SOM, TC, and TN than measured in the conventional orchard.

Conclusions

Significant carbon sequestration was possible in this study after application of plant residues as GMS in Ozark Highlands organic apple orchards, thereby increasing SOM and improving soil quality (Doran et al., 1996). The greatest increases in SOM and C and N contents and concentrations were associated with applications of GC. Less SOM aggradation and C and N sequestration were observed in WC, SP, and MB treatments due to higher C/N ratios, smaller residue masses applied over the span of the study, or a combination of these factors. Compared to apple orchards managed with herbicides and soluble fertilizers, GC, WC, and SP increased soil quality while soil conditions in MB rows were comparable to that in the conventional orchard. It is therefore hypothesized that conditions required for sequestration of C are best achieved with GC due to accelerated formation of C and N-rich SOM. The small physical particle size of GC, along with its low C:N ratio and apparent adequacy in providing for nutritional needs of the soil microbial community (Bhogal et al., 2009; Gunapala and Scow, 1998), permitted the greatest increase in soil C levels since initiation of the study. Likewise sequestration of N occurred as SOM levels increased. Significant amounts of N were provided with GC applications and contributed to significant increases in TN levels, likely across multiple soil N pools. Care should also be taken in organic apple production, however, to ensure nutrients are not over-applied, thereby protecting soil and water resources and maintaining the health of the orchard ecosystem. This research indicates the use of GMS as an orchard floor management tool can affect SOM, soil C, and soil N concentration of mineral soils almost devoid of these important constituents, and soil quality can be expected to improve. Further, soil conditions not ideal for the production of apples may be remediated over a relatively short time when amended with additions of GMS mulches.

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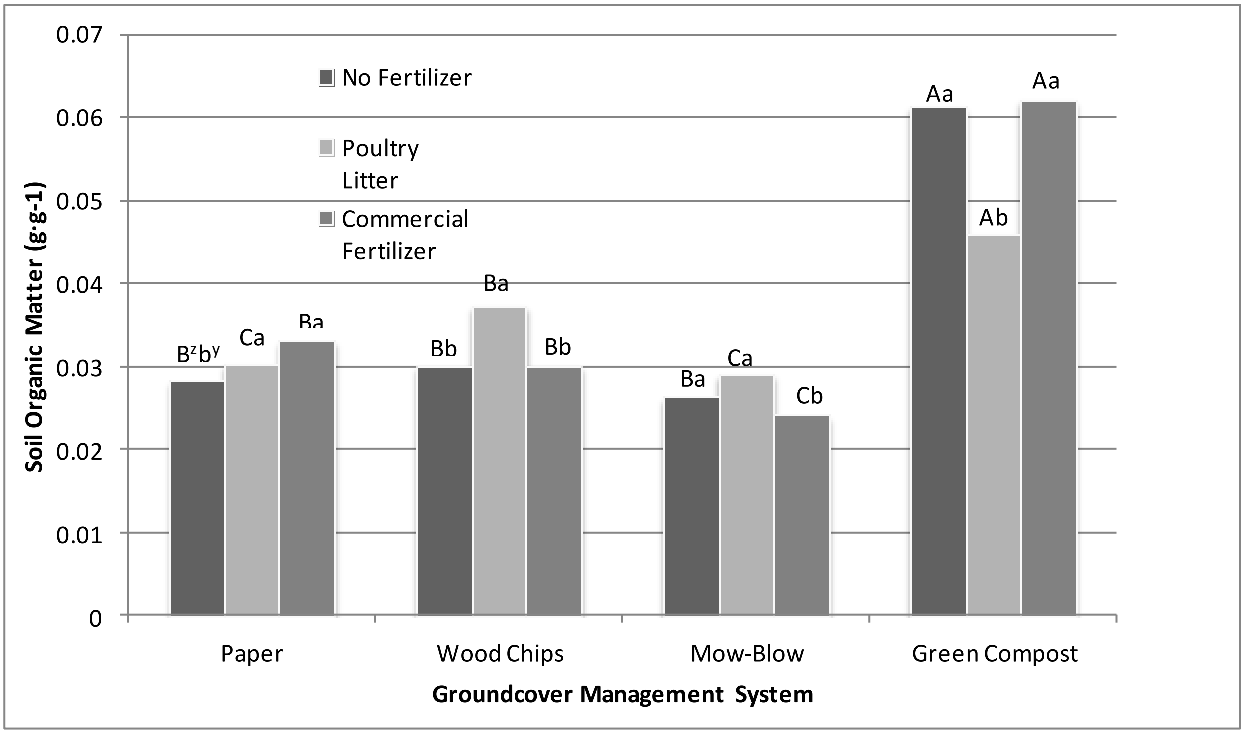

Figure 1. Interaction between groundcover management system and nutrient source on soil organic matter content in an organically-managed apple ('Enterprise'/M.26) orchard. Samples collected within 0.75 m of tree trunk, 0 - 10 cm depth, from a silt loam soil, March 2012, Fayetteville, AR.

[z]Means comparisons among treatments by LSD; uppercase letters atop bars indicate significant differences between GMS treatments receiving same nutrition source, 0.05 level, N=6.

[y]Means comparisons among treatments by LSD; lowercase letters atop bars indicate significant differences among GMS treatments receiving different nutrition sources, 0.05 level, N=6.

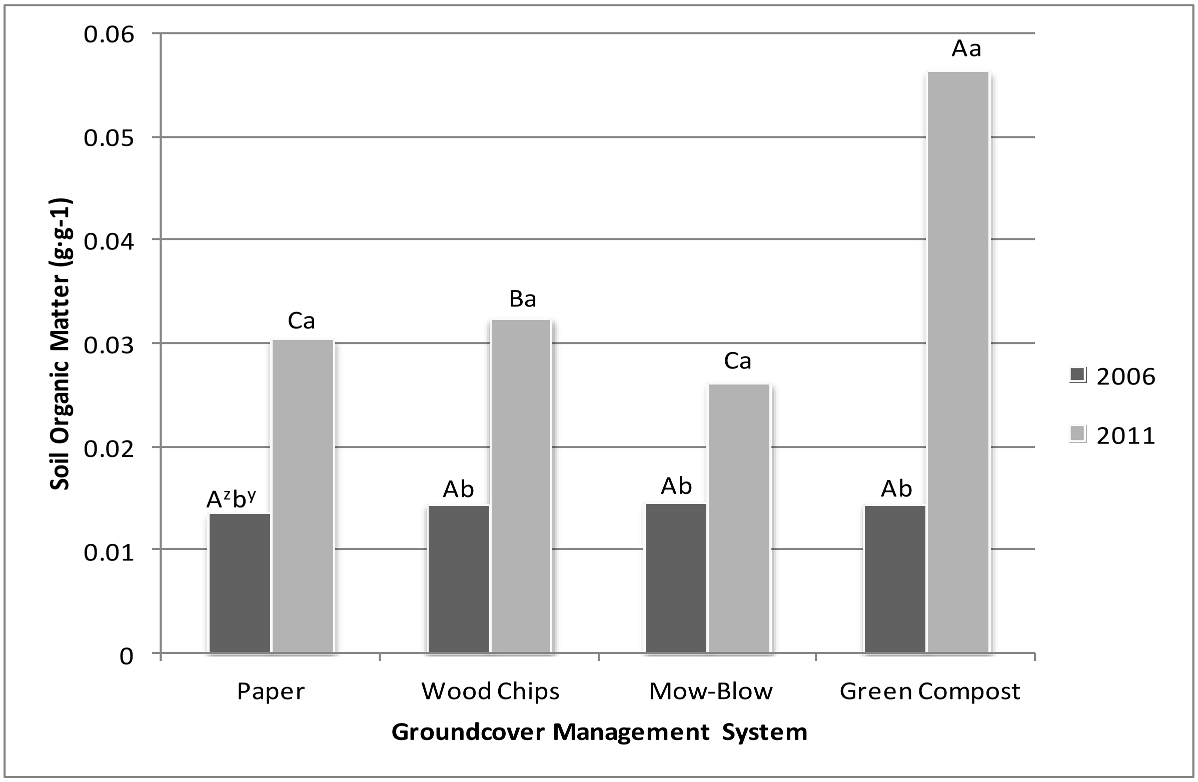

Figure 2. Effects of groundcover management system treatment on soil organic matter since establishment (2006 - 2012) of an organically managed apple ('Enterprise'/M.26) orchard. Samples collected within 0.75 m of tree trunk, 0 - 10 cm depth, from a silt loam soil, March 2012, Fayetteville, AR.

[z]Means comparisons between groundcover management treatments within year by LSD; treatment values within a year with different upper case letters atop their bar are significantly different, 0.05 level, N=6.

[y]Means comparisons within groundcover management treatments between years by LSD; treatment values with different lower case letters atop their bar are significantly different, 0.05 level, N=6.

Table 1. The change in carbon and nitrogen concentrations (g·kg^{-1}) and contents (Mg·ha^{-1}) over 6 years (2006-2012) as affected by groundcover management system in an organically managed apple ('Enterprise'/M.26) orchard, Fayetteville, AR[z].

Soil Quality Indicator	Groundcover Mangement System Treatment	Year 2006	Year 2011
Total Soil Nitrogen (g·kg^{-1})	Paper	0.83 A[y]b[x]	1.23 Ba
	Wood Chips	0.84 Ab	1.35 Ba
	Mow-Blow	0.84 Ab	1.12 Ba
	Green Compost	0.84 Ab	2.75 Aa
Total Soil Carbon (g·kg^{-1})	Paper	7.87 Ab	14.88 BCa
	Wood Chips	7.92 Ab	17.35 Ba
	Mow-Blow	7.93 Ab	11.64 Ca
	Green Compost	7.94 Ab	31.93 Aa
Total Soil Nitrogen (Mg·ha^{-1})	Paper	0.84 Aa	1.03 Ba
	Wood Chips	0.85 Aa	1.03 Ba
	Mow-Blow	0.81 Aa	0.98 Ba
	Green Compost	0.84 Ab	2.10 Aa
Total Soil Carbon (Mg·ha^{-1})	Paper	7.97 Ab	12.43 Ba
	Wood Chips	8.08 Ab	13.19 Ba
	Mow-Blow	7.68 Aa	10.16 Ba
	Green Compost	9.98 Ab	24.27 Aa
C:N	Paper	9.46 Ab	12.08 ABa
	Wood Chips	9.48 Ab	12.69 Aa
	Mow-Blow	9.46 Ab	10.34 Ca
	Green Compost	9.47 Ab	11.80 Ba

[z]Soil sample depth, 0 - 7.5 cm, silt loam soil. Samples collected November 2011.

[y]Means comparisons among treatments within a column by LSD; means followed by different upper case letters within a column are significantly different, 0.05 level, N=6.

[x]Means comparisons between years and across columns by LSD; means followed by different lower case letters between columns and in the same row are significantly different, 0.05 level, N=6.

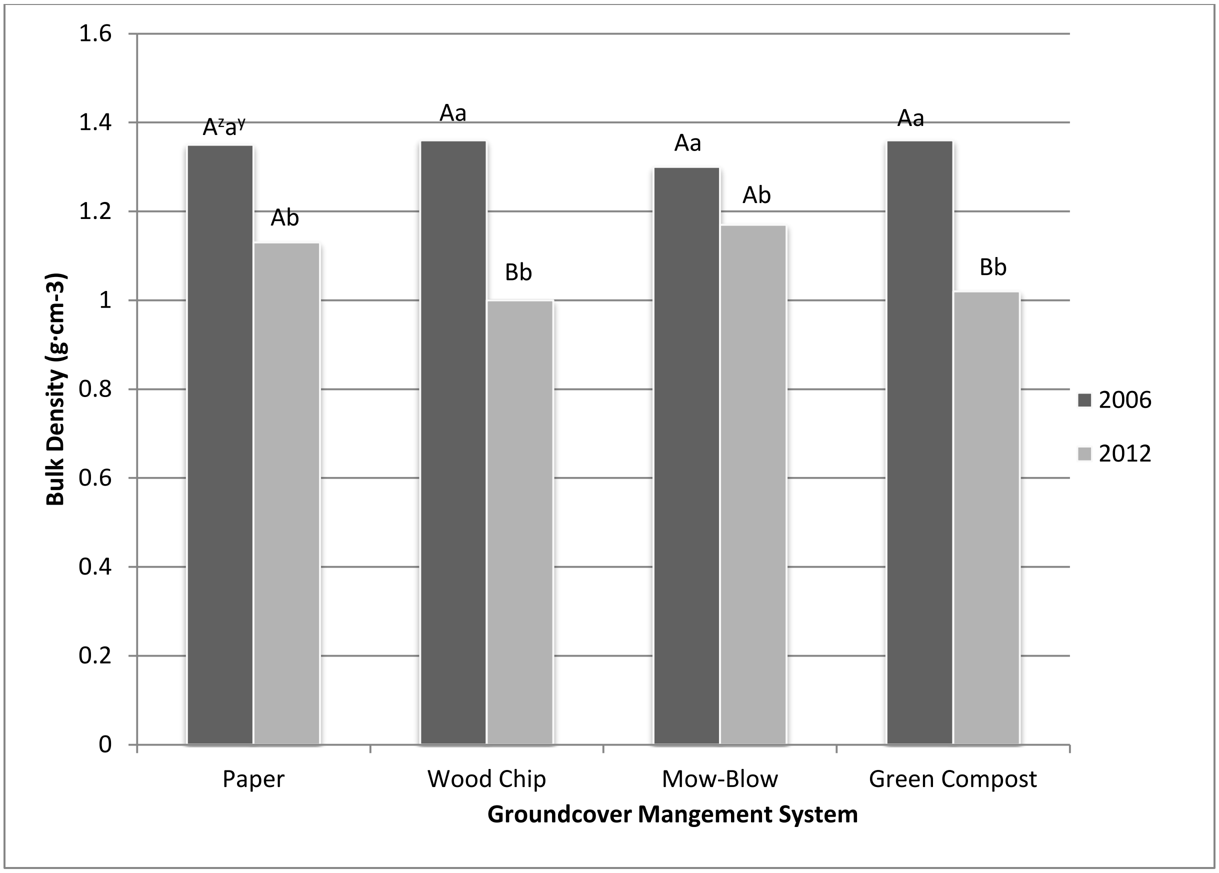

Figure 3. Effects of groundcover management system treatment on soil bulk density since establishment (2006) of an organic apple ('Enterprise'/M.26) orchard. Samples collected within 0.75 m of tree trunk from a silt loam soil, 0 - 6 cm soil depth, November 2006 and June 2012, Fayetteville, AR.

[z]Means comparisons between GMS treatments within year by LSD; treatment values within a year with different upper case letters atop their bar are significantly different, 0.05 level, N=6.

[y]Means comparisons within GMS treatments between years by LSD; treatment values with different lower case letters atop their bar are significantly different, 0.05 level, N=6.

Table 2. Comparison of soil quality indicator levels from a conventionally managed apple orchard and an organically managed apple ('Enterprise'-M.26) research orchard[z].

	Orchard Floor Treatment				
Soil Quality Indicator	Shredded Paper	Wood Chips	Mow Blow	Green Compost	Conv. Orchard
Soil Organic Matter ($g \cdot g^{-1}$)	0.03	0.03	0.03	0.06	0.03
Std. Error	0.001	0.002	0.001	0.004	0.001
Total Soil C ($g \cdot kg^{-1}$)	14.9	17.4	11.6	31.9	10.3
Std. Error	0.9	1.4	0.4	2.9	0.6
Total Soil N ($g \cdot kg^{-1}$)	1.23	1.4	1.1	2.8	1.1
Std. Error	0.07	0.08	0.03	0.2	0.06
Total Soil C ($Mg \cdot ha^{-1}$)	12.4	13.2	10.2	24.3	13.1
Std. Error	0.7	1.2	0.4	2.3	0.7
Total Soil N ($Mg \cdot ha^{-1}$)	1.0	1.0	1.0	2.1	1.4
Std. Error	0.05	0.08	0.03	0.2	0.07

[z]Conventionally managed orchard managed as an apple cultivar trial (M.106 and M.26 rootstocks), 1989 - 2012. Orchard 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 same sampling protocols as described for the organic orchard (N=6). Soil samples were collected for all soil quality indicators except percent organic matter in November 2011. Percent organic matter was determined from samples taken in June 2012. Analyses from conventional orchard based on 12 soil core samples. Both orchards located on a silt loam soil. Sample depth for percent soil organic matter, 0-6 cm. All other sample depths 0-7.5 cm. C:N calculated on $g \cdot kg^{-1}$ basis.

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Appendix 2: Supplemental Tables and Figures Explaining Interactions between Soil Organic Matter, Soil C and N Concentration and Content, Groundcover Management Systems, and Nutrient Sources[z]

[z]Material in Appendix 2 supports Chapter 3.

Table 1. Analysis of variance table showing interaction between groundcover management system (GMS) and nutrient source (NS) treatments and year on chemical soil quality indicators in a six year old (2006-2012) organically managed apple ('Enterprise'/M.26) orchard, Fayetteville, AR[z].

Soil Quality Indicator	Treatment Effects (P>F)						
	GMS	NS	GMS*NS	Year	GMS*Year	NS*Year	GMS*NS*Year
%SOM	<0.001	0.443	0.007	<0.001	<0.001	0.981	0.105
C:N	0.001	0.546	0.82	<0.001	<0.001	0.558	0.826
TN Concentration	<0.001	0.241	0.8	<0.001	<0.001	0.765	0.993
TC Concentration	<0.001	0.653	0.859	<0.001	<0.001	0.801	0.973
TN Content	<0.001	0.699	0.637	<0.001	<0.001	0.88	0.807
TC Content	0.003	0.665	0.832	<0.001	<0.001	0.629	0.97

[z]Percent soil organic matter (SOM) determined March 2012. Total nitrogen (TN) and total carbon (TC) concentrations ($g \cdot kg^{-1}$) and content ($Mg \cdot ha^{-1}$) determined November 2011; N =6.

Table 2. Nutritional analysis of groundcover residues and nutrient source treatments applied to organic apple ('Enterprise'/M.26) orchard since year 1 (2006), Fayetteville, AR[z].

	------------------------ Dry Weight ($g \cdot g^{-1}$)------------------------							
Mulch	**N**	**C**	**C:N**	**P**	**K**	**Ca**	**Mg**	**S**
Green Compost	0.016	0.205	0.135	0.002	0.005	0.033	0.002	0.002
Wood Chips	0.007	0.297	0.392	0.001	0.003	0.015	0.001	0.001
Shredded Paper	0.002	0.368	0.205	0.000	0.000	0.076	0.001	0.001
Mow-Blow	0.022	0.400	0.158	0.003	0.015	0.007	0.002	0.002
Nutrient Source								
Commercial fertilizer	0.044	0.313	0.078	0.014	0.026	0.026	0.006	0.009
Poultry litter	0.017	0.295	0.194	0.013	0.014	0.054	0.003	0.004

[z]Average of GMS and NS concentration data since 2006.

Table 3. Estimates of total C and N applied to individual treatment trees, total C and N applied across all treatments (tree total X 18 replications/groundcover or 24 replications/nutrient source), and over the entire organic apple ('Enterprise'/M.26) orchard including guard trees (treatment total X 3) from 2006 to 2012, Fayetteville, AR.

Treatment	**Tree Totals (kg/tree)**		**Treatment Totals (kg)**		**Orchard Total (kg)**	
Groundcover	C	N	C	N	C	N
Shredded Paper	46	0.2	828	4	2484	12
Wood Chips	108	2	1944	36	5832	108
Mow-Blow	3	0.1	54	2	162	6
Green Compost	89	6	1602	108	4806	324
Nutrient Source						
Commercial Fertilizer	2	0.3	48	7	144	21
Composted Poultry Litter	8	0.3	192	7	576	21
		Total (kg)	4608	164	13824	492

Chapter 4: Conclusions

Application of GMS treatments affected the measured soil quality variables, and the greatest differences were associated with applications of GC. Nutrient source treatments positively impacted SOM, BD, plant available water, and saturated hydraulic conductivity, but no interactions with NS were observed with infiltration rate or soil aggregation. Soil organic matter was most affected by GC, and this GMS consequently produced the most change across all physical soil quality indicators measured. Small, yet significant, increases in plant available water and saturated conductivity were associated with GC applied with NF or CF, which both generated the largest SOM contents measured in the study.

Decreased soil BD was most pronounced with GC treatments. This observation was attributed to increased SOM and a dilution of the mineral soil component, as well as increased formation of water stable soil aggregates. Formation of water stable soil aggregates was most pronounced in the 2.0 - 4.0 mm size class in the GC treatment in the 0 - 7.5 cm soil layer, while aggregate formation was mostly unchanged in the 7.5 - 15 cm layer. As a result, GC applications tended to favor maintaining or improving soil structure more than other GMS evaluated in this study.

Water infiltration rate increased with SP treatments more than any other GMS and was thought to be related to the burrowing activity of macro-organisms, such as voles and earthworms (unquantified observations), and a rodent control program may impact water infiltration rates associated with SP. Green compost and MB treatments produced similar infiltration rates, and infiltration was slowest in association with WC. From an orchard management and soil quality perspective, increased infiltration rates could reduce runoff and thus prove beneficial in making more efficient use of rainfall and irrigation water.

All GMS examined in this study have advantages and disadvantages regarding their use, function, and performance for maintaining or improving physical soil quality indicators. All were derived of products which either came from renewable sources or were waste products diverted from deposition in landfills. However concerns about unintended effects of their application exist. Because of its elevated N concentration, there could be possible leaching and groundwater contamination when GC is applied to the tree row at high rates for an extended time (Choi et al., 2011) or volatilization of nitrous oxide when soil conditions favor denitrification. Soil sodium levels have also increased in association with SP applications (C.R. Rom, personal communication). An advisable compromise might include utilizing GMS treatments in combination, such as a smaller annual application of GC overlain with a layer of WC.

As compared to conventional orchard soil quality observations and measurements taken at the time of organic orchard establishment, the GMS treatments studied have improved physical soil quality. Increased SOM and soil aggregation, decreased soil BD, greater water availability, and increased water infiltration have been positively linked to utilization of the groundcovers studied herein. The results of this study suggest physical soil quality was improved because of application of these groundcovers, and implementation of these or similar groundcover management systems are a tangible means of meeting NOP requirements for improving soil quality concurrent with production of certified organic crops.

Groundcover management systems impacted C and N soil sequestration from 2006 through 2011 in the organic orchard. Green compost had the greatest impact on soil quality indicators measured, indicating the greatest sequestration of C and N was associated with this treatment. Soil organic matter exhibited a four-fold increase in GC treatments since establishment of the orchard, while SOM contents also increased in all other treatments in the years following orchard establishment.

Increased soil TC concentration and content indicated GMS applications facilitated the sequestration of C across all treatments. Total carbon concentration associated with GC applications exhibited a four-fold increase since 2006, while soil TC content increased by 250%. These increases were likely correlated to greater increases in soil TN concentration and content, which were also associated with GC, and soil TN concentrations were significantly greater after six years of GMS applications than determined at the initiation of the study. Himes (1998) suggested the increased stability of C in composted manure increases potential for adding SOM, and therefore C, to soil. Similarly, because it was applied already composted and had greater N concentration than the other GMS treatments, GC probably created soil conditions which were more favorable for soil microbial activity and greater sequestration of C than other GMS treatments (Bhogal et al., 2009).

This research indicated the use of groundcovers as an orchard floor management tool can affect soil C, soil N, and SOM of mineral soils almost devoid of these important constituents, and soil quality can be expected to improve. Further, soil conditions not ideal for the production of apples, or soils that have declined in conventional production practices/systems, may be remediated over a relatively short time when amended with additions of GMS mulches which are easily humified. While GC generated at a municipal facility may not be available to all producers, other composted mulches, such as livestock manure, may provide similar results (Glover et al., 2000, Flieβbach et al., 2007).

As the organic food production system continues to expand, and demand for organically grown products increases, it is likely additional acreage will be established in orchards across the United States. The use of organic residues as GMS provides producers with a tangible means to improve soil quality, while satisfying the soil quality requirements of the National Organic Program. The use of waste products as mulches also promotes environmental stewardship by using a product which might be burned, thereby increasing greenhouse gas emissions, or otherwise be deposited in a landfill.