Orchard Soil Health Protocols: Evaluation and Economic Impacts

by Michelle Marie Leinfelder

ORCHARD SOIL HEALTH PROTOCOLS: EVALUATION AND ECONOMIC IMPACTS

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Michelle Marie Leinfelder

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Michelle Marie Leinfelder, Ph. D.

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Three long-term apple (*Malus* x *domestica* Borkh.) orchard management systems were evaluated in 2007-2008 for effects on soil health, orchard productivity, and carbon storage. The treatments were as follows: tree-row pre-emergence herbicide, post-emergence herbicide, sod, and bark mulch in a groundcover management systems (GMS) study; integrated and organic fruit production (IFP-OFP); and pre-plant compost or fumigation and rootstocks 'CG.6210' and 'M.26' in an apple replant disease (ARD) site. In the GMS study, bark mulch groundcover improved biological, chemical, and physical soil health in the sixteenth and seventeenth years of this study, compared to the other three treatments and commercial orchard averages, which were evaluated in 2008-2009. Total carbon was an important indicator of soil health at this site. Improvements in soil health in the mulch treatment translated into larger tree size and greater system-wide carbon storage, but not to higher cumulative yield, which was similar to that of the post-emergence herbicide treatment. Integrated fruit production – which had bark mulch groundcover, compared to cultivation weed management in the OFP – had greater biological activity but similar chemical and physical soil characteristics as the OFP in the fourth and fifth years of this study. Leaf nitrogen was low in both treatments, and tree size and carbon storage were similar for the two systems. Nevertheless, cumulative yield was greater in the IFP. Vesicular arbuscular mycorrhizae spore count

and soil respiration were important indicators of soil health, and these indicators correlated positively with cumulative yield. In the ARD study, pre-plant compost improved soil chemical properties compared to pre-plant fumigation, with available soil calcium and phosphorus being important indicators of soil health. Pre-plant treatments had no effect on tree growth and yield by the sixth and seventh years of this study, but growth and yield were greater with rootstock ‘CG.6210’ compared to ‘M.26’. Pre-plant compost and rootstock ‘CG.6210’ improved carbon storage in this system. This work illustrates the effects of management on orchard productivity and sustainability.

BIOGRAPHICAL SKETCH

Michelle Marie Leinfelder has roots that grow deeply in agriculture. Raised on a row crop family farm in the Central Valley of California, Michelle was inspired by her family's six generation farming history and pursued agricultural studies. She attended the University of California, Davis and graduated in 2001 with a Bachelor of Science degree in Crop Science and Management. Michelle worked for the University of California Cooperative Extension during her summers as an undergraduate and discovered her interest in the land-grant university mission. Her career interests are in agricultural teaching, research, and outreach and in continuing her family's farming tradition.

Michelle obtained her Master of Science degree in Horticulture from Cornell University in 2005, investigating management strategies for apple replant disease. After completing her M.S., Michelle was awarded the William Fredrick Dreer Fellowship for International Study. Over the course of a year, she traveled to Spain, Chile, and New Zealand studying sustainable management in olive, winegrape, and kiwifruit systems. As a Ph.D student, Michelle served as Vice-President and President of the Graduate and Professional Student Assembly.

Michelle also enjoys countless hobbies and sports. She is an avid runner and cyclist. She has competed in triathlons, and she enjoys softball and volleyball. Michelle also takes pleasure in reading, photography, gardening, and traveling.

To my family – for your inspiration, support, and love.

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A Review of the Literature

> […] Our new-found sources of power – to take the burden of work from our shoulders, to warm us, and cool us, and give us light, to transport us quickly, and to make the things we use and wear and eat – these power sources spew pollution […], so that the rivers and streams are becoming poisonous and lifeless. The birds die for the lack of food; a noxious cloud hangs over our cities that burns our lungs and reddens our eyes. Our ability to conserve has not grown with our power to create […].

John Steinbeck wrote these words in 1966 as part of his essay *America and Americans*. Despite the decades passed, we could read this as modern prose. Steinbeck specifically speaks to air and water, and as environmental resources that we directly consume, these have been given due attention in resource conservation policy. But in a report by the National Research Council (1993), conserving and enhancing soil quality was emphasized as the first step to environmental improvement. Air and water quality are impacted by soil condition, and with little new agricultural land to develop globally, preserving soil quality is critical to sustaining the needs of a growing population (Doran, 2002).

A History of Soil Conservation Policy in the United States

Exploiting agricultural land, abandoning it, and then moving west to develop new agricultural land historically was the American way. In the late 1800s, when soil quality deteriorated and land was no longer productive, the government encouraged westward expansion. It was not until the 1920s and 1930s that this philosophy began to change. In 1929, as a result of the Great Depression, commodity prices dropped. To

reduce surpluses and control prices, President Roosevelt implemented the Agricultural Adjustment Act in 1933, as part of his New Deal policies. The Agricultural Adjustment Act allowed the United States Department of Agriculture (USDA) to pay farmers to take land out of production, but when the Supreme Court deemed the Act coercive and unconstitutional, it was repealed.

It was from that point that policy makers began using soil conservation as a vehicle for commodity-control policies. The Soil Conservation and Domestic Allotment Act (1936) was the first of these commodity-control policies disguised under the cloak of soil conservation policy. It supported soil conservation only tangentially, paying growers to take poor quality land out of production, but it was intended to reduce crop surpluses and mitigate falling commodity prices.

Soil conservation continued to be entwined with commodity-control policies until the 1970s, when sky-rocketing commodity prices meant a trade-off for soil conservation. Secretary of Agriculture, Earl Butz, was known to say "get big or get out" and "plant fencerow to fencerow". Soil conservation policy was essentially abandoned, and it wasn't until the mid-1980s that it was again given attention. Starting with the 1985 Farm Bill, commodity program payments could be refused to growers who did not implement soil conservation practices appropriate for their land, and the Secretary of Agriculture became required to contract with owners to take highly erodible land out of production (O'Brien, 2003).

With that as history, what should be recognized is that soil conservation policy traditionally focused on reducing soil erosion. We know that soil degradation goes beyond erosion potential, to include salinity, acidity, nutrient limitations, among many other maladies, and future policy needs to think beyond erosion to other anthropogenic soil quality parameters. The UN Environmental Program on Global Assessment of Soil Degradation reported that 40% of agricultural land has been degraded due to

human activity and that 6% is in such a state that only major capital investment could restore it to its original, productive capacity (Oldeman, 1994). The National Research Council (1993) deemed protecting soil quality to be *as* important as protecting air and water quality, calling soil quality integral to national environmental policy. That report recommended to the USDA and US Environmental Protection Agency that there be quantifiable standards and cost-effective monitoring methods to evaluate the impacts of farm management on soil health.

An Introduction to Soil Health

Fundamental to the understanding of soil health – a term that will be used here interchangeably with soil quality – is an understanding for just what is soil. Soil – composed of minerals, water, air, and biota – is a "dynamic, living, natural body that plays many key roles in terrestrial ecosystems" (Doran and Parkin, 1996) and is a critical component of the earth's biosphere (Glanz, 1995). The mineral component of soil is the result of geological processes, which brought to the earth's surface various parent materials. These parent materials – when weathered physically or chemically – break down into stone fragments, sand, silt, and clay. The proportions of sand, silt, and clay determine soil textural class. Soil also consists of pore space, which is related to bulk density – its mass by volume. Water and air occupy this pore space, both of which are essential to the plant, animal, and microbial life of the soil. The accumulation and decomposition of organic matter – the living and dead matter of soil – are affected by water and air, and with the mineral component, influence the structure and stability of soil. Certain of these soil properties – such as textural class – are inherent to the parent material and are not changed by land management, but other

properties, such as porosity and organic matter are changed by management and ecosystem interactions.

This introduction of soil may seem elementary, but the terms describing soil are relevant to any discussion of soil health. Soil health was defined by Doran and Parkin (1994) as "the capacity of a soil to function, within ecosystem and land-use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health." Key to that definition is functionality. Larson and Pierce (1991) explained that soil health enhances soil functioning, allowing for plant growth, regulating and partitioning water flow in the environment, and serving as an environmental buffer of hazardous compounds. Attaining soil health should run parallel with fulfilling these functions, given spatial and temporal components (Doran and Parkin, 1996). Wolfe (2006) makes analogies between soil health and human health. Just as a healthy person can buffer disease and show resilience after illness, a healthy soil can filter chemicals and plant pathogens and show resilience after poor conditions.

Missing from these definitions are quantifiable standards to be used as metrics of soil health. Such standards exist for air and water, but soils are usually only labeled as "healthy" or "unhealthy" at best (Romig et al., 1996), where a healthy soil has many desirable characteristics, and essentially, an unhealthy soil lacks those characteristics. The ambiguity over soil health has incited researchers to investigate soil health more closely. Work toward this end encourages the use of a three-step framework to quantify soil health.

The Three-Step Framework

The first step of the framework is selecting a series of biological, chemical, and physical soil properties that characterize soil health. The properties are termed the soil health indicators. Acton and Padbury (1993) defined an indicator as "a measurable soil property that influences the capacity of a soil to perform a specified function."

Selecting indicators that assess various biological, chemical, and physical soil properties is well-supported (Andrews et al., 2004; Reganold et al., 1993; Wolfe, 2006), but an extensive set of indicators was deemed unnecessary by Larson and Pierce (1991), who proposed the concept of a minimum data set (MDS). Sparling et al. (2004) described high variability and cost as reasons why some indicators are not suitable for a MDS. The Cornell Soil Health Team (Gugino et al., 2007) established the following criteria for soil health indicators: measurability at a reasonable cost; sensitivity to changes in management practices; having quantifiable effects on crop health, yield, and/or environmental impact; and having good correlation with other more costly measures (Wolfe, 2006). Drinkwater (2002) explained that multivariate statistics can be used to determine the soil properties that best differentiate management practices in complex, agricultural systems. Recognizing that MDSs are developed by varied approaches, Wolfe (2006) underscored that there is no ideal MDS to serve all purposes. Rather, a MDS should serve to answer established questions that are relevant and site specific (Sarrantonio et al., 1996).

The second step of the framework is to interpret the MDS indicators and rate them based on accepted levels for "healthy" and "unhealthy" soils. A process for this comes from Karlen and Stott (1994) and involves giving each indicator a unitless score, based on mathematical functions. These functions relate to curves illustrating "more is better", "less is better", or "clear optimum". For example, an indicator like

organic matter would be given a score based on a “more is better” pattern, bulk density based on a “less is better” pattern, and pH based on a “clear optimum” pattern.

The third step of the framework integrates indicator ratings into an overall soil health score. The purpose of the score is to give a single value assessment of soil health. This last step, however, has been viewed as an over-simplication (Wolfe, 2006) and is not essential to the framework (Andrews et al., 2004). Instead, individual indicator scores may be studied for an understanding of soil health.

The purpose of a framework is to determine soil quality and describe soil functionality – as determined by land use – in order to influence management practices and promote sustainability. The significance of soil health to agricultural and environmental sustainability was stressed by Larson and Pierce (1994). In their view, sustainability should address simultaneously the stability of production and profitability; protection and enhancement of natural resources, both biotic and abiotic; and maintenance of social order, such as the family farm.

Much of the soil health research has focused on annual cropping systems and the sustainability of management practices – like tillage, rotations, cover-cropping, and organic production – in those systems (Andrews et al., 2002; Gugino et al., 2007; Karlen and Stott, 1994). Soil health investigations of orchard systems are fewer and have focused on organic, integrated, and conventional fruit production (Glover et al., 2000; Goh et al., 2001; Peck, 2010; Werner, 1997). Based on these, it is not well-understood which soil properties indicate orchard soil health under broader management regimes. For this reason, three long-term management studies – described below – at the Cornell Orchards in Ithaca and Lansing, NY have been utilized in the present study for broader investigation.

Groundcover Management Systems Study

An herbicide strip along the tree rows with grass planted in the alleyways – this has become the standard groundcover management system (GMS) in apple (*Malus* X *domestica* Borkh.) orchards worldwide (Merwin, 2003). Because apples are often grown in regions where precipitation spans the year, the sod alleyways provide for easier mobility and soil conservation. The sprayed tree rows decrease groundcover competition for water and nutrients. This is the essential objective of orchard groundcovers – to preserve water and soil resources while reducing competition in critical space and time (Merwin, 2003). However, because of concerns over nutrient and sediment loss, the standard, herbicide-dependent system has come under question, leading scientists to study alternative groundcovers. For example, Mika et al. (1998) examined straw, sawdust, and composted bark groundcovers and found improved nutrient availability and apple yield in the composted bark treatment compared with a pre-emergence herbicide treatment. In an established tart cherry (*Prunus cerasus*) orchard, trunk-to-trunk groundcovers such as mulches, cover crops, and composted manures reduced nitrate leaching by greater than 90 percent and did not reduce yields compared to a pre-emergence herbicide treatment (Sanchez et al., 2003). The results of these studies illustrate the production potential of tree-row groundcover systems that are more beneficial to soil health than the traditional system.

Integrated and Organic Fruit Production Comparison

For about 40 years, scientists have been researching ways to reduce chemical inputs to farms, promoting environmental sustainability while maintaining economic viability (Sansavini, 1997). Evolution of farming methods in this direction has

spanned the decades, and today various terms exist to define these methods. Farming operations that use synthetic pesticides and fertilizers have been termed "conventional"; those that exclude most synthetics have been termed "organic". While there is more to both conventional and organic farming than these definitions would suggest, the language is functional for policy-making and marketing. Specific to orchard systems, Integrated Fruit Production (IFP) is another management system well-established in places like Western Europe and New Zealand. Guidelines out of Europe define IFP as "economical production of high quality fruit, giving priority to ecologically safer methods, minimizing the undesirable side-effects and use of agrochemicals, to enhance the safeguards to the environment and human health" (Sansavini, 1997). In the United States, a generally-accepted definition for IFP and market incentives for implementing it are lacking, which has hindered its acceptance among growers and consumers alike.

Nevertheless, scientists have embraced research comparing conventional fruit production, organic fruit production (OFP), and IFP systems. Though some of this research still favors conventional systems for their yielding potential (Pimentel et al., 1983), OFP and IFP systems stress environmental quality – including soil quality – as well as yield quantity. In Washington state, conventional, integrated, and organic apple production have been compared for soil quality and yielding potential (Glover et al., 2000; Peck et al., 2006; Reganold et al., 2001). Studies in the northeastern United States are fewer because commercial adoption of IFP and OFP has been slow due to the pest and pathogen pressure of humid climates. Nonetheless, disease-resistant varieties like 'Liberty' and 'GoldRush' – and kaolin clay and reduced-risk synthetic pesticides for insect control – provide potential for IFP and OFP in the northeast (Peck et al., 2010). As both IFP and OFP standards stipulate soil quality in protocols and regulations, examining soil health characteristics in these systems is essential.

Apple Replant Disease Study

Apple replant disease (ARD) is a disease complex resulting from the successive planting of apple trees into the same soil. A historical plague – dating back some 200 years in Europe (Traquair, 1984) – ARD was only formally recognized in the last few decades as standard, seedling-rooted orchards were renovated to high-density plantings of lower-vigor, dwarfed trees on clonal rootstocks (Allen and Marks, 1977). The use of soil fumigants improved the growth of dwarfed trees in replanted sites (Mai and Abawi, 1984), and various fungal, bacterial, and nematode pests were suggested as causes. However, abiotic soil disorders are also assumed to contribute to ARD.

There is a natural link between ARD and soil health. Early characterization of ARD came from Savory (1966), who used the German term "Bodenmüdigkeit," or "soil sickness," to describe the apparent restoration of vigor when trees were transferred from replant soil to fresh soil. McKenry (1999) described the problem as "not a result of poor root condition per se, but something in the soil around those roots". He described various physical, chemical, and biological soil conditions as contributors to the problem and suggested that an integrated approach to soil management – including fallowing, rootstock selection, supplemental nutrition, chemical fumigation, and alternatives to chemical fumigation – was important to overcoming the problem.

Soil Health and Orchard Productivity

Many studies have evaluated soil health in annual crop systems (Abawi and Widmer, 2000; Idowu et al., 2008; Karlen et al., 1994; Mitchell et al., 2008), and there

is evidence to suggest that better soil health enhances crop productivity. Abawi and Widmer (2000), who characterized soil health as a reduction in pathogen and nematode pressure, reported increased bean (*Phaseolus vulgaris*) yield when brewery compost application, rye/hairy vetch (*Secale cereale*/*Vicia villosa*) cover cropping, or rotations were employed. Mitchell et al. (2008) observed higher tomato (*Solanum lycopersicum*) yields using conservation tillage, as a result of enhanced organic matter and soil aggregation.

In perennial systems, more work is needed to establish a relationship between soil health and orchard productivity. This comes despite the fact that many studies have shown correlations between specific chemical, physical, and biological soil properties and crop performance. For example, Melakeberhan and Jones (1992) observed tree decline and reduced productivity in sweet cherry (*Prunus avium*) resulting from low pH and consequent macronutrient deficiencies and aluminum toxicity. Fernandez et al. (1995) found that the root distribution and depth of nine apple rootstocks were affected by soil type and a compacted fragipan layer, which in turn affected scion yield. In another study, vesicular arbuscular mycorrhizae (VAM) indirectly influenced crop productivity by increasing rootstock growth and leaf nutrient content in apple (Forge et al., 2001). With these results, one could hypothesize that a comprehensive study of soil chemical, physical, and biological properties could be used to predict orchard productivity. Neither Werner (1997) nor Goh et al. (2001) reported yield in studies of soil quality in IFP and OFP. Glover et al. (2000) reported yield but did not correlate it with soil properties, speculating that yield was influenced more by pruning and thinning.

Sparling et al. (2004) called the lack of knowledge relating soil health and crop production a “research gap” and suggested that researchers embark in a direction to close that gap. A factor slowing research toward this end might be hesitancy to

discover no such correlation. A lack of positive results or economic impacts could impede implementation of management that improves soil health, especially if the sole purpose for healthier soils is higher yields. Rather, soil health should be recognized for its broader influences on crop productivity, such as lower input costs or averted input costs, plant health through disease buffering, and plant resilience after adverse weather conditions. Beyond agricultural production, soil health should also be recognized for its role in ecosystem services, like nutrient cycling and carbon storage. These broader influences suggest that there could be economic or policy incentives for improving soil health, assuming that meaningful and quantifiable soil health criteria could be established.

Soil Health Valuation

The National Research Council (1993) reported that environmental policy should encourage soil health monitoring, and called for "research [toward] the design of market-based incentives to protect soil quality". To understand how market forces can be used to protect environmental resources, one must first understand the means by which non-market goods – like soil health and other environmental resources – are given value. Giving soil health a value could allow for an objective and efficient means of comparing the costs and benefits of various land uses so that socially-optimal land-use decisions can be made (Shultz et al., 1991).

There are several methods by which non-market goods – goods that cannot be bought and sold in the marketplace – are given value (Hanley and Spash, 1993). We considered three methods: production functions, hedonic valuation, and contingent valuation. Production functions relate the value of an environmental good to the output

of a market good. Hanley and Spash (1993) described the avoided-cost approach and dose-response functions. To understand these methods, consider the function:

$$O = f(L, K, I, E)$$

where output (O) is a function of labor (L), capital (K), inputs (I), and an environmental resource (E). The function could describe the output of apples as determined by labor, capital, inputs, and soil health. Using the avoided-cost approach, if input costs decrease because soil health improves, then – all else being equal – soil health is valued as the input costs avoided. Using dose-response functions, L, K, and I are held constant, and O and E change. If the output of apples increases as a result of improved soil health, then – all else being equal – soil health is valued as the value of increased yield.

Hedonic theory was described by Rosen (1974), who defined hedonics as the valuation of goods based on their utility-bearing attributes. The hedonic value of a market good comes from the implicit prices of the attributes that characterize the good and differentiate it based on the type and amount of its attributes. Price functions that use the value of the market good to determine the value of the individual attributes are determined by regression analysis comparing the price of the good and the quantity of its attributes. Hedonic valuation has been used to characterize environmental attributes of agricultural land, as by Palmquist and Danielson (1989), who used the hedonic method to value soil erosion. The problems that could be encountered with this method in valuing agricultural land attributes are the small sample of farms that are sold to remain as farms and the distortion of agricultural land prices when land is sold for development. For reasons like these, one might revert to using a stated preference method, such as contingent valuation.

Contingent valuation involves surveying a population about their maximum willingness to pay for a non-market good in a hypothetical situation. The drawbacks to

this method include its hypothetical nature (Portney, 1994; Arrow et al., 1993), low survey response rate, and the influence of information on responses (Poe and Bishop, 2001). For these reasons, contingent valuation is usually conducted when no appropriate market good – to which to compare the non-market good – is available.

We chose to value soil health in our three long-term management systems using dose-response functions. While a relationship between soil health and apple yield may not yet be fully supported by scientific research, an ecosystem service, like carbon storage, could also be considered the output of interest. Howitt et al. (2009) showed that carbon payments could be used to incentivize growers to employ soil conservation practices in agronomic systems, and the goal of the present study was to consider the same potential incentives in apple orchards.

Conclusion

Pollution studies of air and water have resulted in health and safety standards for these resources. Soil, as another component of the biosphere, deserves similar attention. Today, soil health is of interest not only to scientists, but also to growers of annual and perennial crops alike. And, if the European trend of rewarding growers for "good agricultural practices" takes hold in the United States, then soil health will become important to policy makers, as well.

The purpose of the present study was to investigate soil health in three long-term orchard management systems. In Chapter II, we describe our development of an orchard MDS, first by characterizing soil biological, chemical, and physical properties among GMS, IFP-OFP, and ARD treatments and then by employing multivariate statistics. In Chapter III, we illustrate GMS, IFP-OFP, and ARD treatment effects on leaf nutrients, tree growth, and yield, and we correlate the soil health indicators of the

MDS to these orchard productivity parameters. Finally, in Chapter IV, we model biomass and soil carbon storage for our orchard treatments and value soil health based on carbon storage and published CO_2 prices. Our research made this progression because we envisioned its extension to growers, and we wished for it to be applicable to NYS apple orchards. It is the role of scientists to help growers be better land stewards, and policy makers should recognize growers for their environmental conservation efforts.

Based on history, the United States – and for that matter, the world – have come a long way. "[…] We now know how to grow crops and graze animals in systems that will support biodiversity, soil health, clean water and carbon sequestration" (Pollan, 2008). Integrative thinking, such as this, is what will move science and policy forward.

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Chapter 2

Addition and Maintenance of Biomass Amendments in Three Long-Term Apple Management Systems Enhance Soil Health

Abstract

We are developing a protocol for evaluating soil health in apple (*Malus* X *domestica* Borkh.) orchards of New York State (NYS). Soil health is defined functionally as agricultural productivity, environmental awareness, and resource conservation, but soil health research has focused primarily on annual cropping systems. We evaluated 52 biological, chemical, and physical soil properties in three orchards under long-term management regimes – a groundcover management systems (GMS) study, an integrated and organic fruit production (IFP-OFP) comparison, and an apple replant disease (ARD) study. In order to understand how treatments influenced orchard soil health, we compared soil properties from these systems to upper and lower 25th percentile ranges developed from 15 NYS commercial orchard soils. We then determined which soil properties best separated the treatments and could be considered in a parsimonious set of orchard soil health indicators. Using discriminant analysis, we found total carbon (C) ($P < 0.0001$), vesicular arbuscular mycorrhizae (VAM) spore count ($P = 0.0006$), soil respiration ($P = 0.0021$), available calcium (Ca) ($P < 0.0001$), and available phosphorus (P) ($P < 0.0001$) to be important indicators. Biomass amendments – such as bark mulch groundcover or pre-plant compost – and avoiding tree-row cultivation, improved soil health by enhancing the aforementioned soil properties.

Introduction

Soil health is a concept aptly defined by Doran and Parkin (1994) as "the capacity of a soil to function, within ecosystem and land-use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health." Furthermore, it is the result of inherent soil-forming factors, dynamic changes induced by land management and ecosystem interactions, and even socioeconomic and political priorities (Doran and Parkin, 1996). While there is extensive literature describing soil health and its importance, practical examples of monitoring schemes are still limited (Sparling et al., 2004), and unlike air and water, universally-accepted quality standards for soils have not been determined. Without such standards, soil is usually only labeled as "healthy" or "unhealthy" (Romig et al., 1996), where healthy soils presumably have many desirable characteristics and unhealthy soils lack those characteristics.

Applied field research investigating soil health in relation to cropping systems is still nascent (Sparling et al., 2004), but previous studies suggest using a three-step framework to quantify soil health (Andrews et al., 2004; Karlen and Stott, 1994; Lilburne et al., 2004). The first step is testing and selecting biological, chemical, and physical soil properties that indicate soil health (Papendick and Parr, 1992). Acton and Padbury (1993) defined an indicator as "a measurable soil property that influences the capacity of a soil to perform a specified function". Mitchell et al. (1995) explained that indicators correlate with other soil properties that may be difficult or costly to assess. In addition to these criteria, Wolfe (2006) also cited measurability at a reasonable cost; having quantifiable effects on crop health, yield, and/or environmental impact; and sensitivity to changes in management practices as considerations in indicator selection. Arguably, ability to differentiate management is one of the most important criteria

(Arshad and Coen, 1992). Multivariate statistical procedures – such as discriminant analysis – have proven useful in differentiating soil treatments (Sánchez-Moreno et al., 2008). Additionally, multivariate statistics are appropriate in the evaluation of systems-based investigations, which strive to understand the broader agroecosystem (Drinkwater, 2002). Larson and Pierce (1991) introduced the term Minimum Data Set (MDS) to describe a subset of indicators used to assess soil health.

The second step of the framework is to interpret health scores for these indicators. For example, a soil property like organic matter would be interpreted based on a "more is healthier" scale; a property like compaction based on a "less is healthier" scale; and a property like pH based on a "clear optimum for health" scale (Karlen and Stott, 1994). The Cornell Soil Health Assessment Training Manual (Gugino et al., 2007), which was developed for annual crop systems, uses interpretive scores like those in Karlen and Stott (1994), where indicator values in the upper 25th percentile are considered exceptional, and those in the lower 25th percentile need to be improved by using more sustainable management practices.

Finally, the third step in the framework – which is sometimes considered unnecessary (Wolfe, 2006) – is to integrate the indicator scores into an overall soil health rating. Gugino et al. (2007) used a scale of 1 to 10, where a rating of 1 indicates a soil of poor health and a rating of 10 indicates a very healthy soil. From this framework, conclusions can be made about how to manage land such that agricultural productivity and environmental sustainability are optimized (Larson and Pierce, 1994).

Soil health has been investigated in perennial crop systems to a lesser extent than in annual crop systems. Werner (1997) compared 17 indicators in conventional and transition-organic apple orchards in California and observed few differences between the two systems. Comparing conventional apple production, integrated fruit production (IFP), and organic fruit production (OFP) in Washington State, Glover et

al. (2000) developed a quantitative index for rating soil health and found that IFP had significantly better soil health than conventional orchards. The OFP soil rated between the IFP and conventional soils and was not significantly different from either. In New Zealand, Goh et al. (2001) similarly conducted a soil health study of conventional, IFP, and OFP and observed that bulk density, infiltration rate, and earthworm number differed among the management practices. Peck (2009) compared soil in apple orchards transitioning from conventional to IFP and OFP, and found that biological and chemical soil properties improved in the IFP, but weeds were better controlled in the OFP, where mechanical cultivation was used. Others have examined orchards in broad investigations of land uses that have included urban, forest, grassland, grazing, and cropland soils (Reganold et al., 1993; Sparling et al., 2004). While these studies advanced soil health research by examining perennial systems, the observed treatments were limited to conventional management, IFP, and OFP. More research has been needed to understand which biological, chemical, and physical properties best indicate soil health when other management practices are considered. Furthermore, none of the aforementioned studies, except that of Peck (2009), were conducted in the northeastern United States, which is of particular concern because soil health indicators may vary with region and climate (Werner, 1997).

Developing a regionally-appropriate MDS for NYS orchards could give growers incentive to monitor soil health. The interest of growers – as stakeholders and stewards – would illustrate that sustainability is simultaneously the stability of production and profitability, the protection and enhancement of natural resources, and the maintenance of social order, such as the family farm (Larson and Pierce, 1994). To that end, the objectives of our work were as follows: 1) Understand how long-term orchard management treatments influence biological, chemical, and physical soil properties; 2) Compare the soil health properties of long-term orchard management

systems to those of NYS commercial orchards; and 3) Using discriminant analysis, determine a parsimonious MDS of biological, chemical, and physical soil properties that could indicate orchard soil health in NYS.

Materials and Methods

Orchard Sites and Treatments

The project commenced in 2007 and concentrated initially on three experimental sites at the Cornell Orchards in Ithaca and Lansing, NY. These proximate sites had similar inherent characteristics, and as controlled experiments under long-term management, we had extensive information about soil properties and orchard characteristics for these sites. This allowed for intensive investigation of the long-term management effects on a broad range of soil properties. Soil properties were investigated in 2007 and 2008 at these sites. We coupled these local experimental sites with NYS commercial orchards, where inherent soil properties and site histories differed. Management at the commercial orchards could, generally, be described as conventional. Soil properties at the commercial orchards were studied in 2008 and 2009.

Groundcover Management Systems (GMS) Study

The GMS study was established in 1992 on the east shore of Cayuga Lake, near Ithaca, NY. The 0.8 ha, moderately-sloped site is a Hudson-Cayuga silt loam (mixed, mesic, Glosaquic Hapludalf). Land preparation began in Apr. 1991 with the removal of 15-yr-old trees, and organic matter content at that time was between 4.7 – 5.3%. The land was limed, deep-tilled, seeded with creeping red fescue turfgrass

(*Festuca rubra*), and installed with subsoil drainage. In Apr. 1992, apple trees ('Royal Empire' on 'M.9'/'MM.111' rootstock) were planted at 3 x 6 m spacing among 12 plots. Each 20-tree plot was 9 m wide across the slope and 25 m long down-slope. Four tree rows ran across the slope, each separated by 4 m of grass drive lanes. The groundcovers were applied down the tree row in a 2-m band. The experimental design was a completely randomized design having three replicated plots of the four GMS, where GMS was a fixed effect and plot was a random effect (Fig. 2.1). The groundcover treatments were as follows: 1) Pre-emergence, residual herbicides norflurazon, and diuron, tank-mixed at 3.0 and 2.5 kg a.i.•treated ha^{-1}, respectively, annually applied in mid-May, and paraquat (1992-1998) tank-mixed at 0.5 kg a.i.•treated ha^{-1}, or glyphosate (1999-present) at 2.0 kg a.i.•treated ha^{-1}, annually applied in mid-July (PREHERB); 2) Post-emergence herbicide glyphosate applied annually at 2.0 kg a.i.•treated ha^{-1} in mid-May and July (POSTHERB); 3) Red fescue (*F. rubra*) turfgrass originally seeded in 1991, now a mixture of about 25 herbaceous grass and broadleaf species, mowed monthly during the growing season (SOD); and 4) Shredded, hardwood bark mulch (a mixture of *Acer*, *Quercus*, *Juglans*, *Fraxinus*, and *Tilia* spp.), 15 cm thick, first applied in May 1992, and reapplied in May of 1995, 1998, 2000, 2002, and 2005 (MUL). Glyphosate was used to suppress emergent weeds in the MUL. All plots were similarly fertilized. In mid-Apr. 1992, 1993, and 1994, ammonium-nitrate fertilizer was applied on the soil surface in the tree-row at rates 30, 45, and 65 kg N•ha^{-1}, respectively. Urea and micronutrient foliar sprays were applied annually according to the Pest Management Guidelines for Commercial Tree Fruit Production (Agnello et al., 2007).

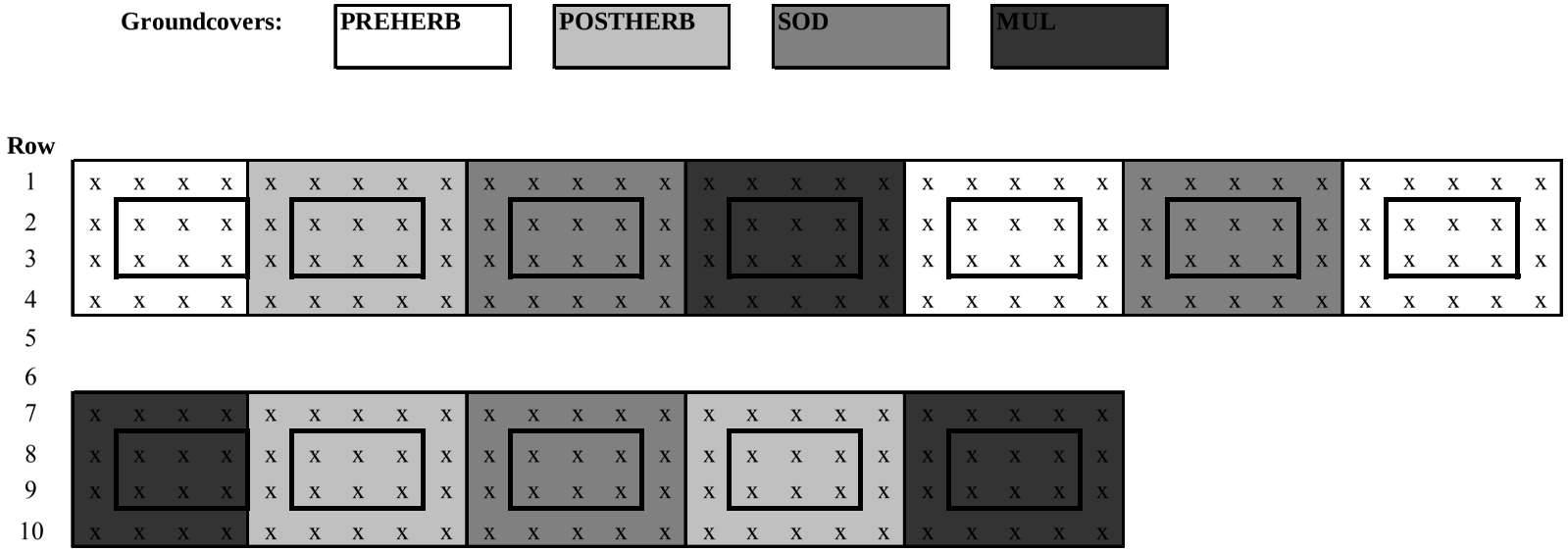

Figure 2.1: Groundcover management systems (GMS) site map. Individual trees are indicated by "x", and groundcovers are differentiated by shading. Data collection trees are bordered by heavy black lines, with other trees excluded to minimize edge effects.

Integrated and Organic Fruit Production (IFP-OFP) Study

The IFP-OFP comparison study was located on a 0.4 hectare site at the Cornell Orchards in Ithaca, NY. The orchard ('Liberty' on 'M.9' rootstock) was planted at 1.5 m x 4.3 m spacing in Apr. 1994 and was under conventional insect and disease management until 2004, when IFP, as defined by Carroll and Robinson (2006), and OFP treatments, as defined by the United States Department of Agriculture National Organic Program (USDA-NOP), were initiated. The soil is characterized as Hudson and Collamer silt loams (mixed, mesic, Glosaquic Hapludalf) and had about 3% organic matter and a pH of 6.4 at the commencement of the experiment. The two treatments were replicated over four blocks in a randomized complete block design, where treatment was a fixed effect and block was a random effect (Fig. 2.2). Each 64-tree plot consisted of four adjacent tree rows of 16 trees. The IFP and OFP differed in their disease and pest management, fertilization, thinning, and soil management. Disease and pest management, fertilization, and thinning were described in detail by Peck (2009). Composted hardwood bark mulch was applied to the IFP tree-rows in Nov. 2005 as 1-m-wide bands. This was the source of nitrogen by slow mineralization in the initial years of the experiment. The OFP plots received chicken manure compost in Oct. 2005 at a rate of 697 kg fresh wt•ha^{-1}, equivalent to 78 kg N•ha^{-1}. In the six years prior to this study, only glyphosate herbicide was used for weed control at this site. The mulch and an annual, June post-emergent glyphosate application (2.9 kg a.i.•ha^{-1}) were used to control weeds in the IFP. Weeds in the OFP were cultivated monthly during the growing season using a tractor-mounted Wonder Weeder (Harris Manufacturing, Burbank, WA) mechanical cultivator.

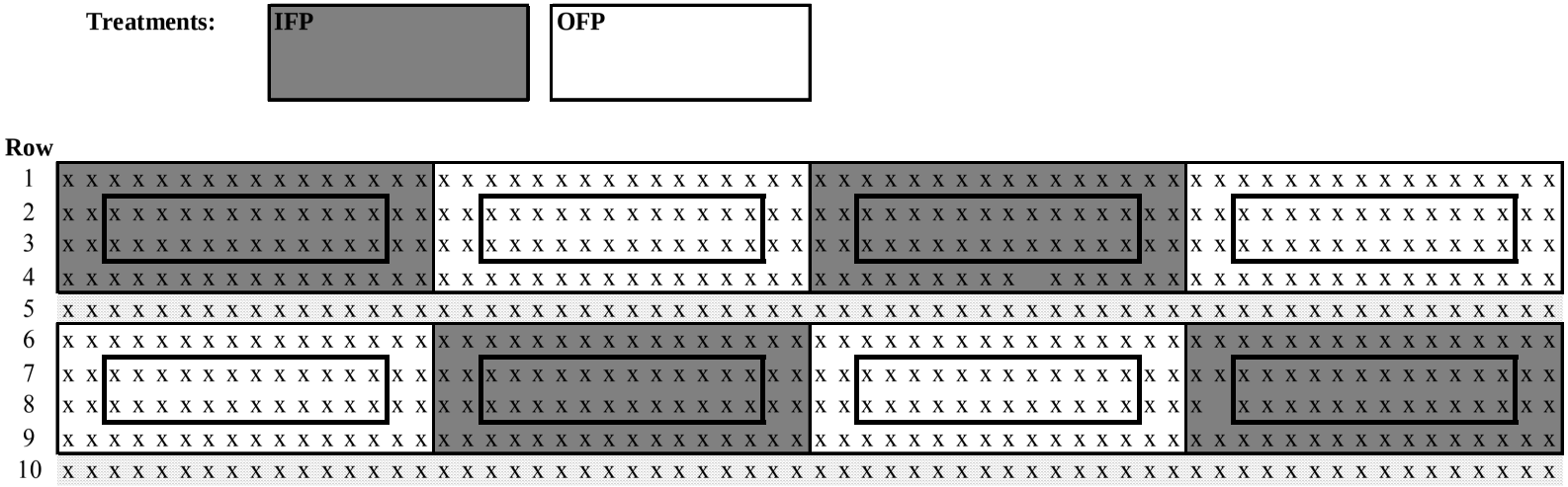

Figure 2.2: Integrated fruit production and organic fruit production (IFP-OFP) site map. Shading indicates treatments, and Rows 5 and 10 were non-study rows. Individual trees are indicated by "x". Data collection trees are bordered by heavy black lines.

Apple Replant Disease (ARD) Study

The ARD study was also located on a 0.4 ha site at the Cornell Orchards in Ithaca, NY. The soil is a glacial lacustrine Hudson silty clay loam (mixed, mesic Udic Hapludalf), slightly-sloped and with limited subsoil drainage. Originally planted to apple around the year 1910, the site was first replanted in 1981 but failed in its establishment, showing many common ARD symptoms (Mai et al., 1994). It was replanted again in 2001; orchard removal, site preparation, and experimental design were described by Leinfelder and Merwin (2006).

The factors of interest were three pre-plant soil treatments (PPST) and two rootstocks in a randomized complete block design, with the PPST and rootstock genotypes as fixed effects, randomized among five blocks (Fig. 2.3). Telone C-17 (Dow AgroSciences, Indianapolis, Ind.) was the pre-plant soil fumigant and is a formulation of the nematicide 1,3 dichloropropene (78% v/v) and the broad-spectrum biocide chloropicrin (17% v/v). It was shank injected in Oct. 2001, to a depth of 25 cm at a rate of 400 L•treated ha^{-1}, and the soil was immediately sealed with a cultipacker. As an alternative to soil fumigation, a compost made of 40% (v/v) ground leaves and wood chips, 40% supermarket vegetable culls, and 20% pre-composted cattle and horse manure in wood shavings (Toad Hollow Farm, Nedrow, NY) was applied in Sept. 2001. The compost was applied in two portions – the first surface applied at 492 kg•treated ha^{-1} and then incorporated with a moldboard plow to a depth of 25 cm. The second portion was applied at the same rate but only rototilled into the upper 10 cm of soil. The macronutrient content of the compost was determined by the Cornell Nutrient Analysis Laboratory (CNAL), and to compensate for indirect fertilization effects of the compost, non-composted plots were treated with a mineral fertilizer (22N-4P-0K) at a rate of 318 kg•treated ha^{-1}. Aside from pre-plant lime and N–P–K, little subsequent fertilizer was applied. Two nitrogen applications were made to all

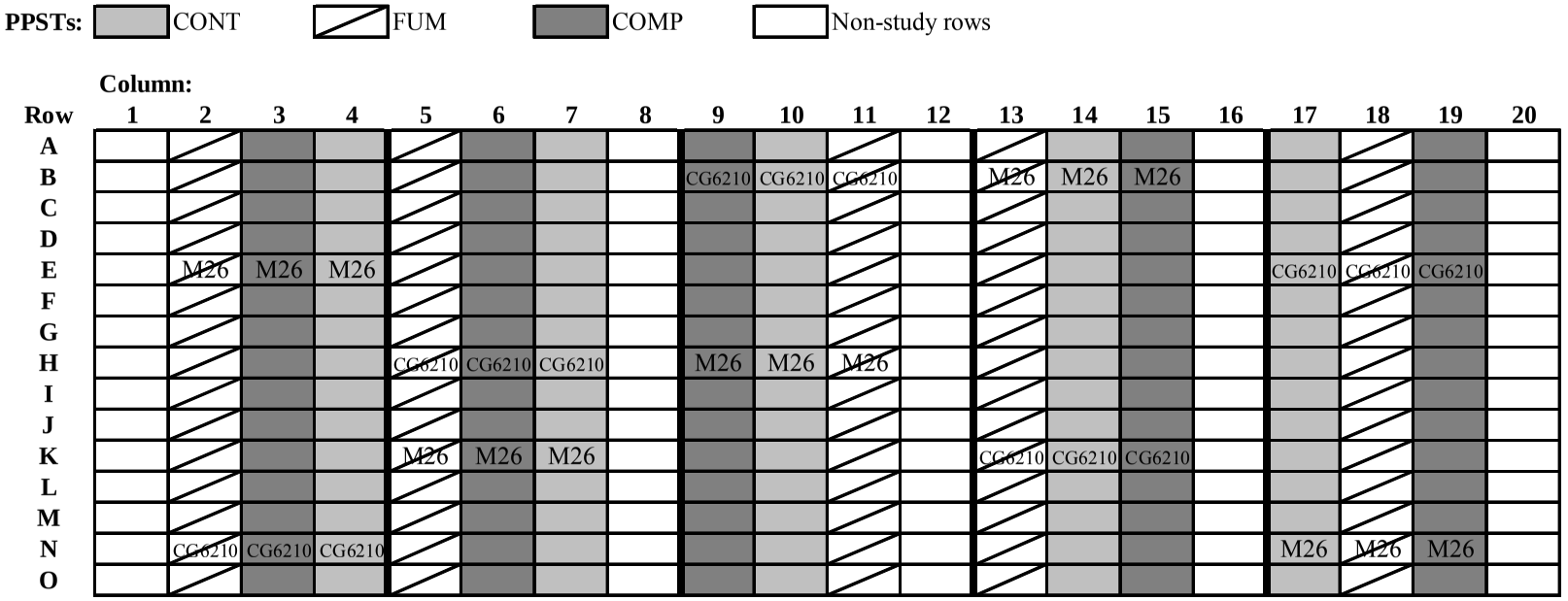

Figure 2.3: Apple replant disease (ARD) site map. Pre-plant soil treatments (PPST) are in vertical columns and differentiated by shading. Each cell represents a tree. Rootstock genotypes are denoted within the cell and represent the 30 data-collection trees.

plots in May 2003 to stimulate growth in the first year – soil-applied ammonium nitrate (34N–0P–0K) at 18.7 kg•ha^{-1} and foliar-applied calcium nitrate (15.5N–0P–0K–19Ca) at 17.1 kg•ha^{-1}. Petal-fall urea and micronutrient foliar sprays were applied annually.

The rootstocks of interest were 'M.26' – an industry-standard, dwarfing rootstock (40% of expected tree size on seedling rootstock) from the East Malling Experiment Station in England, and 'CG.6210' – a semi-dwarfing rootstock (60% of expected tree size on seedling rootstock) from the Cornell-Geneva breeding program. These rootstocks were of interest in our soil health study because 'CG.6210' previously showed ARD tolerance and 'M.26' ARD susceptibility (Leinfelder and Merwin, 2006), and we wished to learn more about soil health/rootstock interactions. The rootstocks were grafted with 'Royal Empire' and planted at 2.1 m x 4.9 m spacing in Nov. 2001. Composted hardwood bark mulch was applied in a 1-m-wide strip to all of the tree rows after planting in 2002 but was not subsequently reapplied. The drive lanes were maintained with a mowed red fescue sod cover. Weeds in the tree rows were controlled by post-emergence glyphosate at the labeled rate (2.9 kg a.i.•ha^{-1}) in May and July, annually.

NYS Commercial Orchard Sites

Soils were collected from orchards in the Lake Ontario, Hudson Valley, and Lake Champlain regions of NYS. We cooperated with 12 commercial growers and collected from five orchards in the Lake Ontario region, six in the Hudson Valley, and four in the Lake Champlain region. Orchard and grower were considered random variables in statistical analyses, with orchard nested within grower. Year was also treated as a random variable, and textural class was treated as a fixed variable.

The oldest commercial orchard was planted in 1965, and the newest was planted in 2006. Rootstocks, varieties, and spacing varied among orchards, and not all orchards were irrigated. Growers used pre-emergence herbicides, post-emergence herbicides, or combinations to control weeds in the tree-row during the growing season. Fertilization varied among orchards but usually included a spring ammonium nitrate or calcium nitrate application, and some growers also applied potash, boron, and/or lime.

Soil Sampling Procedures

Soils were similarly sampled across all three Cornell Orchards experiments, unless otherwise noted. Samples were collected in late July and early Aug. 2007 and 2008. Based on published recommendations (Moebius, 2006; Rumberger et al., 2007), we took annual, summer samples for reasons of replication and heightened biological activity. Soils were collected two or three days after a rain or irrigation event when the soil was near field capacity. Samples were taken from beneath the canopy, approximately 0.5-0.7 m from the tree trunk, and away from treatment edges.

Three sets of soil samples were collected in 2007, and two sets were collected in 2008. The first set was used to conduct a potted seedling bioassay in 2007, which we did not repeat in 2008. For the seedling bioassay, we collected soil from the top 0-20 cm, from six random locations in each plot. Sampling depth was based on previous minirhizotron work at these sites, which showed root growth concentrated at this depth (Yao et al., 2006a). The soil was homogenized by plot and then mixed with perlite at a ratio of 2:1. ‘Gala’ seedlings, which were greenhouse-started (24˚C day, 18˚C night) in sterile vermiculite in late June, were selected for visual uniformity at four to six true leaves. Four replicates were transplanted into 1-L pots containing the field soil and

perlite mixture. The seedlings were grown in an outdoor nursery at the Cornell Orchards and fertilized once with 100 mL of 13% (w/v) solution of 15-5-15 plus micronutrients (Miracle Grow Excel, Scotts Co., Marysville, OH) to overcome transplant shock. They were regularly and uniformly sprinkle-irrigated throughout the 2007 growing season.

Composite bulk soil samples were collected using a 3-cm-diam stainless steel soil corer, to a depth of about 20 cm. Ten to 15 cores were randomly collected, hand-sorted for rocks and surface debris, and homogenized per plot. The soil was stored in a 4°C cooler until needed for testing.

Intact samples were collected using two stainless steel cores, taped vertically together, for a 7-cm internal diam and a 12-cm height. Cores were carefully driven into the soil and lifted out with a shovel to minimize changes to field conditions within the soil cores. Three replicates were randomly taken from each plot in the GMS and IFP-OFP studies, and one sample was taken per plot from the ARD study. Samples were stored in a 4°C cooler until needed for testing.

Samples were collected from the NYS commercial orchard sites in early Sept. 2008 and 2009. Sampling procedures were similar to those employed at the Cornell Orchards sites in 2008. Three replicates of composited samples and three intact cores were collected from each site each year.

Soil Health Indicator Selection and Testing

Indicator Selection

In 2007, we compiled a list of 52 biological, chemical, and physical soil indicators to evaluate (Table 2.1). We used published MDSs (Andrews et al., 2004; Gugino et al., 2007; Reganold et al., 1993; Sparling et al., 2004; Werner, 1994; Wolfe,

Table 2.1: Biological, chemical, and physical soil parameters evaluated in 2007 in a soil health study of GMS, IFP-OFP, and ARD sites. A subset of these were also evaluated in 2008.

Biological	Chemical	Physical
Plant-parasitic nematodes	Phosphorus, available	Bulk Density
Fungal-feeding nematodes	Potassium, available	Macroporosity
Bacterial-feeding nematodes	Magnesium, available	Mesoporosity
Predatory nematodes	Calcium, available	Microporosity
Mycorrhizal fungi	Iron, available	Available water capacity
Organic matter	Aluminum, available	Penetration resistance at 10kPa
Mineralizable nitrogen	Manganese, available	Field surface penetration resistance
Soil respiration	Zinc, available	Field subsurface penetration resistance
Active carbon	Copper, available	Field penetration depth
Microbial biomass carbon	Nitrate-N, available	Water infiltration rate
Microbial biomass nitrogen	pH	Wet aggregate stability
Broadleaf weed seed bank	Nitrogen, total	Saturated hydraulic conductivity
Grasses weed seed bank	Carbon, total	
Root health assessment	Arsenic, total	
Root:shoot ratio	Lead, total	
Earthworms	Cation exchange capacity	
Arthropods	Electrical conductivity	
Molecular fingerprint identification	Sodium absorption ratio	
Soil enzyme activity	Sulfur, available	
Pollutant detoxification		

2006) to assemble our initial list. Andrews et al. (2002) and Gugino et al. (2007) cited *a priori* reasons to eliminate indicators from a MDS without extensive testing, such as practical cost and time constraints, and expert opinion. Like Andrews et al. (2002), we defined expert opinion as consensus of project investigators, published results, or management concerns. Based on published results showing insensitivity to management, we eliminated arthropod counts (Werner, 1994) and saturated hydraulic conductivity (Moebius, 2006) from our list. Electrical conductivity, sodium absorption ratio, and available sulfur were eliminated by consensus because salinity and sodicity are not issues in the humid northeast, and soil sulfur is rarely limiting due to the acidity of local precipitation. Molecular fingerprint methods, soil enzyme activity, and pollutant detoxification were eliminated by consensus because, quantitatively, these are still considered difficult to interpret in the context of soil health.

Biological Soil Properties

The Diagnostics Laboratory at Michigan State University (East Lansing, MI) conducted the nematode community analyses and vesicular arbuscular mycorrhizae (VAM) spore counts, following a modified centrifugation-flotation method, according to Jenkins (1964). The Cornell Nutrient Analysis Laboratory (CNAL) determined organic matter by loss on ignition procedure at 550°C for two hours (Burt, 2004).

Mineralizable nitrogen – a measure of the ability of soil microorganisms to convert organic residues to plant-available ammonium (Gugino et al., 2007) – was determined by 7 d anaerobic incubation methods (Drinkwater et al., 1996). Two sets of 50-mL centrifugation tubes were filled with 10 g of moist soil. One set of tubes was used for baseline extraction of NH_4^+ and NO_3^-. On Day 0, these were filled with 40 mL of 0.05 M K_2SO_4 (Mallinckrodt Baker, Phillipsburg, NJ), shaken for 40 min on a platform shaker, centrifuged for 10 min, and then the supernatant was filtered

(Fisherbrand G6). The samples were stored at -20°C until analysis. The second set of tubes were filled with 10 mL nanopure water and incubated for 7 d. On Day 7, these were filled with 30 mL 0.0667 M K_2SO_4, which in addition to the 10 mL nanopure water, made a solution of 0.05 M K_2SO_4. The tubes were shaken, centrifuged, filtered, and stored frozen, as the Day 0 samples. Samples were thawed and analyzed by a Lachat QuickChem® 800 Flow Injection Analyzer (Loveland, CO) according to manufacturer's standard operating procedure 10-107-06-2-A for NH_4^+ and 10-107-04-1-Q for NO_3^- (Lachat Instruments, 2008). The difference in NH_4^+ from Day 0 to Day 7 was the estimated mineralization of organic N to inorganic N.

Soil respiration was measured over eight weeks by sealed incubation methods (Alef, 1998). Airtight, 240-mL glass jars were filled with 50 g of moist soil and a glass vial of 0.5 M NaOH (Fisher Scientific, Pittsburgh, PA) alkali CO_2 trap. Weekly electrical conductivity measurements were compared with replicated blanks (50 g autoclaved sand) and a 0.25 M Na_2CO_3 (Fisher Scientific) fully-saturated CO_2 standard. Respiration rate was calculated based on the Rodella and Saboya (1999) procedure. While we carried out the experiment over eight weeks, we used respiration after one week in our statistical analyses because treatment differences were evident after one week, statistical differences did not change over the course of the eight week incubation, and differences corresponded with previous six-week results from this site (Yao et al., 2005).

We determined active carbon – the fraction of soil organic matter that is readily available as an energy source for soil microorganisms (Gugino et al., 2007) – by permanganate oxidation of organic matter (Weil et al., 2003). An oven-dry (40°C) 2.5 g soil sample was measured into a 50-mL centrifugation tube and filled with 20 mL of 0.02 M $KMnO_4$. Samples were shaken on a platform shaker for 2 min and centrifuged for 5 min. Diluted supernatant was measured for absorbance at 550 ηm

using a pocket colorimeter (Hach Company, Loveland, CO). Comparison to a standard curve converted the absorbance to active C.

Microbial biomass carbon (C) and nitrogen (N) were determined by direct chloroform ($CHCl_3$) fumigation extraction (Gregorich et al., 1990), as modified by Fierer and Schimel (2003). Two 60-mL glass jars were filled with 10 g of moist soil and 40 mL of 0.05 M K_2SO_4 (Mallinckrodt Baker, Phillipsburg, NJ). One set of jars was fumigated with 0.5 mL ethanol-free $CHCl_3$, sealed, and placed on a rotary shaker for 4 h at 150 RPM. The jars sat for 30 min after shaking to allow the soil to settle, and then the supernatant was decanted into 50 mL centrifuge tubes and centrifuged for 10 min. The samples were filtered (Fisherbrand G6) and stored at -20°C until analyzed. The $CHCl_3$ was purged from the samples with a 30 min lab air sparge. Liquid samples were run for total C on a Shimadzu TOC 5050A with ASI-5000A autosampler (Kyoto, Japan), using platinum-coated alumina beads. Organic C that was not purged was then converted to CO_2 by combustion at 680°C and quantified with a non-dispersive infrared detector. An alkaline $K_2S_2O_8$ solution in a standard autoclave was used to predigest total N for 50 min. A Lachat QuickChem® 800 Flow Injection Analyzer (Loveland, CO) – method 10-107-04-1-Q (Lachat Instruments, 2008) – was used for analyses. Microbial biomass was calculated as the difference between unfumigated and fumigated samples, with soilless blanks accounting for background C and N. Extraction inefficiencies were accounted for using a k_{EC} value of 0.45 (Joergensen, 1996) and k_{EN} value of 0.54 (Brookes et al., 1985).

The potted apple seedling bioassay was used to estimate the weed seed bank, according to Brainard (2007), and determine seedling root health and the root:shoot ratio, according to Isutsa and Merwin (2000). Total grasses and broadleaves were counted in late August and then pulled from the pots. A second count was made in mid-October before destructively harvesting the apple seedlings. It was estimated that

only weed seeds in the upper 3 cm would germinate, for a total soil volume of 460 cm^3. For the root health and root:shoot ratio tests, intact seedlings were carefully pulled from the pots, and soil was gently shaken and washed from the roots. Roots were subjectively rated for pathogen damage based of a scale of 0-4, where 0 = 0% damage, 1 = 1-25%, 2 = 26-50%, 3 = 51-75%, and 4 = 76-100%. Above-ground biomass was then severed from the roots. Above and below-ground biomass were separately bagged, dried at 40°C, and weighed for the root:shoot ratio.

Field earthworm count procedures were modified from Raw (1959). Counts were made in mid-November when soils were roughly at field capacity but before a freezing event had occurred. Eight liters of a 0.25% formalin solution were applied over 0.25 m^2 of each plot, and earthworms that surfaced in 10 min were counted.

Chemical Soil Properties

The Cornell Nutrient Analysis Laboratory (CNAL) determined all chemical indicators by standard procedures (Burt, 2004). Macro and micronutrients were extracted in Morgan's solution (10% (w/v) sodium acetate in 3% acetic acid, buffered to a pH of 4.8), using a soil-to-solution ratio of 1:5 (v/v). The extracted mixture was filtered and passed through an automated rapid flow analyzer to detect plant-available PO_4-P, while macro and micronutrients were detected by inductively coupled argon plasma (ICP) spectrophotometry. Soil pH was determined using a 1:1 (v/v) soil to 0.01 M $CaCl_2$ solution, and total C and N by Dumas combustion. Total arsenic and lead were determined by microwave acid digestion. Cation exchange capacity was determined by extraction in 1.0 N ammonium acetate at pH 7.0.

Physical Soil Properties

Soil texture is not listed in Table 2.1 as a physical soil health indicator because it is an inherent soil property that is not usually changed by management. Soil texture was evaluated by the CNAL using standard fractionation procedures (Burt, 2004).

The intact soil cores were used to test bulk density, porosity, available water capacity, and penetration resistance at 10kPa, using procedures described by Moebius-Clune et al. (2008). Taped cores were carefully separated into "upper" and "lower" cores, which represented 0-6 cm and 6-12 cm soil depths, respectively. Nylon gauze was attached to the bottom of each core with a rubber band. The cores were saturated (Ψ = 0 kPa) over 48 h from the bottom up to prevent air-trapping in pores. Macroporosity (pore diam > 1000 μm) was determined after 3 h gravimetric drainage (Ψ = -0.3 kPa). Cores were then placed on a vacuum-regulated sand tension table and equilibrated to Ψ = -10 kPa to determine mesoporosity (pore diam 30-1000 μm). We measured penetration resistance at -10 kPa using a 30° tip angle, 4-mm-diam cone micro-penetrometer, pushed into the soil 50 mm at a rate of 8 $mm \cdot s^{-1}$, using a manual, modified drill press. Three presses in three ring locations were averaged. The soil was then dried at 105°C to determine bulk density and total porosity. Soil was removed from the cores and sieved through a 2 mm sieve. Microporosity (pore diam 0.2-30 μm) was measured on a ceramic high-pressure plate (Ψ = -1500 kPa), and available water capacity was calculated as the water loss between Ψ = -10 and Ψ = -1500 kPa. Mesoporosity and microporosity were converted to 10-1000 μm and 0.2-10 μm, respectively, using equations reported by van Genuchten (1980), to account for shallower soil.

Soil penetration resistance, penetration depth, and water infiltration were performed *in situ*. Penetrometer readings were taken at soil sampling. Using a 1.3 cm diam tip on a dial penetrometer, surface resistance was measured as the maximum

pressure (MPa) registered in the top 15 cm of soil. Subsurface resistance was measured as the maximum pressure (MPa) registered between 15 and 45 cm depth. If compaction was such that the penetrometer could not be pushed to a depth of 45 cm, a maximum depth was recorded. Water infiltration rate was measured in late October when the soil was near field capacity. We used a Cornell Sprinkle Infiltrometer (Ogden et al., 1997) that combines the advantages of ponded ring infiltration and simulated rainfall. A 241-mm inner diam infiltration ring was inserted 7 cm into the ground, where the round overflow hole was flush with the soil surface. The rainfall simulator – calibrated to drop approximately 0.5 cm•min^{-1} – was placed on top of the infiltration ring. Water infiltration was calculated by measuring volume of runoff from the overflow hole at 2 min intervals until runoff was constant.

Oven-dry soil aggregates (40°C) were shaken over stacked 2 mm and 0.25 mm mesh sieves and a catch pan, as a preliminary procedure for wet aggregate stability. Aggregated crumbs 0.25-2 mm in size were distributed one-layer thick on a 0.25 mm sieve and placed 50 cm below a rain simulator, calibrated to sprinkle 1.25 cm for 5 min. Soil remaining on the sieve and disaggregated soil falling through the sieve onto a filter were collected, dried, and weighed to determine wet aggregate stability (Ogden et al., 1997; van Es et al., 2006).

Orchard Management and Performance Assessments

Trees at the Cornell Orchards sites were managed by commercial orchard practices. Pathogens and insect pests were sprayed according to the Pest Management Guidelines for Commercial Tree Fruit Production (Agnello et al., 2007) or the USDA-NOP standards. Trees were chemically-thinned with appropriate formulations, and the OFP block was additionally hand-thinned each year in June to one fruit per cluster.

Drip and microsprinkler irrigation was used during dry periods of the summer and before soil sampling if a rain event had not recently occurred. Trees were pruned annually in winter to a modified vertical axe. Trees at the NYS commercial orchard sites were managed by the growers, most of whom also used the Pest Management Guidelines for Commercial Tree Fruit Production (Agnello et al., 2007).

Statistical Analyses

All statistical analyses were performed using JMP® 8.0 Statistical Software (SAS Institute, Inc., Cary, NC). A Multivariate Analysis of Variance (MANOVA) was conducted to determine whether there were inherent soil textural class differences among treatments within the Cornell Orchards experimental sites ($P \leq 0.05$). Mixed model and Tukey means separation procedures were used to detect differences in soil properties across GMS and ARD PPST. Student *t* means separation was used for the IFP-OFP study, ARD rootstocks, and NYS commercial orchards by texture. Scoring functions were determined by distribution analyses of commercial orchard soil properties (Gugino et al., 2007). Physical soil properties from intact upper and lower cores were averaged. We inferred significance at $P \leq 0.05$.

Discriminant analysis (DA) was the multivariate procedure used to determine the MDS because it differentiates treatments (Sánchez-Moreno et al., 2008) and is robust to independent variable interactions that are common with soil and systems-based investigations (Drinkwater, 2002). Discriminate analysis determined which soil properties differentiated the GMS, IFP-OFP, and ARD treatments and which could be eliminated for lack of descriptive power. Properties were supplied to the DA model as transformed data when transformation was necessary to meet assumptions for normal distribution of residuals and homogeneity of variances. Forward stepwise variable

selection was used to find the most parsimonious set of indicators that would discriminate the treatments. We considered correlations at $R^2 > 0.50$ and used the Wilks' Lambda test of significance at $P \leq 0.05$.

Results

Determination of Site Textural Class

Soil textural class for the GMS and IFP-OFP sites was silty loam, and the ARD site was silty clay loam. The MANOVA analyses confirmed that soil textural class was the same across treatments at each site: GMS (P = 0.9589), IFP-OFP (P = 0.5662), and ARD (P = 0.1503).

Soil textural class was also determined for each of the NYS commercial orchards. Soils were either silty or sandy, and results are presented separately by textural class.

Soil Biological, Chemical, and Physical Properties

Soil biological, chemical, and physical properties for the GMS, IFP-OFP, and ARD studies are provided (Tables 2.2-2.10). Active C, microbial biomass C and N, weed seed counts, root health rating, root:shoot ratio, earthworm count, CEC, heavy metal content, penetration resistance measures, penetration depth, and water infiltration rate are only presented for 2007 because they were eliminated from the MDS in the second year. Soil biological, chemical, and physical properties for the NYS commercial orchard sites are presented according to texture (Tables 2.11-2.13).

Groundcover Management Systems Study

Soil biological properties differed among GMS in 2007 and 2008 (Table 2.2). In 2007, the number of fungal-feeding nematodes was greater in the SOD than in the PREHERB. Their numbers in the MUL and POSTHERB were not different from those in either the SOD or PREHERB. The number of bacterial-feeding nematodes also differed among GMS in 2007, with the highest count in the MUL, followed by the POSTHERB, SOD, and PREHERB. Vesicular arbuscular mycorrhizae (VAM) spore counts, active C, and microbial biomass C were greater in the MUL than in the other three treatments, which did not differ from one another. Microbial biomass N was greatest in the MUL, followed by the SOD, POSTHERB, and PREHERB. Grasses in the weed seed bank were greater in the POSTHERB than in the others, and earthworm populations were greater in the MUL and POSTHERB than in the PREHERB. In both 2007 and 2008, we saw differences in organic matter, mineralizable N, and soil respiration among treatments. All of these tests showed greater levels in the MUL compared to the other treatments.

Soil chemical properties also varied among GMS in both years (Table 2.3). In 2007, available P was greater in the MUL than in the other three treatments, but this was not observed 2008. Available Ca differed among treatments in both years, with content greater in the MUL than in the other three treatments. Available Fe differed among plots in 2008, with content in the MUL greater than in the PREHERB, but not different from the SOD and POSTHERB. In both years, available Mn differed among GMS. In 2007, the greatest Mn content was in the MUL, and in 2008, the MUL differed from the POSTHERB and PREHERB. In 2008, available Zn was greater in the MUL than in the PREHERB. Available Cu differed among GMS in both years. In 2007, available Cu was greater in the MUL than in the SOD and PREHERB; the

Table 2.2: Soil biological properties in a GMS study. Certain properties were excluded in 2008 because they did not meet indicator selection criteria. Means with different letters were statistically different according to Tukey means separation procedures ($P \leq 0.05$). Nematode, VAM spore, weed seed, and earthworm counts were ln(x+1) transformed. Microbial biomass C and N were ln transformed. Data that were transformed for analysis were back-transformed for presentation.

Year	Soil Property	MUL	SOD	POST-HERB	PRE-HERB	SE	P value
2007	Plant-parasitic nematodes†	10	30	5	4	10	0.1925
	Fungal-feeding nematodes†	35 ab	62 a	40 ab	15 b	10	0.0293
	Bacterial-feeding nematodes†	390 a	40 bc	70 b	8 c	95	0.0012
	Predatory nematodes†	3	3	0	0	2	0.3033
	VAM spores†	927 a	67 b	58 b	30 b	54	0.0003
	Organic matter^	8.7 a	3.5 b	3.1 b	2.9 b	0.4	< 0.0001
	Mineralizable N‡	14.4 a	7.8 b	5.7 bc	2.8 c	0.7	< 0.0001
	Soil respiration^^	1.4 a	0.8 b	0.6 b	0.6 b	0.1	0.0004
	Active C*	1003 a	574 b	476 b	540 b	50	0.0003
	Microbial biomass C††	430 a	207 b	178 b	125 b	37	0.0021
	Microbial biomass N**	57 a	17 b	13 bc	4 c	7	0.0008
	Broadleaf weed seeds‡‡	7	8	9	3	2	0.2049
	Grass weed seeds‡‡	3 b	3 b	12 a	1 b	2	0.0059
	Root health ratingΔ	1	1	0	1	0.3	0.0672
	Root:shoot ratioΩ	2.3	2.1	2.2	2.2	0.2	0.8922
	EarthwormsΔΔ	61 a	41 ab	21 a	4 b	2	0.0014
2008	Plant-parasitic nematodes†	34	159	87	52	40	0.1136
	Fungal-feeding nematodes†	73	78	62	65	10	0.6162
	Bacterial-feeding nematodes†	40	37	20	32	12	0.658
	Predatory nematodes†	5	0	5	3	3	0.4246
	VAM spores†	47	87	75	28	18	0.161
	Organic matter^	6.8 a	3.2 b	3.1 b	2.9 b	0.3	< 0.0001
	Mineralizable N‡	14.9 a	4.4 b	4.6 b	2.5 b	1.1	0.0002
	Soil respiration^^	1.1 a	0.6 b	0.4 b	0.3 b	0.1	0.0012

† #•100 cm^3 $soil^{-1}$

^ %

‡ µg NH_4^+•g dry $soil^{-1}$

^^ mg CO_2•g dry $soil^{-1}$

* mg C•kg dry $soil^{-1}$

†† µg C•g dry $soil^{-1}$

** µg N•g dry $soil^{-1}$

‡‡ #•460 cm^3 $soil^{-1}$

Δ scale 0-4

Ω $g•g^{-1}$

ΔΔ #•0.25 m^2 quadrat

Table 2.3: Soil chemical properties in a GMS study. Means with different letters were statistically different according to Tukey means separation procedures ($P \leq 0.05$). In 2007, NO_3^- and As were ln transformed, and in 2008 P was ln transformed, while pH was exponentially transformed. Data that were transformed for analysis were back-transformed for presentation.

Year	Soil Property	MUL	SOD	POSTHERB	PREHERB	SE	P value
2007	P†	4.40 a	0.37 b	0.57 b	0.01 b	0.35	< 0.0001
	K†	133.0	85.3	95.3	84.7	15.8	0.1802
	Mg†	337.8	357.8	358.2	383.2	28.4	0.7389
	Ca†	4248.7 a	1372.0 b	1360.3 b	1495.3 b	118.9	< 0.0001
	Fe†	3.2	1.7	1.5	1.4	0.6	0.1319
	Al†	10.6	10	11.9	9.1	1.8	0.7455
	Mn†	28.2 a	13.1 b	14.5 b	11.9 b	1.6	0.0003
	Zn†	2.4	2.2	1.7	1.5	0.4	0.4246
	Cu†	4.9 a	2.1 c	3.7 ab	2.8 bc	0.3	0.0008
	NO_3^-†	10.6 a	0.0 b	0.0 b	0.0 b	0.7	< 0.0001
	pH	7.5 a	6.8 b	6.9 b	7.1 ab	0.1	0.0046
	N^	0.33 a	0.18 b	0.17 b	0.16 b	0.01	< 0.0001
	C^	5.6 a	2.0 b	1.6 b	1.6 b	0.2	< 0.0001
	As‡	0.00	0.00	0.02	0.07	0.03	0.5052
	Pb‡	0.05	0.07	0.13	0.15	0.05	0.4203
	CEC^^	29.4 a	15.6 b	16.4 b	16.9 b	1.62	0.0009
2008	P†	5.6	0.8	0.8	0.4	2.00	0.2711
	K†	161.6	131.4	110.5	132.5	27.50	0.6427
	Mg†	357.3	371.7	394.1	407.7	24.60	0.5106
	Ca†	3128.1 a	1163.4 b	1246.7 b	1326.8 b	114.20	< 0.0001
	Fe†	2.0 a	0.8 ab	0.8 ab	0.6 b	0.30	0.0392
	Al†	6.6	9.1	9.5	6.6	1.90	0.5944
	Mn†	8.2 a	4.4 ab	4.3 b	3.8 b	0.80	0.0198
	Zn†	1.7 a	1.3 ab	1.2 ab	0.9 b	0.20	0.0442
	Cu†	4.7 a	2.1 b	1.5 b	2.2 b	0.40	0.0014
	NO_3^-†	15.3 a	6.3 b	3.4 b	2.0 b	2.00	0.0071
	pH	7.4 a	6.8 b	6.9 b	7.0 ab	0.10	0.0238
	N^	0.28 a	0.16 b	0.16 b	0.13 b	0.02	0.0018
	C^	4.5 a	1.7 b	1.6 b	1.4 b	0.2	< 0.0001

† available, mg•kg soil^{-1}

^ total, %

‡ total, mg•kg soil^{-1}

^^ cmol•kg soil^{-1}

POSTHERB also had greater Cu content than the SOD. In 2008, the MUL had greater available Cu than the other three treatments. Available NO_3^-, pH, total N, and total C differed among GMS in both years. Available NO_3^-, total N, and total C followed the same trend, with content greater in the MUL than in the other three treatments. In both years, pH followed the same trend, with the MUL having higher pH than the SOD and POSTHERB, but with the PREHERB not differing from MUL, SOD, or POSTHERB. Cation exchange capacity was greatest in the MUL.

Bulk density, porosity, and available water capacity were the physical properties that differed among GMS (Table 2.4). Bulk density differed among treatments in both 2007 and 2008, with lower bulk density in the MUL. Mesoporosity, microporosity, and available water capacity differed among GMS in 2008. Mesoporosity and available water capacity were higher in the MUL compared to the SOD, POSTHERB, and PREHERB. Microporosity was greater in the MUL than in the PREHERB.

Integrated and Organic Fruit Production Study

Differences in soil biological properties were observed in 2007 and to a lesser extent in 2008 (Table 2.5). In 2007, VAM spore count, organic matter, soil respiration, broadleaf weed seed count, and the root:shoot ratio differed between IFP and OFP. With the exception of broadleaf weed seed count, each of these was greater in the IFP. In 2008, only the plant-parasitic nematode count and soil respiration differed between treatments, with more plant-parasitic nematodes in the OFP, and higher soil respiration in the IFP.

There were no differences in soil chemical properties in 2007; but in 2008, available Ca and Cu, and total C were greater in the IFP (Table 2.6).

Table 2.4: Soil physical properties in a GMS study. Certain parameters were excluded in 2008 because they did not meet indicator selection criteria. Means with different letters were statistically different according to Tukey means separation procedures ($P \leq 0.05$).

Year	Soil Property	MUL	SOD	POSTHERB	PREHERB	SE	P value
2007	Bulk Density†	1.08 b	1.45 a	1.44 a	1.46 a	0.04	0.0005
	Macroporosity^	0.05	0.04	0.05	0.04	0.01	0.6034
	Mesoporosity^	0.22	0.18	0.18	0.19	0.01	0.1499
	Microporosity^	0.16	0.16	0.14	0.15	0.01	0.5139
	Available water capacity‡	0.23	0.21	0.19	0.19	0.01	0.0731
	Penetration resistance at 10kPa^^	0.81	1.09	0.98	1.01	0.13	0.5133
	Field surface penetration resistance^^	1.59	1.59	1.59	1.93	0.21	0.4861
	Field subsurface penetration resistance^^	3.45	3.38	3.38	3.45	0.07	0.5122
	Field penetration depth*	24	27	28	23	3	0.4976
	Water infiltration rate††	30.7	12.1	8.7	15.8	5.8	0.1087
	Wet aggregate stability**	28.5	26.5	14.7	14.2	5.3	0.1822
2008	Bulk Density†	1.00 b	1.34 a	1.42 a	1.44 a	0.04	0.0002
	Macroporosity^	0.01	0.04	0.05	0.04	0.01	0.6634
	Mesoporosity^	0.27 a	0.19 b	0.19 b	0.18 b	0.02	0.0081
	Microporosity^	0.18 a	0.12 ab	0.11 ab	0.08 b	0.02	0.0094
	Available water capacity‡	0.23 a	0.17 b	0.15 b	0.16 b	0.01	0.0035
	Wet aggregate stability**	61.1	45.9	50.3	41.3	4.70	0.0827

† $g \cdot cm^{-3}$

^ cm^3 pore space$\cdot cm^3$ $soil^{-1}$

‡ g water$\cdot$g $soil^{-1}$

^^ Mpa

* cm

†† $cm \cdot hr^{-1}$

** 0.25-2 mm crumbs, %

Table 2.5: Soil biological properties in an IFP-OFP study. Certain properties were excluded in 2008 because they did not meet indicator selection criteria. Means with different letters were statistically different according to Student *t* means separation procedures ($P \leq 0.05$). In 2007, plant-parasitic and bacterial-feeding nematodes, VAM spores, and weed seeds were ln(x+1) transformed, and microbial biomass C was ln transformed. In 2008, bacterial-feeding and predatory nematodes were ln(x+1) transformed, and mineralizable N was ln transformed. Data that were transformed for analysis were back-transformed for presentation.

Year	Soil Property	IFP	OFP	SE	P value
2007	Plant-parasitic nematodes†	4	12	4	0.5269
	Fungal-feeding nematodes†	30	33	12	0.8361
	Bacterial-feeding nematodes†	190	80	67	0.1180
	Predatory nematodes†	0	0	0	NS
	VAM spores†	520 a	26 b	81	0.0021
	Organic matter^	3.5 a	3.1 b	0.1	0.0298
	Mineralizable N‡	7.6	10.1	2.0	0.4289
	Soil respiration^^	1.0 a	0.6 b	0.1	0.0094
	Active C*	663.6	625.2	55.7	0.5946
	Microbial biomass C††	220.2	193.4	27.7	0.0601
	Microbial biomass N**	14.4	12.2	3.1	0.4117
	Broadleaf weed seeds‡‡	7 b	19 a	2	0.0062
	Grass weed seeds‡‡	3	7	1	0.0688
	Root health ratingΔ	1	1	0	NS
	Root:shoot ratioΩ	1.9 a	1.4 b	0.2	0.0455
	EarthwormsΔΔ	76	62	11	0.371
2008	Plant-parasitic nematodes†	43 b	70 a	10	0.022
	Fungal-feeding nematodes†	279	259	35	0.6962
	Bacterial-feeding nematodes†	148	125	41	0.5892
	Predatory nematodes†	8	3	3	0.2332
	VAM spores†	133	111	27	0.3489
	Organic matter^	2.7	2.5	0.15	0.3189
	Mineralizable N‡	5.5	10.4	4.2	0.6274
	Soil respiration^^	0.94 a	0.62 b	0.04	0.0021

† #•100 cm^3 $soil^{-1}$

^ %

‡ µg NH_4^+•g dry $soil^{-1}$

^^ mg CO_2•g dry $soil^{-1}$

* mg C•kg dry $soil^{-1}$

†† µg C•g dry $soil^{-1}$

** µg N•g dry $soil^{-1}$

‡‡ #•460 cm^3 $soil^{-1}$

Δ scale 0-4

Ω $g•g^{-1}$

ΔΔ #•0.25 m^2 quadrat

Table 2.6: Soil chemical properties in an IFP-OFP study. Means with different letters were statistically different according to Student *t* means separation procedures ($P \leq 0.05$). In 2007, available Zn and total As were ln transformed. Data that were transformed for analysis were back-transformed for presentation.

Year	Soil Property	IFP	OFP	SE	P value
2007	P†	3.8	4.7	0.9	0.5286
	K†	212.8	206.5	25.2	0.5491
	Mg†	302.3	323.9	13.8	0.0864
	Ca†	1332.8	1226.5	47.5	0.1645
	Fe†	2.8	2.3	0.6	0.5741
	Al†	17.4	14.3	1.47	0.1601
	Mn†	11.3	8.2	0.9	0.0546
	Zn†	3.7	1.5	1.5	0.4662
	Cu†	2.2	3.2	0.6	0.2830
	NO_3^-†	0.0	3.2	1.3	0.1340
	pH	7.01	6.92	0.04	0.1345
	N^	0.15	0.16	0.01	0.2446
	C^	2.1	1.8	0.1	0.2546
	As‡	0.20	0.10	0.2	0.3351
	Pb‡	3.0	4.9	1.1	0.3205
	CEC^^	15.0	16.0	1.1	0.5217
2008	P†	3.7	3.4	0.8	0.8609
	K†	245.2	259.2	39.8	0.7567
	Mg†	293.0	312.4	15.0	0.1997
	Ca†	1238.2 a	1096.4 b	52.0	0.0417
	Fe†	2.4	1.9	0.3	0.2590
	Al†	16.3	13.9	1.5	0.3320
	Mn†	5.0	4.0	0.5	0.2061
	Zn†	1.50	1.48	0.46	0.9742
	Cu†	2.1 a	1.3 b	0.2	0.0493
	NO_3^-†	3.3	7.9	1.7	0.0829
	pH	7.00	6.88	0.04	0.0941
	N^	0.15	0.16	0.01	0.1942
	C^	1.9 a	1.6 b	0.1	0.0500

† available, mg•kg soil^{-1}

^ total, %

‡ total, mg•kg soil^{-1}

^^ cmol•kg soil^{-1}

Among physical soil properties, macroporosity differed in 2007, with greater macropore volume percentage in the OFP (Table 2.7). There were no differences in physical properties in 2008.

Apple Replant Disease Study

Active C and microbial biomass N differed in 2007, and VAM spore count and soil respiration differed in 2008 (Table 2.8). Active C was greater in the COMP than in the FUM and CONT. Microbial biomass N was greater in the COMP than in the FUM, but the CONT differed from neither the COMP nor the FUM. In 2008, VAM spore count and soil respiration differed among treatments, with higher levels in the COMP compared to the FUM and CONT.

There were many differences in chemical soil properties in both years (Table 2.9). Available P differed among treatments in both years, with the COMP having greater content than the FUM and CONT. Available Ca followed the same trend in 2007, but there were no differences in available Ca in 2008. There were differences in available Fe in both years. In 2007, available Fe was greater in the FUM than in the COMP. In 2008, available Fe was similar for the FUM and CONT, which was greater than content in the COMP. This was the same trend seen for available Al in both 2007 and 2008. The opposite was seen for available Cu and pH in both years, where the FUM and CONT were similar, but these were lower than content in the COMP. In 2007, total N was greater in the COMP than in the CONT, and in 2008, total N was greater in the COMP than in both the CONT and FUM. Total C was greater in the COMP than in the CONT and FUM in both years. In 2007, total Pb was greater in the FUM and CONT than in the COMP, and cation exchange capacity was greater in the COMP than the FUM.

Table 2.7: Soil physical properties in an IFP-OFP study. Certain properties were excluded in 2008 because they did not meet indicator selection criteria. Means with different letters were statistically different according to Student *t* means separation procedures ($P \leq 0.05$). Wet aggregate stability was ln transformed in 2007. Data that were transformed for analysis were back-transformed for presentation.

Year	Soil Property	IFP	OFP	SE	P value
2007	Bulk Density†	1.31	1.30	0.03	0.1288
	Macroporosity^	0.015 b	0.019 a	0.001	0.0262
	Mesoporosity^	0.14	0.16	0.01	0.1159
	Microporosity^	0.27	0.24	0.01	0.0769
	Available water capacity‡	0.28	0.26	0.02	0.1602
	Penetration resistance at 10kPa^^	1.22	1.27	0.13	0.2961
	Field surface penetration resistance^^	1.38	1.59	0.14	0.2070
	Field subsurface penetration resistance^^	3.31	3.38	0.07	0.5060
	Field penetration depth*	40	36	3	0.1982
	Water infiltration rate††	2.6	1.5	0.9	0.2402
	Wet aggregate stability**	13.9	11.1	1.6	0.1633
2008	Bulk Density†	1.30	1.28	0.02	0.4706
	Macroporosity^	0.021	0.025	0.00	0.4105
	Mesoporosity^	0.14	0.17	0.01	0.0591
	Microporosity^	0.24	0.22	0.01	0.0516
	Available water capacity‡	0.27	0.26	0.01	0.7713
	Wet aggregate stability**	34.5	22.8	5.50	0.1203

† $g \cdot cm^{-3}$

^ cm^3 pore space$\cdot cm^3$ $soil^{-1}$

‡ g water•g $soil^{-1}$

^^ Mpa

* cm

†† $cm \cdot hr^{-1}$

** 0.25-2 mm crumbs, %

Table 2.8: Soil biological properties in an ARD study. Certain variables were excluded in 2008 because they did not meet indicator selection criteria. Means with different letters were statistically different according to Tukey means separation procedures ($P \leq 0.05$). Nematode, VAM spore, and weed seed counts were ln(x+1) transformed and organic matter was logit transformed in both years. Data that were transformed for analysis were back-transformed for presentation.

Year	Soil Property	COMP	FUM	CONT	SE	P value
2007	Plant-parasitic nematodes†	1	1	0	1	0.1146
	Fungal-feeding nematodes†	45	40	35	14	0.9321
	Bacterial-feeding nematodes†	32	28	44	12	0.2103
	Predatory nematodes†	0	1	1	1	0.4447
	VAM spores†	178	193	117	33	0.1632
	Organic matter^	3.1	2.8	2.6	0.1	0.0639
	Mineralizable N‡	8.3	8.6	9.6	0.9	0.5312
	Soil respiration^^	0.6	0.6	0.5	0.1	0.3500
	Active C*	569 a	500 b	478 b	10.3	< 0.0001
	Microbial biomass C††	265	210	242	16	0.0869
	Microbial biomass N**	22 a	13 b	18 ab	2.2	0.0198
	Broadleaf weed seeds‡‡	7	8	8	1	0.9601
	Grass weed seeds‡‡	3	3	5	1	0.4453
	Root health ratingΔ	1	1	1	0	NS
	Root:shoot ratioΩ	1.53	1.5	1.68	0.11	0.4364
	EarthwormsΔΔ	18	19	26	5	0.3427
2008	Plant-parasitic nematodes†	8	0	1	3	0.0572
	Fungal-feeding nematodes†	110	74	115	20	0.1398
	Bacterial-feeding nematodes†	40	23	29	9	0.3135
	Predatory nematodes†	2	3	1	1	0.6204
	VAM spores†	382 a	249 b	157 b	71	0.0009
	Organic matter^	2.51	2.36	2.23	0.09	0.0847
	Mineralizable N‡	6.9	8.6	6.7	1.0	0.2265
	Soil respiration^^	0.7 a	0.5 b	0.5 b	0.04	0.0063

† #•100 cm^3 $soil^{-1}$

^ %

‡ µg NH_4^+•g dry $soil^{-1}$

^^ mg CO_2•g dry $soil^{-1}$

* mg C•kg dry $soil^{-1}$

†† µg C•g dry $soil^{-1}$

** µg N•g dry $soil^{-1}$

‡‡ #•460 cm^3 $soil^{-1}$

Δ scale 0-4

Ω $g•g^{-1}$

ΔΔ #•0.25 m^2 quadrat

Table 2.9: Soil chemical properties in an ARD study. Means with different letters were statistically different according to Tukey means separation procedures ($P \leq 0.05$). Available P, K, Ca, Al, Mn, Zn, and total Pb were ln transformed in 2007. Available Mg, Fe, Al, and Zn were ln transformed in 2008. Data that were transformed for analysis were back-transformed for presentation.

Year	Soil Property	COMP	FUM	CONT	SE	P value
2007	P†	12.3 a	5.1 b	5.3 b	1.1	0.0004
	K†	170.3	166.6	171.8	11.8	0.7568
	Mg†	274.0	302.2	306.1	10.3	0.0558
	Ca†	2015.3 a	1065.1 b	1034.4 b	126.9	< 0.0001
	Fe†	3.1 b	6.1 a	4.3 ab	0.9	0.0214
	Al†	17.5 b	32.3 a	26.9 a	3.2	0.0021
	Mn†	11.9	11.9	10.9	1.0	0.5395
	Zn†	0.8	1.0	0.8	0.1	0.7208
	Cu†	2.2 a	1.1 b	0.8 b	0.3	0.0045
	NO_3^-†	0	0	0	0	NS
	pH	7.09 a	6.39 b	6.50 b	0.11	0.0003
	N^	0.173 a	0.154 ab	0.147 b	0.006	0.0192
	C^	2.44 a	1.96 b	1.83 b	0.13	0.0133
	As‡	0	0	0	0	NS
	Pb‡	2.2 b	13.9 a	8.6 a	2.4	0.0005
	CEC^^	18.0 a	14.4 b	15.3 ab	0.9	0.0336
2008	P†	9.9 a	3.8 b	3.7 b	0.4	< 0.0001
	K†	204.4	190.6	183.5	10.6	0.321
	Mg†	285.8	310.1	302.7	11.1	0.0753
	Ca†	1884.6	1036.8	996.7	67.1	< 0.0001
	Fe†	2.6 b	5.0 a	4.5 a	0.6	0.0038
	Al†	18.0 b	36.2 a	36.9 a	3.2	< 0.0001
	Mn†	6.4	6.1	5.8	0.4	0.4095
	Zn†	0.67	0.67	0.74	0.1	0.5741
	Cu†	2.6 a	1.7 b	1.7 b	0.2	0.0098
	NO_3^-†	0	0	0	0	NS
	pH	7.22 a	6.50 b	6.54 b	0.1	< 0.0001
	N^	0.170 a	0.148 b	0.144 b	0.0	0.0074
	C^	2.07 a	1.74 b	1.58 b	0.1	0.0052

† available, mg•kg soil^{-1}

^ total, %

‡ total, mg•kg soil^{-1}

^^ cmol•kg soil^{-1}

There were no statistical differences in physical soil properties in the ARD study in either 2007 or 2008 (Table 2.10).

NYS Commercial Orchard Sites

Results from the NYS commercial orchards are presented as means and lower 25th and upper 25th percentile ranges for silty and sandy soils. These percentile ranges are akin to the graphical scoring functions for annual crop systems presented in Gugino et al. (2007). Among the soil biological properties (Table 2.11), the only statistical difference between textural classes was for organic matter, with the silty soils having more organic matter than the sandy soils. Among the chemical properties (Table 2.12), available Mn, total N, and total C differed between textural classes, with silty soils having more of each compared to the sandy soils. Available water capacity and wet aggregate stability also differed by textural class (Table 2.13), with the silty soils having higher levels than the sandy soils. Random variability in the data was attributed to site and year differences.

Determination of Orchard MDS

The Discriminant Analysis (DA) results for the GMS, IFP-OFP, and ARD sites are summarized in Table 2.14. The number of independent variables entered into the discriminant analyses in 2008 was reduced compared to the number inputted in 2007 because we did not repeat-test all of the same variables in 2008. The reasons for reducing the number of variables tested in 2008 – and the influence this reduction may have had on the results – will be addressed in the discussion of this chapter. Discriminant analysis was not conducted on the NYS commercial orchard soil properties because there were no experimental treatments at these sites.

Table 2.10: Soil physical properties in an ARD study. Certain properties were excluded in 2008 because they did not meet indicator selection criteria. Means with different letters were statistically different according to Tukey means separation procedures ($P \leq 0.05$). In 2007, macroporosity was reciprocal transformed, and microporosity was ln transformed. Data that were transformed for analysis were back-transformed for presentation.

Year	Soil Property	COMP	FUM	CONT	SE	P value
2007	Bulk Density†	1.38	1.39	1.42	0.03	0.2901
	Macroporosity^	0.02	0.024	0.024	0.003	0.9996
	Mesoporosity^	0.167	0.158	0.152	0.008	0.2300
	Microporosity^	0.183	0.185	0.189	0.009	0.5988
	Available water capacity‡	0.253	0.247	0.245	0.012	0.6231
	Penetration resistance at 10kPa^^	1.46	1.54	1.6	0.08	0.6539
	Field surface penetration resistance^^	2.07	2.21	2.14	0.14	0.4182
	Field subsurface penetration resistance^^	3.31	3.31	3.31	0.07	0.8762
	Field penetration depth*	33	30	33	2	0.4405
	Water infiltration rate††	4.9	6.3	5.7	1.3	0.7664
	Wet aggregate stability**	14.9	13.2	11.7	1.2	0.2053
2008	Bulk Density†	1.41	1.37	1.34	0.03	0.0594
	Macroporosity^	0.026	0.030	0.033	0.004	0.4503
	Mesoporosity^	0.133	0.143	0.144	0.007	0.1880
	Microporosity^	0.182	0.180	0.185	0.011	0.8495
	Available water capacity‡	0.212	0.207	0.218	0.02	0.5800
	Wet aggregate stability**	23.4	26.9	23.5	2.10	0.3158

† $g \cdot cm^{-3}$

^ cm^3 pore space$\cdot cm^3$ $soil^{-1}$

‡ g water•g $soil^{-1}$

^^ Mpa

* cm

†† $cm \cdot hr^{-1}$

** 0.25-2 mm crumbs, %

Table 2.11: Soil biological scoring functions developed from Ontario, Hudson, and Champlain commercial orchards (n = 15), averaged across 2008 and 2009. Means are presented plus or minus standard errors. Organic matter was statistically different by texture according to Student *t* means separation procedures ($P \leq 0.05$), which is denoted by asterisks. Nematode and VAM spore counts were ln(x+1) transformed, and soil respiration and mineralizable N were ln transformed. Data that were transformed for analysis were back-transformed for presentation.

			25th Percentile Ranges	
Texture	**Soil Property**	**Mean**	**Lower**	**Upper**
Silt	Plant-parasitic nematodes†	26 ± 9	0 - 8	37 - 75
	Fungal-feeding nematodes†	36 ± 15	0 - 20	45 - 105
	Bacterial-feeding nematodes†	113 ± 60	5 - 30	140 - 710
	Predatory nematodes†	1 ± 0	0 - 0	10 - 15
	VAM spores†	57 ± 21	10 - 30	70 - 230
	Organic matter^	3.9 ± 0.4*	2.4 - 3.0	4.3 - 6.9
	Mineralizable N‡	5.4 ± 0.8	0.8 - 3.7	6.9 - 12.4
	Soil respiration^^	0.42 ± 0.10	0.13 - 0.22	0.52 - 0.87
Sand	Plant-parasitic nematodes†	29 ± 9	0 - 12	36 - 246
	Fungal-feeding nematodes†	51 ± 15	10 - 23	65 - 220
	Bacterial-feeding nematodes†	194 ± 60	30 - 75	228 - 1150
	Predatory nematodes†	1 ± 0	0 - 2	13 - 15
	VAM spores†	79 ± 21	10 - 25	100 - 375
	Organic matter^	2.8 ± 0.4*	0.9 - 2.0	3.2 - 4.3
	Mineralizable N‡	4.1 ± 0.8	1.1 - 2.1	6.0 - 12.3
	Soil respiration^^	0.37 ± 0.10	0.09 - 0.22	0.54 - 1.16

† #•100 cm^3 $soil^{-1}$

^ %

‡ µg NH_4^+•g dry $soil^{-1}$

^^ mg CO_2•g dry $soil^{-1}$

Table 2.12: Soil chemical scoring functions developed from Ontario, Hudson, and Champlain commercial orchards (n = 15), averaged across 2008 and 2009. Means are presented plus or minus standard errors. Available Mn, total N, and total C were statistically different by texture according to Student *t* means separation procedures ($P \leq 0.05$), which is denoted by asterisks. All data were ln transformed, except available Mg, pH, and total N. Data that were transformed for analysis were back-transformed for presentation.

			25th Percentile Ranges	
Texture	**Soil Property**	**Mean**	**Lower**	**Upper**
Silt	P†	5.3 ± 2.7	0.5 - 1.7	7.5 - 13.5
	K†	214.0 ± 52.9	86.7 - 140.6	284.4 - 439.4
	Mg†	171.6 ± 32.6	33.0 - 125.0	232.4 - 333.0
	Ca†	2087.0 ± 817.3	415.0 - 994.0	1906.0 - 12287.0
	Fe†	3.2 ± 1.0	0.6 - 2.0	3.8 - 8.9
	Al†	38.4 ± 10.0	10.3 - 19.1	44.0 - 127.3
	Mn†	10.9 ± 2.2*	4.1 - 8.0	13.0 - 23.4
	Zn†	1.9 ± 0.7	0.8 - 1.3	2.4 - 6.2
	Cu†	3.1 ± 1.1	0.4 - 1.4	2.7 - 18.5
	NO_3^-†	16.6 ± 4.2	0.0 - 10.3	23.9 - 42.4
	pH	6.3 ± 0.3	5.2 - 6.0	6.6 - 7.7
	N^	0.19 ± 0.02*	0.12 - 0.14	0.23 - 0.28
	C^	2.2 ± 0.2*	1.3 - 1.6	2.6 - 3.5
Sand	P†	9.3 ± 2.7	0.6 - 1.6	15.6 - 29.3
	K†	192.3 ± 52.9	85.2 - 129.7	211.2 - 476.9
	Mg†	134.7 ± 32.6	52.4 - 67.6	172.8 - 250.6
	Ca†	1050.5 ± 817.3	305.0 - 832.1	1147.6 - 2772.5
	Fe†	2.8 ± 1.0	0.8 - 1.4	3.3 - 7.8
	Al†	26.3 ± 10.0	7.0 - 14.4	28.2 - 41.2
	Mn†	6.5 ± 2.2*	2.9 - 4.3	8.1 - 14.5
	Zn†	2.7 ± 0.7	0.5 - 1.2	3.5 - 9.9
	Cu†	1.6 ± 1.1	0.3 - 1.2	2.0 - 3.3
	NO_3^-†	10.5 ± 4.2	0.0 - 5.3	13.9 - 50.6
	pH	6.6 ± 0.3	5.6 - 6.0	7.1 - 7.4
	N^	0.13 ± 0.02*	0.05 - 0.11	0.15 - 0.23
	C^	1.5 ± 0.2*	0.52 - 1.19	1.87 - 2.64

† available, mg•kg $soil^{-1}$

^ total, %

Table 2.13: Soil physical scoring functions developed from Ontario, Hudson, and Champlain commercial orchards (n = 15), averaged across 2008 and 2009. Means are presented plus or minus standard errors. Available water capacity and wet aggregate stability were statistically different by texture according to Student *t* means separation procedures ($P \leq 0.05$), which is denoted by asterisks. Macroporosity and available water capacity were ln transformed. Data that were transformed for analysis were back-transformed for presentation.

			25th Percentile Ranges	
Texture	**Soil Property**	**Mean**	**Lower**	**Upper**
Silt	Bulk Density†	1.29 ± 0.05	1.08 - 1.21	1.36 - 1.52
	Macroporosity^	0.055 ± 0.004	0.015 - 0.043	0.067 - 0.106
	Mesoporosity^	0.27 ± 0.01	0.17 - 0.23	0.30 - 0.35
	Microporosity^	0.14 ± 0.01	0.06 - 0.13	0.16 - 0.20
	Available water capacity‡	0.19 ± 0.01*	0.12 - 0.15	0.22 - 0.26
	Wet aggregate stability^^	68.4 ± 5.0*	43.8 - 59.6	78.1 - 97.6
Sand	Bulk Density†	1.28 ± 0.05	0.75 - 1.16	1.39 - 1.66
	Macroporosity^	0.042 ± 0.004	0.023 - 0.033	0.047 - 0.092
	Mesoporosity^	0.3 ± 0.01	0.20 - 0.27	0.33 - 0.51
	Microporosity^	0.15 ± 0.01	0.06 - 0.13	0.17 - 0.36
	Available water capacity‡	0.13 ± 0.01*	0.08 - 0.11	0.16 - 0.19
	Wet aggregate stability^^	54.4 ± 5.0*	26.7 - 40.5	72.2 - 88.8

† $g \cdot cm^{-3}$

^ cm^3 pore space•cm^3 $soil^{-1}$

‡ g water•g $soil^{-1}$

^^ 0.25-2 mm crumbs, %

Table 2.14: Soil indicators that differentiated soil treatments in GMS, IFP-OFP, and ARD study sites.

	Biological		**Chemical**		**Physical**		**Combined**	
	2007	2008	2007	2008	2007	2008	2007	2008
GMS:								
Soil Indicators	OM	OM	Total C	Total C	Bulk Density	Bulk Density	Total C	Total C
P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0005	0.0002	< 0.0001	< 0.0001
Can. Corr. (R^2)	0.97	0.97	0.99	0.98	0.94	0.95	0.99	0.98
IFP-OFP:								
Soil Indicators	VAM	Soil Resp.	Mn† pH	Cu† pH Fe†	Microporosity	Mesoporosity	VAM	Soil Resp.
P value	0.0006	0.0021	0.0500	0.0462	0.0466	0.0500	0.0006	0.0021
Can. Corr. (R^2)	0.94	0.90	0.82	0.92	0.84	0.71	0.94	0.90
ARD:								
Soil Indicators	Active C	Soil Resp. Nmin VAM	Ca†	P†	All Indicators	All Indicators	Ca†	P†
P value	< 0.0001	0.0118	< 0.0001	< 0.0001	NS	NS	< 0.0001	< 0.0001
Can. Corr. (R^2)	0.83	0.61	0.83	0.92			0.83	0.92

OM = organic matter
VAM = VAM spores
Soil Resp. = Soil Respiration
NMin = Mineralizable N
† available

GMS Biological Indicators

The first variable added by stepwise selection to the DA model, which discriminated GMS, was organic matter. With organic matter alone, the model was significant ($P < 0.0001$), and the canonical correlation was $R^2 = 0.97$. Adding the next variable – mineralizable N – to the model did not improve the canonical correlation ($R^2 = 0.99$). We would consider a change of > 0.05 a significant change in the canonical correlation.

In 2008, we replicated a subset of the tests from 2007, including the full nematode community analysis, VAM spore count, organic matter, mineralizable N, and soil respiration. Organic matter was, again, the first indicator added by stepwise selection to the DA model ($P < 0.0001$), with $R^2 = 0.97$. Adding the next variable (soil respiration) did not change the canonical correlation.

IFP-OFP Biological Indicators

The first variable added to the DA model, which discriminated IFP and OFP, was VAM spore count ($P = 0.0006$), with $R^2 = 0.94$. Adding the next variable to the model (weed count) did not change the canonical correlation ($R^2 = 0.98$). In 2008, running the subset of tests previously mentioned, the first variable added to the model by stepwise selection was soil respiration ($P = 0.0021$), with $R^2 = 0.90$, and adding the next variable (plant-parasitic nematode count) did not improve the canonical correlation.

ARD Biological Indicators

Active C was the first variable added to the DA model ($P < 0.0001$), with $R^2 = 0.83$, discriminating the PPST. Adding the next variable (microbial biomass N) did not improve the canonical correlation. In 2008, running the subset of tests previously

mentioned, soil respiration, mineralizable N, and VAM spore count were the variables added to the model (P = 0.0130), with $R^2 = 0.66$. Adding the fourth variable (fungal-feeding nematodes) did not improve the model.

GMS Chemical Indicators

Stepwise variable selection designated total C as the most discriminating indicator of the GMS in both 2007 (P < 0.0001) and 2008 (P < 0.0001), with canonical correlations of $R^2 = 0.99$ and $R^2 = 0.98$, respectively. In both years, adding the next variable (pH and total As, respectively) did not improve the canonical correlations.

IFP-OFP Chemical Indicators

Available Mn produced a significant DA model (P = 0.0429), with $R^2 = 0.72$. The next indicator added was pH (P = 0.05), and this addition improved the canonical correlation ($R^2 = 0.82$). Adding a third indicator (total As) made the model insignificant (P = 0.1122). In 2008, available Cu was the first indicator added to the model (P = 0.0283, $R^2 = 0.76$), pH was the second (P = 0.0434, $R^2 = 0.85$), and finally available Fe was added (P = 0.0462, $R^2 = 0.92$). Adding a fourth indicator (total C) no longer improved the canonical correlation.

ARD Chemical Indicators

In 2007, available Ca produced a significant DA model (P < 0.0001), with $R^2 = 0.83$. Adding the next indicator to the model (available Zn) did not improve the canonical correlation. In 2008, available P produced a significant model (P < 0.0001), with $R^2 = 0.92$. Adding the next indicator (total Pb) did not improve the canonical correlation.

GMS Physical Indicators

In 2007, the stepwise variable selection added bulk density first to the DA model ($P = 0.0005$), with $R^2 = 0.94$. Adding the next variable (wet aggregate stability) did not improve the canonical correlation. In 2008, we tested a subset of the indicators, including bulk density, porosity, available water capacity, and wet aggregate stability. The first variable added to the model was, again, bulk density, with $P = 0.0002$ and $R^2 = 0.95$. Adding the next indicator (microporosity) did not improve the canonical correlation.

IFP-OFP Physical Indicators

In 2007, microporosity was the first indicator added by stepwise selection to the model ($P = 0.0441$, $R^2 = 0.72$). Adding the next indicator (macroporosity) made the model insignificant. In 2008, running the subset of tests previously mentioned, mesoporosity was the only indicator needed in the model ($P = 0.05$, $R^2 = 0.71$). Adding the next indicator – microporosity – would have resulted in a model that was no longer significant.

ARD Physical Indicators

In 2007 and 2008, even with all the indicators added, we could not get a significant model from the DA.

GMS Biological, Chemical, and Physical Indicators Combined

When organic matter, total C, and bulk density were combined in DA for 2007 and 2008, we found that total C was the first variable selected in both years. The model was highly significant ($P < 0.0001$) in both years, with $R^2 = 0.99$ and $R^2 = 0.98$ for 2007 and 2008, respectively.

IFP-OFP Biological, Chemical, and Physical Indicators Combined

When we combined the 2007 indicators, we found that VAM spore count alone produced a significant model ($P = 0.0006$), with $R^2 = 0.94$. Adding available Mn did not improve the canonical correlation. In 2008, soil respiration produced a significant model ($P = 0.0021$), with $R^2 = 0.90$. Adding pH to the model did not improve the canonical correlation.

ARD Biological, Chemical, and Physical Indicators Combined

When the 2007 indicators were combined, available Ca produced a significant model ($P < 0.0001$), with $R^2 = 0.83$. Adding the next indicator (active C) did not improve the canonical correlation. In 2008, available P produced a significant model ($P < 0.0001$), with $R^2 = 0.92$. Adding the next indicator (soil respiration) did not improve the correlation.

Correlations among Soil Health Properties

The soil health indicators that best discriminated GMS, IFP-OFP, and ARD treatments correlated with other soil biological, chemical, and physical properties (Table 2.15). In the GMS study, total soil C correlated positively with bacterial-feeding nematodes, organic matter, available Ca, available Mg, available Zn, available Cu, and total N in both years. In addition, total soil C correlated positively with soil respiration, minerizable N, and wet aggregate stability in 2008. Total soil C correlated negatively with available Al and bulk density in both years. Additionally, it correlated negatively with available Fe in 2007 and plant-parasitic nematodes, fungal-feeding nematodes, and macroporosity in 2008. In the IFP-OFP study, VAM spore count correlated positively with bacterial-feeding nematodes, available P, available K,

Table 2.15: Correlations among soil health indicators and soil biological, chemical, and physical properties in GMS, IFP-OFP, and ARD study sites. Correlations were inferred at $R^2 > 0.50$.

	Study Site:	**GMS**		**IFP-OFP**		**ARD**	
	Year:	2007	2008	2007	2008	2007	2008
	Soil Health Indicator:	**Total C**	**Total C**	**VAM Spore Count**	**Soil Respiration**	**Available Ca**	**Available P**
Soil Property:	Plant-parasitc nematodes	NS	-0.63	NS	NS	NS	NS
	Fungal-feeding nematodes	NS	-0.59	NS	NS	NS	NS
	Bacterial-feeding nematodes	0.53	0.60	0.69	NS	NS	NS
	VAM spore count	NS	NS	1.00	NS	NS	NS
	Soil respiration	NS	0.51	NS	1.00	NS	NS
	Mineralizable N	NS	0.54	NS	NS	NS	NS
	Organic matter	0.93	0.55	NS	NS	0.71	NS
	P, available	NS	NS	0.59	NS	0.84	1.00
	K, available	NS	NS	0.58	-0.69	NS	0.51
	Ca, available	0.61	0.81	NS	NS	1.00	NS
	Mg, available	0.77	0.90	NS	-0.68	NS	NS
	Fe, available	-0.78	NS	-0.72	0.62	-0.52	-0.51
	Al, available	-0.80	-0.83	-0.85	0.78	-0.58	-0.51
	Mn, available	NS	NS	-0.60	NS	NS	NS
	Zn, available	0.74	0.86	0.59	NS	0.51	NS
	Cu, available	0.65	0.62	-0.54	0.59	0.76	NS
	pH	NS	0.74	0.64	NS	0.68	NS
	C, total	1.00	1.00	NS	NS	0.60	NS
	N, total	0.78	0.97	NS	NS	0.70	NS
	Bulk density	-0.60	-0.54	-0.50	NS	NS	NS
	Macroporosity	NS	-0.58	NS	NS	NS	NS
	Mesoporosity	NS	NS	NS	0.62	NS	NS
	Microporosity	NS	NS	0.69	NS	NS	NS
	Available water capacity	NS	NS	0.64	NS	NS	NS
	Wet Aggregate Stability	NS	0.60	0.50	NS	NS	NS

available Zn, pH, microporosity, available water capacity, and wet aggregate stability in 2007; and it correlated negatively with available Fe, available Al, available Mn, available Cu, and bulk density. Soil respiration correlated positively with available Fe, available Al, available Cu, and mesoporosity in 2008; and it correlated negatively with available K and Mg. In the ARD study, available Ca correlated positively with organic matter, available P, available Zn, available Cu, pH, total C, and total N in 2007; and it correlated negatively with available Fe and Al. In 2008, available P correlated positively with available K, and negatively with available Fe and Al.

Discussion

Determination of Site Textural Class

Because textural class is an inherent soil property that cannot be easily changed by management, and because it has a strong influence on other soil properties, if the textural class within experimental sites had varied, soil property analyses would have needed to be conducted separately for each textural class (Gugino et al., 2007). If this had been the case at our three Cornell sites, it would have prevented comparison across treatments within a site. Since this was not the case, we could compare biological, chemical, and physical soil properties within the GMS, IFP-OFP, and ARD studies.

Because the NYS commercial orchard soils differed in textural class, we presented results separately for silty and sandy soils. None of the soils we collected were characterized as clayey.

Soil Biological, Chemical, and Physical Properties

Soil health properties have been examined in apple orchards previously (Glover et al., 2000; Goh et al., 2001; Peck, 2009; Werner, 1997), but what distinguished our study from others was its comprehensive consideration of soil biological, chemical, and physical properties across three long-term systems approaches to orchard management. We looked beyond organic, integrated, and conventional fruit production and investigated other commercial orchard practices.

Determination of Soil Health Indicator Criteria

We tested 44 soil health properties in 2007, and we replicated 27 of those tests in 2008. We tested fewer parameters in 2008 because we reconsidered published soil health indicator criteria – such as relevance to soil processes and functions, consistency and reproducibility, cost constraints, and sensitivity to management (Gugino et al., 2007), as well as expert opinion (Andrews et al., 2002) – and we adapted these criteria for our sites. For example, a previous potted bioassay using soil from these sites produced variable results (St. Laurent et al., 2008), and we considered the difficulty of maintaining consistency and reproducibility of potted seedling studies from year to year. Thus, we did not re-measure the weed seed bank, root health, and the root:shoot ratio in 2008. We recognize that these measures may be important for sites having high weed or disease pressure, but we would suggest – instead of testing these in pots – that these be conducted *in situ*.

Earthworm count was another biological test eliminated after the first year. While Werner (1997) found differences in earthworm populations between conventional and transition-organic apple orchard soils, these differences were found using hand-sorting procedures. We employed the formalin method, which is

considered more accurate than hand-sorting (Raw, 1959), but because formalin is toxic and must be applied *in situ* – directly to field soil – we considered this an unsuitable procedure for repetition and broader grower application in an orchard MDS.

In the interest of parsimony, we did not repeat microbial biomass in 2008 because it has been correlated with soil respiration (Anderson and Domsch, 1990) and because previous studies of these soils have identified soil respiration as a consistent discriminator of GMS, IFP-OFP, and ARD treatments (Peck, 2009; Rumberger et al., 2004; Yao et al., 2005; Yao et al., 2006b). Also in the interest of parsimony, active C and cation exchange capacity were eliminated because these correlated with organic matter and other biological and chemical indicators (data not shown). We recognize, however, that where changes in management have been recently implemented, active C might be a better indicator of soil health because – as a measure of labile C – active C may change in the soil more rapidly that organic matter (Weil et al., 2003). Heavy metals were eliminated because of additional costs associated with analysis, and because total Pb and As were generally low at these sites. Laboratory penetration resistance at 10kPa, field surface and subsurface penetration resistance, field penetration depth, and water infiltration rate were eliminated because – across all three experimental sites – they failed to show sensitivity to management.

We recognize the role of inherent soil characteristics, climate and other regional factors, and cropping history and management in influencing soil health properties, and thus, in determining an orchard soil health MDS (Glover et al., 2000; Gugino et al., 2007; Werner, 1997). We support further testing of our MDS and adaptations of it that are site-specific. However, in the GMS, IFP-OFP, and ARD orchard sites, we believe that the tests we repeated in 2008 were pertinent to understanding treatment influences on soil health at these sites.

Applying Criteria to Soil Health Evaluations of Long-Term Sites

Bark mulch groundcover: The bark mulch groundcover in the GMS study and the IFP treatment improved soil health compared to other treatments at these sites. We observed enhanced soil respiration under bark mulch, and this is consistent with previous findings from these sites (Peck, 2009; Yao et al., 2005). Rom et al. (2008) similarly found soil respiration to be an important discriminator of tree-row groundcovers, with soil under wood chip mulch having higher respiration than soil under sod and other groundcovers. These previous findings and our results suggest that decomposing mulch is providing an energy source for microbial activity, which in turn, improves nutrient cycling and availability, and overall soil health.

Total N was also greater in soil under bark mulch groundcover in the GMS study and IFP treatment. Yao et al. (2005) previously explained the importance of bark mulch as an N source at the GMS site, annually contributing 0.63 tonnes $N \cdot ha^{-1}$. Additionally, N may be better retained in a bark mulch system because of the high C:N ratio of bark mulch (Yao et al., 2005) and because of the higher microbial biomass and activity supported by bark mulch cover (Tables 2.2 and 2.5). TerAvest et al. (in press) found apple roots growing up into wood chip groundcover during the growing season and concluded that the wood chips became a significant source of N as the growing season progressed.

There were no statistical differences in total soil N between IFP and OFP, but there was a trend for it to be greater in the IFP. While total soil N is an important indicator of overall soil N status, mineralizable N is the labile fraction of N that can be used by plants within a growing season (Drinkwater et al., 1996; Duxbury et al., 1991) and might be a more appropriate indicator for detecting short-term soil N fluctuations. The Cornell Soil Health Assessment Training Manual uses mineralizable N as a soil health indicator (Gugino et al., 2007), and we recognize its importance in quantifying

soil health, even if it did not differentiate our treatments. Peck (2009) previously detected higher mineralizable N in the OFP treatment of our site 10 months after chicken compost application. This suggests that chicken compost is a more labile source of N than bark mulch groundcover. However, since we did not observe differences in mineralizable N two and three years after chicken compost application, and because we observed total N and mineralizable N differences in the GMS, it appears bark mulch groundcover is a better long-term N management strategy than chicken compost. Given the challenges of nutrient management in both IFP and OFP systems (Chapter 3; Granatstein, 1994), bark mulch groundcover should be further researched in tree rows of conventional, integrated, and organic fruit production systems for its ability to improve nutrient availability, soil biological activity, and tree health over the long-term.

Fewer differences in soil physical properties were observed under the bark mulch, which is perplexing given higher soil organic matter (Tables 2.2 and 2.5) and the relationship between organic matter and soil structure, depth, and drainage (Magdoff, 2001). Lack of statistical differences could be due to data variability resulting from sampling procedures.

Cultivation: Cultivation is a common weed control strategy in organic apple production (Granatstein, 2004) but can have negative impacts on biological soil properties (Hoagland et al., 2008; Moreno et al., 2007; Peck, 2009; TerAvest et al., in press). Similar to these previous reports, we detected decreased biological soil health in the OFP, where cultivation occurred monthly during the growing season. The VAM spore count and organic matter were diminished in the OFP in 2007 – and soil respiration in both years – compared to the IFP. The difference in VAM spore count could have been influenced by bark mulch groundcover in the IFP – as suggested by Nappi et al. (1985), who found greater VAM spore count in vineyard soils covered in

bark mulch or sod – or it could have been influenced by cultivation – as the work of Sanchez et al. (2007) would suggest because of decreased soil food web diversity and lower soil organic matter in an organic apple orchard under cultivation weed management. Cultivation can decrease water availability, which can decrease microorganism abundance and activity (Williams and Rice, 2007), and seasonal differences in VAM spores (Purin et al, 2006) were likely the reason we observed a difference in 2007 – a warm, dry summer in the northeast – but not in 2008 – a mild, humid summer.

The root:shoot ratio was also reduced in the OFP in 2007, which relates to the results of TerAvest (in press), who found decreased new shoot growth on excavated trees when tree-row cultivation had occurred. Furthermore, the broadleaf weed seed bank was greater in the OFP in 2007, and plant-parasitic nematode count was higher in 2008. Granatstein (2004) noted that cultivation is often ineffectual in controlling weeds, making it a costly endeavor and contradictory to soil quality, and Neher (2001) explained that plant-parasitic nematodes are often enriched under cultivation. In regard to chemical and physical soil properties, TerAvest (in press) noted that available soil nutrients and water may be compromised under cultivation. Our data show few differences in available soil nutrients, which corresponds with previous results (Peck, 2009). However, we did observe lower total soil C in the OFP, which was likely – at least in part – due to the high C:N of the bark mulch in the IFP (Peck, 2009), and could also have been a result of soil de-aggregation and resulting C oxidization due to cultivation (Mitchell et al., 2008; Post and Kwon, 2000).

Living Cover Crops: Living cover crops in the tree-row have been studied for their effect on soil quality and orchard productivity, and leguminous mixes have been shown to increase total soil N, organic matter, and biological activity (Hoagland et al. 2008; Sanchez et al, 2007), even if they may decrease soil water availability (Merwin

et al., 1994). In the GMS site, we did not examine a leguminous cover, but rather, a mix of red fescue sod and native broadleaf weeds, including clover. Generally, soil properties did not differ among the SOD, POSTHERB, and PREHERB, and they were less-favorable than soil properties in the MUL. While a fescue cover has been shown to improve biological and chemical soil properties when mixed with alfalfa (*Medicago sativa*) (Sanchez et al., 2007), from our data of a mostly non-leguminous cover, we cannot recommend a living cover crop for improving soil health in the orchard tree-row.

Herbicide Tree-Row Maintenance: We did not observe diminished soil quality in the POSTHERB and PREHERB compared to the SOD, which is in contrast to the results observed by Moreno et al. (2009) and Yao et al. (2005), who found differences among pre-emergence herbicide treatments and other GMS. In olive, Moreno et al. (2009) found degraded soil quality, particularly biological quality, as a result of pre-emergent simazine and diuron compared to a mowed cover, and they also noted decreased N, P, and S availability as a result of the diminished microbial activity. Yao et al. (2005) previously found the fewest culturable bacteria in the PREHERB of our GMS site and suggested that the lack of weed root exudates reduced bacterial energy sources. This, however, did not translate into differences in soil respiration throughout the course of a six-week incubation, which was similar across PREHERB, POSTHERB, and SOD treatments. Our results similarly showed no differences in soil respiration among PREHERB, POSTHERB, and SOD after one week of incubation (Table 2.2) or over the course of an eight-week incubation (data not shown).

Similarly, our results suggest that post-emergent glyphosate is not hindering soil quality or tree productivity (Chapter 3) at the GMS site, even though glyphosate may diminish beneficial soil bacterial and fungal communities, and/or inhibit

phytoalexin synthesis, making plants more susceptible to soilborne pathogen infection (Kremer, 2009).

Pre-plant Compost or Fumigation: Our soil health investigation allowed us to observe the residual effects of pre-plant compost and fumigation on the replant problem and on soil properties six years after application. We know from our previous work at this site that bacterial and fungal fingerprints differed among PPST in the first year after planting, with populations in the COMP distinctly separating from those in the FUM (Rumberger et al., 2004; Yao et al., 2006b); however, these differences diminished by the second year. We also know that the PPST influenced nutrient availability in the first and second years, with the COMP generally having higher nutrient availability than the FUM (Leinfelder and Merwin, 2006). What we found through our soil health investigation corresponds with these previous findings: differences in soil biological properties have diminished with time since pre-plant applications, but differences in nutrient availability – particularly macronutrient availability – are still apparent. An exception to this was active C – a measure of the labile soil C that fuels the soil food web (Weil et al., 2003) – which differed among PPST in 2007. Using compost-amended soil from organic orchards, Weil et al. (2003) found that active C was an earlier indicator of changes in management compared to soil organic C – which is a measure of labile and humified C – and total soil C – which is a measure of organic and inorganic (carbonate) C. The Cornell Soil Health Assessment Training Manual also evaluates active C (Gugino et al., 2007). We only measured active C among our GMS, IFP-OFP, and ARD treatments in 2007, and we recognize that this was probably an oversight and should have measured it again in 2008 because it separated ARD PPST. Our data suggest that pre-plant compost could be beneficial for long-term nutrient availability and biological functioning in nutrient-limited soils.

Scoring Functions to Compare Soil Health Indicators to Commercial Orchard Database

The influence of the aforementioned management practices on soil health properties can be further assessed by comparing GMS, IFP-OFP, and ARD treatment effects (Tables 2.2-2.10) to upper and lower 25th percentile ranges of soil properties at NYS commercial orchards (Tables 2.11-2.13). We observed that bark mulch groundcover, cultivation weed management, and pre-plant compost improved soil health properties compared to commercial, conventional orchard soils. Biological properties that were improved by MUL in the GMS study – including bacterial-feeding nematodes, VAM spore count, organic matter, mineralizable N, and soil respiration – were within or exceeded the upper 25th percentile range for comparably silty soil. Available Ca, Mn, and Cu; pH; total N and C; microporosity; and available water capacity also met or exceeded the upper 25th percentile range for the MUL, and bulk density – which we would desire to be in the lower 25th percentile – was, indeed, in the lower range. Bark mulch in the IFP improved VAM spore count and soil respiration so that these were in the upper 25th percentile for silty soil, and cultivation in the OFP decreased VAM spore count such that it was in the lower 25th percentile for silty soil. Most chemical and physical properties were not affected by IFP-OFP, but of those that differed, all but macroporosity were in the middle, satisfactory range relative to commercial orchards. Macroporosity was in the lower 25th percentile range for both treatments, but high macroporosity is generally only desirable in clayey soils. In the ARD study, COMP improved VAM spore count, soil respiration, available P and Ca, pH, and total C in one or both years, such that these met or exceeded the upper 25th percentile range. Available Al decreased as a result of COMP, and available Al for the COMP was in the lower 25th percentile compared to commercial orchards.

While O'Neill et al. (2005) stated that "high" and "low" threshold values for soil health indicators are difficult to establish – due to the many factors in addition to management that influence soil quality, such as climate, topography, parent material, and soil age – they noted that thresholds may serve as a basis for understanding soil conditions. We believe these upper and lower percentile ranges are representative of NYS orchard soils that are silty or sandy because they were collected from the three commercial apple growing regions of the state, having different parent material and soil-forming factors. These soils also represented 20 grower-cooperators who had varying degrees of interest in orchard soil health. Comparing the Cornell soils to the NYS soils allowed us to observe the improvements that can be made to orchard soil health through biomass amendments. The next step to this work would be to refine the percentile ranges using a larger database of orchard soil information from NYS and the northeastern United States.

Determination of Orchard MDS

In a discriminant analysis, predictor variables are entered into the statistical model to determine which separate the treatments of interest. We used discriminant analysis to determine an orchard MDS because multivariate statistical approaches are robust to systems-based research where independent variables are often correlated (Drinkwater, 2002), and because discriminant analysis can differentiate treatments to find a parsimonious set of soil health indicators (Sánchez-Moreno et al., 2008). We considered parsimony an important outcome in the development of an orchard MDS, in order to augment grower acceptance and implementation of the MDS (Lobry de Bruyn and Abbey, 2003). We recognize that – in the interest of parsimony – we have eliminated indicators that would be important under other conditions, such as

mineralizable N and active C. We also recognize that growers may be interested in the ability of a MDS to predict orchard productivity, and hence, the predictive power of our MDS is described in Chapter 3.

Neher (2001) and Magdoff (2001) supported using fewer indicators to describe soil health. Neher (2001) advocated using plant-parasitic and free-living nematodes as indicators of soil health because they respond to land management and correlate with ecological processes, such as N cycling and residue decomposition. Based on the GMS, IFP-OFP, and ARD results, we could not suggest solely using nematode populations as predictors of soil health. Plant-parasitic nematodes were below the threshold level for apple – 140·100 cm^{-3} soil (Jaffee et al., 1982) – in all cases except the SOD in 2008 (Table 2.2). Only in the GMS study in 2007 did fungal-feeding and bacterial-feeding nematodes differ (Table 2.2), which would not implicate them as consistent discriminators of soil health at our study sites.

Magdoff (2001) championed organic matter as the most important soil health indicator because it correlates with plant-health-promoting organisms, nutrient availability, soil depth, and drainage; it can be augmented by management practices; and it aids in soil functionality, such as plant health, reduced inputs, and habitat conservation. Bark mulch groundcover was influential in augmenting soil health in the GMS study; and organic matter, total soil C, and bulk density best differentiated biological, chemical, and physical soil characteristics of the MUL. These properties were strongly correlated, which would be expected for a soil inherently low in carbonates (USDA-NRCS Web Soil Survey, 2010). Thus, only one indicator was needed to parsimoniously model the effect of the MUL, and that was total soil C. The enhancement of soil C as a metric of sustainable management in perennial systems was advocated by Deurer et al. (2008) and Morlat and Chaussod (2008). Deurer et al. (2008) found that soil C management accounted for up to 81% of the enhancement or

degradation in biological and physical soil properties in integrated and organic apple production. In one of the few comparable long-term, perennial fruit crop studies, Morlat and Chaussod (2008) found that – without biomass amendments like prunings, manure, or compost – total organic C declined, negatively impacting vineyard soil quality.

Bark mulch and cultivation in the IFP and OFP, respectively, were management practices that influenced VAM spore count and soil respiration. Biological organisms as indicators of soil health were championed by Doran and Zeiss (2000) because of their sensitivity to management and correlation with ecosystem functions, and VAM spores and soil respiration best separated IFP and OFP in our discriminant analyses. Other perennial crop studies have shown that mycorrhizae and microbial activity are enhanced by bark mulch (Nappi et al., 1985; Rom et al., 2008) and diminished by cultivation (Baumgartner et al., 2005; Moreno et al., 2009). For these reasons, we suggest that biological soil properties – like VAM spores and soil respiration – should be included in an orchard MDS.

The effects of the ARD PPST have diminished greatly in the years since planting, and this was reflected in the discriminant analyses. While, of the biological indicators, active C effectively discriminated the PPST in 2007, of the tests run in 2008, more biological indicators were needed to effectively discriminate the treatments. In both years, no combination of physical indicators resulted in a significant model that discriminated the PPST. The most descriptive soil health indicators at the ARD site were macronutrients. This is likely a result of the break-down of compost over time, and increased nutrient availability. The diminishing effect of compost on microbial diversity and activity (Yao et al., 2006b) probably also diminished the influence of soil biological properties on treatment separation.

Across GMS, IFP-OFP, and ARD studies, biological and chemical soil properties best discriminated long-term soil management practices. These management practices were separated by total soil C, VAM spore count, soil respiration, and macronutrients in parsimonious discriminant analyses. The long-term, on-going GMS treatments have resulted in obvious impact on soil health and definitive characterization of soil health based on soil C. Nevertheless, shorter-term treatments, as in the IFP-OFP and ARD studies, illustrate that other indicators, particularly biological indicators and available nutrients, should be considered in orchard soil health characterization.

Correlations among Soil Health Properties

The correlations among soil health indicators illustrate the interconnections of soil biological, chemical, and physical properties. In the GMS study, total soil C correlated with several biological, chemical, and physical soil properties, and it consistently correlated with organic matter, which gives credence to the point made by Magdoff (2001) that organic matter, alone, sufficiently indicates soil health.

Monthly tillage in the OFP degraded soil biological properties like VAM spore count and soil respiration. Because of the correlations among these indicators and other soil properties, this suggests that repeated cultivation harms biological soil health.

In the ARD study, PPST followed by five years of static management diminished biological complexity. Thus, Ca and P availability best indicated soil health differences, but these correlated with broader nutrient availability. All of these indicators, in a web of correlations, illustrate the complexity of orchard soil health in long-term management systems.

Conclusions

Soil biological, chemical, and physical properties can be enhanced by orchard management. The improvements to soil health made by the addition and maintenance of biomass amendments were observed when compared to scoring functions developed from NYS commercial orchard soils. A parsimonious set of soil health properties can discriminate orchard soils when management includes bark mulch groundcover, cultivation, or pre-plant compost, but the MDS identified by this study is not intended as a definition of soil health in orchard systems. We are not suggesting that orchard soil health is exclusively the augmentation of soil C, VAM spores, soil respiration, and macronutrient availability because these indicators were correlated with many other soil properties. Rather, these indicators can be used to illustrate trends in ecosystem functioning (O'Neill et al., 2005) because they were changed significantly by the long-term management practices employed at our GMS, IFP-OFP, and ARD sites. We view this MDS as a benchmark for further soil health exploration in orchards.

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Chapter 3

Relationship among Soil Health, Tree Growth, and Yield in Three Long-Term Apple Management Systems

Abstract

Groundcover management systems (GMS), integrated and organic fruit production (IFP-OFP), and rootstocks and pre-plant soil treatments (PPST) in an apple replant disease (ARD) site were examined for effect on apple (*Malus* X *domestica* Borkh.) growth and yield in three long-term studies in New York State (NYS). The treatments had limited effect on leaf nutrient status but influenced tree growth. Trees with bark mulch groundcover (MUL) had greater trunk cross-sectional area (TCSA) compared to sod (SOD), pre-emergence herbicide (PREHERB), and post-emergence herbicide (POSTHERB) treatments 16 and 17 years after treatment implementation. Cumulative yield (CY) did not differ among GMS in these years, but there was a trend for the MUL and POSTHERB to yield more than the SOD and PREHERB. Despite similar CY between the MUL and POSTHERB, soil health properties were improved in the MUL, and these properties correlated positively with TCSA and CY in simple linear and multiple regression analyses, respectively. In the IFP-OFP comparison study, TCSA did not differ between treatments, but CY was greater in the IFP than in the OFP starting in the third year. Soil biological properties were improved in the IFP compared to the OFP, where bark mulch and cultivation, respectively, were used for weed management. Soil biological properties correlated positively with CY in simple linear regression analyses. Pre-plant soil treatments in an ARD study did not influence TCSA or CY, but pre-plant compost (COMP) improved chemical soil health properties compared to fumigation treatment (FUM) and the control (CONT).

Chemical soil properties correlated positively with TCSA and CY when rootstock was used as a covariate. This work showed that the use of tree-row bark mulch or pre-plant compost improved soil health, tree growth, and/or yield in the long-term. Relationships among soil health properties and tree growth or yield demonstrate that orchard productivity and sustainability need not be mutually exclusive.

Introduction

Soil health is defined functionally as agricultural productivity, environmental awareness, and resource conservation (Doran and Parkin, 1994; Larson and Pierce, 1991). A healthy soil would fulfill these functions, in a given space and time (Doran and Parkin, 1996), based on its biological, chemical, and physical properties (Papendick and Parr, 1992). These properties are the result of inherent soil-forming factors, dynamic changes induced by land management and ecosystem interactions, and even socioeconomic and political priorities (Doran and Parkin, 1996). A minimum data set (MDS) is a selection of soil biological, chemical, and physical indicators used to describe soil health (Larson and Pierce, 1991). Generally-applicable selection criteria for soil health indicators in a MDS include measurability at a reasonable cost; sensitivity to changes in management practices; having good correlation with other more costly measures; and having quantifiable effects on crop health, yield, and/or environmental impact (Wolfe, 2006). A MDS may also be determined using multivariate statistics, where interactions from soil management are quantified for soil processes (Drinkwater, 2002).

In annual crop systems, management practices, soil health, and crop productivity have been linked. Abawi and Widmer (2000) characterized soil health as a reduction in pathogen and nematode pressure – a characterization supported by

others (Janvier et al., 2007; van Bruggen and Semenov, 2000) – and found that soil health and bean (*Phaseolus vulgaris*) yield improved when brewery compost application, rye/hairy vetch (*Secale cereale*/*Vicia villosa*) cover cropping, or rotations out of bean were employed. Mitchell et al. (2008) observed higher tomato (*Solanum lycopersicum*) yields under conservation tillage, which reduced the number of passes through the field by 50% compared to standard tillage practices. Total and respirable in-field dust concentrations were reduced under conservation tillage, and it was supposed that this was a result of increased soil aggregation and organic matter.

Linking management, soil health, and crop productivity has not often been attempted in perennial agricultural systems, despite correlations between specific chemical, physical, and biological soil properties and crop performance. For example, Melakeberhan and Jones (1992) surveyed sweet cherry (*Prunus avium*) orchards under varying soil management and discovered tree decline and reduced productivity resulting from low pH and consequent macronutrient deficiencies and aluminum toxicity. Fernandez et al. (1995) found that apple root distribution and depth were hindered by a compacted fragipan layer, which in turn affected scion yield.

Glover et al. (2000) endeavored to find correlations among orchard management, soil health, and yield in OFP, IFP, and conventional fruit production systems. While positive correlations existed between OFP and IFP and soil health – compared to conventional management – yield was similar across management regimes. They concluded that pruning and thinning influenced yield more than soil health. Werner (1997) and Goh et al. (2001) investigated soil health in OFP, IFP, and conventional apple production systems but did not report yield in their findings.

Sparling et al. (2004) called the lack of knowledge relating soil health and crop production a "research gap" and suggested that researchers work in a direction to close that gap. Crop production is an important function of soil (Lal, 1993), and economic

farm viability is an important consideration of growers (Doran, 2002; Romig et al., 1996). In grower interviews, Lobry de Bruyn and Abbey (2003) found that crop yield was growers' top priority and that their attention to soil health was contingent upon relationships between productivity and sustainability. They cited the adage, "it's hard to be green when you're in the red". In forest systems where soil health has been integrated into ecosystem inventory and health assessments, O'Neill et al. (2005) advocated for statistical relationships linking soil quality and vegetation characteristics.

The other limitation of previous orchard soil health research is that it focused on OFP, IFP, and conventional fruit production (Glover et al., 2000; Goh et al, 2001; Werner, 1997). Investigation of other systems has been needed, and our work has done that, investigating soil health not only in OFP and IFP, but also among four GMS and two PPST in an ARD site (Chapter 2).

The standard GMS in apple orchards worldwide is an herbicide strip within the tree rows and sod-planted alleyways (Merwin, 2003). The sprayed tree rows decrease crop competition for water and nutrients; however, with concerns over nutrient and sediment loss, the standard, herbicide-dependent regime has come under question, leading scientists to study alternative groundcovers like mulches and cover crops (Rom et al., 2008; Sánchez et al., 2007; Sanchez et al., 2003).

Apple replant disease is a disease complex resulting from the successive planting of apple trees into the same soil, and there is a natural link between ARD and soil health. Early characterization of ARD came from Savory (1966), who used the German term "Bodenmüdigkeit," or "soil sickness," to describe the apparent restoration of vigor when trees were transferred from replant soil to fresh soil. McKenry (1999) described the problem as "not a result of poor root condition per se, but something in the soil around those roots". He described various physical,

chemical, and biological soil conditions as contributors to the problem and suggested an integrated approach to soil management – including fallowing, rootstock selection, supplemental nutrition, chemical fumigation, and alternatives to chemical fumigation – to overcome the problem.

With this as background, we set out to better understand how soil health – as influenced by management – may be used to predict apple orchard productivity. The objectives of our work were to 1) understand the influence of GMS, IFP-OFP, and ARD treatments on leaf nutrients, tree growth and yield; and 2) establish linkages among orchard management, soil health, and productivity.

As described in Chapter 2, we used multivariate statistics to determine which soil health indicators best differentiated treatments in our three orchard systems. In this chapter, we have modeled orchard growth and yield based on these indicators, integrating systems-based and factorial analytical approaches (Drinkwater, 2002). We recognize that comparing soil health indicators to growth and yield deconstructs systems in order to find a cause-effect relationship that might be more complex, but the integration of systems-based and factorial analyses could help in understanding short and long-term changes in soils (Drinkwater, 2002). We also recognize that validating soil health on the basis of yield alone may be inappropriate in orchards or other perennial systems (Glover et al., 2000). Crop production is just one function of soil that may be used to evaluate soil health (Doran, 2002). Additionally, healthy soils function to reduce input costs, buffer crops from disease, recover after flooding or drought, and fulfill ecosystem services such as nutrient cycling and carbon storage. In Chapter IV, we discuss validating soil health on the basis of carbon storage.

Materials and Methods

This project coincided with a 2-yr, in-depth investigation of orchard soil health using three long-term experimental sites at the Cornell Orchards in Ithaca and Lansing, NY. In Chapter 2, we described the methods for determining biological, chemical, and physical indicators of soil health, which led us to consider a subset of properties as potential orchard soil health indicators (Table 3.1).

Orchard Sites and Treatments

Groundcover Management Systems Study

The GMS study was established in 1992 on the east shore of Cayuga Lake, near Ithaca, NY. The 0.8 ha, moderately-sloped site is a Hudson-Cayuga silt loam (mixed, mesic, Glosaquic Hapludalf). Land preparation began in Apr. 1991 with the removal of 15-yr-old trees, and organic matter content at that time was between 4.7 – 5.3%. The land was limed, deep-tilled, seeded with creeping red fescue turfgrass (*Festuca rubra*), and installed with subsoil drainage. In Apr. 1992, apple trees ('Royal Empire' on 'M.9'/'MM.111' rootstock) were planted at 3 x 6 m spacing among 12 plots. Each 20-tree plot was 9 m wide across the slope and 25 m long down-slope. Four tree rows ran across the slope, each separated by 4 m of grass drive lanes. The GMS were applied down the tree row in a 2-m band. The experimental design was a Completely Randomized Design having three replicated plots of the four GMS, where GMS was a fixed effect and plot was a random effect. The GMS were as follows: 1) Pre-emergence, residual herbicides norflurazon, and diuron, tank-mixed at 3.0 and 2.5 kg a.i.•treated ha^{-1}, respectively, annually applied in mid-May, and paraquat (1992-1998), tank-mixed at 0.5 kg a.i.•treated ha^{-1} or glyphosate (1999-present) at 2.0 kg

Table 3.1: Biological, chemical, and physical soil properties evaluated in a soil health study of GMS, IFP-OFP, and ARD sites. Methods were as follows: nematode community analysis and vesicular arbuscular mycorrhizae spores (Jenkins, 1964), all chemical tests and organic matter by standard methods (Burt, 2004), mineralizable nitrogen (Drinkwater et al., 1996), soil respiration (Alef, 1998; Rodella and Saboya, 1999), and all physical tests (Gugino et al., 2007; Moebius-Clune et al., 2008).

Biological	Chemical	Physical
Plant-parasitic nematodes	Phosphorus (P), available	Bulk Density
Fungal-feeding nematodes	Potassium (K), available	Macroporosity
Bacterial-feeding nematodes	Magnesium (Mg), available	Mesoporosity
Predatory nematodes	Calcium (Ca), available	Microporosity
Vesicular arbuscular mycorrhizae spores	Iron (Fe), available	Available water capacity
Organic matter	Aluminum (Al), available	Wet aggregate stability
Mineralizable nitrogen	Manganese (Mn), available	
Soil respiration	Zinc (Zn), available	
	Copper (Cu), available	
	Nitrate-N (NO_3^-), available	
	pH	
	Nitrogen (N), total	
	Carbon (C), total	
	Arsenic (As), total	
	Lead (Pb), total	

a.i.•treated ha^{-1}, annually applied in mid-July (PREHERB); 2) Post-emergence herbicide glyphosate applied annually at 2.0 kg a.i.•treated ha^{-1} in mid-May and July (POSTHERB); 3) Red fescue (*F. rubra*) turfgrass originally seeded in 1991, now a mixture of about 25 herbaceous grass and broadleaf species, mowed monthly during the growing season (SOD); and 4) Shredded, hardwood bark mulch (a mixture of *Acer*, *Quercus*, *Juglans*, *Fraxinus*, and *Tilia* spp.), 15 cm thick, first applied in May 1992, and reapplied in May of 1995, 1998, 2000, 2002, and 2005 (MUL). Glyphosate was used to suppress emergent weeds in the mulch treatment. All plots were similarly fertilized. In mid-Apr. 1992, 1993, and 1994, ammonium-nitrate fertilizer was applied on the soil surface in the tree row at rates 30, 45, and 65 kg N•ha^{-1}, respectively. Annual spring urea and micronutrient foliar sprays were applied at petal fall according to the Pest Management Guidelines for Commercial Tree-Fruit Production (Agnello et al., 2007).

Integrated and Organic Fruit Production Study

The IFP-OFP comparison study was located on a 0.4 hectare site at the Cornell Orchards in Ithaca, NY. The orchard ('Liberty' on 'M.9' rootstock) was planted at 1.5 m x 4.3 m spacing in Apr. 1994 and was under conventional insect and disease management until 2004, when IFP, as defined by Carroll and Robinson (2006), and OFP treatments, as defined by the United States Department of Agriculture National Organic Program (USDA-NOP), were initiated. The soil is characterized as Hudson and Collamer silt loams (mixed, mesic, Glosaquic Hapludalf) and had about 3% organic matter and a pH of 6.4 at the commencement of the experiment. The two treatments were replicated over four blocks in a Randomized Complete Block Design, where treatment was a fixed effect and block was a random effect. Each 64-tree plot consisted of four adjacent tree rows of 16 trees. The IFP and OFP differed in their

disease and pest management, fertilization, thinning, and soil management. Disease and pest management, fertilization, and thinning were described in detail by Peck (2009). Composted hardwood bark mulch was applied to the IFP tree rows in Nov. 2005 as 1-m-wide bands. This was the source of nitrogen by slow mineralization in the initial years of the experiment. The OFP plots received chicken manure compost in Oct. 2005 at a rate of 697 kg fresh wt•ha^{-1}, equivalent to 78 kg N•ha^{-1}. In the six years prior to this study, only glyphosate was used for weed control at this site. The mulch and an annual, June post-emergent glyphosate application (2.9 kg a.i.•ha^{-1}) were used to control weeds in the IFP. Weeds in the OFP were cultivated monthly during the growing season using a tractor-mounted Wonder Weeder (Harris Manufacturing, Burbank, WA) mechanical cultivator.

Apple Replant Disease Study

The ARD study was also located on a 0.4 ha site at the Cornell Orchards in Ithaca, NY. The soil is a glacial lacustrine Hudson silty clay loam (mixed, mesic Udic Hapludalf), slightly-sloped and with limited subsoil drainage. Originally planted to apple around the year 1910, the site was first replanted in 1981 but failed in its establishment, showing many common ARD symptoms (Mai et al., 1994). It was replanted again in 2001; orchard removal, site preparation, and experimental design were described by Leinfelder and Merwin (2006).

The factors of interest were three PPST and two rootstocks in a Randomized Complete Block Design, with the PPST and rootstock genotypes as fixed effects, randomized among five blocks. Telone C-17 (Dow AgroSciences, Indianapolis, Ind.) was the pre-plant soil fumigant and is a formulation of the nematicide 1,3 dichloropropene (78% v/v) and the broad-spectrum biocide chloropicrin (17% v/v). It was shank injected in Oct. 2001, to a depth of 25 cm at a rate of 400 L•treated ha^{-1},

and the soil was immediately sealed with a cultipacker. As an alternative to soil fumigation, a compost made of 40% (v/v) ground leaves and wood chips, 40% supermarket vegetable culls, and 20% pre-composted cattle and horse manure in wood shavings (Toad Hollow Farm, Nedrow, NY) was applied in Sept. 2001. The compost was applied in two portions – the first surface applied at 492 kg•treated ha^{-1} and then incorporated with a moldboard plow to a depth of 25 cm. The second portion was applied at the same rate but only rototilled into the upper 10 cm of soil. The macronutrient content of the compost was determined by the Cornell Nutrient Analysis Laboratory (CNAL), and to compensate for indirect fertilization effects of the compost, non-composted plots were treated with a mineral fertilizer (22N-4P-0K) at a rate of 318 kg•treated ha^{-1}. Aside from pre-plant lime and N–P–K, little subsequent fertilizer was applied. Two nitrogen applications were made to all plots in May 2003 after poor tree growth in the first year – soil-applied ammonium nitrate (34N–0P–0K) at 18.7 kg•ha^{-1} and foliar-applied calcium nitrate (15.5N–0P–0K–19Ca) at 17.1 kg•ha^{-1}. Spring urea and micronutrient foliar sprays were applied annually at petal fall.

The rootstocks of interest were ‘M.26’ – an industry-standard, dwarfing rootstock (40% of expected tree size on seedling rootstock) from the East Malling Experiment Station in England, and ‘CG.6210’ – a semi-dwarfing rootstock (60% of expected tree size on seedling rootstock) from the Cornell-Geneva breeding program. These rootstocks were of interest in our soil health study because ‘CG.6210’ previously showed ARD tolerance and ‘M.26’ ARD susceptibility (Leinfelder and Merwin, 2006), and we wished to learn more about soil health/rootstock interactions. The rootstocks were grafted with ‘Royal Empire’ and planted at 2.1 m x 4.9 m spacing in Nov. 2001. Composted hardwood bark mulch was applied in a 1-m-wide strip to all of the tree rows after planting in 2002 but was not subsequently reapplied. The drive

lanes were maintained with a mowed red fescue sod cover. Weeds in the tree rows were controlled by post-emergence glyphosate at the labeled rate (2.9 kg a.i.•ha^{-1}) in May and July, annually.

Orchard Management and Performance Assessments

Trees were managed by typical commercial orchard practices for NYS. Pathogens and insect pests were sprayed according to the Pest Management Guidelines for Commercial Tree-Fruit Production (Agnello et al., 2007), and the OFP according to the USDA-NOP standards. Trees were chemically-thinned with appropriate formulations, and the OFP was additionally hand-thinned in June to one fruit per cluster. Drip and microsprinkler irrigation was used during dry periods of the summer and before soil sampling if a rain event had not recently occurred. Trees were pruned annually in winter to a modified vertical axe, using minimal pruning.

Leaf nutrition, growth, and yield data were collected annually. Leaves were sampled in July from mature leaves of the current season's growth (Stiles and Reid, 1991). Because leaf washing does not appreciably affect leaf nutrient concentrations (Stiles and Reid, 1991), only IFP-OFP leaves were washed, in order to remove kaolin clay residues – used for insect pest management – from the OFP leaves. The CNAL determined macro and micronutrients by inductively coupled argon plasma (ICP) spectrophotometry, and total C and N by Dumas combustion. Tree size was measured as trunk circumference in the GMS and IFP-OFP studies and by trunk caliper in the ARD study. Measurements were taken on each tree at 45 cm above the ground during the dormant season and then calculated into an average trunk cross-sectional area (TCSA) per treatment-plot. Fruit were harvested in early October as number and

weight of fruit per tree. Cumulative yield (CY) was calculated as the sum total weight of fruit per tree over the course of the study.

Statistical Analyses

All statistical analyses were performed using JMP® 8.0 Statistical Software (SAS Institute, Inc., Cary, NC). A mixed model was used to detect differences in leaf nutrients, TCSA, and CY across GMS, IFP-OFP, and ARD treatments. Tukey means separation procedures were used for the GMS and ARD PPST, and Student *t* procedures were used for the IFP-OFP and ARD rootstocks. Simple and multiple linear regression were used to compare soil indicators with leaf nutrients, TCSA, and CY. Plot and block were used as random covariates in GMS and IFP-OFP regression analyses, respectively. Block and rootstock were used as random and fixed covariates, respectively, in ARD regression analyses. Data were transformed as necessary to meet assumptions for normal distribution of residuals and homogeneity of variances. Significance was inferred at $\alpha = 0.05$, unless otherwise denoted.

Results

Treatment Effects on Leaf Nutrient Status

Leaf Ca differed among GMS in 2007, and leaf C, N, Mn, and Al differed among GMS in 2008 (Table 3.2). In 2007, leaf Ca was higher in the MUL than in the POSTHERB. In 2008, total leaf C was higher in the POSTHERB than in the other three GMS, and total leaf N was higher in the POSTHERB than in the SOD. Leaf Mn

Table 3.2: Leaf nutrients by GMS in 2007 and 2008. Means followed by different letters were statistically different according to Tukey mean separation procedures ($P \leq 0.05$). Available Ca was Box Cox transformed for analysis in 2007. Data that were transformed for analysis were back-transformed for presentation.

Year	GMS	C (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	B (ppm)	Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)	Al (ppm)
2007	MUL	45.91	2.12	0.16	1.07	1.58 a	0.34	26.1	32.9	6.5	37.7	47.5	46.1
	SOD	46.23	2.06	0.15	1.03	1.50 ab	0.35	25.0	31.0	6.2	41.2	45.4	45.0
	POSTHERB	46.90	2.14	0.15	0.93	1.28 b	0.35	26.0	29.9	6.5	49.2	42.4	45.9
	PREHERB	46.92	2.21	0.14	1.02	1.30 ab	0.33	26.7	31.4	5.9	46.8	46.2	49.2
	SE	0.30	0.08	0.01	0.05	0.07	0.00	1.8	3.5	0.2	4.8	2.0	2.4
	P value	0.13	0.64	0.29	0.36	0.03	0.30	0.92	0.91	0.26	0.37	0.38	0.66
2008	MUL	46.53 b	2.14 ab	0.15	1.32	1.02	0.29	32.2	13.2	6.2	19.0 b	38.3	50.9 ab
	SOD	46.35 b	2.01 b	0.14	1.30	0.94	0.30	30.9	12.7	6.2	21.9 ab	42.9	57.7 a
	POSTHERB	47.02 a	2.23 a	0.15	1.33	0.93	0.32	32.9	13.7	6.5	25.9 a	38.6	47.9 b
	PREHERB	46.40 b	2.05 ab	0.14	1.37	0.92	0.31	31.3	11.8	6.4	26.7 a	37.5	48.3 b
	SE	0.06	0.04	0.01	0.04	0.05	0.01	1.0	1.0	0.1	1.4	1.5	1.9
	P value	0.0002	0.02	0.38	0.67	0.47	0.28	0.48	0.58	0.41	0.01	0.13	0.02

Table 3.3: Leaf nutrients by IFP-OFP in 2007 and 2008. Means followed by different letters were statistically different according to Student *t* mean separation procedures ($P \leq 0.05$). Available Al was ln transformed for analysis in 2007. Data that were transformed for analysis were back-transformed for presentation.

Year	Treatment	C (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	B (ppm)	Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)	Al (ppm)
2007	IFP	46.10	1.83	0.24	1.23	1.25	0.28	28.9	27.3 a	6.4	19.7	48.3 b	37.8 b
	OFP	45.60	1.80	0.23	1.39	1.38	0.29	26.7	34.7 b	7.5	18.9	66.7 a	508.9 a
	SE	0.30	0.10	0.01	0.05	0.07	0.00	1.5	1.4	0.5	0.9	2.1	22.4
	P value	0.21	0.90	0.58	0.07	0.20	0.05	0.14	0.01	0.09	0.54	0.0009	< 0.0001
2008	IFP	45.91 a	1.50	0.21	1.28 b	1.02	0.23	31.3	17.9 b	5.4 b	17.9	34.4	25.3 b
	OFP	44.72 b	1.41	0.19	1.44 a	1.11	0.23	30.5	28.7 a	6.2 a	18.1	37.1	207.5 a
	SE	0.30	0.10	0.01	0.04	0.04	0.01	0.5	1.1	0.2	0.9	2.1	11.4
	P value	0.03	0.40	0.33	0.03	0.14	0.89	0.25	0.0003	0.02	0.85	0.18	0.0005

was higher in the PREHERB and POSTHERB compared to the MUL, and leaf Al was higher in the SOD compared to the POSTHERB and PREHERB.

In the IFP-OFP study, treatment differences were observed in leaf Zn, Fe, and Al in 2007, and in 2008, leaf C, K, Zn, Cu, and Al differed (Table 3.3). In both years, there was higher leaf Al in the OFP than in the IFP. In 2007, there was higher leaf Fe in the OFP compared to the IFP. Leaf Zn was higher in the IFP than the OFP, but the reverse was true in 2008. Also in 2008, leaf K, Cu, and Zn were higher in the OFP compared to the IFP. Total leaf C was higher in the IFP.

Only leaf Mn and Mg differed among ARD PPST; although, several nutrients differed between the rootstocks (Table 3.4). In 2007, only leaf Mn differed among PPST, with the CONT and FUM having higher leaf Mn than the COMP. Trees on rootstock 'CG.6210' had higher leaf K and Cu than trees on rootstock 'M.26', but the reverse was true for leaf Mg, Mn, and N. In 2008, leaf Mn and Mg differed among PPST, with leaf Mn higher in the CONT and FUM than in the COMP, and with leaf Mg higher in the CONT compared to the COMP. Between the rootstocks, 'CG.6210' had higher leaf P, K, and Cu, but 'M.26' had higher Mg and Mn.

Treatment Effects on Tree Growth

Treatments effects on growth, expressed as trunk cross-sectional area (TCSA), were observed in the GMS study (Fig. 3.1). Differences in TCSA were observed infrequently in the first 10 years of this study but were more consistent starting in 2002. In 1992, TCSA was greater among trees in the POSTHERB and PREHERB than among trees in the SOD. The trees in the MUL had a TCSA that did not differ from the other treatments. In 1993, the TCSA for the POSTHERB was, again, the largest and different from the TCSA of the SOD trees, but not different from the MUL

Table 3.4: Leaf nutrients by ARD PPST and rootstock in 2007 and 2008. Means followed by different letters were statistically different according to Tukey mean separation procedures ($P \leq 0.05$). In 2007, available Mg, Ca, and Mn were ln transformed for analysis; in 2008, available Mn was ln transformed. Data that were transformed for analysis were back-transformed for presentation

Year	Treatment	C (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	B (ppm)	Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)	Al (ppm)
2007	COMP	46.30	2.10	0.34	1.09	1.60	0.31	23.4	19.3	6.1	36.7 b	87.4	58.9
	FUM	46.20	2.10	0.39	1.19	1.45	0.34	25.6	18.3	6.2	47.6 a	64.1	50.8
	CONT	46.40	2.00	0.39	1.11	1.47	0.35	24.9	20.0	5.6	48.9 a	60.0	48.6
	SE	0.20	0.10	0.04	0.05	0.07	0.02	1.2	1.0	0.3	3.4	15.8	8.1
	P value	0.61	0.37	0.50	0.18	0.23	0.16	0.35	0.49	0.09	0.01	0.60	0.31
	CG.6210	46.20	2.00 b	0.40	1.19 a	1.49	0.28 b	23.4	19.3	6.4 a	25.7 b	58.8	46.4
	M.26	46.50	2.10 a	0.34	1.07 b	1.53	0.39 a	25.9	19.2	5.6 b	63.1 a	82.2	59.1
	SE	0.10	0.10	0.02	0.04	0.07	0.01	0.9	0.8	0.2	2.8	13.1	6.5
	P value	0.19	0.02	0.09	0.02	0.83	<0.0001	0.06	9.95	0.0041	<0.0001	0.11	0.17
2008	COMP	46.10	2.10	0.44	1.23	1.45	0.32 b	31.7	14.7	6.1	30.8 b	46.2	30.5
	FUM	46.30	2.30	0.42	1.16	1.34	0.33 ab	30.0	13.8	5.8	41.3 a	47.5	31.6
	CONT	45.90	2.10	0.51	1.24	1.45	0.35 a	31.3	13.8	5.6	42.3 a	43.0	28.4
	SE	0.20	0.10	0.03	0.04	0.05	0.01	1.1	0.7	0.2	2.2	1.5	1.5
	P value	0.16	0.08	0.12	0.28	0.29	0.01	0.39	0.62	0.23	0.0012	0.12	0.15
	CG.6210	45.90	2.20	0.53 a	1.26 a	1.44	0.28 b	31.0	13.7	6.2 a	20.4 b	44.0	31.2
	M.26	46.30	2.20	0.38 b	1.16 b	1.38	0.38 a	31.1	14.5	5.5 b	55.8 a	47.1	29.1
	SE	0.20	0.04	0.03	0.04	0.05	0.01	1.0	0.6	0.2	2.0	1.2	0.9
	P value	0.08	0.80	0.00	0.03	0.34	<0.0001	0.91	0.39	0.0015	<0.0001	0.08	0.15

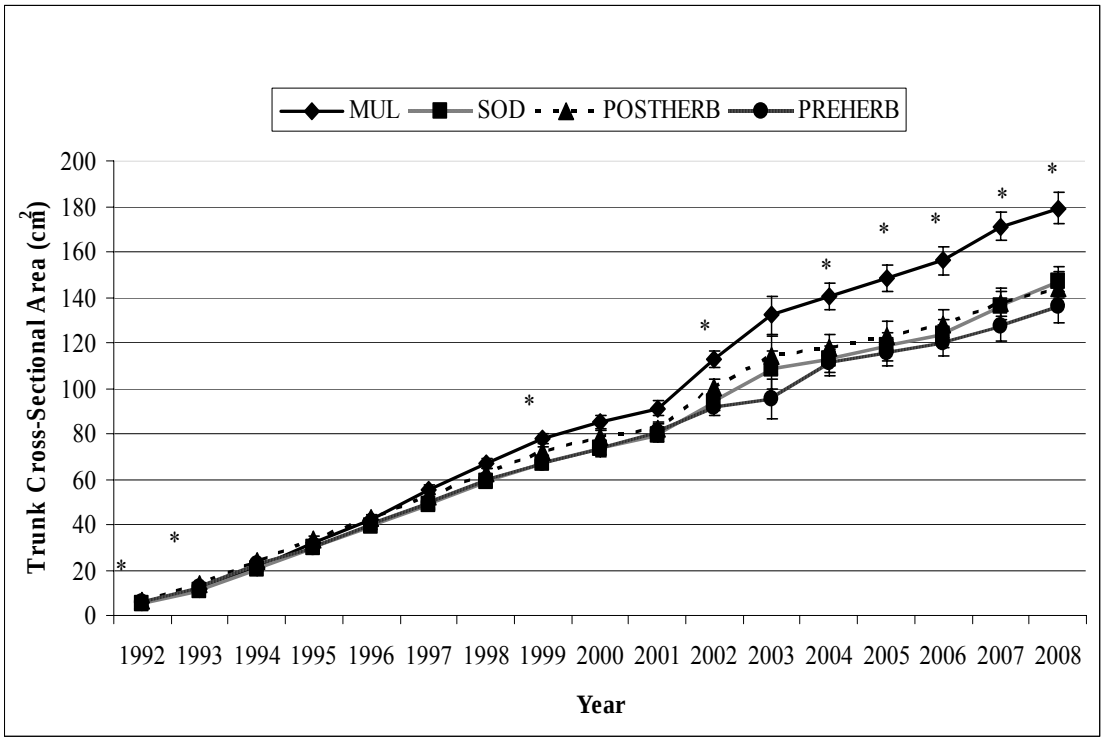

Figure 3.1: Trunk cross-sectional area, averaged per tree, across GMS treatments. Significant differences within each year were inferred by Tukey means separation procedures ($\alpha = 0.05$) and are denoted by asterisks. Error bars are standard errors of the means. Response data from 2008 were Box Cox transformed for analysis but were back-transformed for presentation.

or PREHERB trees. The TCSA of trees in the MUL exceeded the TCSA of trees in the PREHERB and SOD in 1999, but it did not differ from the TCSA of trees in the POSTHERB. The same was true in years 2002, 2004, 2005, and 2006. In 2007 and 2008, the TCSA of trees in the MUL was larger than the TCSA of trees in the other three treatments.

There were no differences in TCSA between IFP and OFP (Fig. 3.2), as reported for previous years by Peck (2009). There was a trend for OFP trees to be larger than the IFP trees, even if not statistically different.

In the ARD study, there were no statistical differences in TCSA among the PPST, but there were differences between rootstocks (Fig. 3.3). Trees on rootstock 'CG.6210' were larger than trees on 'M.26' from 2002 through 2008. By 2008, trees on 'M.26' were only 40% of the size of trees on 'CG.6210'. We would expect trees on 'M.26' to be 66% of the size of trees on 'CG.6210', given previously mentioned size ratios.

Treatment Effects on Yield

Differences in cumulative yield (CY) were inferred at $\alpha = 0.1$ in order to better visualize long-term trends. In the GMS study (Fig. 3.4), differences occurred in 1994 through 1996 and in 1999 through 2003. In 1994, the MUL and POSTHERB had higher CY than the PREHERB and SOD. In 1995 and 1996, the MUL and POSTHERB differed from the SOD, but the PREHERB did not differ from any treatments. In 1999 through 2003, we observed higher CY in the POSTHERB than in the SOD, with the MUL and PREHERB having CY in between, but not different from, the POSTHERB and SOD. While statistical differences were not inferred in

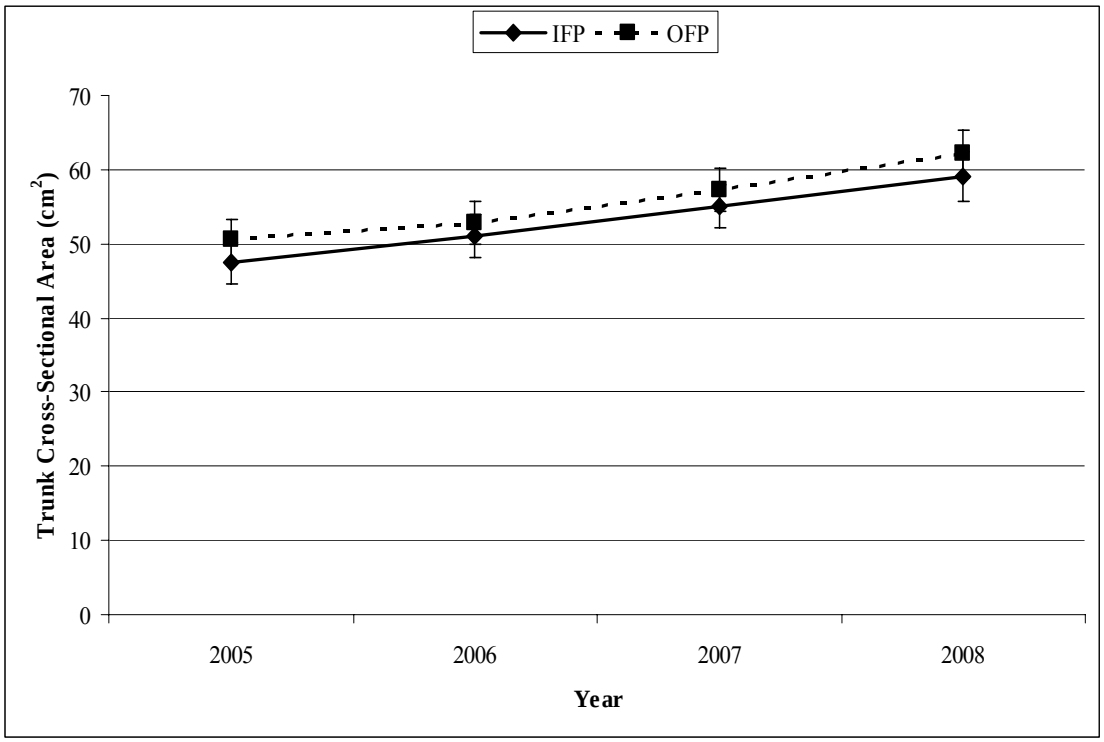

Figure 3.2: Trunk cross-sectional area, averaged per tree, across IFP-OFP treatments. No significant differences were inferred by Student *t* means separation procedures ($\alpha = 0.05$). Error bars are standard errors of the means.

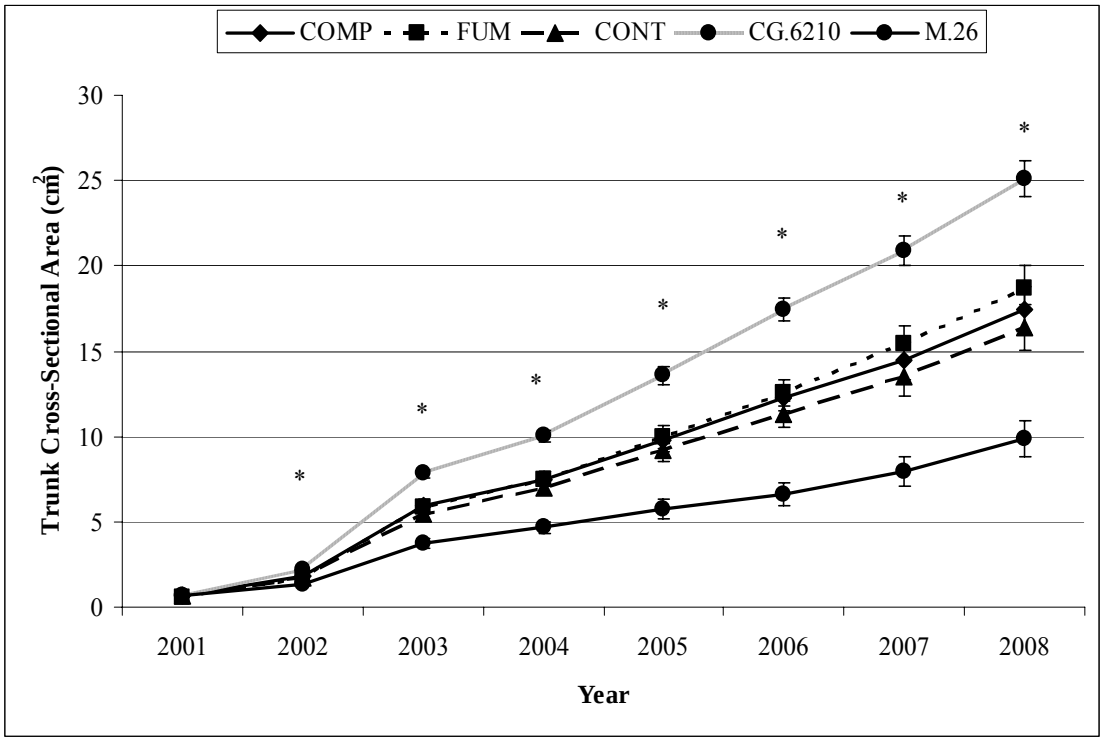

Figure 3.3: Trunk cross-sectional area, averaged per tree, across ARD treatments. No significant differences were inferred among pre-plant soil treatments by Tukey means separation procedures ($\alpha = 0.05$). Differences between rootstocks within years were inferred by Student *t* means separation procedures and are denoted by asterisks. Error bars are standard errors of the means.

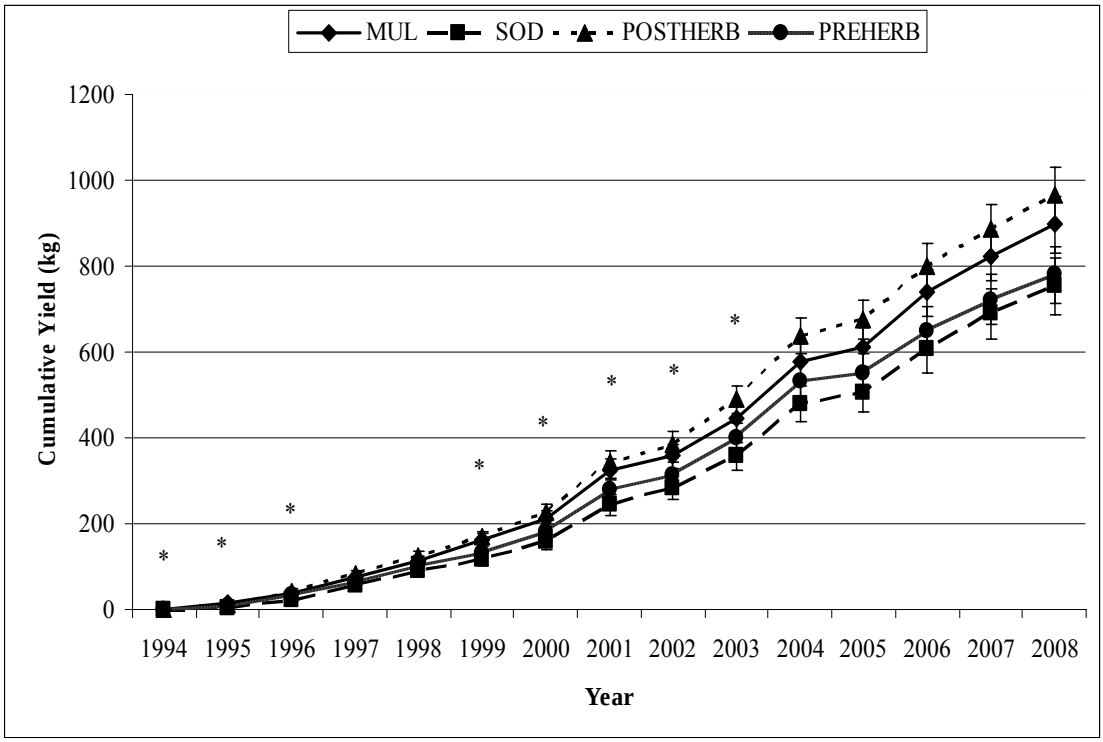

Figure 3.4: Cumulative yield, averaged per tree, across GMS treatments. Significant differences within years were inferred by Tukey means separation procedures (α = 0.10) and are denoted by asterisks. Error bars are standard errors of the means. Response data from 1994 were ln transformed, and data from 1997, 1999, 2001, 2002, and 2003 were reciprocal transformed. Data that were transformed for analysis were back-transformed for presentation.

years after 2003, the MUL began clustering with the POSTHERB, and the PREHERB began clustering with the SOD.

Differences in CY were observed in the IFP-OFP study in three of the four years (Fig. 3.5). The OFP yielded more than the IFP in 2005, but the IFP yielded more in 2007 and 2008.

In the ARD study, there were no differences in CY among PPST, but there were differences between rootstocks (Fig. 3.6). From 2005-2008, trees on rootstock 'CG.6210' yielded more than trees on 'M.26'.

Soil Health Indicator Correlations with Leaf Nutrients, Tree Growth, and Yield

Of the soil properties considered to be potential orchard soil health indicators (Table 3.1), certain of them differentiated GMS, IFP-OFP, and ARD management practices, and in Chapter 2, we reported the indicators most important for monitoring changes in orchard soil health. Treatment separation of those indicators is summarized for the GMS, IFP-OFP, and ARD studies (Table 3.5).

Soil health indicators did not correlate with leaf nutrients, but they did correlate with tree growth and yield to varying degrees among the GMS, IFP-OFP, and ARD studies when significance was inferred at $\alpha = 0.10$. Correlations between soil health indicators and TCSA or CY were examined if the TCSA or CY differed statistically among management treatments.

Groundcover Management Systems Study

In the GMS study, relationships existed between total soil C and TCSA. Total soil C correlated positively with TCSA in both 2007 and 2008 (Fig. 3.7).

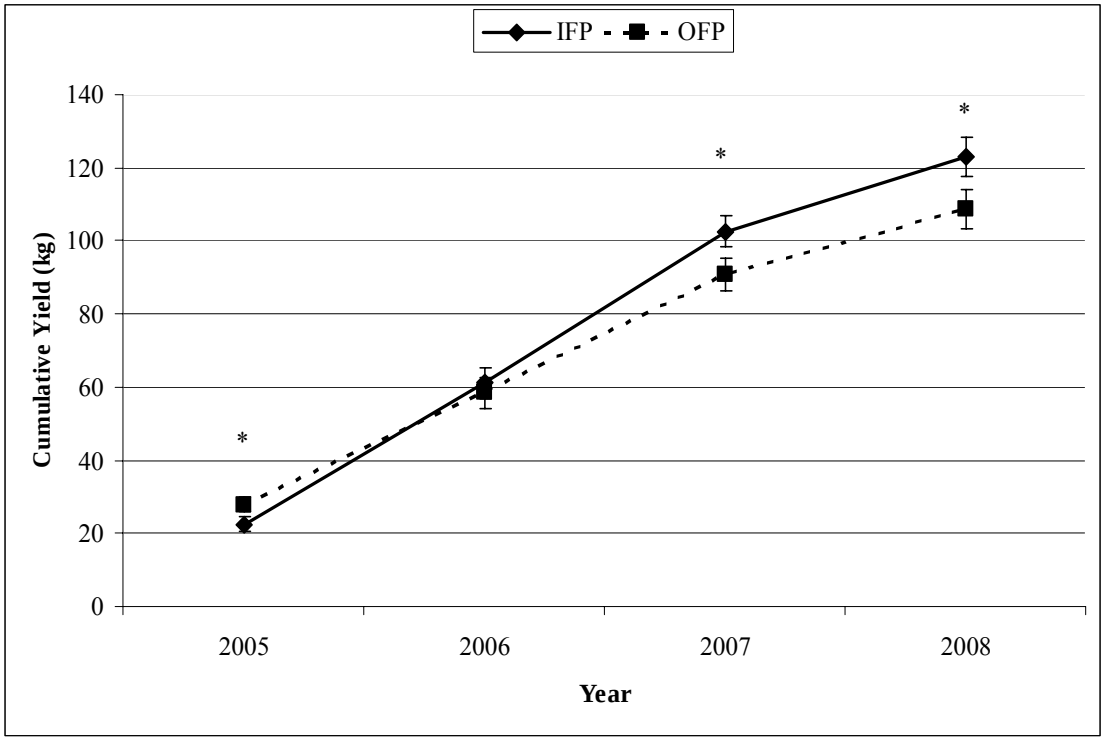

Figure 3.5: Cumulative yield, averaged per tree, across IFP and OFP treatments. Significant differences within years were inferred by Student *t* means separation procedures ($\alpha = 0.10$) and are denoted by asterisks. Error bars are standard errors of the means.

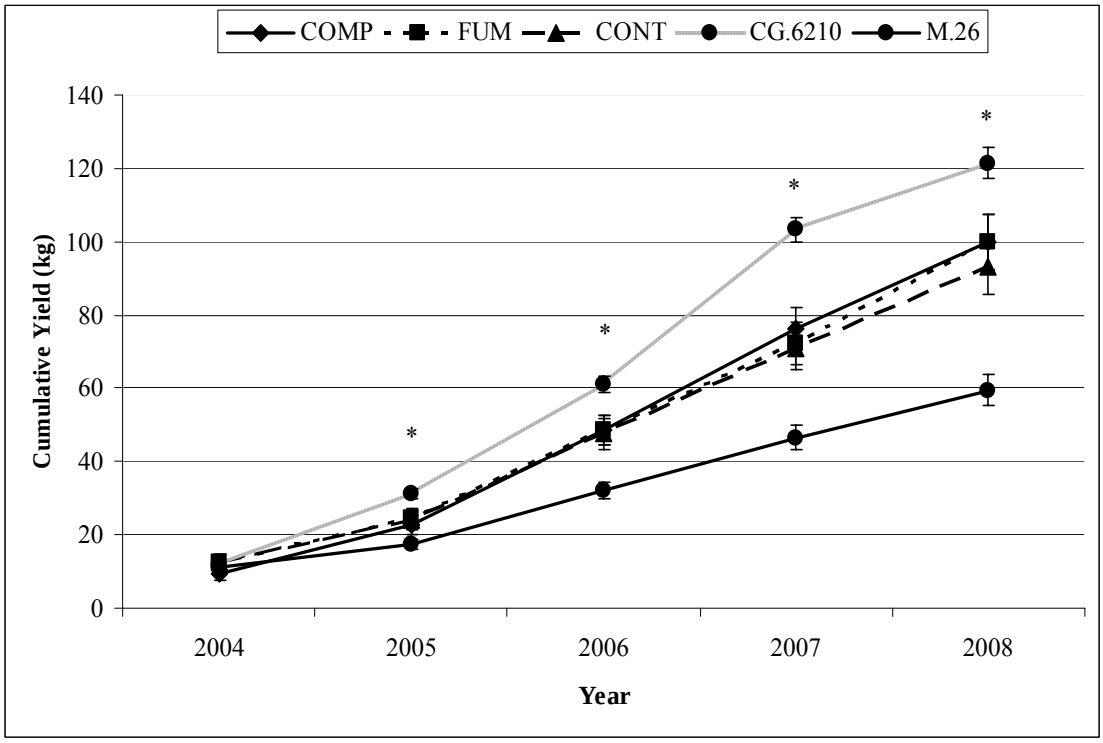

Figure 3.6: Cumulative yield, averaged per tree, across ARD treatments. No significant differences among pre-plant soil treatments were inferred by Tukey means separation procedures ($\alpha = 0.05$). Differences between rootstocks within years were inferred by Student *t* means separation procedures and are denoted by asterisks. Error bars are standard errors of the means.

Table 3.5: Tukey and Student *t* mean separation of soil health indicators that differentiated treatments in three long-term management studies. Means followed by different letters were statistically different. Vesicular arbuscular mycorrhizae (VAM) spore count was ln(x+1) transformed for analysis, and available Ca was ln transformed for analysis. Data that were transformed for analysis were back-transformed for presentation.

	2007	2008
GMS:		
Soil Indicators	Total C (%)	Total C (%)
MUL	5.6 a	4.5 a
SOD	2.0 b	1.7 b
POSTHERB	1.6 b	1.6 b
PREHERB	1.6 b	1.4 b
SE	0.2	0.2
P value	< 0.0001	< 0.0001
IFP-OFP:		
Soil Indicators	VAM Spores‡	Soil Respiration#
IFP	520 a	0.94 a
OFP	26 b	0.62 b
SE	81	0.04
P value	0.0021	0.0021
ARD:		
Soil Indicators	Available Ca^	Available P^
COMP	2015.3 a	9.9 a
FUM	1065.1 b	3.8 b
CONT	1034.4 b	3.7 b
SE	126.9	0.4
P value	< 0.0001	< 0.0001

‡ expressed as #•100 cm^3 $soil^{-1}$

† expressed as cm^3 pore space•cm^3 $soil^{-1}$

expressed as mg CO_2•g dry $soil^{-1}$

^ expressed as mg•kg $soil^{-1}$

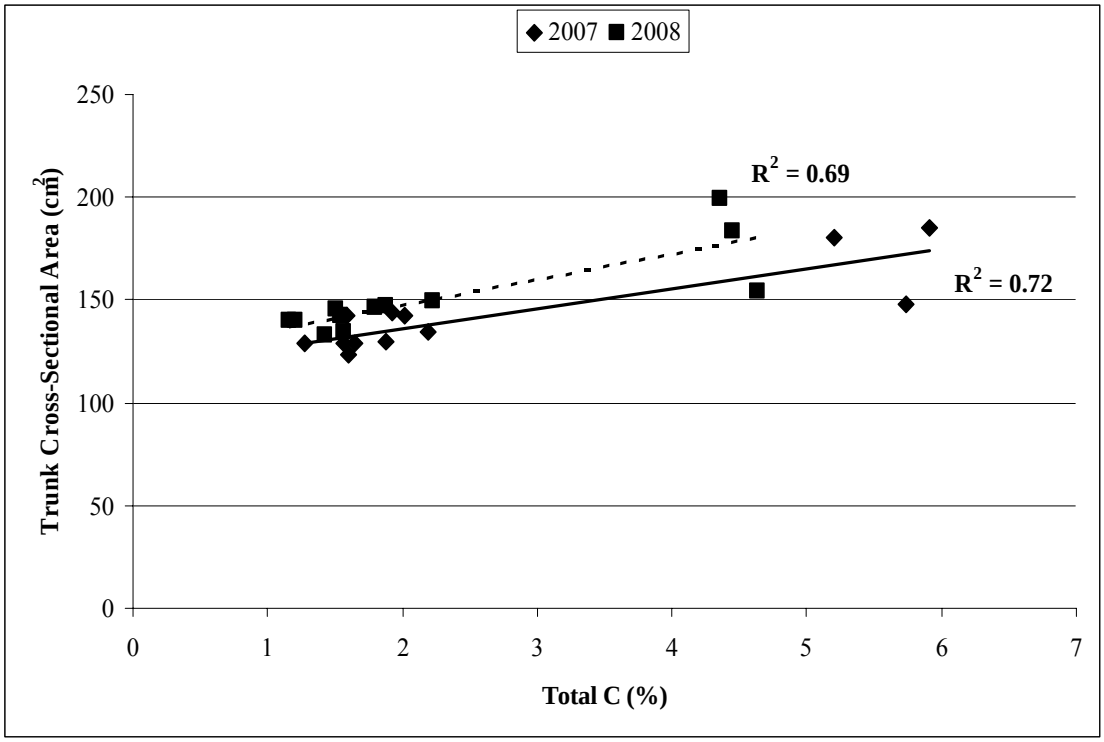

Figure 3.7: Regression correlations between total soil C and trunk cross-sectional area in a GMS study in 2007 (P = 0.0005) and 2008 (P = 0.0009).

While there were no relationships between total soil C and CY using simple linear regression, combinations of soil health indicators (Table 3.1) in multiple regression models correlated with CY. In 2007, total soil C ($P = 0.0003$), available P ($P = 0.0130$), mineralizable N (NMin, $P = 0.0014$), pH ($P = 0.0003$), and macroporosity (MCP, $P = 0.0143$) predicted CY with an adjusted $R^2 = 0.87$ and equation:

$CY = -279(C) + 86(P) + 46(NMin) + 629(pH) + 4498(MCP) – 3079.$

In 2008, organic matter (OM, $P < 0.0001$), bacterial-feeding nematodes (BFN, $P = 0.0005$), available K ($P = 0.0009$), available Al ($P = 0.0002$), pH ($P = 0.0001$), mesoporosity (MSP, $P = 0.0008$), and wet aggregate stability (WAS, $P < 0.0001$) modeled CY with an adjusted $R^2 = 0.98$ and equation:

$CY = -246(OM) + 4(BFN) + 3(K) + 131(Al) + 2017(pH) – 6242(MSP) + 43(WAS) - 14680.$

Integrated and Organic Fruit Production Study

In the IFP-OFP study, soil health indicators correlated with CY. In 2007, VAM spore count correlated positively with CY (Fig. 3.8), and soil respiration correlated positively with CY in 2008 (Fig. 3.9).

Apple Replant Disease Study

With rootstock as a covariate ($P < 0.0001$), available soil Ca ($P = 0.0149$) correlated positively with TCSA in 2007, with adjusted $R^2 = 0.90$ (Fig. 3.10). In a multiple regression model, rootstock ($P < 0.0001$), available soil Ca ($P = 0.0036$), and bacterial-feeding nematodes (BFN, $P = 0.0005$) predicted CY with adjusted $R^2 = 0.88$ and equation:

$CY = 26(CG.6210) – 26(M.26) + 0.014(Ca) + 0.297(BFN) + 42.$

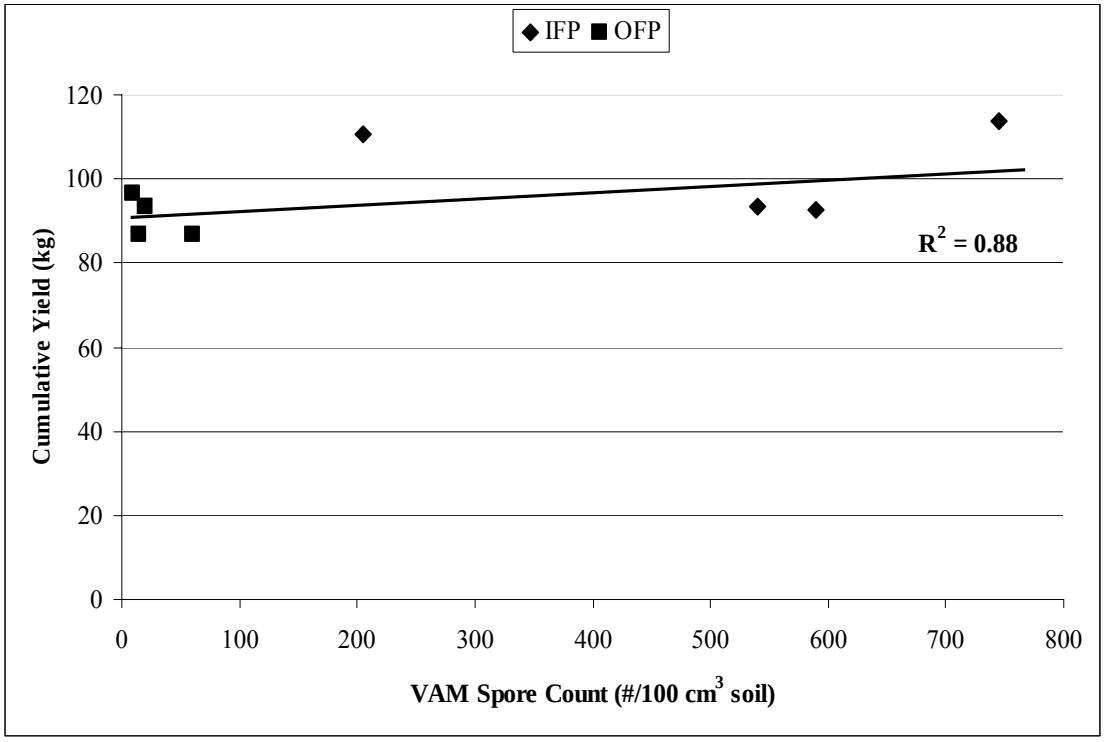

Figure 3.8: Regression correlation between vesicular arbuscular mycorrhizae (VAM) spore count and cumulative yield (P = 0.0648) in an IFP-OFP study in 2007. Block was a significant, random covariate in the analysis, but blocks were pooled for presentation.

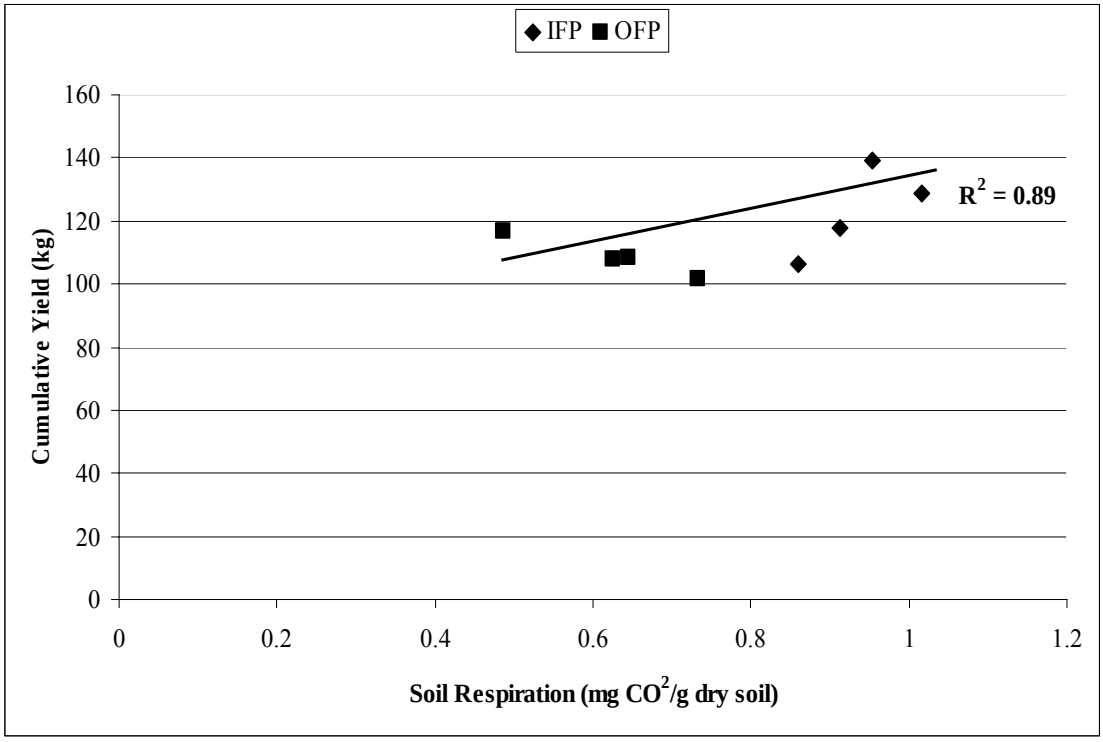

Figure 3.9: Regression correlation between soil respiration after one week of incubation and cumulative yield (P = 0.0357) in an IFP-OFP study in 2008. Block was a significant, random covariate in the analysis, but blocks were pooled for presentation.

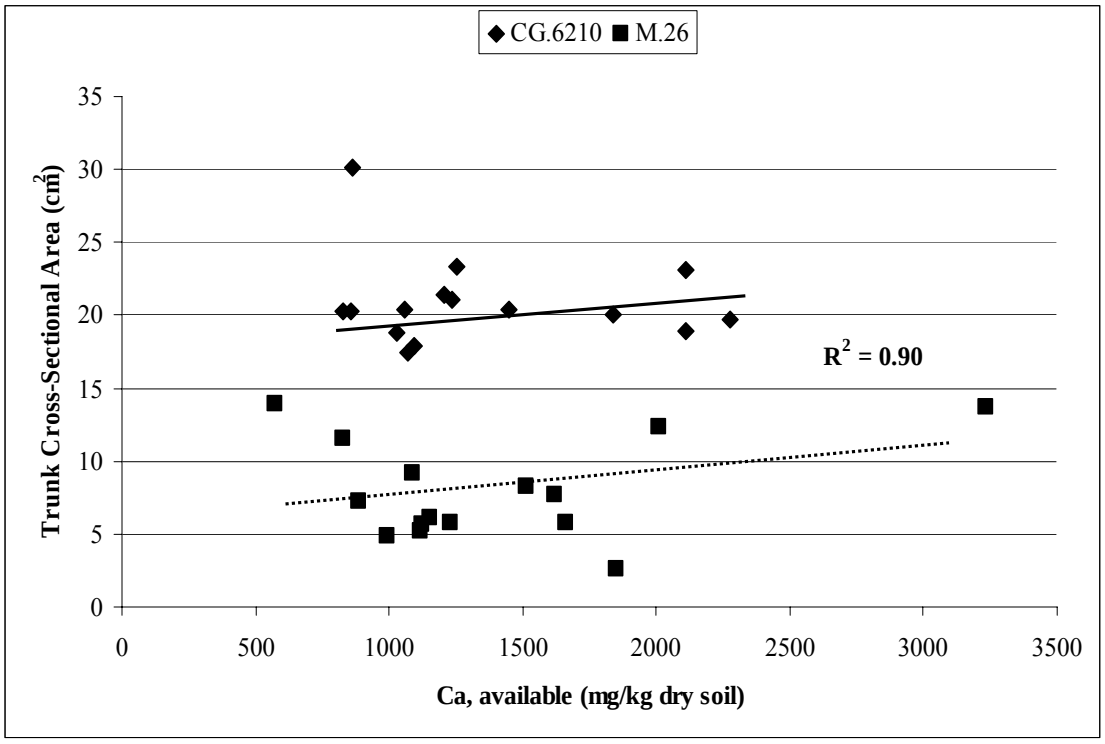

Figure 3.10: Regression correlation between available soil Ca and trunk cross-sectional area (P = 0.0149) in an ARD study in 2007. Rootstock was a significant covariate (P < 0.0001).

In 2008, rootstock ($P < 0.0001$), available soil P ($P = 0.0218$) and BFN ($P = 0.0140$) predicted TCSA in a multiple regression model, having an adjusted $R^2 = 0.89$ and an equation:

TCSA = 7(CG.6210) – 7(M.26) + 0.43(P) – 0.06(BFN) + 16.

Rootstock ($P < 0.0001$) and available soil P ($P = 0.0277$) modeled CY with an adjusted $R^2 = 0.84$ (Fig. 3.11).

Discussion

Treatment Effects on Leaf Nutrient Status

Many factors influence leaf nutrient status in apple trees, including variety, rootstock, tree spacing, and tree size, among others. Leaves are local sources of nutrients, and leaf nutrients reflect year-to-year variation in soil supply, climate, and crop load (Neilsen and Neilsen, 2003). Leaf nutrients were not consistently influenced by GMS. We observed that leaf nitrogen (N) differed among GMS in 2008, with the lowest leaf N in the SOD. Tworkoski and Glenn (2001) similarly saw reduced leaf N in peach when tree-row grass cover was compared to herbicide treatments. Nevertheless, since leaf N was within the recommended range for mature apple trees for all GMS treatments (Stiles and Reid, 1991), we conclude that tree-row groundcovers can be used in mature orchards without having a negative influence on leaf N status. Leaf K, Ca, Mg, B, Zn, Cu, Mn, and Fe were marginally-low in both years; however, there were no apparent deficiencies in the orchard. Because there were few treatment differences, and since observed differences were not consistent from year to year, it appears that other management and climatic factors were more influential on leaf nutrient status than soil nutrient availability in the orchard.

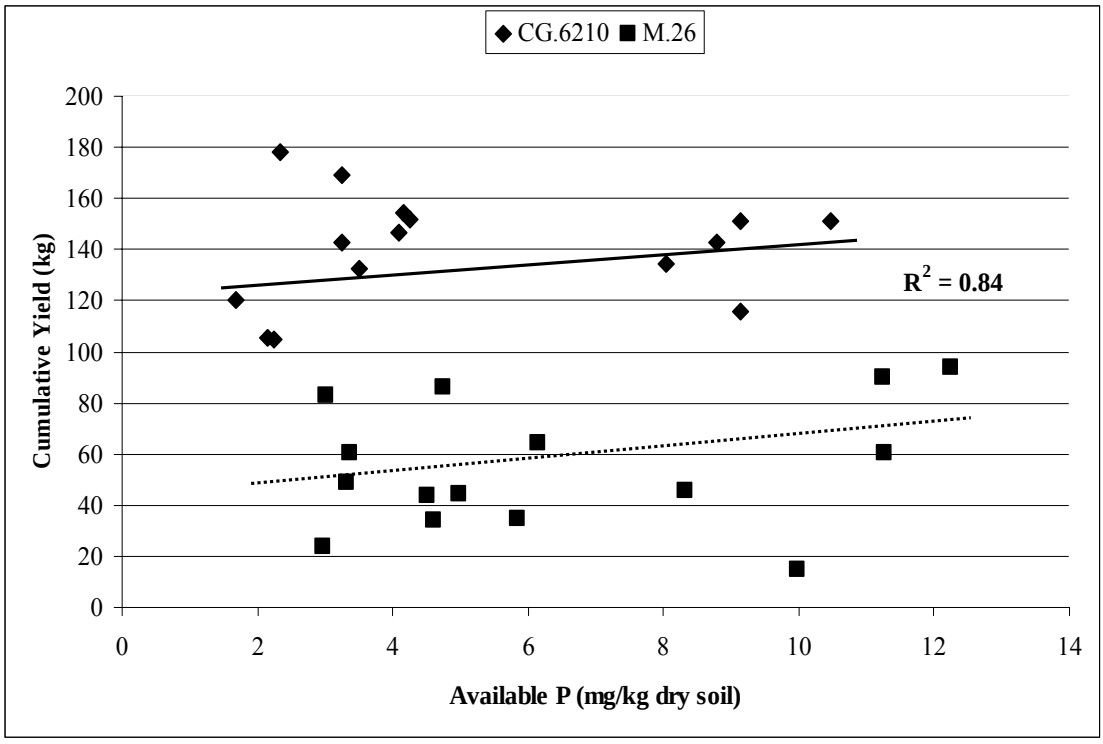

Figure 3.11: Regression correlation between available soil P and cumulative yield (P = 0.0277) in an ARD study in 2008. Rootstock was a significant covariate (P < 0.0001).

Leaf nutrients were low in the IFP-OFP experiment compared to recommended ranges. Leaf K, Ca, Mg, B, Zn, Cu, Mn, and Fe were marginally-deficient in both years; though, trees showed no deficiency symptoms for these nutrients in the orchard. We did, however, observe leaf yellowing and early leaf drop in both years. Peck (2009) reported these symptoms in previous years of this study and stated that leaf yellowing and drop were most severe in the IFP. He suggested that either an epiphytic yeast (*Aureobasidium pullulans*) became pathogenic or that ozone damage was occurring, and lime sulfur and kaolin clay, respectively, prevented damage from these in the OFP. Our data showed that leaf N was low in both treatments; and therefore, we suggest that these symptoms could also be the result of overall low N status. Leaf N was within the recommended range in 2007 but was at the low-end of the range for a mature orchard, and leaf N was deficient in 2008. Guak et al. (2001) observed that early leaf drop in apple resulted in decreased N reserves and poor shoot growth the following season, and Cheng and Fuchigami (2002) observed that N reserves were more important than spring N fertilization of apple, with 50% of N reserves being remobilized for growth in the spring. Peck (2009) reported moderately-low leaf N in previous years of this study, and more years of these treatments have demonstrated increasing difficulty managing N in both IFP and OFP. While low leaf N could be the result of weed competition in the tree row (Peck, 2009), especially in OFP where weed management is a key production challenge (Granatstein, 1994), because we saw deficiency in both treatments in 2008, and because we were attentive to N fertilization, it appears that low N reserves – compounding over the years – is contributing to N deficiency in both our IFP and OFP. Fertility management was cited by Granatstein (1994) as a key challenge in OFP systems, and he recommended that research was needed to understand nutrient management in OFP. Our data support this recommendation. Furthermore, we believe that fertility management needs to be better

understood for IFP, especially when biomass amendments – such as bark mulch – are used as slow-release fertilizers.

In addition to low leaf N in both treatments, leaf Al was high in the OFP in both years. We attribute this to the use of kaolin clay, an aluminum silicate, in OFP insect pest management. While leaf Al was high, we did not observe Al toxicity in the orchard, which resembles P deficiency (dark green or purple leaves) or Ca deficiency (leaf curling) (Foy et al., 1978). However, kaolin clay is repeatedly applied at high rates (approximately 30 $kg \cdot ha^{-1}$) during the growing season in organic orchards, and this amount of Al addition to orchards could eventually result in high soil Al and plant toxicity.

There were few differences in leaf nutrients among PPST in the ARD study, despite higher soil macronutrient availability in the COMP (Chapter 2). Leaf N was sufficient in all treatments in both years. Leaf K, Mg, B, Zn, Cu, and Mn were moderately-low compared to recommended levels, and leaf P was moderately-high. Nevertheless, trees showed no signs of deficiency or toxicity in the orchard.

There were more statistical differences among leaf nutrients between rootstocks 'CG.6210' and 'M.26', which illustrates the role of rootstock in nutrient uptake and partitioning. Previous rhizotron work at this site investigated the PPST and rootstocks for influence on root lifespan and distribution and found no PPST effect but a dominant influence of rootstock genotype, with 'CG.6210' roots having the longest lifespan and deepest distribution among the rootstocks (Yao et al., 2006a). The larger root system of 'CG.6210' reflected larger annual growth and overall tree size for this rootstock (Leinfelder and Merwin, 2006). Nutrient reserves in the larger tree structure and broader root system range of 'CG.6210' may interplay with seasonal climate and crop load conditions to result in the differentiated leaf nutrient availability we observed between 'CG.6210' and 'M.26'.

Treatment Effects on Tree Growth

Groundcover Management Systems Study

A broad array of tree-row GMS have been investigated in apple, ranging from bark and paper mulches, composts, cover crops, plastics, and weedy or weed-free strips (Hoagland et al., 2008; Merwin and Stiles, 1994; Merwin et al., 1994; Mika et al., 1998; Neilsen et al., 2003; Rom et al., 2008; TerAvest et al., in press). What made our investigation unique was its longevity. While many studies have reported findings in the establishment years of orchards, we have presented 17 years of data. In the first two years after planting, the vegetation-free, herbicide treatments reduced competition for water and nutrients, and trees in the PREHERB and POSTHERB were larger than trees in the SOD. Hoagland et al. (2008) also observed reduced apple tree growth during the establishment years when living groundcovers were used. During establishment, low-density apple roots must compete with fibrous grass roots for water and nutrients (Neilsen and Neilsen, 2003). Alternatively, Rom et al. (2008) showed that wood chip mulch improved tree growth compared to a sod treatment, and our data show similar trends. Trees in MUL outgrew trees in SOD during tree establishment, and over the long-term, tree growth in the MUL surpassed that of all other treatments.

The substantial influence of MUL on tree growth at this site may have several explanations. Yao et al. (2009) previously reported more roots at the 0-20 cm depth among MUL trees at this study site. Root proliferation coupled with enhanced soil organic matter, water and nutrient availability, and biological activity (Chapter 2; Yao et al., 2005) likely contributed to larger tree size. The bark mulch used at this site was previously reported as having a high C:N ratio of 98:1, and was credited with substantial N retention in the system (Yao et al., 2005). The break-down of the mulch by microorganisms – and the high soil organic matter and nutrient availability –

presumably enhanced tree growth during the growing season. We would also suggest that larger size of the MUL trees (Fig. 3.1) means greater nutrient reserves in the permanent scaffold, which would improve early spring growth before microbial activity resumes from the winter.

Integrated and Organic Fruit Production Comparison

The IFP-OFP study commenced 10 years into the life of the orchard, which prior to this experiment had been under conventional management. Many IFP and OFP studies have compared these systems from planting (Glover et al., 2000; Peck et al., 2006; Reganold et al., 2001), and Peck et al. (2006) and Reganold et al. (2001) reported that TCSA did not differ between IFP and OFP in the first few years of tree establishment. We also saw no treatment differences in TCSA when IFP and OFP were implemented in a mature orchard, despite changes to soil biological properties that occurred during this time (Chapter 2; Peck, 2009). We conclude that when IFP and OFP are implemented in a mature orchard, they will not affect tree size differentially under otherwise healthy conditions. With time, if the low N status previously described is not corrected, or if changes to soil biological traits continue to differentiate the treatments, variation in tree size may be observed.

Apple Replant Disease Study

Leinfelder and Merwin (2006) previously reported the influence of rootstock on tree growth at this site and the lack of difference made by pre-plant compost or fumigation on TCSA. This occurred despite concurrent, enhanced nutrient availability and soil respiration in the COMP (Yao et al., 2006b), and despite the improvement pre-plant compost (Granatstein and Mazzola, 2001) and fumigation (McKenry, 1999) made in previous replant studies. Forshey and Elving (1989) called rootstock genetics

the dominant management influence over the apportionment of dry matter in apple, and replicated rootstock trials have suggested that inherent rootstock traits overshadow site factors in influencing apple tree growth (NC-140 Committee, 1987).

We continued to observe no TCSA differences among PPST six and seven years after planting at this site, even while nutrient availability and soil respiration continued to be higher in the COMP (Chapter 2). We also continued to observe drastic differences in TCSA and yields between rootstocks. This further illustrates the decoupling of soil characteristics and tree performance at this replant site and the importance of rootstock selection in the establishment and continued growth of apple trees in replant sites.

Treatment Effects on Yield

Groundcover Management Systems Study

We analyzed yield cumulatively (CY) in order to illustrate the long-term impacts of these treatments on orchard productivity. Analyzing yield on a per tree or yield efficiency basis distracted from the long-term trends because of biennial bearing peaks and troughs.

Throughout the GMS study, there was a trend for trees in the POSTHERB to have the highest CY, and it was often significantly higher than that for trees in the SOD. There was also a trend for trees in the MUL to yield similarly to trees in the POSTHERB. Remembering that the POSTHERB and MUL trees had the largest TCSA (Fig. 3.1), our data show that the largest trees also had the highest CY (Fig. 3.4). These trees grew well in the establishment years, and like Merwin and Stiles (1994), we would suggest that the reduction in weed pressure and water and nutrient competition, compared to the SOD, allowed for improved early growth in the

POSTHERB and MUL. In addition, this early growth likely contributed to sustained productivity throughout the longevity of the orchard. Given similar yield trends for the POSTHERB and MUL – yet better soil health in the MUL – it appears that MUL is a productive and environmentally-sustainable tree-row groundcover in orchards.

Integrated and Organic Fruit Production Comparison

One year after IFP and OFP treatments commenced, yield was highest in the OFP, but this reversed by the third and fourth years of fruiting under these systems. This differs from observations made by Glover et al. (2000) and Reganold et al. (2001), where IFP and OFP yielded the same in the first year of fruiting and then again in the third and fourth years. By the fifth year of fruiting, Reganold et al. (2001) saw yield differences, with the IFP out-yielding the OFP.

Factors such as pest, disease, and horticultural management have been cited as important research topics for IFP and OFP (Granatstein, 2004; Sansavini, 1997), and we recognize the role these factors had in our study (Peck, 2009). Nonetheless, we also suggest that soil management was influencing orchard productivity at this site. With clear differences in soil health by the third and fourth years of these systems – with the IFP having significantly more soil biological activity (Chapter 2) – we conclude that the bark mulch groundcover in the IFP and cultivation weed management in the OFP were affecting soil health and CY. Under the bark mulch of the IFP, soil respiration was significantly higher in both the third and fourth years of fruiting (Chapter 2). This corresponds with results previously seen at this site (Peck, 2009). Nutrient availability showed year-to-year variability (Chapter 2; Peck, 2009), but when differences were observed, nutrient availability was usually higher in the IFP. In contrast, cultivation can negatively influence nutrient availability by compromising soil organic matter (Merwin et al., 1994; Mitchell et al., 2008), and

with more years of cultivation, we would suspect reduced nutrient availability in the OFP, which is already under N stress. Cultivation could also be damaging roots in the OFP. As distant sinks, photosynthate partitioning is greatly reduced to the roots during the growing season (Forshey and Elving, 1989) – the season when cultivation was occurring on a monthly basis. In addition, root damage from cultivation has been suggested to increase soilborne disease susceptibility in orchards (Oliveria et al., 1981). We suspect that these consequences of bark mulch and cultivation management practices on biological and chemical soil characteristics contributed to the shift in CY in favor of the IFP in the third and fourth years of this study.

Apple Replant Disease Study

Fumigation has, traditionally, been a successful means of improving early yield in replant sites (Mai and Abawi, 1981; McKenry, 1999; Smith, 1994). Less is known about the role of pre-plant compost in improving early yield in replant sites, but when compost was surface-applied in a tree-row band in a high-density apple planting, Neilsen et al. (2003) found CY to increase, compared to a glyphosate-treated control. Despite higher nutrient availability in COMP (Chapter 2), we did not see differences in CY among PPST six and seven years after treatment, which corresponds with previous findings from this site (Leinfelder and Merwin, 2006). Therefore, based on our results, we would not be able to recommend pre-plant compost or fumigation as reliable solutions for improving CY in a replant site.

Rather, rootstock continued to be the dominant factor in determining CY at this site, corresponding with previous studies evaluating the ‘CG.6210’ and ‘M.26’ rootstocks (Isutsa and Merwin, 2000; Robinson et al., 1996; Robinson et al., 2002). While we would expect ‘CG.6210’ to yield more than ‘M.26’ based on its inherently higher vigor (Robinson et al., 2002), when vigor was accounted for in yield efficiency

calculations (Marini et al., 2002) (data not shown), 'CG.6210' still out-yielded 'M.26'. Furthermore, in the next section, we discuss the positive interaction of 'CG.6210' with soil macronutrient availability in predicting CY.

Soil Health Indicator Correlations with Leaf Nutrients, Tree Growth, and Yield

We reported in Chapter 2 that total soil C, VAM spore count, soil respiration, and available soil Ca and P differentiated soil treatments in the GMS, IFP-OFP, and ARD studies. These soil properties indicated improved soil health as a result of bark mulch groundcover, lack of cultivation, and pre-plant soil compost amendment. We attributed these soil health improvements to the application of biomass amendments in these treatments.

Along with indicating soil health, total soil C, VAM spore count, soil respiration, and available Ca and P also predicted tree growth and yield in simple and multiple linear regression models. In the GMS study, total soil C correlated positively with TCSA in 2007 and 2008, with trees in the MUL segregating from trees in the other three treatments, having significantly higher total soil C and significantly larger TCSA (Fig. 3.7). Hoagland et al. (2008) similarly saw linkages among total soil C, tree size, and tree-row wood chip mulch. TerAvest et al. (in press) found that trees were larger when grown under wood chip mulch but attributed the larger tree size to N uptake from the mulch. They further suggested that this N source could be taken up during the growing season and stored as reserves for early growth the following spring. Our data show that total soil C correlated with organic matter, total soil N, and several other biological, chemical, and physical soil properties (Chapter 2). Thus, we infer that overall soil quality was represented by total soil C in the modeling. Larger tree size in the MUL was due to better overall soil health, soil nutrient retention and

tree uptake during the growing season, and larger nutrient reserves in MUL tree scaffolds, all compounded over 17 years of observations and treatments.

While total soil C was not correlated with CY in either year using simple linear regression, other soil health properties predicted CY in multiple linear regression analyses. In combination with other biological, chemical, and physical soil indicators, total soil C correlated negatively with CY in 2007, and organic matter – which was highly collinear with total C (Chapter 2) – correlated negatively with CY in 2008. The opposite effects that total soil C and organic matter had on growth versus yield suggest that different GMS could be important in accomplishing varied goals throughout the life of the orchard (Hoagland et al., 2008). Bark mulch groundcover, which enhances total soil C and organic matter (Chapter 2), could be used in the years after planting to aid in tree establishment, but when trees begin yielding, reducing the frequency of mulch applications or converting to post-emergence herbicide tree-row management may be best for limiting vigorous vegetative growth. This could encourage resource allocation to fruit quantity and quality, instead of vegetative growth (Forshey and Elving, 1989). While yield was not compromised by MUL throughout our experiment, in 2000, it was recognized that biennial mulch applications were no longer necessary to control weeds and maintain soil quality, and that there was potential for the frequency of these applications to hinder cropping and increase N and P leaching. Thus, mulch applications became triennial and were not made after 2006.

Since there were no differences in TCSA between IFP and OFP, we did not fit predictive models between soil health indicators and TCSA. We did, however, find correlations between soil health indicators and CY in 2007 and 2008. Previously, Purin et al. (2006) found that VAM spore count was higher in conventional apple management compared to organic management when cultivation was used in organic weed control, and Goh et al. (2001) found that soil respiration did not differ between

IFP and OFP when neither system employed cultivation. These studies did not correlate mycorrhizae spore count and soil respiration to yield, but their findings and ours suggest that cultivation hinders biological soil functions. Because biological soil properties may be used to predict orchard productivity over the long-term, cultivation represents a down-side in organic weed management. Rather, thermal methods, mulching, and biocontrol (weed pathogens) may be alternative strategies to controlling weeds in OFP (Granatstein, 1994).

Rootstock influenced tree growth and yield in the ARD study (Leinfelder and Merwin, 2006) and also influenced the comparisons between soil health indicators and TCSA or CY. Available soil Ca correlated positively with TCSA in 2007, which suggested that nutrients from the compost were still influencing tree growth six years after that treatment. Available soil Ca and bacterial-feeding nematodes correlated positively with CY in 2007. In 2008, bacterial-feeding nematodes and available soil P predicted TCSA, and available soil P alone predicted CY. The role of bacterial-feeding nematodes in these predictions could be associated with the differences in bacterial communities previously reported for the 'CG.6210' and 'M.26' rootstocks at this study site (Rumberger et al., 2004; Yao et al., 2006b).

What all of these experiments suggest is that soil health can be used to understand orchard productivity, but the relationships are complex and variable. Simple linear models are not always appropriate for modeling complex perennial systems. Many management factors must be considered when evaluating perennial systems (Glover et al., 2000), but our work shows that soil health supports optimal orchard performance. We would also suggest that soil health may lower the need for outside inputs which would otherwise be needed to maintain optimal orchard performance. We would recommend that future research investigate the role of soil health in lowering input costs.

Conclusion

By showing linkages among long-term management, soil health characteristics, and apple tree growth and yield, this work demonstrates the complex influence of soil health in orchard productivity and sustainability. This interdependence has been understood in annual crop systems, but previous work in perennial systems did not establish this connection. In Chapter 2, we reported how GMS, IFP-OFP, and ARD treatments influenced soil health properties, and we developed a Minimum Data Set to describe soil health among these sites. With this work, we showed how treatments influenced tree growth and yield and the complex relationships among soil health indicators and orchard productivity. Yield is an important function of soils, and perhaps the most important function according to growers – who are the land managers and stewards. This work gives new relevance to soil health in orchard systems, and with this progress, a new community of growers may be drawn to soil health research.

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Chapter 4
Carbon Storage and Valuation in Three Long-Term Apple Management Systems

Abstract

We examined groundcover management systems (GMS), integrated and organic fruit production (IFP-OFP), and rootstocks and pre-plant soil treatments (PPST) in an apple replant disease (ARD) site for effects on soil, groundcover, and woody biomass carbon (C) storage of apple (*Malus* X *domestica* Borkh.) in three New York State (NYS) orchard studies. Carbon storage was of interest because previous work found it to be a metric of soil health at these sites. Total soil C was determined in 2007 and differed among GMS ($P < 0.0001$) and ARD PPST ($P = 0.0016$). Allometric equations were used to model woody biomass C, which differed among GMS ($P = 0.0042$) and ARD rootstocks ($P < 0.0001$). Tree-row bark mulch and sod groundcover C storage were also calculated, and values for the sod tree-row were scaled to the drive lanes to express C storage on a hectare basis. Total carbon storage differed among GMS ($P < 0.0001$), ARD PPST ($P = 0.0045$), and ARD rootstocks ($P = 0.0006$), with bark mulch groundcover, pre-plant compost, and rootstock 'CG.6210' having higher C storage compared to other treatments. There was not a difference in C storage between IFP and OFP. We valued C storage by treatment using a range of prices – from market price to social costs that accounted for externalities. We found the bark mulch GMS, pre-plant compost, and rootstock 'CG.6210' systems to range in value from \$800-23000·ha^{-1}, \$400-12000·ha^{-1}, and \$400-12000·ha^{-1}, respectively, based on C storage in 2007. The IFP and OFP had similar C values, ranging from

approximately \$500-15000·ha^{-1}. These results illustrate the importance of soil quality and rootstock genetics in orchard C storage and valuation.

Introduction

Soil health is defined functionally as agricultural productivity, environmental awareness, and resource conservation (Doran and Parkin, 1994; Larson and Pierce, 1991). A healthy soil would fulfill these functions, in a given space and time (Doran and Parkin, 1996), based on its biological, chemical, and physical properties (Papendick and Parr, 1992). These biological, chemical, and physical properties are termed indicators when they differentiate management practices (Arshad and Coen, 1992). Acton and Padbury (1993) defined an indicator as "a measurable soil property that influences the capacity of a soil to perform a specified function", and Mitchell et al. (1995) explained that indicators correlate with other soil properties that may be difficult or costly to assess. Larson and Pierce (1991) introduced the term Minimum Data Set (MDS) to describe a set of indicators used to assess soil health.

Soil health studies have evaluated varying MDSs depending on the agricultural systems being assessed (Andrews et al., 2002; Gugino et al., 2007; Karlen et al, 1994; Reganold et al, 1993; Werner, 1997), illustrating that there is no ideal MDS to serve all purposes (Wolfe, 2006). We previously reported (Chapter 2) that total soil carbon (C) alone differentiated pre-emergence herbicide, post-emergence herbicide, red fescue turfgrass (*Festuca rubra*), and bark mulch groundcover management systems (GMS) with 99% and 98% accuracy in 2007 and 2008, respectively. Similarly, we reported that total soil C differed between integrated and organic fruit production systems (IFP-OFP) and between pre-plant compost and fumigation treatments in an apple replant disease (ARD) study, suggesting that total soil C is an important metric

of soil health in long-term orchard management systems that are inherently low in carbonates (USDA-NRCS Web Soil Survey, 2010).

Others have also used soil C as a metric of soil health in perennial agricultural systems. In kiwifruit (*Actinidia deliciosa*) and apricot (*Prunus armeniaca*) systems, Montanaro et al. (2009) observed linkages among "soil-protecting management" (i.e. cover cropping, compost application, and mulching) and soil health, as measured by soil organic carbon. Deuer et al. (2008) assessed total and labile soil C management in apple and found that soil C sequestration correlated with organic production and soil biological and physical properties. Soil C has also been an important metric of soil health – and overall ecosystem health – in urban landscapes (Golubiewski, 2006; Pouyat et al., 2006) and forests (Birdsey, 1992; O'Neill et al., 2005).

O'Neill et al. (2005) described soils as "…the fundamental support system for forest ecosystems…", and further stated that "…any environmental stressor that alters the natural function of the soil has the potential to influence the vitality, productivity, species composition, and hydrology of the forest systems." In other words, changes in soil quality can alter the functioning of the forest. Concerns over climate change have resulted in C storage being perceived as a primary function of forests (Sampson and Winnett, 1992). Forest soils are an important store of terrestrial C (Sampson and Winnett, 1992), but Birdsey (1992) showed that tree biomass – which is approximately 50% C (Nowak and Crane, 2002) – and understory biomass may be as important or more important stores of C as the soil, depending on tree species present and climatic region.

Intensive ecological studies of forest woody biomass have generally only been conducted on small plots that were not randomly-selected, and systematic methodologies have not been employed among studies (Schoeder et al., 1997). It is more common for above-ground biomass (AGB) to be estimated by allometric

equations (Peper and McPherson, 1998), which link relative growth of a plant part – such as tree height, canopy, and/or diameter at breast height (DBH) – to growth of the entire plant. Allometric equations have been developed from forest systems by measuring selected dimensions of sample trees, felling the trees, and then weighing the trees – green and then oven-dried (Tritton and Hornbeck, 1982). Regression analyses relate the tree dimensions to oven-dry AGB. The data are smoothed by natural log transformation and have the general form:

$$\ln(AGB) = a + (b)\ln(DBH)$$

where a and b are species-specific coefficients (Smith and Brand, 1983). Coefficients have also been developed for general hardwood and softwood equations, and in a review by Tritton and Hornbeck (1982), general equations were characterized as good approximations of stand biomass where species were mixed or where species-specific coefficients had not yet been developed.

General allometric equations for hardwoods and softwoods have been compiled by Smith and Brand (1983) and Tritton and Hornbeck (1982), among others. The equations are in the aforementioned, logarithmic form but vary in their coefficients because they were developed from different regions, tree species, and soil types, among other factors. For example, the stem, branch, and leaf biomass equations proposed by Harris et al. (1973):

$$\ln(\text{stem biomass}) = -2.437 + (2.418)\ln(DBH)$$

$$\ln(\text{branch biomass}) = -3.188 + (2.226)\ln(DBH)$$

$$\ln(\text{leaf biomass}) = 03.498 + (1.695)\ln(DBH)$$

differ from those of Kinerson and Bartholomew (1977):

$$\ln(\text{stem biomass}) = 4.623 + (2.428)\ln(DBH)$$

$$\ln(\text{branch biomass}) = 1.914 + (2.676)\ln(DBH)$$

$$\ln(\text{leaf biomass}) = 1.356 + (2.527)\ln(DBH)$$

even though all equations were developed from forests in the northeastern United States. The Harris et al. (1973) equations were developed for trees > 10 cm DBH; whereas, the Kinerson and Bartholomew (1977) equations were developed for trees < 12 cm DBH. This size differentiation is an important consideration in selecting and applying general allometric equations; however, Tritton and Hornbeck (1982) also recognized the importance of forest latitude in the development and application of general allometric equations. Thus, the aforementioned equations would be regionally important in the northeastern United States.

In addition to forests, allometric equations have also been applied to landscapes to determine AGB and C stored in urban settings (Golubiewski, 2006; Jo and McPherson, 1995; Nowak and Crane, 2002; Peper and McPherson, 1998). Allometric equations have been found to slightly overestimate actual AGB in pruned landscapes (Golubiewski, 2006; Nowak, 1994; Nowak and Crane, 2002; Peper and McPherson, 1998), so a conversion factor of 0.8 has been used to relate forest-derived allometric equations to urban trees. Woody biomass C is then summed with soil organic C and herbaceous biomass C to estimate total C storage in the systems (Golubiewski, 2006; Jo and McPherson, 1995).

Furthermore, system C storage has been used to value ecosystem health using prices for C developed from social cost modeling of CO_2 emissions (Kroodsma and Field, 2006; Nowak and Crane, 2002). Production functions are used to value environmental quality based on agricultural output (Hanley and Spash, 1993). Two methods of production function valuation – avoided costs and dose-response – can be considered using the function:

$$O = f(L, K, I, E)$$

where output (O) is a function of labor (L), capital (K), inputs (I), and an environmental resource (E). With the avoided costs method, O, L, and K remain

constant, but as E increases, I decreases. The value of E is the value of input costs avoided. With the dose-response method, L, K, and I are held constant, but O increases as a result of E increasing. The value of E is determined as the increased value in O. In agricultural systems, O is most obviously crop yield, but O could also be an ecosystem service, such as C storage. In this chapter, we have considered a dose-response function where O is C storage and E is soil health. We have estimated values for soil health based on a market price and social costs for C (Fankhauser, 1994; Nordhaus, 1991; Stern Review, 2006).

Research on C storage and C valuation in agricultural systems is relatively nascent (De Gryze et al., 2009; Howitt et al., 2009; Kroodsma and Field, 2006). Kroodsma and Field (2006) modeled C storage in annual and perennial agricultural systems in California based on area planted, but they did not consider management influences on C storage. De Gryze et al. (2009) found that management practices like cover cropping, manure application, and conservation tillage increased soil organic C in annual systems, and thus, offset greenhouse gas emissions. These studies illustrate that area and management are important considerations of future studies of C storage in agricultural systems. Moreover, Howitt et al. (2009) reported that growers had more incentive to adopt sustainable management practices if paid for C retained in the system.

The objectives of our work were to consider all of these studies in order to better understand C storage in perennial agricultural systems. More specifically, we wished to 1) model woody biomass C across GMS, IFP-OFP, and ARD treatments and evaluate forest-derived allometric equations for validity in orchard systems; 2) quantify stored C above and below ground across treatments – as a metric of sustainable management; and 3) value C stored, as based on market price and social cost modeling of CO_2 emissions. Toward this last objective, we are not suggesting that

C payments be made to subsidize sustainable orchard management practices. Rather, we use C pricing to further illustrate that orchards store large quantities of C and that certain orchard management practices augment C storage.

It should be understood that we make a distinction between C storage and C sequestration, and that our study evaluated C storage for these long-term management treatments, not C sequestration. Carbon sequestration would account for C emissions from the system, due to machinery or fertilizer use (Golubiewski, 2006). In perennial agricultural systems, C emissions would also result from pruning and harvest. For this study, we present snapshots of C stored in the orchards at the end of the 2007 growing season. When valuing various ecosystem services, Costanza et al. (1997) similarly presented snapshots, noting the difficulty in valuing dynamic systems and processes. We used our snapshots of C storage to compare treatment differences within the GMS, IFP-OFP, and ARD sites. The values for C represent aggregate, cumulative values from treatment initiation to the end of the 2007 growing season.

Materials and Methods

Orchard Sites and Treatments

The project was conducted in 2007 and concentrated on three experimental sites at the Cornell Orchards in Ithaca and Lansing, NY. These proximate sites had similar inherent soil characteristics, and as controlled experiments under long-term management, there was extensive, background information on these sites. This allowed for intensive investigation of the long-term management effects on tree and soil C storage.

Groundcover Management Systems Study

The GMS study was established in 1992 on the east shore of Cayuga Lake, near Ithaca, NY. The 0.8 ha, moderately-sloped site is a Hudson-Cayuga silt loam (mixed, mesic, Glosaquic Hapludalf). Land preparation began in Apr. 1991 with the removal of 15-yr-old trees, and organic matter content at that time was between 4.7 – 5.3%. The land was deep-tilled, seeded with creeping red fescue turfgrass (*F. rubra*), and installed with subsoil drainage. In Apr. 1992, apple trees ('Royal Empire' on 'M.9'/'MM.111' rootstock) were planted at 3 x 6 m spacing among 12 plots. Each 20-tree plot was 9 m wide across the slope and 25 m long down-slope. Four tree rows ran across the slope, each separated by 4 m of grass drive lanes. The groundcovers were applied down the tree row in a 2-m band. The experimental design was a completely randomized design (CRD) having three replicated plots of the four GMS, where GMS was a fixed effect and plot was a random effect. The groundcover treatments were as follows: 1) Pre-emergence, residual herbicides norflurazon, and diuron, tank-mixed at 3.0 and 2.5 kg a.i.•treated ha^{-1}, respectively, annually applied in mid-May, and paraquat (1992-1998), tank-mixed at 0.5 kg a.i.•treated ha^{-1} or glyphosate (1999-present) at 2.0 kg a.i.•treated ha^{-1}, annually applied in mid-July (PREHERB); 2) Post-emergence herbicide glyphosate applied annually at 2.0 kg a.i.•treated ha^{-1} in mid-May and July (POSTHERB); 3) Red fescue (*F. rubra*) turfgrass originally seeded in 1991, now a mixture of about 25 herbaceous grass and broadleaf species, mowed monthly during the growing season (SOD); and 4) Shredded, hardwood bark mulch (a mixture of *Acer*, *Quercus*, *Juglans*, *Fraxinus*, and *Tilia* spp.), 15 cm thick, first applied in May 1992, and reapplied in May of 1995, 1998, 2000, 2002, and 2005 (MUL). Glyphosate was used to suppress emergent weeds in the mulch treatment. All plots were similarly fertilized. In mid-Apr. 1992, 1993, and 1994, ammonium-nitrate fertilizer was applied on the soil surface in the tree row at rates 30, 45, and 65 kg N•ha^{-1}, respectively.

Annual spring urea and micronutrient foliar sprays were applied at petal fall according to the Pest Management Guidelines for Commercial Tree Fruit Production (Agnello et al., 2007).

Integrated and Organic Fruit Production Study

The IFP-OFP comparison study was located on a 0.4 hectare site at the Cornell Orchards in Ithaca, NY. The orchard ('Liberty' on 'M.9' rootstock) was planted at 1.5 m x 4.3 m spacing in Apr. 1994 and was under conventional insect and disease management until 2004, when IFP, as defined by Carroll and Robinson (2006), and OFP treatments, as defined by the United States Department of Agriculture National Organic Program (USDA-NOP), were initiated. The soil is characterized as Hudson and Collamer silt loams (mixed, mesic, Glosaquic Hapludalf) and had about 3% organic matter and a pH of 6.4 at the commencement of the experiment. The two treatments were replicated over four blocks in a Randomized Complete Block Design (RCBD), where treatment was a fixed effect and block was a random effect. Each 64-tree plot consisted of four adjacent tree rows of 16 trees. The IFP and OFP differed in their disease and pest management, fertilization, thinning, and soil management, as described in detail by Peck (2009). Composted hardwood bark mulch was applied to the IFP tree rows in Nov. 2005 as 1-m-wide bands. This was the source of nitrogen by slow mineralization in the initial years of the experiment. The OFP plots received chicken manure compost in Oct. 2005 at a rate of 697 kg fresh wt•ha^{-1}, equivalent to 78 kg N•ha^{-1}. In the six years prior to this study, only glyphosate herbicide was used for weed control at this site. The mulch and an annual, June post-emergent glyphosate application (2.9 kg a.i.•ha^{-1}) were used to control weeds in the IFP. Weeds in the OFP were cultivated monthly during the growing season using a tractor-mounted Wonder Weeder (Harris Manufacturing, Burbank, WA) mechanical cultivator.

Apple Replant Disease Study

The ARD study was also located on a 0.4 ha site at the Cornell Orchards in Ithaca, NY. The soil is a glacial lacustrine Hudson silty clay loam (mixed, mesic Udic Hapludalf), slightly-sloped and with limited subsoil drainage. Originally planted to apple around the year 1910, the site was first replanted in 1981 but failed in its establishment, showing many common ARD symptoms (Mai et al., 1994). It was replanted again in 2001; orchard removal, site preparation, and experimental design were described by Leinfelder and Merwin (2006).

The factors of interest were three pre-plant soil treatments (PPST) and two rootstocks in a RCBD, with the PPST and rootstock genotypes as fixed effects, randomized among five blocks. Telone C-17 (Dow AgroSciences, Indianapolis, Ind.) was the pre-plant soil fumigant and is a formulation of the nematicide 1,3 dichloropropene (78% v/v) and the broad-spectrum biocide chloropicrin (17% v/v). It was shank injected in Oct. 2001, to a depth of 25 cm at a rate of 400 L•treated ha^{-1}, and the soil was immediately sealed with a cultipacker. As an alternative to soil fumigation, a compost made of 40% (v/v) ground leaves and wood chips, 40% supermarket vegetable culls, and 20% pre-composted cattle and horse manure in wood shavings (Toad Hollow Farm, Nedrow, NY) was applied in Sept. 2001. The compost was applied in two portions – the first surface applied at 492 kg•treated ha^{-1} and then incorporated with a moldboard plow to a depth of 25 cm. The second portion was applied at the same rate but only rototilled into the upper 10 cm of soil. The macronutrient content of the compost was determined by the Cornell Nutrient Analysis Laboratory (CNAL), and to compensate for indirect fertilization effects of the compost, non-composted plots were treated with a mineral fertilizer (22N-4P-0K) at a rate of 318 kg•treated ha^{-1}. Aside from pre-plant lime and N–P–K, little subsequent fertilizer was applied. Two nitrogen applications were made to all plots in

May 2003 after poor growth in the first year: soil-applied ammonium nitrate (34N–0P–0K) at 18.7 kg•ha^{-1} and foliar-applied calcium nitrate (15.5N–0P–0K–19Ca) at 17.1 kg•ha^{-1}. Spring urea and micronutrient foliar sprays were applied annually at petal fall.

The rootstocks of interest were 'M.26' – an industry-standard, dwarfing rootstock (40% of expected tree size on seedling rootstock) from the East Malling Experiment Station in England, and 'CG.6210' – a semi-dwarfing rootstock (60% of expected tree size on seedling rootstock) from the Cornell-Geneva breeding program. These rootstocks were of interest in our soil health study because 'CG.6210' previously showed ARD tolerance and 'M.26' ARD susceptibility (Leinfelder and Merwin, 2006), and we wished to learn more about soil health/rootstock interactions. The rootstocks were grafted with 'Royal Empire' and planted at 2.1 m x 4.9 m spacing in Nov. 2001. Composted hardwood bark mulch was applied in a 1-m-wide strip to all of the tree rows after planting in 2002 but was not subsequently reapplied and was scarcely-existent in 2007 and 2008. The drive lanes were maintained with a mowed red fescue sod cover. Weeds in the tree rows were controlled by post-emergence glyphosate at the labeled rate (2.9 kg a.i.•ha^{-1}) in May and July, annually.

Orchard Management

Trees were managed by representative commercial orchard practices for NYS. Pathogens and insect pests were sprayed according to the Pest Management Guidelines for Commercial Tree Fruit Production (Agnello et al., 2007) or the USDA-NOP standards. Trees were chemically-thinned with appropriate formulations, and the OFP block was additionally hand-thinned to one fruit per cluster. Drip and microsprinkler irrigation was used during dry periods of the summer and before soil

sampling if a rain event had not recently occurred. Trees were pruned annually in winter to a modified vertical axe.

Soil Sampling Procedures and Soil C Storage

Soils were similarly sampled across all three experiments, unless otherwise noted. Samples were collected in late July 2007. Based on published recommendations (Moebius, 2006; Rumberger et al., 2007), we took annual, summer samples for reasons of replication and heightened biological activity. Samples were collected two or three days after a rain or irrigation event when the soil was near field capacity, from beneath the canopy, approximately 0.5-0.7 m from the tree trunk, and away from treatment edges.

Composite bulk soil samples were collected using a 3-cm-diam stainless steel soil corer, to a depth of about 20 cm. Ten to 15 cores were randomly collected, hand-sorted for rocks and surface debris, and homogenized per plot. The soil was stored in a 4°C cooler until needed for testing total soil C.

Intact samples were collected using two stainless steel cores, taped vertically together, for a 7-cm internal diam and a 12-cm height. Cores were carefully driven into the soil and lifted out with a shovel to minimize changes to field conditions within the cores. Three replicates were randomly taken from each plot in the GMS and IFP-OFP studies, and one sample was taken per plot from the ARD study. Samples were stored in a 4°C cooler until needed for bulk density testing.

The Cornell Nutrient Analysis Laboratory (CNAL) determined total soil C by Dumas combustion, using standard procedures (Burt, 2004). Because these soils are inherently low in carbonates (USDA-NRCS Web Soil Survey, 2010), and because

total soil C was strongly correlated with organic matter at these sites (Chapter 2), we assumed that total soil C was essentially organic C in our calculations and analyses.

To determine bulk density, taped intact cores were carefully separated into "upper" and "lower" cores, which represented 0-6 cm and 6-12 cm soil depths, respectively. The soil was dried at 105°C and weighed for the known volume. Bulk density for the upper and lower cores was used to calculate soil C on a volume basis. Soil C by volume was scaled to an area basis by multiplying by the depth of the intact cores, as described by Golubiewski (2006). Soil C in the GMS SOD treatment was used to calculate C stored in the soil of the grass drive lanes for the GMS, IFP-OFP, and ARD studies.

Herbaceous Above-ground Biomass C and Mulch C Storage

Herbaceous AGB and the C:N ratio of that biomass were determined for the GMS treatments in 2007 (Atucha, unpublished). Above-ground biomass was determined by stripping surface vegetation from a 0.5 m^2 plot, according to procedures described by Purohit (2006). The C:N ratio was determined by Dumas combustion at the CNAL (Burt, 2004). Herbaceous AGB of the PREHERB, POSTHERB, and MUL consisted of emergent weeds, and the SOD biomass has been previously described. The C stored in the herbaceous biomass was scaled to tree-row area. Additionally, the C stored in SOD biomass was extrapolated for the grass drive lane area of all three sites, since sod biomass and C were not determined for the IFP-OFP or ARD sites. This gave us a complete picture of C storage in herbaceous groundcover on a hectare basis.

The C:N ratios were determined for the bark mulches of the MUL and IFP treatments by Dumas combustion (Burt, 2004) and were previously reported in Yao et

al. (2005) and Peck (2009), respectively. Carbon stored in the bark mulch was scaled to tree-row area using the known dry weight application rate (27 kg DW·m^2).

Tree-row groundcover C for the MUL treatment was the sum of herbaceous above-ground biomass C and bark mulch C. For the SOD, POSTHERB, and PREHERB, tree-row groundcover C was herbaceous biomass C only. For the IFP treatment, because herbaceous biomass C was not determined, tree-row groundcover C was only the bark mulch C. For the OFP treatment and the PPST and rootstock systems of the ARD study, we have presented no data because there was no bark mulch groundcover in these treatments and because we do not have herbaceous above-ground biomass data for these treatments. Considering that herbaceous above-ground biomass C is considered negligible (Jo and McPherson, 1995), we do not consider this absence of data detrimental to the overall picture of C storage in these systems.

Tree Growth and Woody Biomass C Storage

Tree size was measured in 2007 as trunk circumference in the GMS and IFP-OFP studies and by trunk caliper in the ARD study. Measurements were taken on each tree at 45 cm above the ground during the dormant season and then calculated into diameter, as needed. We used general hardwood allometric equations to calculate stem and branch dry mass from diameter at 45 cm above the ground. Equations from Harris et al. (1973) were used for the GMS trees, which were > 10 cm diam, and equations from Kinerson and Bartholomew (1977) were used for the IFP-OFP and ARD trees, which were < 12 cm diam. While these equations were developed from forest systems using diameter at breast height (DBH), we have assumed that diameter at 45 cm above the ground – which is below all lateral branching – is consistent with DBH for forest and landscape trees, given tree-form modeling described by Shinozaki et al. (1964).

Stem and branch dry weights were summed for total above-ground biomass·tree^{-1} (AGB). Consistent with procedures in Nowak (1994), we adjusted AGB by a factor of 0.8 to account for annual pruning maintenance. Root biomass (below-ground biomass·tree^{-1}, BGB) was calculated using a root:shoot ratio of 0.26 (Cairns et al., 1997). We used this estimate because it was based on a meta-analysis of 165 root biomass records, where sampling methodologies were controlled. The estimate was also consistent with that made by Kroodsma and Field (2006) for orchards. Above-ground biomass and BGB were summed for total biomass·tree^{-1} (TB). Woody biomass C·tree^{-1} was calculated as 45% of total biomass (Kroodsma and Field, 2006) and was multiplied by the number of trees·ha^{-1} for each site to normalize woody biomass C on an area basis.

Woody biomass was quantified by tree excavations for the GMS study in 2000. These data were previously published by Purohit (2006), and we used them to test the validity of the Harris et al. (1973) allometric equations for this site.

System C Storage and Valuation

System C storage for the GMS, IFP-OFP, and ARD treatments was estimated by summing tree-row soil C, tree-row groundcover C (where applicable), drive lane soil and biomass C, and woody biomass C. We calculated values for C, for each treatment, on a per hectare basis. We used a 2007 market value of \$3·tonne CO_2^{-1} (www.chicagoclimatex.com) and contrasted it with social costs that account for externalities: \$8·tonne CO_2^{-1} (Nordhaus, 1991), \$23·tonne CO_2^{-1} (Fankhauser, 1994), \$73·tonne CO_2^{-1} (Nordhaus, 1991), and \$85·tonne CO_2^{-1} (Stern Review, 2006). The values calculated are the aggregated values for C, from treatment initiation to after the 2007 growing season. The calculations are not annual values for C.

Statistical Analyses

All statistical analyses were performed using JMP® 8.0 Statistical Software (SAS Institute, Inc., Cary, NC). A mixed model was used to detect differences in across GMS, IFP-OFP, and ARD treatments. Plot was a random covariate in GMS analyses, and block was a random covariate in IFP-OFP and ARD analyses. Tukey mean separation procedures were used for the GMS and ARD PPST, and Student *t* procedures were used for the IFP-OFP and ARD rootstocks. Tree-row groundcover C, drive lane C, and monetary values for C were not statistically analyzed because these were calculated from averages. Data were transformed as necessary to meet assumptions for normal distribution of residuals and homogeneity of variances. Significance was inferred at $\alpha = 0.05$, unless otherwise denoted.

Results

Soil, Herbaceous, Bark Mulch, and Drive Lane C Storage

Tree-row soil C·ha^{-1} differed among GMS and ARD PPST but did not differ between IFP and OFP or between ARD rootstocks (Table 4.1). Tree-row soil C was greater in the MUL compared to the other GMS, and constituted over 24000 kgC·ha^{-1} in the system. In the ARD study, COMP soil contributed nearly 8100 kgC·ha^{-1}, which was greater than that of FUM and CONT soil. The tree-row bark mulch represented additional C in the MUL and IFP treatments – approximately 6400 kgC·ha^{-1} (inclusive of herbaceous biomass C) and 1000 kgC·ha^{-1} (exclusive of herbaceous biomass C), respectively. Tree-row and drive lane grass contributed to the total C pool in an amount that could probably be considered negligible – approximately 280 kgC·ha^{-1}

Table 4.1: Soil and groundcover carbon (C) storage in GMS, IFP-OFP, and ARD studies in 2007. Tree-row groundcover C for the GMS study is a sum of herbaceous biomass C (Atucha, unpublished) and bark mulch C (where applicable). Herbaceous biomass C data were not collected for the IFP-OFP or ARD studies, so only bark mulch C is presented for the IFP treatment. GMS and ARD PPST means followed by different letters were statistically different according to Tukey mean separation procedures ($P \leq 0.05$). IFP-OFP and ARD rootstock means followed by different letters were statistically different according to Student *t* mean separation procedures ($P \leq 0.05$). Drive lane soil and grass C storage were calculated for all three studies using data from the GMS SOD treatment. Total soil C (%) was previously presented in Chapter 2.

Treatment	Total Soil C (%)	Tree-row Soil C (kgC/ha)	Tree-row Groundcover C (kgC/ha)	Drive Lane Soil C (kgC/ha)	Drive Lane Sod C (kgC/ha)
GMS:					
MUL	5.6 a	24708 a	6381	22983	574
SOD	2.0 b	11840 b	287	22983	574
POSTHERB	1.6 b	9401 b	106	22983	574
PREHERB	1.6 b	9527 b	65	22983	574
SE	0.2	643			
P value	< 0.0001	< 0.0001			
IFP-OFP:					
IFP	2.1	7117	1009	27162	672
OFP	1.8	6469	No data available	27162	672
SE	0.1	488			
P value	0.2546	0.3902			
ARD:					
COMP	2.4 a	8098 a	No data available	27858	689
FUM	2.0 b	6512 b	No data available	27858	689
CONT	1.8 b	6193 b	No data available	27858	689
SE	0.1	361			
P value	0.0133	0.0016			
CG.6210	2.10	6952	No data available	27858	689
M.26	2.10	6917	No data available	27858	689
SE	0.10	301			
P value	0.8161	0.9315			

and 570 kgC·ha^{-1} for the SOD treatment and drive lanes, respectively, in the GMS study. Drive lane grass contributed just under 700 kgC·ha^{-1} in the IFP-OFP and ARD studies. Drive lane grass contributed slightly more C to these systems because the tree-rows were narrower in these systems. Drive lane soil contributed a substantial amount of C to the systems, given area occupied by drive lanes and the amount of C that can be stored in soil covered with grass (Golubiewski, 2006). We estimated drive lane soil C to be approximately 23000 kgC·ha^{-1}, 27000 kgC·ha^{-1}, and 28000 kgC·ha^{-1} for the GMS, IFP-OFP, and ARD sites, respectively.

Woody Biomass C Storage

Using allometric modeling, we found woody biomass to differ among GMS treatments and between ARD rootstocks (Table 4.2). The trees in the MUL had statistically greater AGB, BGB, TB, woody biomass C·tree^{-1}, and woody biomass C·ha^{-1} compared to the other three GMS. Woody biomass C·ha^{-1} for the MUL was approximately 19000 kgC·ha^{-1}, compared to 15000 kgC·ha^{-1}, 15000 kgC·ha^{-1}, and 13000 kgC·ha^{-1} for the SOD, POSTHERB, and PREHERB. Rootstock 'CG.6210' was greater than rootstock 'M.26' in all biomass and C storage measures, storing approximately 2600 kgC·ha^{-1} in woody biomass compared to 800 kgC·ha^{-1} for rootstock 'M.26'. There were no differences in biomass or C storage between IFP and OFP, or among ARD PPST.

Despite differences in woody biomass C in the GMS study in 2007, there were no differences in either actual biomass C or allometrically-modeled biomass C in 2000 (Table 4.3). Allometrically-modeled biomass C·ha^{-1} overestimated actual biomass C·ha^{-1} by 1.5 for MUL, and by 1.4 for SOD, POSTHERB, and PREHERB.

Table 4.2: Allometric equation modeling of woody biomass carbon (C) storage in GMS, IFP-OFP, and ARD studies in 2007. BGB was calculated using a root:shoot ratio of 0.26 (Cairns et al., 1997), and biomass C as 45% of total biomass (Kroodsma and Field, 2006). GMS and ARD PPST means followed by different letters were statistically different according to Tukey mean separation procedures, and IFP-OFP and ARD rootstock means followed by different letters were statistically different according to Student t procedures ($P \leq 0.05$). Data were Box Cox transformed for analysis but back-transformed for presentation. Because BGB, TB, and Biomass C are transformations of AGB, P values did not change.

Treatment	AGB†	BGB^	TB‡	Biomass C (kgC/tree)	Biomass C/Tree-row Area (kgC/ha)
GMS:					
MUL	61a	16 a	77 a	34 a	19319 a
SOD	46 b	12 b	58 b	26 b	14598 b
POSTHERB	47 b	12 b	59 b	26 b	14803 b
PREHERB	42 b	11 b	53 b	24 b	13462 b
SE	2.7	0.1	3.4	1.6	871
P value	0.0042	0.0042	0.0042	0.0042	0.0042
IFP-OFP:					
IFP	15.8	4.1	19.9	9.0	13215
OFP	16.6	4.3	20.9	9.4	13843
SE	1.0	0.3	1.3	0.6	864
P value	0.4691	0.4691	0.4691	0.4691	0.4691
ARD:					
COMP	3.1	0.8	4.0	1.8	1722
FUM	3.4	0.9	4.3	2.0	1874
CONT	2.9	0.8	3.7	1.7	1583
SE	0.3	0.1	0.3	0.2	144
P value	0.4151	0.4151	0.4151	0.4151	0.4151
CG.6210	4.8 a	1.3 a	6.1 a	2.7 a	2627 a
M.26	1.5 b	0.4 b	1.9 b	0.9 b	826 b
SE	0.20	0.10	0.30	0.10	118
P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

† Above-ground biomass (kg dry weight/tree)
^ Below-ground biomass (kg dry weight/tree
‡ Total biomass (kg dry weight/tree)

System C Storage and Valuation

When C was summed for tree-row soil, tree-row groundcovers, drive lane soil and groundcover, and woody biomass, there were differences among GMS and ARD treatments (Table 4.4). More C was stored in the MUL than in the SOD, POSTHERB, and PREHERB, totaling approximately 74000 kgC·ha^{-1}, 50000 kgC·ha^{-1}, 48000 kgC·ha^{-1}, and 47000 kgC·ha^{-1}, respectively. More C was stored in the ARD COMP system (38000 kgC·ha^{-1}), compared to the FUM (37000 kgC·ha^{-1}) and CONT (36000 kgC·ha^{-1}). There was also a difference between ARD rootstocks, with the 'CG.6210' system storing approximately 38000 kgC·ha^{-1}, compared to the 'M.26' system storing 36000 kgC·ha^{-1}.

We calculated the C stored in the MUL system to be 1.5 to 1.6 times more per hectare than that for the SOD, POSTHERB, and PREHERB systems (Table 4.4). The market price for C stored in the MUL would be \$813·ha^{-1}, and the social costs would range from \$2168-23035·ha^{-1}. There would essentially be no difference in C valuation between the IFP and OFP, with a market price at approximately \$180·ha^{-1} and social costs approximately \$540-15000·ha^{-1}. In the ARD system, the value of C in the COMP would be similar to that for rootstock 'CG.6210' – approximately \$420·ha^{-1} at market price and ranging from approximately \$1120-11900·ha^{-1} at social cost. By comparison, the FUM, CONT, and 'M.26' systems would have C values of about \$130·ha^{-1} at market price and ranging from approximately \$130-11300·ha^{-1} at social cost. These calculations represent one-time values for C at the end of the 2007 growing season.

Table 4.3: Actual woody biomass carbon (C) storage by GMS treatment versus allometrically-modeled biomass C (Harris et al., 1973) for the year 2000. Actual biomass data were previously reported by Purohit (2006). No statistical differences were detected in biomass or biomass C by Tukey mean separation procedures ($P \leq 0.05$).

Actual:	AGB†	BGB^	TB‡	Biomass C (kgC/tree)	Biomass C/Tree-row Area (kgC/ha)
MUL	14.5	7.5	22.0	9.9	5547
SOD	13.3	6.4	19.6	8.8	4949
POSTHERB	13.8	8.0	21.8	9.8	5506
PREHERB	13.1	6.8	19.9	9.0	5030
SE	1.6	0.6	2.0	0.9	498
P value	0.9206	0.3007	0.7575	0.7613	0.7613
Allometric:					
MUL	26.3	6.8	33.2	14.9	8369
SOD	23.8	6.2	27.8	12.5	7024
POSTHERB	22.0	5.7	30.0	13.5	7578
PREHERB	22.1	5.7	27.7	12.5	6991
SE	1.2	0.3	1.5	0.7	371
P value	0.0941	0.0941	0.0941	0.0941	0.0941

† Above-ground biomass (kg dry weight/tree)
^ Below-ground biomass (kg dry weight/tree)
‡ Total biomass (kg dry weight/tree)

Table 4.4: Total carbon (C) storage in 2007 GMS, IFP-OFP, and ARD studies, as the sum of woody biomass C, soil C, ground-cover C, and drive lane C. We used the atomic mass conversion ratio (44/12) to convert C equivalents to CO_2 equivalents. We used a market price from 2007 of \$3/tonne CO_2 equivalent (www.chicagoclimatex.com), and social costs of \$8 (Nordhaus, 1991), \$23 (Fankhauser), \$73 (Nordhaus), and \$85/tonne CO_2 equivalent (Stern Review, 2006) to price C for each treatment. Statistics are only shown for Total C (kgC/ha) because subsequent columns are transformations of that data.

Treatment	Total C (kgC/ha)	Total C (tonne CO_2 eq/ha)	Market Price for C ($/ha)	Social Cost of C (Nordhaus, 1991) ($/ha)	Social Cost of C (Fankhauser, 1994) ($/ha)	Social Cost of C (Nordhaus, 1991) ($/ha)	Social Cost of C (Stern Review, 2006) ($/ha)
GMS:							
MUL	73965 a	271	813	2168	6233	19783	23035
SOD	50282 b	184	552	1472	4232	13432	15640
POSTHERB	47867 b	176	528	1408	4048	12848	14960
PREHERB	46611 b	171	513	1368	3933	12483	14535
SE	1565.0						
P value	< 0.0001						
IFP-OFP:							
IFP	49175	180	540	1440	4140	13140	15300
OFP	48146	177	531	1416	4071	12921	15045
SE	1159						
P value	0.0986						
ARD:							
COMP	38367 a	141	423	1128	3243	10293	11985
FUM	36932 b	135	405	1080	3105	9855	11475
CONT	36324 b	133	399	1064	3059	9709	11305
SE	405						
P value	0.0045						
CG.6210	38126 a	140	420	1120	3220	10220	11900
M.26	36290 b	133	399	1064	3059	9709	11305
SE	331						
P value	0.0006						

Discussion

Soil, Herbaceous, Bark Mulch, and Drive Lane C Storage

Soil C contributed substantially to the total C being stored in all orchard systems. In the GMS study, where one-third of the area was the tree-row treatment, soil C in the bark mulch plots was 35% of the total C in the system. Compare that with the SOD, POSTHERB, and PREHERB tree-row soils, which stored 24%, 20%, and 20%, respectively, of the system-wide C. Greater tree-row C in the MUL can presumably be attributed to the inputs of the mulch itself. This C is not internally-derived from the system and actually represents a transfer of C from forests to orchards. Because we are presenting a snapshot of C storage in these systems, we have included C from mulch in our modeling. However, in modeling C sequestration – which, as previously described, accounts for storage, emissions, and transfers – this transfer of C from forests to orchards would need to be considered.

Another consideration of bark mulch systems is that the mulch decomposes – feeding biological activity (Chapter 2; Yao et al., 2005) – but the C does not. In the IFP, where bark mulch was also used as a groundcover, the tree-row soil stored 14% of the total C. While this is a smaller proportion than that stored in the GMS MUL, the tree-row is narrower in the IFP-OFP study, accounting for only about 20% of the total area. Also, there were only four previous years of bark mulch cover (one single application) in the IFP, compared to 16 years – and 6 applications – in the GMS MUL. Tree-row soil in the OFP stored 13% of the system-wide C, which was not statistically different from that stored in the IFP, despite the tree-row bark mulch in the IFP and tree-row cultivation in the OFP. We would have anticipated less soil C in the tree-row of the OFP, given cultivation weed management, but others have similarly observed

that soil C is not sensitive to changes in short-term soil management (Marriott and Wander, 2006). This may be particularly true in the three to four years of transition from conventional to organic management (Wander et al., 1994), which was the timeline preceding our study. Tree-row soil C storage in the COMP, FUM, and CONT of the ARD study was 20%, 18%, and 17%, respectively, of the total C stored in those systems. Higher tree-row soil C in the COMP mirrors heightened chemical and biological soil quality seen in the early years of this study (Leinfelder and Merwin, 2006; Yao et al., 2006b) and illustrates the influence of pre-plant compost on soil C even six years after application.

When soil C in the tree-rows was summed with drive lane soil C, approximately two-thirds of the system-wide C was found to be retained in the soil for all treatments. In general, it is assumed that two-thirds of C in terrestrial systems resides in the soil, regardless of temperature, precipitation, and vegetation (Post et al., 1982). Our results correspond with this assumption in all cases except the ARD study, where > 90% of the system-wide C was stored in the soil. We attribute the higher proportion of soil C to the smaller trees in that study, with proportionally-less woody biomass C.

The large proportion of C stored in our soils can, in part, be attributed to the large proportion of area that was non-tilled, grass-covered drive lane. Soil genesis studies of grassland prairie mollisols have illustrated their fertility and high C storage. Similarly, the influence of a grass cover on soil C storage is supported by work done in urban landscapes. Pouyat et al. (2006) found that residential lawn soils held more C than forest soils. Golubiewski (2006) found that residential soil C could recover from construction in 25 years if non-tilled and covered in grass, but annual crop agricultural soils under conservation tillage would need 50 years to recover soil C to pre-agriculture, grassland levels. We can, thus, interpret that perennial agricultural systems

are good stores of C because of the limited, if any, disturbance of the soil surface and the large potential for C storage in the grassland soil.

At that interface of the soil surface, groundcovers in the tree-rows and drive lanes contributed substantially less C to the systems. Tree-row bark mulch contributed 9% of the system-wide C in the GMS MUL, but it contributed only 2% in the IFP. This discrepancy can likely be attributed to the 16 years of bark mulch cover in the GMS – and the several reapplications – compared to the four years of bark mulch in the IFP – and no reapplications. The difference could also be due to variability in mulches. Even though the mulches in the GMS and IFP studies were purchased from the same vendor, they differed in moisture, C:N ratio, and other chemical and biological properties at the time of application (Peck, 2009; Yao et al., 2005).

By comparison, tree-row herbaceous biomass contributed only 0.4% of the system-wide C in the SOD GMS, and all the grass in the drive lanes accounted for only 0.8%, 1.4%, and 1.8% of the total C for the GMS, IFP-OFP, and ARD systems, respectively. In residential greenspace, Jo and McPherson (1995) found that grass contributed only 0.5-0.7% of the C stored, compared to 79-89% stored in soil. Given our data and previous studies, it appears that herbaceous above-ground grass biomass itself is a negligible component of system-wide C storage, but the influence of grass cover on soil C storage is substantial.

Our soil C values represent an estimate for the top 20 cm of the tree-rows and drive lanes. We would suspect that, compared to deeper levels, the top 20 cm stores more C than lower depths due to the influence of groundcover decomposition, tree roots, and soil biology (Peck, 2009; Yao et al., 2005; Yao et al., 2006b). Work by Golubiewski (2006), who found that soil C decreased with depth due to decreased biological activity, would support this supposition. Because we homogenized our soil samples, we could only estimate soil C for the top 20 cm. While we suspect that the

top 20 cm had the largest pool of soil C, we would recommend that future research on orchard C storage stratify soil samples by depth and perhaps sample to lower depths to get a more accurate estimate of soil C storage.

Woody Biomass C Storage

Woody biomass C storage differed among GMS treatments and ARD rootstocks. Given modeling procedures, we presumed that we would see these differences because we saw differences in trunk cross-sectional area at these sites (Chapter 3). Our explanations for tree size differences (Chapter 3) would also justify differences in woody biomass C storage, since we used a constant proportion for C across treatments. In short, in the GMS study, it appears that the larger tree biomass and biomass C of the MUL was due to the fertility and biological activity of the MUL soil (Chapter 2; Yao et al., 2005). Woody biomass differences between the ARD rootstocks illustrate the role of genetics over PPST in tree growth, and thus C storage, at this replant site (Leinfelder and Merwin, 2006).

Application of Allometric Modeling to Orchards

In our review of the literature, we did not find a species-specific allometric equation for apple (*Malus* spp.), so instead we considered general hardwood equations for modeling AGB in the GMS, IFP-OFP, and ARD studies. We used the equations of Harris et al. (1973) and Kinerson and Bartholomew (1977) to quantify AGB in our studies because the equations were developed from northeastern United States forests having a wide variety of tree species and soil conditions. Latitude has been cited as influencing the validity of allometric equations for a particular site. Separate sets of

equations, both of which were developed in West Virginia, predicted similar biomass when applied to forests in West Virginia (Brenneman et al., 1978; Wiant et al., 1977). However, when equations developed in Maine (Ribe, 1973; Young et al., 1964) were applied to forests in West Virginia, ABG predictions differed by as much as 66% (Tritton and Hornbeck, 1982). Cairn et al. (1997) similarly described the importance of latitude in BGB estimations, showing that latitude correlated with root:shoot ratio and root biomass density. That work did not show relationships between root growth and AGB, tree age, temperature, or precipitation. For all three studies, we considered total AGB the sum of stem and branch biomass. We did not include leaf biomass in total AGB because leaves were a small proportion of total dry weight – ranging from 1.8-2.4 kg dry weight·tree in the GMS study (Atucha, unpublished) – and it is generally presumed that leaves do not account for major differences in AGB estimates (Tritton and Hornbeck, 1982).

Applying the Harris et al. (1973) equations to our historical GMS excavation data from 2000 illustrated that forest-derived allometric equations may not be appropriate for characterizing AGB in apple orchards. The Harris et al. (1973) equations overestimated actual biomass by 1.4 to 1.5 times, depending on treatment. Peper and McPherson (1998) similarly found that the Harris et al. (1973) equations overestimated actual AGB in urban plantings of Chisos cherry (*Prunus serotina* var. *rufula*), but not of white mulberry (*Morus alba*). They concluded that, because the cherry trees were heavily-pruned compared to the white mulberry, the equations could be applied to urban landscapes if the landscapes were only lightly-pruned. Annual pruning is one likely explanation for the over-estimation of AGB at our GMS site. (Another explanation would be annual fruit biomass removal.) We did not have biomass excavation data for the IFP-OFP and ARD studies; thus, we were not able to test the validity of the Kinerson and Bartholomew (1977) allometric equations.

Nevertheless, based on the GMS study, it appears that the application of forest-derived allometric equations to apple trees may not be appropriate if AGB, in absolute terms, is of interest.

Modeling apple root biomass based on a forest-derived, constant root:shoot ratio also may not be appropriate. The root:shoot ratio of orchards is influenced by irrigation and fertilization, which may result in proportionally less BGB than AGB compared to forests. Also, previous work at the GMS (Yao et al., 2009) and ARD (Yao et al., 2006a) sites would indicate that BGB is not proportionally constant across treatments. In the GMS study, trees in the PREHERB had more total roots and new roots than all other treatments but also had greater root mortality during a hot growing season due to higher soil temperatures. The MUL trees had proportionally more shallow roots, and the SOD trees had proportionally more deep roots. In the ARD study, the PPST did not influence root systems, but rootstock significantly influenced root lifespan and depth. Given this, using a constant root:shoot ratio to model BGB may not be appropriate in managed agricultural systems.

Expense and lack of time have been cited as reasons prohibiting the development of allometric equations for more tree species (Tritton and Hornbeck, 1982). Certainly, the felling of trees in a commercial orchard would not be desirable where fruit is the marketable product and not the wood. For this reason, we would not necessarily expect allometric equations to be developed for *Malus* spp. Additionally, biomass excavation studies are laborious, and roots – especially fine roots – are difficult to extract. Nevertheless, as interest in C storage and valuation increases, we suspect that the development of allometric equations for fruit tree species will become important. Development of such equations could come with the cooperation of growers, as orchards are renovated or land is sold for development.

System C Storage and Valuation

We had extensive soil and tree-row groundcover information for the GMS site, and we used that information to estimate soil and groundcover C storage in the tree-rows and drive lanes of all three long-term management orchards. To estimate woody biomass C storage, we used forest-derived allometric equations and found that these may overestimate C storage in absolute terms. For this reason, our system-wide C storage and valuation calculations may not represent C storage accurately in absolute terms. Nevertheless, our calculations do illustrate treatment differences across our three sites. We would expect differences among GMS treatments, since soil C storage and woody biomass C storage were both greatest in the MUL compared to the SOD, POSTHERB, and PREHERB. Similarly, we would not expect differences between IFP and OFP C storage since these treatments neither differed in soil C storage nor in woody biomass C storage. The results that we find particularly intriguing come from the ARD study and show that *either* pre-plant compost *or* a semi-dwarfing, replant disease-tolerant rootstock could similarly enhance system C storage.

Juxtaposing market value for C storage in these systems with social costs for C storage illustrates discrepancies in C valuation. The social costs are higher than the market price because social costs account for externalities that influence human welfare but are not valued in the market (Costanza et al., 1997). The $\$85 \cdot tC^{-1}$ of the Stern Review is higher than the other estimates. Nowak and Crane (2002) used an estimate of $\$20.30 \cdot tC^{-1}$ made by Fankhauser (1994). Kroodsma and Field (2006) valued C in California annual and perennial agricultural systems using a European price of $\$64.94 \cdot tC^{-1}$. Nevertheless, Costanza et al. (1997) stated that social costs for ecosystem services – like C storage – are often under-represented because there are

huge uncertainties not only in selecting a marginal value, but also in quantifying the service.

We have chosen to quantify and value C in these systems for two reasons: 1) soil C was determined to be a metric for soil health among these systems in a previous study (Chapter 2); and 2) a relationship between soil health and orchard yield could not be consistently illustrated (Chapter 3). Valuing C could give growers incentive to enhance soil health and ecosystem services in their orchards, even if these environmental improvements do not improve yields. The value added to an orchard based on the market price for C would likely not provide enough incentive for growers to change management, but a price that accounts for externalities may. While currently there is no policy in the United States to reward growers for C storage, this could be the direction of agricultural policy in the future, given the example set by the European Union (Sansavini, 1997). While future work should look at net C sequestration, accounting for C emissions from farms, our work serves to illuminate this new research direction, highlighting orchard management that enhances C storage and the added value of that management practice based on the value of C.

Conclusion

We have modeled apple orchard C storage for three long-term management systems and have found that C storage differs among GMS and ARD treatments, but not between IFP and OFP systems. Soil C storage in the tree-rows substantially differed among GMS and ARD treatments and was highest in systems where biomass soil amendments were involved, as with bark mulch groundcover or pre-plant compost. Soil C storage in the drive lanes between tree-rows was also a substantial component of system-wide C storage, but surface herbaceous and bark mulch

groundcover added little to system-wide C storage as a proportion. Like soils, woody biomass also contributed substantially to C storage in these systems. We modeled woody biomass in these systems based on forest-derived allometric equations and a forest-derived root:shoot ratio, which is similar to what has been done in pioneering work in urban landscapes. As in urban landscapes, there may be inaccuracies in applying these models to orchards, at least in absolute terms. Nevertheless, our work shows that these modeling procedures can be used to illustrate differences in C storage among orchard systems, and thus may be used to differentiate the sustainability of these systems, as it relates to C storage.

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