ECOLOGICALLY INTEGRATED PECAN PRODUCTION SYSTEMS OF THE SOUTHEASTERN UNITED STATES

by

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(Under the Direction of Lenny Wells)

ABSTRACT

The United States is one of the world's leading pecan producers, and Georgia has historically been the leading pecan-producing state. Soils throughout the southeastern Coastal Plain are low in natural fertility and overall quality. Due to the importance of pecans in this growing region, much focus has been placed on improving yields and maintaining orchard health. Increasing orchard soil health and fertility is essential to produce high yields and improve the soil quality found throughout the southeastern Coastal Plain. As a consequence of the high level of rainfall and humidity in this region, pecan scab [*Venturia effusa* (G. Winter) Rossman & W. C. Allen (basyonym *Fusicladium effusum*)] is prevalent. The use of disease resistant cultivars such as 'Lakota', 'McMillan', and 'Excel' may help producers increase net returns while reducing the amount of fungicides needed to manage pecan scab. Soil quality of commercial pecan orchards were assessed throughout a major commercial pecan producing region of South Georgia. Low input disease resistant pecan cultivars were evaluated for scab incidence at the University of Georgia Ponder Research Farm. Results from orchard soil studies demonstrate that pecan orchards under commercial management exhibited much higher levels of soil health and fertility compared to row crop fields in the southeastern Coastal Plain. Selected soil quality indicators provide evidence that the soil quality of commercial pecan orchards in this region is significantly improved over time. Results from the low input cultivar trials suggest that the utilization of scab resistant cultivars can reduce the amount of fungicides needed for optimal yields; thus providing a more sustainable means of production.

INDEX WORDS: *Carya illinoinensis*, Coastal Plain, *Fusicladium effusum*, Soil quality, Sustainability, Cultivar

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The United States and Mexico are the world's leading pecan producers. In the U.S., Georgia has historically been a leading pecan-producing state. Georgia produced 64.4 million kilograms of pecans in 2020, which accounted for almost half of all U.S. production (USDA 2021). Due to the importance of pecans in this region, much focus has been placed on improving yields and maintaining orchard health. Increasing orchard soil health and fertility is essential to promote soil sustainability and improve the soil quality found throughout the southeastern Coastal Plain. Soil quality is characteristically low in the loamy-sand, low pH soils found in this region. In addition, much of the agricultural land in this region is dominated by row crop production. These soils contain very little organic matter. A considerable number of pecan orchards throughout the southeastern United States are established from land previously used for row cropping systems. As a result, the amount of soil organic matter in pecan orchards of this region receives little attention (Wells 2009).

Changes in land use are known to exhibit different effects on soil quality. The conversion of an entire cropping system can change the physical and chemical properties of the soil (Lu et al. 2015). The concept of soil quality gives us a tool to quantify the responses of biological, physical, and chemical soil properties to varying changes in land use and management practices (Masto et al. 2008). Doran and Parkin (1994) defined soil quality as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health". Thornton et al. (1998) concluded that conversion of existing cropland to woody crops improved surface runoff and groundwater quality in the first year of establishment. Lee and Jose (2003) suggest that the incorporation of pecan trees in agroforestry systems enhance soil fertility and sustainability of agricultural land due to improvements in the amount of microbial activity and residual soil carbon. Pecan orchard systems have the ability to minimize soil erosion and increase water infiltration (Kremer and Kussman 2011), improve soil respiration (Lee and Jose 2003), increase soil organic matter (Wells 2009; Idowu et al. 2017), as well as improve enzymatic activity and nutrient cycling (Cabrera-Rodriguez et al. 2020; Wang et al. 2022). Despite the large pool of literature available, no studies specifically address soil enhancement from converting row crop land to pecan orchards in the southeastern United States. Environmental and economic benefits have not been thoroughly weighed for this change in land use and soil quality. We hypothesize that soil quality increases over time when land is converted from row crops to pecan production. The characterization of soil quality would require the selection of soil quality indicators that are sensitive to changing agricultural practices (Doran et al. 1994). This would allow us to better determine the effect of pecan orchards on soil enhancement over time.

Soil Quality Indicators

Organic matter is considered to be one of the most important indicators used to identify soil health. Organic matter represents a fraction of soil that contains plant and animal tissue in various stages of decomposition (Fenton et al. 2008). It encompasses many characteristics that give it the ability to influence other soil properties that make up soil quality as a whole. These characteristics include plant residues and living microbials, dead microorganisms and insects, along with more stable residues like humus. The living microorganisms in soil are largely responsible for breaking down and decomposing plant residues. The breakdown of these plant residues allows for the release of plant nutrients such as nitrogen, phosphorus, and potassium back into the soil (Fenton et al. 2008). Stable portions of organic matter don't affect fertility as much (Fenton et al. 2008); however, it does play a significant role in maintaining soil structure. The physical benefits of having good organic matter are just as important as the chemical and biological benefits. Proper levels of organic matter improve aggregate stability and help air and water to infiltrate the soil profile. This helps to promote water retention while reducing runoff and erosion (Gregorich et al. 1994). Organic matter can increase a soils cation exchange capacity, allowing a soil to retain more nutrients for plant uptake. Organic matter can also improve microbial diversity, which largely contributes back to soil fertility and plant health (Kirk et al. 2004). How we manage our soils can dictate the form, distribution, and overall amount of organic matter we have present in our soils (Soane 1990). Most Georgia soils typically contain anywhere from 0% to 2% organic matter. This is relatively low as Fenton et al. (2008) describes that most productive agricultural land contains between 3% and 6% organic matter. A soil's organic matter as a whole often does not change very rapidly (Carter 2002). It would need large inputs to change the total measurement of organic matter. Therefore, other attributes of organic matter that are more sensitive to change are often tested to map and track changes in soil's organic matter (Carter 2002).

Carbon is the foundation of organic matter in soil. It is the main food source for soil microorganisms. Soil organic carbon is a fundamental property to measure for determining soil health; however, it responds somewhat slowly to changes in soil management (Pulleman et al. 2021). Active carbon is a relatively new tool used to measure changes in soil carbon (Culman et al. 2012). Active carbon makes up about 1% to 4% of the total organic carbon in soil (Breker 2021a). This active carbon is often regarded as permanganate-oxidizable carbon (POXC) due to the development of a more efficient testing method by Weil et al. (2003), where POXC is measured from the chemical oxidation of organic matter by a potassium permanganate solution (Weil et al. 2003; Hurisso et al. 2016). Experiments conducted by Culman et al. (2012) and Hurisso et al. (2016) suggest that POXC is a suitable test to quickly indicate changes in land management. Active carbon is best utilized as a tool to track improvements in soil quality (Culman et al. 2012). This fraction of soil carbon is able to detect improvements in soil quality sooner than total carbon measurements (Hurisso et al. 2016); therefore, active carbon is considered a key soil health indicator (Breker 2021a).

Soil aggregates are the foundation of soil structure. Soil structure is the arrangement of sand, silt, and clay particles in soil. When these particles adhere together, aggregates are formed. Soil aggregates are held together by various organic and inorganic materials such as organic matter, plant root exudates, and fungi (Amezketa 1999; Breker 2021b). Good soil structure is a desirable trait of soils being used for agricultural production (Amezketa 1999). The presence of stable soil aggregates are a prerequisite to good soil structure. Blanco-Canqui and Lal (2004) explain that soil structure is a dynamic property that is extremely sensitive to soil management. A soil's aggregate stability is a crucial property due to the influence it has on physical and biological processes that take place within the soil profile (Amezketa 1999). Aggregate stability can give us important information about the capacity of a soil to function (Arshad and Coen 1992; Seybold and Herrick 2001). Maintaining high aggregate stability is important for improving soil health and reducing soil degradation (Amezketa 1999). Reduced tillage, no-till cropping systems, diversified crop rotations and cover cropping are important management practices that improve aggregate stability (Breker 2021b).

Bulk density is an important property of soil health that fluctuates with the structural state of soil (Chaudhari et al. 2013). According to USDA-NRCS (2019), this measurement is the ‘oven-dry weight of soil per unit of volume at field moisture capacity or at another specified moisture content.’ It influences soil characteristics such as available water capacity, infiltration, aeration, porosity, and available nutrients within the soil (USDA-NRCS 2019). Bulk density has been shown to be highly correlated with soil compaction (Al Shammary et al. 2018; USDA-NRCS 2019). Soil compaction can be a major problem for agricultural land due to the detrimental effects it can have on soil quality and crop productivity (Logsdon and Karlen 2004; Al Shammary et al. 2018). Soils are composed of four basic components; mineral matter, organic matter, air, and water. Each of which represents approximately 45%, 5%, 25%, and 25%, respectively. Soils with good bulk density should provide a strong foundation for plants while also supplying the correct amount of air and water to give plants enough pore space for unrestricted root exploration (Chaudhari et al. 2013). Knowing bulk density values are important for soil management practices. Bulk density values commonly increase deeper down into the soil profile (Chaudhari et al. 2013; USDA-NRCS 2019). High bulk density can be an indicator of compacted soils and low porosity (USDA-NRCS 2019). If bulk density were to become too high, root growth could be inhibited (Logsdon and Karlen 2004). Restricting root growth and water infiltration can lead to a negative impact on crop yield (Logsdon and Karlen 2004; USDA-NRCS 2019).

In short, porosity is the amount of soil that is occupied by pore spaces (Hao et al. 2008). The disposition and texture of soil particles are key factors determining porosity (Hao et al.

2008); however, the pore spaces are just as important as the soil particles surrounding them (Shaxson and Barber 2003). Understanding the distribution and size of soil pores is useful for measuring the structure of the soil (Carter and Ball 1993; Hao et al. 2008). Hao et al. (2008) considers pore size and distribution to be a leading indicator of a soil's physical condition. Pagliai and Vignozzi (2002) suggest porosity to be the best indicator of a soil's structural quality. Generally, soil porosity is inversely related to a soil's bulk density (Chaudhari et al. 2013). As bulk density increases, soil porosity decreases (Hao et al. 2008). Sandy soils are comprised of mostly large pores but have less porosity than clay soils that contain much smaller pores (Hao et al. 2008); however, fine textured soils like clay are more susceptible to compaction (Shaxson and Barber 2003). Good soil porosity serves an important role in environmental stability and crop productivity. These pore spaces allow for water and air to move through the soil as well as allow plant roots to explore to reach water and nutrients (Kay and VandenBygaart 2002; Shaxson and Barber 2003).

The cation exchange capacity (CEC) of a soil is the amount of total negative charges in the soil that can retain cations such as calcium, magnesium and potassium (Sonon et al. 2017). The CEC is a property of soil that describes the overall amount of exchangeable cations that can be adsorbed by the soil (Ketterings et al. 2007). CEC influences nutrient availability, soil pH, structural stability of soil (Hazelton and Murphy 2016), as well as fertilizer and liming applications (Sonon et al. 2017). Cation exchange sites exist on clay minerals and organic matter in the soil (Ross and Ketterings 1995). These cations remain in the soil profile and are available to restore ions in soil solution and for plant uptake (Ketterings et al. 2007; Sonon et al. 2017). Sandy soils that have very little organic matter or clay content exhibit a lower CEC. Soils with a higher CEC are able to retain more nutrients than soils with a low CEC (Ross and Ketterings

1995). Soils with low CEC are more susceptible to nutrient deficiencies as they are more prone to leaching due to less adsorption of cations (Ketterings et al. 2007). High CEC soils also resist changes in pH much better than soils with low CEC; therefore, low CEC sandy soils have to be limed more often (Sonon et al. 2017). Inversely, soils with a high CEC require larger quantities of lime to raise its pH (Ketterings et al. 2007). As the pH of a soil increases with liming, the CEC generally increases as well (Sonon et al. 2017). Ross and Ketterings (1995) suggest that when coupled with other soil fertility measurements, CEC makes for a good indicator of soil quality.

Solvita CO_2 Burst is a biological soil test that measures CO_2 respiration in an aerobic soil sample (Moore et al. 2019a) with the use of gel paddles that are sensitive to CO_2 concentrations (Haney et al. 2008; Solvita 2011). This test is used to quantify soil respiration due to biologically active microbes in the soil. Soil respiration is a key property of soil quality that also serves as an indicator for soil fertility (Haney et al. 2008). Soils with dense populations of microbes are considered to be biologically active and productive (Moore et al. 2019b). CO_2 respiration in soil is an important measurement used to quantify the effect of various management practices on soil microbial activity (Haney et al. 2008). The total amount of CO_2 released from a soil sample is a strong indicator of biological activity and soil health (Solvita 2011; Brinton 2019b). Data from Haney et al. (2008) indicate that the Solvita CO_2 Burst test can serve as an efficient way to quantify soil microbial activity. Moore et al. (2019a; 2019b) suggest that this method can also serve as an indicator of nitrogen mineralization.

The Solvita SLAN test stands for Solvita Soil Labile Amino-Nitrogen. This is a relatively new test that uses an alkali-extraction to measure labile soil nitrogen (Solvita 2011; Moore et al. 2019a). SLAN tests aim to measure and quantify the pool of potential plant available organic nitrogen that is present in the soil (Solvita 2011; Brinton 2019a). This fraction of soil nitrogen is important to assess due to its mineralization potential and ability to provide available nitrogen to plants (Chen et al. 2018; Moore et al. 2019c) which corresponds well with soil fertility and biological soil health. SLAN has primarily been used in recent years (Moore et al. 2019a; 2019c) to measure crop responses to additions of organic nitrogen in varying concentrations. When combined with Solvita CO_2 Burst, this test provides an in-depth view of available soil nitrogen (Solvita 2011; Moore et al. 2019a).

Pecan Scab and Cultivar Resistance

Georgia's location falls in the southeastern pecan growing region. This region is known to have long growing seasons with hot summers and frequent rainfall (Conner 2014). Due to the high level of rainfall and humidity in this region, pecan scab [*Venturia effusa* (G. Winter) Rossman & W. C. Allen (basyonym *Fusicladium effusum*)] is extremely prevalent. Pecan scab is the most detrimental pecan disease in the southeastern United States (Gottwald and Bertrand 1983; Bock et al. 2016). With increasing scab susceptibility and fungicide resistance, more fungicide applications are required throughout the growing season on scab susceptible cultivars (Wells 2014). Fungicides used to control scab can account for more than 12% of variable production cost (Wells 2021). More fungicide applications mean more fuel, equipment and labor, all of which increase the cost of production. At 2014-2015 variable production cost, growers spent $1628 /acre to produce pecans with 16 fungicide sprays (Wells 2014, 2018). Since then, chemical prices have increased even more with variable costs for 16 spray applications in 2018 being up to $1800 /acre (Wells 2018).

Pecan cultivars in this region must possess some level of resistance to scab in order to be successfully managed with fungicides (Conner 2014). Proper cultivar selection is one of the most important decisions a grower can face. The 'Desirable' cultivar has been considered the standard for nut quality in the southeast and is the most widely established variety in Georgia (Wells and Conner 2015). However, the more widely a cultivar is planted, the more likely it is that resistance will eventually break down (Conner 2002). In the past, the ‘Desirable’ cultivar was considered highly resistant to pecan scab. However, ‘Desirable’ is now one of the most susceptible cultivars to pecan scab and is no longer recommended for planting in southern Georgia (Wells and Conner 2015; Conner 2022). Widespread popularity of the cultivar has allowed scab fungal races able to infect ‘Desirable’ to evolve over time and become prominent in orchards throughout the southeast (Conner 2002).

There are several practices used today to manage pecan scab. Application of fungicides and careful selection and implementation of resistant cultivars are among the most heavily used methods (Bock et al. 2016). However, resistant varieties still require scheduled applications of fungicides (Turechek and Stevenson 1998). Reduced input orchards have been studied in apple orchards where reduced fungicide programs are matched with apple cultivars with varying levels of scab resistance (Brun et al. 2007). The number of fungicide applications can be significantly reduced over the course of a season for a cultivar that is resistant compared to one that is not. Orchard strategies that integrate resistant cultivars with conventional cropping systems are needed to increase the durability of cultivar resistance (Didelot et al. 2016). Optimizing yield while minimizing profit loss to scab could be achievable by creating specific management practices for cultivars that exhibit some scab resistance (Turechek and Stevenson 1998). This could potentially be a successful alternative for pecan production in the southeastern United States.

Many growers in the southeast now opt to plant more resistant cultivars due to the difficulty and expense of managing ‘Desirable’ trees (Conner 2014). Cultivars that have high levels of resistance to scab may help growers increase profits by having a significantly reduced fungicide program. The disease resistant cultivars ‘Lakota’, ‘McMillan’, and ‘Excel’ were the subjects this study. ‘Excel’ has been widely planted in the southeast since 2005 (Conner 2014). It has been highly recommended for growers due to its excellent scab resistance (Wells and Conner 2015). The ‘Excel’ variety produces a large nut similar in size to ‘Desirable”. However, it has a thick shell, and this factor limits its’ percent kernel, which is a primary measure of nut quality (Wells and Conner 2015). The ‘McMillan’ cultivar has also been selected for excellent levels of resistance to pecan scab (Wells and Conner 2015). Nut quality is average with this variety and as a result, ‘McMillan’ has been regarded as a cultivar that is good for low input operations (Conner 2014). The ‘Lakota’ variety was released in 2007 and has not been widely planted in the southeastern United States. It has shown some variability in nut size and alternate bearing; however, trials have shown it to have very high levels of resistance to scab (Wells and Conner 2015). It is believed that mechanical fruit thinning or hedging to manage the crop load may minimize its alternate bearing tendency (Wells, unpublished data).

Although scab resistant cultivars are available, pecan scab has the ability to persist and adapt to new cultivars over time (Conner 2002). Regardless, planting resistant cultivars is still the most desirable practice for controlling scab (Bock et al. 2016). Integrating resistant cultivars into commercial orchards may lower costs for producers throughout the growing season, thus allowing for a larger profit margin.

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CHAPTER 2

SOIL QUALITY ENHANCEMENT OVER TIME IN PECAN ORCHARD SYSTEMS OF THE SOUTHEASTERN COASTAL PLAIN [1]

[1] Slade H., Wells L. Submitted to *HortScience*, 05/04/22.

Abstract

Pecan orchards in Georgia and throughout the southeastern United States are commonly established from land that had previously been used for row cropping systems. Soil quality is characteristically low in the loamy-sand, low pH soils of the southeastern Coastal Plain. Changes in land use are known to exhibit different effects on soil quality; however, no studies specifically address soil enhancement from converting row crop land to pecan orchards in this region. Studies were conducted in eight counties throughout the coastal plain of South Georgia in 2020 and 2021. The objectives of this study were to analyze and compare soil quality indicators of pecan orchards of varying ages and adjacent row crop fields. Soil quality indicators analyzed include soil organic matter (SOM), active carbon (POXC), aggregate stability, cation exchange capacity (CEC), bulk density, porosity, Solvita CO_2 Burst, Solvita SLAN, pH, and total N. Results from this study show that pecan orchards under commercial management exhibited much higher levels of soil health and fertility compared to row crop fields in the southeastern Coastal Plain. Selected soil quality indicators provide evidence that the soil quality of commercial pecan orchards in this region is significantly improved over time.

Introduction

The United States is one of the world's leading pecan producers, and Georgia has historically been the leading pecan-producing state, typically accounting for about 33 percent of U.S. production (USDA 2015). Pecans are one of Georgia's most valuable horticultural crops, being grown on 54,227 hectares throughout the state (USDA 2021). Georgia produced 64.4 million kilograms of pecans in 2020, which accounted for almost half of all U.S. production (USDA 2021). Given the importance of pecans in this region, much focus has been placed on improving yields and maintaining orchard health. As input costs increase each year, growers have to rely on sustainable orchard production. Increasing orchard soil health and fertility is essential to promote soil sustainability and improve the soil quality found throughout the southeastern Coastal Plain.

Doran and Parkin (1994) defined soil quality as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health". The concept of soil quality gives us a tool to quantify the responses of biological, physical, and chemical soil properties to varying changes in land use and management practices (Masto et al. 2008). Changes in land use are known to exhibit different effects on soil quality; however, there is little data available that specifically analyzes the enhancement of soil quality from converting row crop land to pecan orchards in the southeastern U.S. Soil quality is characteristically low in the loamy-sand, low pH soils found in this region. These soils contain very little organic matter and as a result, the amount of soil organic matter in pecan orchards of this region receives little attention (Wells 2009).

Thornton et al. (1998) concluded that conversion of existing cropland to woody crops improved surface runoff and groundwater quality in the first year of establishment. Lee and Jose

(2003) suggest that the incorporation of pecan trees in agroforestry systems enhance soil fertility and sustainability of agricultural land due to improvements in the amount of microbial activity and residual soil carbon. Pecan orchard systems have the ability to minimize soil erosion and increase water infiltration (Kremer and Kussman 2011), improve soil respiration (Lee and Jose 2003), increase soil organic matter (Wells 2009; Idowu et al. 2017), as well as improve enzymatic activity and nutrient cycling (Cabrera-Rodriguez et al. 2020; Wang et al. 2022).

Much of the agricultural land in this region is dominated by row crop production. Thus, many pecan orchards in Georgia and throughout the entire southeastern United States are established from land that had previously been used for row cropping systems. We hypothesize that soil quality increases over time when land is converted from row crops to pecan production. The soils associated with these two different cropping systems are affected by numerous factors. Thus, the characterization of soil quality would require the selection of soil quality indicators that are sensitive to changing agricultural practices (Doran et al. 1994). This would allow us to better determine the effect of pecan orchards on soil enhancement over time.

The objectives of this study were to analyze and compare physical, chemical, and biological soil quality indicators of pecan orchards of varying ages and adjacent row crop fields. Our goal was to assess the response of these soil properties to changes in land use. Soil quality indicators selected in this study include organic matter (SOM), active carbon (POXC), aggregate stability, cation exchange capacity (CEC), bulk density, porosity, Solvita CO2 Burst, Solvita SLAN, pH, and total N.

Materials and Methods

Studies were conducted in eight counties throughout the coastal plain of South Georgia in 2020 and 2021 (Fig. 2.1). This is a major region of commercial pecan production. The conditions observed throughout the sampled area exemplify agricultural soils of the southeastern U.S. coastal plain (Wells 2009). Commercial pecan orchards established from land previously in row crop production and located directly adjacent to row crop fields were selected for sampling. Adjacent row crop fields were also sampled to determine differences in soil quality with minimal variation in soil type and texture. Pecan orchards were separated into age groups of 1-4, 5-10, 11-20, and >20 years old to analyze changes in soil quality over time. Orchards and corresponding row crop fields sampled across all sites were largely comprised of seven different soil types. These include Tifton (fine-loamy, kaolinitic, thermic Plinthic Kandiudults), Dothan (fine-loamy, kaolinitic, thermic Plinthic Kandiudults), Fuquay (loamy, kaolinitic, thermic Arenic Plinthic Kandiudults), Greenville (fine, kaolinitic, thermic Rhodic Kandiudults), Faceville (fine, kaolinitic, thermic Typic Kandiudults), Orangeburg (fine-loamy, kaolinitic, thermic Typic Kandiudults), and Red Bay (fine-loamy, kaolinitic, thermic Rhodic Kandiudults). All of the orchards selected for sampling are managed for commercial production in accordance with University of Georgia Cooperative Extension recommendations (Wells 2017a). Row crop fields sampled followed conventional farming practices with both conventional and conservation tillage methods. These fields were either in cotton, peanut, or corn production each year.

Soil sampling was conducted from June 1 to July 31 in 2020 and from June 1 to July 30 in 2021. Soil samples were pulled at random throughout each pecan orchard and row crop field. Samples were collected from the row middles of orchards and row crop fields at a depth of 0-15 cm each year. Four composites were collected from each pecan orchard and each corresponding row crop field. In 2021, an additional round of soil samples was collected at a depth of 91-106 cm. Cores taken at this depth were combined to create one composite for each pecan orchard and corresponding row crop field. A total of 496 composites were collected throughout 41 commercial pecan orchards and row crop fields across the sampled region.

Soil was analyzed by Waters Agricultural Laboratory (Camilla, GA) each year. Samples were dried and sieved using a 2 mm mesh before analysis. Soil quality indicators were tested at 0-15 cm both years and 91-106 cm in 2021. Soil pH was determined with a soil/water ratio of 1:1 and read with a hydrogen probe. Organic matter was determined by the loss on ignition method. Total nitrogen was determined using the Kjeldahl method. Cation exchange capacity (CEC) was determined by the ammonium acetate method (pH 7). Aggregate stability was determined using the Volumetric Aggregate Stability Test (Woods End Laboratories). Bulk density and porosity were calculated using the core method. Solvita CO_2 Burst and SLAN tests were conducted according to Woods End Laboratories guidelines (Brinton 2019a; 2019b). Active carbon measurements were determined following UIUC Soils Lab POXC procedure (SOP: POXC 2021).

Analysis of variance (ANOVA) was used to determine significant changes in soil quality by comparing soil analysis results of pecan orchards with that of adjacent row crop fields. All statistical analyses were performed using SigmaPlot 14 statistical software. All pairwise multiple comparison procedures were performed using Tukey’s Test ($P < 0.05$). Pearson linear correlation coefficients (r) were calculated for SOM and biological soil properties at 0-15 cm.

Results and Discussion

Significant differences in soil organic matter were observed between sites with samples taken from 0-15 cm. Soil organic matter (SOM) was significantly higher ($p < 0.001$) in orchards 11 years and older than that of row crop fields in 2020 (Table 2.1). Orchards from the 11-20 and >20 year old group contained 1.08% and 1.85% SOM, respectively, while row crop fields contained only 0.73%. In 2021, soil analysis showed that organic matter was significantly higher ($p < 0.05$) in orchards 1-4 and >20 years old compared to row crop fields (0-15 cm) (Table 2.1). Orchards 1-4 and >20 years old contained 0.99% and 1.17% SOM, respectively, while row crop fields contained 0.71%. Samples taken at 91 cm gave us a value of the more stabilized amount of organic matter present in the soil profile throughout these sites. These values from deeper in the soil profile have greater potential significance with regard to long-term carbon storage (Tautges et al. 2019). At this depth, mean values of orchard soils ranged from 0.84% to 1.03% organic matter while row crop fields contained an average of 0.98%. There were no significant differences in the amount of soil organic matter present throughout orchards and row crop fields at a depth of 91 cm in the soil profile (Table 2.2). Variations in organic matter between 2020 and 2021 at the 0-15 cm depth are likely related to microbial activity as influenced by variations in temperature and/or rainfall. The southeastern United States is more susceptible to organic matter decomposition due to our warm and wet climate (Triplett Jr. and Dick 2008). It is also particularly favorable to microbial activity throughout the majority of the year which prevents organic matter from building up (Wells 2009). However, compared to conventionally farmed row crop fields from the same region, pecan orchards do tend to hold more organic matter (Giddens 1957; Wells 2009). Higher levels of organic matter in pecan orchards are likely the result of the accumulation of plant biomass that is returned to the soil each year. According to

Idowu et al. (2017), pecan husks alone account for 25-30% of the total mass of the pecan. These husks dry out and fall to the orchard floor each growing season, bringing a considerable amount of plant material back to the soil. Decomposition of leaves and woody plant debris on the orchard floor (Wells 2009) along with orchard soils being left uncultivated after each cropping season (Giddens 1957) contribute to the increased levels of organic matter in pecan orchards.

In 2020, active carbon was significantly higher ($p < 0.001$) in orchards 5 years and older compared to row crop fields (Table 2.1). Active soil carbon from orchards 5-10, 11-20, and >20 years old measured 405.28 mg/kg^{-1}, 485.19 mg/kg^{-1}, and 715.05 mg/kg^{-1} respectively, while row crop fields measured 333.47 mg/kg^{-1}. In 2021, active carbon at 0-15 cm was significantly higher ($p < 0.001$) in orchards 11 years and older than that of row crop fields (Table 2.1). Orchards from the 11-20 and >20 year old group measured 322.95 mg/kg^{-1} and 476.85 mg/kg^{-1} respectively, while row crops contained 246.13 mg/kg^{-1}. Active carbon levels were significantly lower ($p < 0.001$) in samples taken at 91 cm. We observed no significant differences in the amount of active carbon between orchards and row crop fields at this depth (Table 2.2). This active portion of soil carbon has been found to strongly correlate with improved microbial activity and other soil carbon functions (Weil et al. 2003; Culman et al. 2012). Orchards from the >20 year old group exhibited 2.1x and 1.9x the amount of active carbon in 2020 and 2021, respectively, than row crop fields at 0-15 cm. These data indicate that microbially available energy sources are increasing in pecan orchard soils over time. Active carbon generally has a strong relationship with total SOM (Breker 2021a), but it responds much sooner to differences in crop and soil management (Hurisso et al. 2016). We found active carbon to be positively correlated with SOM ($R^2 = 0.659$) throughout this study (Fig. 2.2). Observed SOM data does show significant increases in orchard soils, but the overall amount is still relatively low (< 2%). The relatively low

SOM levels in the Georgia Coastal Plain compared to soils in other regions are a result of the highly weathered soils, the warm, humid climate, and the resulting rapid breakdown of OM by soil microbes. Breker (2021a) suggests that active carbon measurements help explain why soils with similar levels of organic matter have the ability to exhibit much different levels of biological activity.

The Solvita CO_2 Burst test was used to evaluate soil respiration as a result of microbial activity. Solvita CO_2 Burst measurements were significantly higher ($p < 0.001$) in orchards 1-4 years old and older compared to row crop fields in 2020 (Table 2.1). Orchard soils exhibited an increase in CO_2 Burst values as they increased with age (Table 2.1). Mean CO_2 Burst values ranged from 39.12 mg/kg^{-1} (1-4 year old orchards) to 54.49 mg/kg^{-1} (>20 year old orchards), while row crop fields measured 25.97 mg/kg^{-1}. In 2021, Solvita CO_2 Burst measurements at 15 cm were also significantly higher ($p < 0.001$) in orchards 1-4 years old and older than that of row crop fields (Table 2.1). Orchard soils' mean values ranged from 31.05 mg/kg^{-1} to 49.65 mg/kg^{-1}, while row crop fields measured 21.52 mg/kg^{-1}. CO_2 Burst values were significantly lower ($p < 0.001$) in samples taken at 91 cm (Table 2.2). There were no significant differences observed between orchards and row crop fields at this depth. The Solvita CO_2 Burst test has been used to evaluate soil CO_2 respiration in various crops (Goupil and Nkongolo 2014; Sadeghpour et al. 2016; Sciarappa et al. 2017; Chahal and van Eerd 2018; Moore et al. 2019b); however, there is little to no information regarding the use of this test to measure soil respiration in pecan orchard systems. The soil data from this study demonstrates that soil respiration is significantly enhanced in pecan orchards in this region when compared to conventionally farmed row crop fields. This increase in soil respiration could be due to an increase in total microbes present in the soil or to increased activity of the microbes present as a result of higher active carbon levels. We found that active carbon and CO_2 Burst measurements were positively correlated ($R^2 = 0.421$) (Fig. 2.3), which agrees with the findings of Bongiorno et al. (2019). Orchard soils also contained larger amounts of organic matter which would allow for the increase of microbial diversity and microbial activity (Cotrufo et al. 2013). We found CO_2 Burst values to be positively correlated with SOM ($R^2 = 0.404$), indicating that soil respiration increases as more organic matter is present in the soil (Fig. 2.4).

The Solvita SLAN test was used to measure the amount of potential plant available organic nitrogen in the soil. In 2020, Solvita SLAN was significantly higher ($p < 0.001$) in orchards 5 years and older than that of row crop fields (Table 2.1). Orchards 5-10, 11-20, and >20 years old measured 75.81 mg/kg^{-1}, 82.15 mg/kg^{-1}, and 134.19 mg/kg^{-1} respectively, whereas row crop fields measured 57.42 mg/kg^{-1}. Solvita SLAN measurements were significantly higher ($p < 0.001$) in orchards >20 years old compared to that of row crop fields in 2021 at the 15 cm depth (Table 2.1). Orchards >20 years old measured 75.88 mg/kg^{-1}, while row crop fields measured 43.70 mg/kg^{-1}. Solvita SLAN values were significantly lower ($p < 0.001$) in samples taken at 91 cm (Table 2.2). There were no significant differences between orchards and row crop fields at this depth. Increasing SLAN concentrations indicate a larger pool of amino N present in pecan orchards. This increase of plant available organic nitrogen is tied to the increase in the stable humus portion of organic matter (Kelley and Stevenson 1995; Brinton 2019a). Larger pools of amino N present may also indicate more nitrogen mineralization taking place in orchard soils. An increase in available N reserves translates well to the enhancement of soil health and fertility in pecan orchards.

Soil pH was significantly higher ($p < 0.001$) in pecan orchard soils than that of row crop fields in 2020 and 2021 at 15 cm (Table 2.1). At this depth, mean soil pH values averaged 6.4

and 6.5 for all orchards in 2020 and 2021, respectively, whereas mean soil pH of row crop fields averaged 5.9 each year. Soil pH is likely buffered in orchards by lack of cultivation and the increase in SOM (Helling et al. 1964). Samples taken at 91 cm in 2021 exhibit significantly lower ($p < 0.001$) soil pH values; however, we observed no significant differences between the soil pH of orchards and row crop fields at this depth (Table 2.2). Soils of the southeastern Coastal Plain are inherently acidic. The growth of pecans can be sensitive to soil pH (Wells 2009), as a soil with low pH can negatively affect the tree's roots by restricting their growth (White et al. 1982). Raising soil pH with liming materials is common practice in pecan orchards throughout the Southeast to ensure the availability of essential nutrients. Generally, maintaining a soil pH of 6.0 to 6.5 is recommended for pecan orchards in this region (Wells 2017a).

Cation exchange capacity (CEC) was significantly higher ($p < 0.001$) in orchards 11 years and older than that of row crops in 2020 (Table 2.1). Orchards 11-20 and >20 years old measured 6.37 meq/100g and 9.26 meq/100g, respectively, whereas row crop fields measured 4.88 meq/100g. In 2021, CEC was also significantly higher ($p < 0.001$) in orchards 11 years and older compared to that of row crop fields at 15 cm (Table 2.1). Orchards 11-20 and >20 years old measured 5.89 meq/100g and 8.61 meq/100g, respectively, while row crop fields measured 4.59 meq/100g. Soil samples taken at 91 cm indicate that CEC decreased slightly with depth. We observed no significant differences in CEC values between orchards and row crop fields at this depth (Table 2.2). Soils throughout the southeastern coastal plain region have an average cation exchange capacity of approximately 6 meq/100g (Sonon et al. 2017). The data observed here indicates that over time, pecan orchard soils exceed average CEC values for the coastal plain region. The soils sampled across all sites have similar soil textures, so increases observed in CEC are likely partially due to the increase of organic matter content in pecan orchard soils. Ramos et al. (2018) found that soil CEC was reduced considerably in soils absent of organic matter. Soil pH also plays a considerable role in cation exchange capacity. CEC generally increases with increasing soil pH (Sonon et al. 2017). Pecan orchard soils exhibited higher soil pH values, likely contributing to the enhanced cation exchange capacity of these soils. Saikh et al. (1998) suggests that cultivation tends to reduce a soil's CEC, which helps to explain the lower CEC values obtained from row crop fields.

Total N levels were significantly higher ($p < 0.05$) in orchards 11-20 years old compared to row crop fields in 2020 (Table 2.1). Orchards 11-20 years old measured 0.31%, while row crop fields measured 0.22%. In 2021, total N levels were significantly higher ($p < 0.05$) in orchards 5-10 and >20 years old compared to row crop fields at 15 cm (Table 2.1). Orchards 5-10 and >20 years old measured 0.22% and 0.23%, respectively, whereas row crop fields measured 0.17%. Measurements taken from samples at 91 cm revealed that mean values for total nitrogen were slightly higher than values obtained at 15 cm in 2021 (Table 2.2). We observed no significant differences in total nitrogen values between orchards and row crop fields at 91 cm; however, the data may indicate nitrate leaching through the soil profile in pecan orchards and row crop fields. The total N levels we observed at this depth may be due to the increase in rainfall we received in 2021, as nitrate is easily lost through the soil profile due to rainfall and irrigation (Wang et al. 2015). The higher levels of total nitrogen observed in orchard soils at 0-15 cm could be due to the amount of fertilizer applied to pecans throughout the year. According to Wells (2017b), mature pecan trees require 34-68 kg of nitrogen each growing season. We observed higher levels of organic matter and microbial activity in orchard soils which also contribute to increased soil N levels. The fact that total N levels in orchard soils were higher than that of row crops at 0-15 cm but similar at 91 cm indicates that tree roots are removing considerable amounts of nitrogen from the soil profile. This is supported by Allen et al. (2004), who suggest that pecan tree roots were able to capture N in a cotton-pecan alley-cropping system, resulting in lower rates of leaching below the root zone. Lower levels of total nitrogen observed in row crop fields are likely attributed to the degradation of organic matter and soil structure after cultivation (Emiru and Gebrekidan 2013).

Aggregate stability in orchards >20 years old was significantly higher ($p < 0.05$) than row crop fields in 2020 (Table 2.1). Pecan orchards >20 years old exhibited 7.05% aggregate stability while row crop fields only 5.16%. In 2021, aggregate stability was significantly higher ($p < 0.05$) in orchards 1-4 and 11-20 years old compared to row crop fields at 15 cm (Table 2.1). Orchards from the 1-4 and 11-20 year old group measured 8.90% and 9.90% aggregate stability, respectively, whereas row crop fields measured 6.79%. Data from samples taken at 91 cm demonstrate that aggregate stability decreased slightly with depth; however, there were no significant differences between orchards and row crop fields at this depth (Table 2.2). The improved aggregate stability of pecan orchard soils is likely due to the significant increases in the amount of organic matter present. Increasing levels of organic matter help to improve the formation of stable soil aggregates. This increase in aggregate stability could also have been due to the significant increase of microbial activity we observed in pecan orchards. Microbial activity in soil has shown the ability to increase the formation of soil aggregates (Six et al. 2004; Idowu et al. 2017). Good aggregate stability improves pore space, which can increase water and air infiltration as well as allow for deeper root exploration (Kemper and Rosenau 1986; Amezketa 1999; Breker 2021b). Faster water infiltration coupled with better water retention can help to reduce runoff and erosion throughout pecan orchards. Good aggregate stability also promotes a better habitat for microorganisms (Breker 2021b).

Bulk density measurements were nearly identical across all sites in 2020. We observed no significant difference in bulk density between orchards and row crop fields (Table 2.1). Mean bulk density values averaged 1.34 g/cm^3 for all orchards, whereas row crop fields measured 1.40 g/cm^3. Soil samples taken in 2021 yielded similar results. No significant differences in bulk density were observed between soils of pecan orchards and row crop fields at 15 cm (Table 2.1). Mean bulk density values averaged 1.61 g/cm^3 for all orchards, while row crop fields measured 1.59 g/cm^3. Bulk density measurements from samples taken at 91 cm were significantly lower ($p < 0.001$) than the values obtained from samples at 15 cm; however, we observed no significant differences between orchards and row crop fields at this depth (Table 2.2). The bulk density measurements from samples taken at 91 cm are much lower than expected, as bulk density generally increases with soil depth. Other soil quality indicators analyzed in this study that correlate with bulk density indicate that the values obtained at 91 cm should have been higher. This may be due to a sampling error at this depth. Higher bulk density values near the soil surface could also indicate some compaction, which could likely be attributed to equipment traffic due to management practices. Sandier soils generally have higher bulk densities than clay or silt soils because they have less porosity (Hao et al. 2008; USDA-NRCS 2019). The average range of bulk densities for sandy soils is 1.2 to 1.8 g/cm^3 (Chaudhari et al. 2013). The ideal bulk density for unrestricted root growth in sandy soils throughout this region is $\leq$1.60 g/cm^3 (USDA-NRCS 2019). The bulk density measurements we obtained align with these thresholds; however, we saw no significant enhancement of bulk density in pecan orchards compared to row crop fields.

In 2020, we observed no significant differences in soil porosity between pecan orchards and row crop fields (Table 2.1). Mean soil porosity values of pecan orchards ranged from

56.18% to 63.74%, whereas row crop fields measured 59.99%. Soil samples taken in 2021 yielded similar results, in which no significant differences were observed between orchards and row crop fields at 15 cm (Table 2.1). Mean soil porosity values of pecan orchards ranged from 61.87% to 66.27%, while row crop fields measured 62.88%. Porosity measurements from samples taken at 91 cm were significantly lower ($p < 0.001$) than porosity values obtained from samples at 15 cm; however, we observed no significant differences between orchards and row crop fields at this depth (Table 2.2). At 91 cm, mean porosity values for pecan orchards ranged from 39.24% to 46.83%, whereas row crop fields measured 43.80%. Soil porosity values obtained from 0-15 cm are higher than average as Hazelton and Murphy (2016) suggest that the porosity of a typical agricultural soil is about 47%. Hao et al. (2008) reported that the porosity of sandy soils generally ranges from 35% to 50%, but can extend up to 60% with some finer textured sands. Porosity and bulk density values were consistent across all sites in 2020 and 2021 (0-15 cm); therefore, we did not observe any significant improvements in pecan orchards compared to row crop fields. These results are likely due to the uniformity of soil texture throughout the sampled areas in this region.

Conclusion

Pecan orchards under commercial management exhibited much higher levels of soil health and fertility at 15 cm compared to row crop fields in the southeastern Coastal Plain. The management practices of these two different cropping systems have a considerable influence on soil quality. The annual cultivation of row crop land aids in soil degradation and reduced biological activity, while the largely undisturbed soils of pecan orchards allow for perennial accumulation of organic matter. We observed significantly higher levels of SOM in pecan orchards of various ages both years of the study. Active carbon and Solvita CO_2 Burst measurements indicated that pecan orchards exhibited significantly higher rates of microbial activity and soil respiration. Although we observed no differences in bulk density and porosity between pecan orchards and row crop fields, aggregate stability did significantly increase in orchard soils over time. Pecan orchards exhibited a much higher cation exchange capacity (CEC) with age when compared to row crop fields. The higher Solvita SLAN and total N measurements we observed in pecan orchards are associated with an increase in soil fertility. These results also suggest that pecan roots are capable of removing excessive nitrogen from the soil profile, reducing nitrate leaching. Results from the selected soil quality indicators provide evidence that the soil quality of land previously used for conventional row cropping systems in the southeastern Coastal Plain is significantly improved over time when converted to commercial pecan production.

Table 2.1. Synopsis of all soil quality indicator measurements from soil samples taken in 2020 and 2021 at 0-15 cm in depth.

		Soil Quality Indicators									
Year	Site[x]	Active Carbon (mg/kg^{-1})	Aggregate Stability (%)	Bulk Density (g/cm^{3})	CEC (meq/100g)	Organic Matter (%)	Porosity (%)	Solvita CO2 Burst (mg/kg^{-1})	Solvita SLAN (mg/kg^{-1})	Soil pH	Total N (%)
2020	1-4 yr.	353.10 cd	6.30 ab	1.32 a	5.00 c	0.80 bc	63.65 a	39.12 c	58.88 c	6.25 ab	0.23 ab
	5-10 yr.	405.28 c	5.75 ab	1.34 a	5.08 c	0.94 bc	60.58 a	48.28 b	75.81 b	6.34 a	0.20 b
	11-20 yr.	485.19 b	6.17 ab	1.38 a	6.37 b	1.08 b	56.18 a	48.94 b	82.15 b	6.65 a	0.31 a
	>20 yr.	715.05 a	7.05 a	1.32 a	9.23 a	1.85 a	63.74 a	54.49 a	134.19 a	6.53 a	0.25 ab
	Row Crop	333.47 d	5.16 b	1.40 a	4.88 c	0.73 c	59.99 a	25.97 d	57.42 c	5.96 b	0.22 b
2021	1-4 yr.	305.75 bc	8.90 ab	1.62 a	5.35 bc	0.99 a	66.27 a	36.28 b	49.50 b	6.51 a	0.17 b
	5-10 yr.	276.05 bc	7.60 bc	1.64 a	4.77 c	0.66 b	63.10 a	31.05 b	47.50 b	6.44 a	0.22 a
	11-20 yr.	322.95 b	9.90 a	1.57 a	5.89 b	0.91 ab	61.87 a	38.21 b	49.90 b	6.47 a	0.19 ab
	>20 yr.	476.85 a	7.50 bc	1.62 a	8.61 a	1.17 a	64.58 a	49.65 a	75.88 a	6.54 a	0.23 a
	Row Crop	246.13 c	6.79 c	1.59 a	4.59 c	0.71 b	62.88 a	21.52 c	43.70 b	5.95 b	0.17 b
		P	P	P	P	P	P	P	P	P	P
Year (Y)		< 0.001	< 0.001	< 0.001	0.102	0.015	0.041	< 0.001	< 0.001	0.485	0.003
Site (S)		< 0.001	< 0.001	0.884	< 0.001	< 0.001	0.097	< 0.001	< 0.001	< 0.001	0.046
Y x S		< 0.001	0.186	0.068	0.498	0.01	0.907	0.012	< 0.001	0.101	0.067

[x]1-4 yr. = Pecan Orchards 1-4 years old; 5-10 yr. = Pecan Orchards 5-10 years old; 11-20 yr. = Pecan Orchards 11-20 years old; >20 yr. = Pecan Orchards >20 years old.

Table 2.2. Soil quality indicators measured at 0-15 cm and 91-106 cm for each site in 2021.

		Soil Quality Indicators at Depth (2021)									
Site[x]	Depth	Active Carbon (mg/kg^{-1})	Aggregate Stability (%)	Bulk Density (g/cm^3)	CEC (meq/100g)	Organic Matter (%)	Porosity (%)	Solvita CO2 Burst (mg/kg^{-1})	Solvita SLAN (mg/kg^{-1})	Soil pH	Total N (%)
1-4 yr.	0-15 cm	305.75 bc	8.90 ab	1.62 a	5.35 bc	0.99 a	66.27 a	36.28 b	49.50 b	6.51 a	0.17 b
5-10 yr.	0-15 cm	276.05 bc	7.60 bc	1.64 a	4.77 c	0.66 b	63.10 a	31.05 b	47.50 b	6.44 a	0.22 a
11-20 yr.	0-15 cm	322.95 b	9.90 a	1.57 a	5.89 b	0.91 ab	61.87 a	38.21 b	49.90 b	6.47 a	0.19 ab
>20 yr.	0-15 cm	476.85 a	7.50 bc	1.62 a	8.61 a	1.17 a	64.58 a	49.65 a	75.88 a	6.54 a	0.23 a
Row Crop	0-15 cm	246.13 c	6.79 c	1.59 a	4.59 c	0.71 b	62.88 a	21.52 c	43.70 b	5.95 b	0.17 b
1-4 yr.	91-106 cm	78.67 a	2.67 a	1.01 a	5.07 a	0.90 a	39.24 a	6.37 a	5.00 a	5.90 a	0.27 a
5-10 yr.	91-106 cm	196.33 a	7.33 a	1.09 a	5.03 a	0.92 a	46.83 a	6.33 a	5.00 a	5.70 a	0.24 a
11-20 yr.	91-106 cm	105.00 a	5.33 a	1.13 a	4.93 a	0.84 a	40.18 a	5.17 a	5.00 a	6.00 a	0.28 a
>20 yr.	91-106 cm	125.00 a	7.67 a	1.12 a	5.43 a	1.03 a	39.68 a	4.73 a	3.33 a	5.57 a	0.27 a
Row Crop	91-106 cm	114.67 a	5.50 a	1.12 a	5.18 a	0.98 a	43.80 a	5.15 a	4.38 a	5.64 a	0.28 a
		P	P	P	P	P	P	P	P	P	P
Site (S)		0.01	0.698	0.94	< 0.001	0.147	0.748	0.021	0.071	0.021	0.75
Depth (D)		< 0.001	0.035	< 0.001	0.04	0.563	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
S x D		0.008	0.353	0.831	0.002	0.146	0.319	0.021	0.043	0.301	0.149

[x]1-4 yr. = Pecan Orchards 1-4 years old; 5-10 yr. = Pecan Orchards 5-10 years old; 11-20 yr. = Pecan Orchards 11-20 years old; >20 yr. = Pecan Orchards >20 years old.

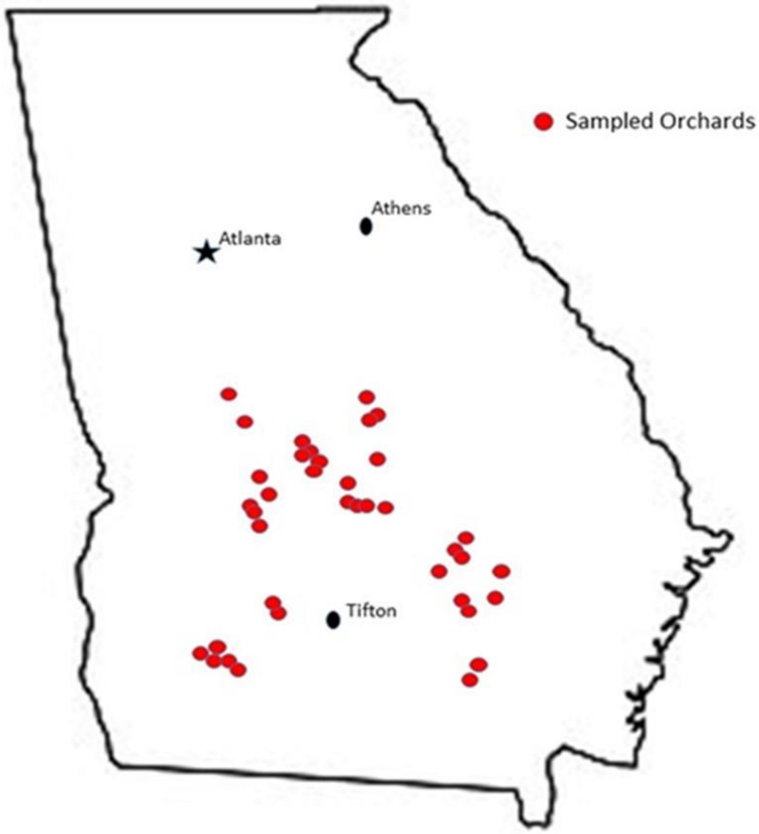

Figure 2.1. Map of commercial pecan orchards sampled in 2020 and 2021.

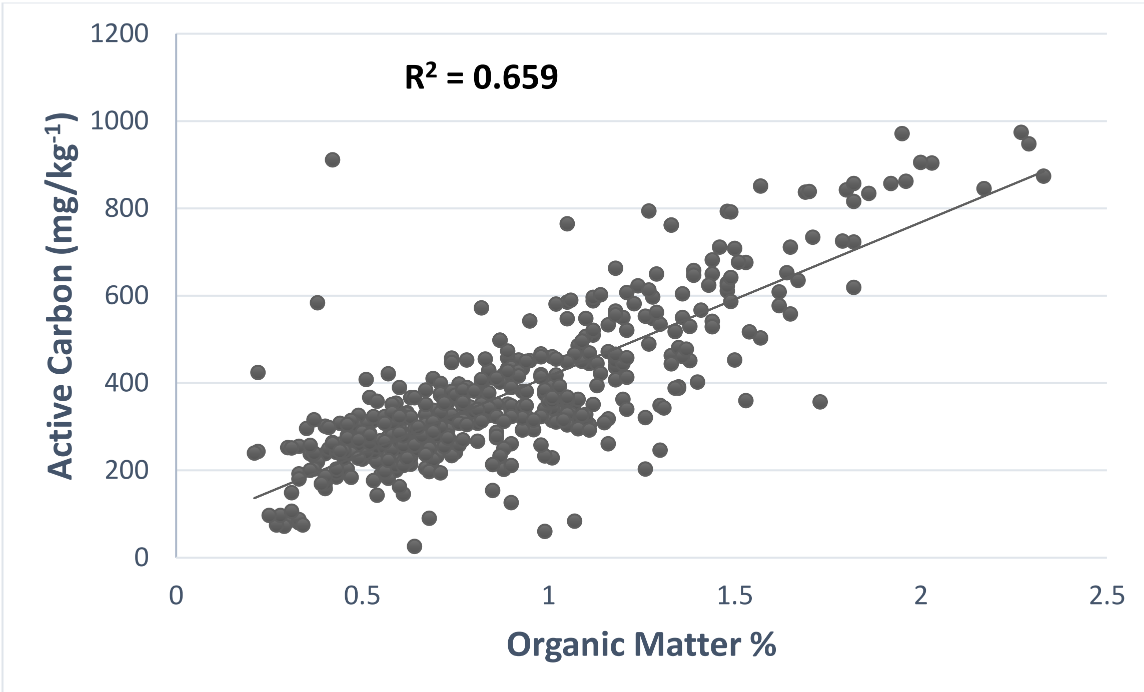

Figure 2.2. Correlation between SOM and Active Carbon. Results are shown for soil analysis of 2020 and 2021 combined.

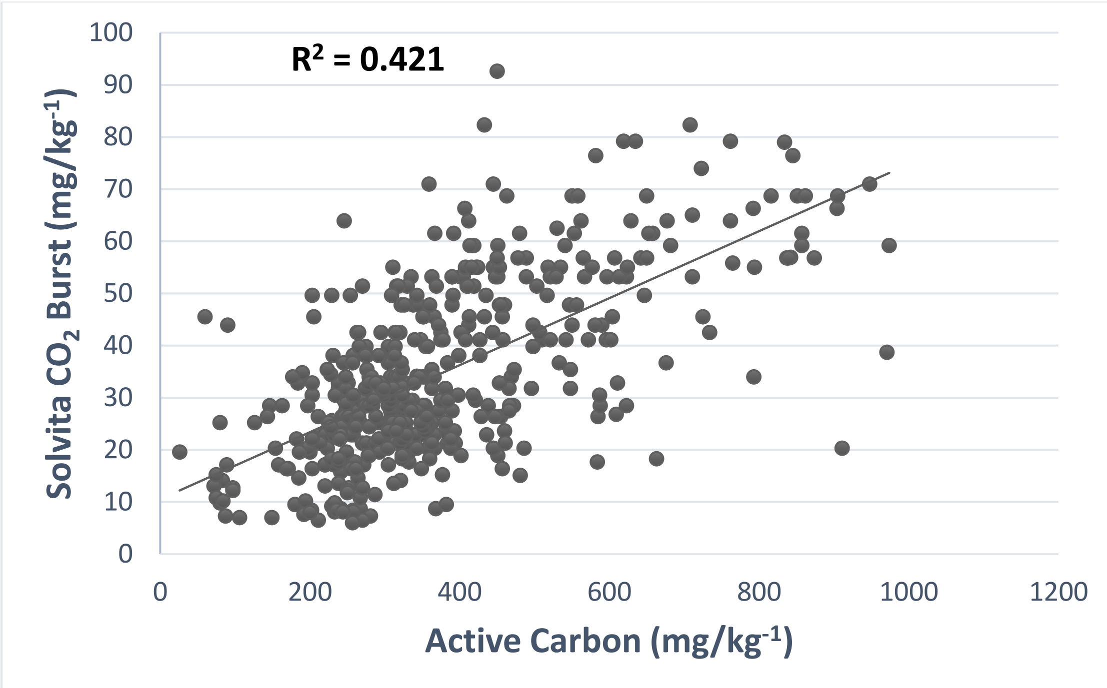

Figure 2.3. Correlation between Active Carbon and Solvita CO_2 Burst. Results are shown for soil analysis of 2020 and 2021 combined.

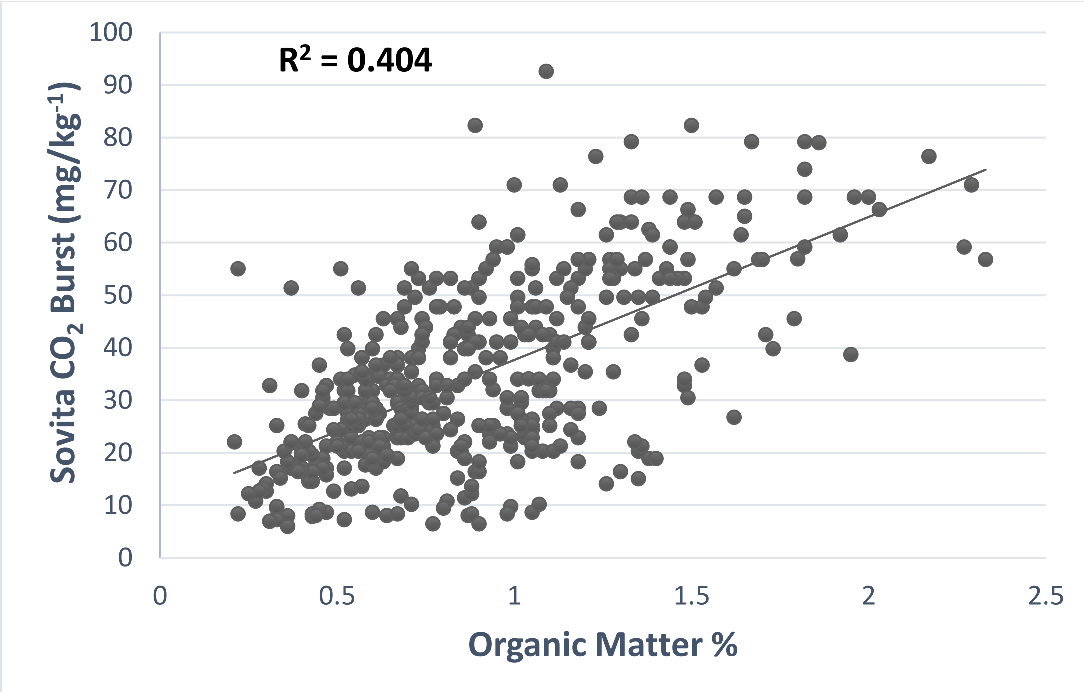

Figure 2.4. Correlation between SOM and Solvita CO_2 Burst. Results are shown for soil analysis of 2020 and 2021 combined.

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CHAPTER 3

EVALUATING SOIL NUTRIENT STATUS OF COMMERCIAL PECAN ORCHARDS IN THE SOUTHEASTERN COASTAL PLAIN OF THE UNITED STATES [1]

[1] Slade H., Wells L. To be submitted to *HortTechnology*.

Abstract

This study addresses the current soil fertility status of commercial pecan orchards typical of much of the southeastern Coastal Plain of the United States. Evaluating orchard soil fertility status helps producers monitor nutritional requirements and gives important information regarding nutrient availability. Soil surveys were conducted throughout a major commercial pecan producing region of South Georgia in 2020 and 2021. All of the orchards selected for sampling were managed for commercial production in accordance to University of Georgia Cooperative Extension recommendations. The data presented here suggests that growers could likely consider reducing annual applications of K, Ca, and Mg. Results from this study indicate that the highest potential of soil nutrient deficiencies throughout this region currently exist in younger orchards with P, Zn, B, S, and Mn. Special attention should be paid to supplementation of young orchard soils in the Southeastern U.S. Coastal Plain with nutrients such as P and Zn, which are inherently low and remain relatively stable once built up to sufficient levels. These results suggest that pecan orchard soil nutrition status in the Southeastern Coastal Plain improves with age. Growers throughout the southeastern Coastal Plain could likely reduce costs by applying only the nutrients that are required as determined by soil and leaf analysis.

Introduction

Pecan (*Carya illinoinensis*) is one of the most economically valuable tree nut crops in the United States. The southeastern U.S. Coastal Plain is a major region of commercial pecan production. Georgia alone typically accounts for approximately 33% of the United States total production (USDA 2015). This region is known to have a humid subtropical climate that averages more than 76 cm of rainfall each year (Wells 2009). Soils found throughout this region are low in natural fertility; however, they can support extremely productive orchards with the correct nutrient amendments (Wells 2017). Regional conditions, seasonal variability in crop load, and management practices have a considerable effect on soil fertility and nutrient status in pecan orchards (Wells 2009; Omer et al. 2018). Therefore, to increase sustainability and maximize yield, it is important to monitor the soil fertility status of commercial orchards.

A similar study in 2005 and 2008 (Wells 2009) was conducted to assess soil fertility and leaf nutrition status of commercial pecan orchards. Results from that study indicated that the greatest potential for nutrient deficiencies in commercial pecan orchards throughout the southeastern Coastal Plain existed with nitrogen (N), potassium (K), sulfur (S), and copper (Cu). Wells (2009) found that growers could potentially reduce input costs by only applying the specific nutrients required, as indicated by yearly soil and leaf analysis.

Soil sampling lays the foundation for evaluating soil nutrient status. Although soil analysis alone is not enough to guide fertility programs in commercial pecan orchards (Pond et al. 2006; Smith et al. 2012); it can be used as a tool to make decisions regarding nutrient availability, interactions, and potential problems (Wells 2009). Soil nutrient surveys carried out across a given region can provide insight as to what nutrient challenges and limitations may exist there (Pond et al. 2006; Wells 2009; Bhat et al. 2017). This study addresses the current fertility status of commercial pecan orchard soils typical of the southeastern Coastal Plain.

Materials and Methods

Soil surveys were conducted throughout a major portion of the commercial pecan producing region of Georgia in 2020 and 2021 (Fig. 3.1). The soils observed throughout the sampled area exemplify pecan orchard soils across the southeastern U.S. coastal plain (Wells 2009). Commercial pecan orchards in eight different counties were selected for sampling to assess soil fertility status. Pecan orchards were separated into age groups of 1-4, 5-10, 11-20, and >20 years old to analyze changes in nutrient content over time. The orchards sampled in this study were largely comprised of seven different soil types. These include Tifton (fine-loamy, kaolinitic, thermic Plinthic Kandiudults), Dothan (fine-loamy, kaolinitic, thermic Plinthic Kandiudults), Fuquay (loamy, kaolinitic, thermic Arenic Plinthic Kandiudults), Greenville (fine, kaolinitic, thermic Rhodic Kandiudults), Faceville (fine, kaolinitic, thermic Typic Kandiudults), Orangeburg (fine-loamy, kaolinitic, thermic Typic Kandiudults), and Red Bay (fine-loamy, kaolinitic, thermic Rhodic Kandiudults). Orchard floor vegetation and fertility practices varied; however, all of the orchards selected for sampling are managed for commercial production in accordance with University of Georgia Cooperative Extension recommendations (Wells 2017a).

Soil sampling was conducted from June 1 to July 31 in 2020 and from June 1 to July 30 in 2021. Soil samples were pulled at random from the row middles between tree rows of each pecan orchard at a depth of 0-15 cm each year. Four composites were collected from each pecan orchard. A total of 236 composites were collected throughout 41 commercial pecan orchards across the sampled region.

Soil was analyzed by Waters Agricultural Laboratory (Camilla, GA) each year. Samples were dried and sieved through a 2 mm mesh before analysis. Soil samples were analyzed for pH, phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), zinc (Zn), sulfur (S), boron (B), manganese (Mn), iron (Fe), copper (Cu), nitrate (NO_3), and ammonium (NH_4). Soil pH was determined with a soil/water ratio of 1:1 and read with a hydrogen probe. Mehlich 1 (double acid) extractable nutrients were analyzed by ICP. Nitrate (NO_3) and ammonium (NH_4) were determined by the KCL-Cadium Reduction method and Flow Injection Analysis.

Analysis of variance (ANOVA) was used to determine significant changes in soil nutrient content by comparing soil analysis results of commercial pecan orchards. Statistical analyses were performed using SigmaPlot 14 statistical software. All pairwise multiple comparison procedures were performed using Tukey's Test ($p < 0.05$).

Results and Discussion

At 0-15 cm, mean soil pH averaged 6.4 and 6.5 for all orchards in 2020 and 2021, respectively (Table 3.1). There were no age class differences with regard to pH in either year of the study (Table 3.1). Soils in the southeastern Coastal Plain are characteristically acidic. Exceedingly low soil pH can restrict pecan root growth (White et al. 1982; Wells 2009). However, important micronutrients like Zn become less available for uptake as pH increases. Therefore, maintaining a soil pH of 6.0 to 6.5 is recommended for pecan orchards in this region (Wells 2017a). Raising soil pH to this desired range with liming materials is common practice in pecan orchards throughout this region to ensure the availability of essential nutrients.

In 2020, mean soil P in pecan orchards ranged from 50.41 kg/ha^{-1} to 115.53 kg/ha^{-1} (Table 3.1). Orchards 1-4 and 5-10 years old exhibited the lowest mean amount of P (55.01

kg/ha^{-1} and 50.41 kg/ha^{-1}, respectively). Pecan orchards >20 years old contained a significantly higher ($p < 0.001$) P content than any other age group. In 2021, mean soil P ranged from 44.11 kg/ha^{-1} (1-4 year old orchards) to 125.48 kg/ha^{-1} (>20 year old orchards) (Table 3.1). Orchard soils of each age group contained sufficient levels of P each year, as each orchard group was within or exceeded the desired range of 33.6 kg/ha^{-1} to 67.3 kg/ha^{-1}. However, uptake of P may still be poor since it is relatively immobile in soil (Wells 2009; Smith and Cheary 2013). P deficiencies can be difficult to correct in a timely manner, so soil P levels should be carefully managed (Wells 2009). Polozola et al. (2019) suggest that P uptake by pecan roots is inefficient due to their lack of root hairs. The lower levels of soil P observed in orchards 10 years old and younger is a reflection of the fact that Coastal Plain soils are generally low in P as a result of inherently low mineral P in the soil parent material, the soil's advanced stage of weathering, and the tendency of orthophosphate to adsorb on hydrous metal oxides or become occluded in the secondary mineral structure (Scott and Bliss 2012). Thus, the addition of P until appropriate soil levels are met should be given specific attention in newly planted orchards in the region.

Orchard soil mean K content ranged from 161.43 kg/ha^{-1} to 179.14 kg/ha^{-1} in 2020 (Table 3.1). Mean soil K levels fluctuated slightly among orchard age groups. In 2021, mean soil K ranged from 151.04 kg/ha^{-1} to 185.89 kg/ha^{-1} (Table 3.1). We observed no significant differences in mean soil K content between orchard age class either year. Orchards of each age group in 2020 and 2021 contained adequate levels of soil K in accordance with the desired range (Table 3.1). However, coarse textured, sandy, acidic soils are often low in K (Kolanchi and Jalali 2007; Zorb et al. 2013). According to Zorb et al. (2013), 90-98% of K in soil is unavailable for direct plant uptake. K deficiencies are commonly seen in commercial pecan orchards during years of heavy production (Wood et al. 2010). Therefore, soil K should be monitored closely.

In 2020, mean soil Zn in pecan orchards ranged from 8.92 kg/ha^{-1} to 61.97 kg/ha^{-1} (Table 3.1). Soil data indicates that orchards 1-4 and 5-10 years old contained less than sufficient levels of Zn. Orchards >20 years old contained a significantly higher ($p < 0.001$) mean level of Zn than younger orchards. In 2021, mean Zn of orchard soils ranged from 11.12 kg/ha^{-1} to 51.26 kg/ha^{-1} (Table 3.1). Mean soil Zn content was less than adequate in orchards 1-4 years old. We found that orchards 5-10 and >20 years old exhibited significantly higher ($p < 0.001$) mean Zn levels than orchards 1-4 and 11-20 years old in 2021. Soils throughout the southeastern U.S. Coastal Plain are inherently deficient in zinc (Wood 2007). Thus, Zn deficiency is one of the most common micronutrient deficiencies of pecan in the region (Wells 2009). The higher soil Zn content seen in older pecan orchards is likely due to the numerous applications made over the years. Uptake of Zn applied to the soil can be slow and sometimes ineffective (Wood 2007; Wells 2009), so deficiencies are often corrected with soil and foliar applications (Wood and Payne 1997; Ojeda-Barrios et al. 2014). Producers with newly planted orchards should give specific attention to enhancing soil Zn levels.

Mean soil Ca levels ranged from 1044.02 kg/ha^{-1} to 2664.40 kg/ha^{-1} in pecan orchards sampled in 2020 (Table 3.1). We observed mean Ca content increase as orchards increased with age. Orchards >20 years old exhibited a significantly higher ($p < 0.001$) mean Ca level than the younger orchards sampled. In 2021, orchard soil mean Ca ranged from 1202.95 kg/ha^{-1} to 2449.40 kg/ha^{-1} (Table 3.1). We saw a slight dip in soil Ca content in orchards 5-10 years old; however, mean Ca levels did begin to increase as orchards increased with age. Soil Ca content throughout the sampled orchards exceeded the sufficiency range in 2020 and 2021. The higher Ca levels observed in orchards >20 years old is a result of frequent liming in order to maintain soil pH (Wells 2009).

Mean Mg levels in orchard soils ranged from 139.46 kg/ha^{-1} to 271.16 kg/ha^{-1} in 2020 (Table 3.1). Mean Mg content of orchard soils increased as orchards increased in age. In 2021, mean Mg ranged from 134.11 kg/ha^{-1} to 227 kg/ha^{-1} in orchard soils (Table 3.1). Soil Mg levels throughout the sampled orchards exceeded the sufficient range both years. The high Mg content seen in orchard soils, like that of Ca, is likely a byproduct of liming applications. Dolomite lime is often utilized to raise soil pH in pecan orchards across the southeastern Coastal Plain; therefore, these orchards are rarely deficient in Mg (Wells 2009).

In 2020, mean S of orchard soils ranged from 15.79 kg/ha^{-1} to 54.59 kg/ha^{-1} (Table 3.1). Orchards 5-10 years old exhibited the highest mean S level that year. In 2021, mean S of orchard soils ranged from 9.36 kg/ha^{-1} to 18.66 kg/ha^{-1} (Table 3.1). Our data shows that mean S content in soils of the 5-10 and 11-20 year old orchards were just below the desired range of 11.2 kg/ha^{-1} to 56 kg/ha^{-1}. Soils throughout this region are inherently low in S (Wells 2009). According to Scherer (2001), approximately 95% of S in soil exists as organic S and is unavailable for direct plant uptake. S also leaches very easily in the sandy loam soils of the southeastern U.S. Coastal Plain (Wells 2014), making it difficult to supply adequate levels of S.

Orchard soil mean B content ranged from 0.51 kg/ha^{-1} to 1.12 kg/ha^{-1} in 2020 (Table 3.1). These results show that orchards 1-4 and 5-10 contained marginally lower than sufficient levels of B. In 2021, mean B of orchard soils ranged from 0.50 kg/ha^{-1} to 0.91 kg/ha^{-1} (Table 3.1). Similar to the previous year; orchards 1-4 and 5-10 again contained slightly lower than sufficient levels of B, as the desired range is 0.56 kg/ha^{-1} to 1.12 kg/ha^{-1}. However, mean B content of orchard soils increased with orchard age both years. B is very mobile in the coarse sandy soils found throughout the southeastern Coastal Plain (Wells 2009). As a result, less than 3% of total soil B is readily available for plant uptake (Xu et al. 2001).

Mean Mn content of orchard soils ranged from 16.62 kg/ha^{-1} to 22.67 kg/ha^{-1} in 2020 (Table 3.1). Orchards 5-10 years old exhibited a mean soil Mn level that was marginally below the sufficient range of 16.8 kg/ha^{-1} to 44.8 kg/ha^{-1}. In 2021, mean Mn of orchard soils ranged from 22.64 kg/ha^{-1} to 31.78 kg/ha^{-1} (Table 3.1). Up to 90% of Mn in soil solution is bound to organic matter, reducing its availability for plant uptake (Smith and Cheary 2001). Mn deficiencies are more commonly seen in pecan orchards with alkaline soils in the southwestern U.S. (Sherman et al. 2017).

In 2020, mean Fe content of orchard soils ranged from 18.68 kg/ha^{-1} to 23.06 kg/ha^{-1} (Table 3.1). In 2021, mean Fe of orchard soils ranged from 15.80 kg/ha^{-1} to 21.07 kg/ha^{-1} (Table 3.1). Mean soil Fe levels varied with orchard age; however, orchards of each age group contained adequate levels of Fe in 2020 and 2021. According to Wells (2010), Fe deficiencies are usually induced by over-liming, cold, wet soils in the spring, or high levels of Zn, P, or Mn in the soil.

Orchard soil mean Cu content ranged from 0.68 kg/ha^{-1} to 1.10 kg/ha^{-1} in 2020 (Table 3.1). In 2021, orchards soils mean Cu ranged from 0.75 kg/ha^{-1} to 1.23 kg/ha^{-1} (Table 3.1). Mean soil Cu levels varied with orchard age; however, orchards of each age group contained sufficient levels of soil Cu in 2020 and 2021. Cu requirements in pecan are relatively low (Wells 2009; Salas-Leiva et al. 2021). Soil pH below 6 can improve Cu uptake; however, Cu is largely bound to organic matter, which decreases its availability (Gonzaga et al. 2020). Excessively high Zn levels can also reduce the uptake of Cu in pecans (Pisani 2021).

Nitrogen is the most important nutrient required for pecan growth (Wells 2009). According to Wells (2017b), mature pecan trees require 34-68 kg of nitrogen for optimum growth and production each season. In 2020, mean NH_4 concentrations of orchard soils ranged from 1.20 mg/kg^{-1} to 2.12 mg/kg^{-1} (Table 3.2). In 2021, mean NH_4 concentrations of orchard soils ranged from 1.81 mg/kg^{-1} to 2.83 mg/kg^{-1} (Table 3.2). In 2020, mean NO_3 concentrations of orchard soils ranged from 3.87 mg/kg^{-1} to 9.15 mg/kg^{-1} (Table 3.2). In 2021, mean NO_3 concentrations of orchard soils ranged from 3.78 mg/kg^{-1} to 7.82 mg/kg^{-1} (Table 3.2). Mean NO_3 concentrations of orchard soils increased with orchard age in 2020 and 2021. Ammonium and nitrate are the most dominant forms of nitrogen utilized by plants. Ammonium nitrate (NH_4NO_3) and Urea ($CO(NH_2)_2$) are some of the most commonly soil applied N fertilizers in commercial pecan orchards across the southeastern Coastal Plain (Kim et al. 2002; Wells 2021). Previous studies (Kraimer et al. 2001, 2004; Rey et al. 2006; Smith et al. 2007) have demonstrated the importance of maintaining optimum soil N levels in pecan orchards year after year, as much of the nitrogen used during the growing season is acquired from applications made in previous years.

Conclusion

Soil sampling is an integral part of sustainable nutrient management in commercial pecan orchards. Evaluating orchard soil fertility status helps producers monitor nutritional requirements and gives important information regarding nutrient availability. The addition of leaf tissue analysis would be helpful in evaluating nutrient uptake and deficiencies as well as to make fertilizer recommendations. Growers throughout the southeastern Coastal Plain could likely cut costs by applying only the nutrients that are required as determined by soil and leaf analysis. Based on the results presented from this soil survey, growers could likely consider reducing annual applications of K, Ca, and Mg. Due to the high levels of Ca and Mg found throughout the sampled region, growers should apply lime only when soil analysis indicates a low soil pH. Orchards >20 years old could likely forgo annual soil applications of Zn due to the high concentrations found throughout the sampled region. The results from this study suggest that the highest potential of soil nutrient deficiencies throughout this region currently exist in younger orchards with P, Zn, B, S, and Mn. Although young pecan trees do not require the same amount of nutrients as older and larger trees, special attention should be paid to supplementation of young orchard soils in the Southeastern U.S. Coastal Plain with nutrients such as P and Zn, which are inherently low and remain relatively stable once built up to sufficient levels. These results suggest that pecan orchard soil nutritional status in the Southeastern Coastal Plain improves with age. This is likely a result both of successive fertilizer applications of various nutrients throughout the years and also of nutrient cycling in orchard soils, which are non-tilled and supply significant organic matter back to the soil in the deposition of orchard debris in the form of leaves, shucks, bark, and sticks.

Table 3.1. Synopsis of soil nutrient analysis and pH from 2020 and 2021 commercial pecan orchards, including recommended soil nutrient sufficiency range.

		Soil Nutrient Analysis[z]										
Year	Site[x]	pH	P (kg/ha^{-1})	K (kg/ha^{-1})	Zn (kg/ha^{-1})	Mg (kg/ha^{-1})	Ca (kg/ha^{-1})	S (kg/ha^{-1})	B (kg/ha^{-1})	Mn (kg/ha^{-1})	Fe (kg/ha^{-1})	Cu (kg/ha^{-1})
2020	1-4 yr.	6.25 a	55.01 c	179.14 a	8.92 c	139.46 c	1044.02 c	37.75 ab	0.51 c	21.16 ab	20.01 ab	1.10 a
	5-10 yr.	6.34 a	50.41 c	162.78 a	15.18 bc	164.85 c	1165.41 c	54.59 a	0.52 c	16.62 b	19.67 ab	0.68 bc
	11-20 yr.	6.65 a	81.61 b	171.05 a	18.69 b	212.59 b	1717.49 b	15.79 b	0.78 b	19.86 ab	18.68 b	0.73 bc
	>20 yr.	6.53 a	115.53 a	161.43 a	61.97 a	271.16 a	2664.40 a	19.39 b	1.12 a	22.67 a	23.06 a	0.82 b
	Desired Range	6.0-6.5	33.6-67.3	67.3-168	16.8-22.4	100.8-112	448-1009	11.2-56	0.56-1.12	16.8-44.8	13.4-28	0.56-1.68
2021	1-4 yr.	6.51 a	44.11 c	151.15 a	11.12 b	134.11 bc	1240.50 c	13.17 a	0.50 bc	23.15 b	21.07 a	1.23 a
	5-10 yr.	6.44 a	66.52 b	151.04 a	36.96 a	142.07 b	1202.95 c	9.36 a	0.50 bc	22.64 b	15.80 b	0.75 b
	11-20 yr.	6.47 a	66.19 b	185.89 a	17.74 b	168.58 b	1489.39 b	10.87 a	0.68 b	27.13 ab	19.45 ab	0.81 b
	>20 yr.	6.54 a	125.48 a	165.61 a	51.26 a	227.31 a	2449.40 a	18.66 a	0.91 a	31.78 a	16.81 ab	0.84 b
		P	P	P	P	P	P	P	P	P	P	P
Year		0.485	0.941	0.773	0.282	< 0.001	0.244	< 0.001	0.024	< 0.001	0.406	0.092
Site		< 0.001	< 0.001	0.416	< 0.001	< 0.001	< 0.001	0.344	< 0.001	0.026	< 0.001	< 0.001
Y x S		0.101	0.192	0.168	< 0.001	0.045	0.09	0.128	0.296	0.624	0.469	0.519

[x]1-4 yr. = Pecan Orchards 1-4 years old; 5-10 yr. = Pecan Orchards 5-10 years old; 11-20 yr. = Pecan Orchards 11-20 years old; >20 yr. = Pecan Orchards >20 years old.
[z]Soil pH (pH); Phosphorus (P); Potassium (K); Zinc (Zn); Magnesium (Mg); Calcium (Ca); Sulfur (S); Boron (B); Manganese (Mn); Iron (Fe); Copper (Cu)
[v]1 kg/ha^{-1} = 0.8922 lb/acre.

Table 3.2. Soil analysis of mean ammonium-nitrogen (NH_4-N) and nitrate-nitrogen (NO_3-N) of commercial pecan orchards in 2020 and 2021.

		Soil Analysis[z]	
Year	Site[x]	NH_4-N (mg/kg^{-1})	NO_3-N (mg/kg^{-1})
2020	1-4 yr.	1.49 a	3.87 b
	5-10 yr.	2.12 a	4.32 b
	11-20 yr.	1.20 a	4.89 b
	>20 yr.	1.57 a	9.15 a
2021	1-4 yr.	1.84 a	3.78 b
	5-10 yr.	2.16 a	4.83 ab
	11-20 yr.	1.81 a	5.88 ab
	>20 yr.	2.83 a	7.82 a
		P	P
Year (Y)		0.386	0.859
Site (S)		0.533	< 0.001
Y x S		0.093	0.934

[x]1-4 yr. = Pecan Orchards 1-4 years old; 5-10 yr. = Pecan Orchards 5-10 years old; 11-20 yr. = Pecan Orchards 11-20 years old; >20 yr. = Pecan Orchards >20 years old.
[z]Ammonium (NH_4-N); Nitrate (NO_3-N).
[v]1 mg/kg^{-1} = 1 ppm.

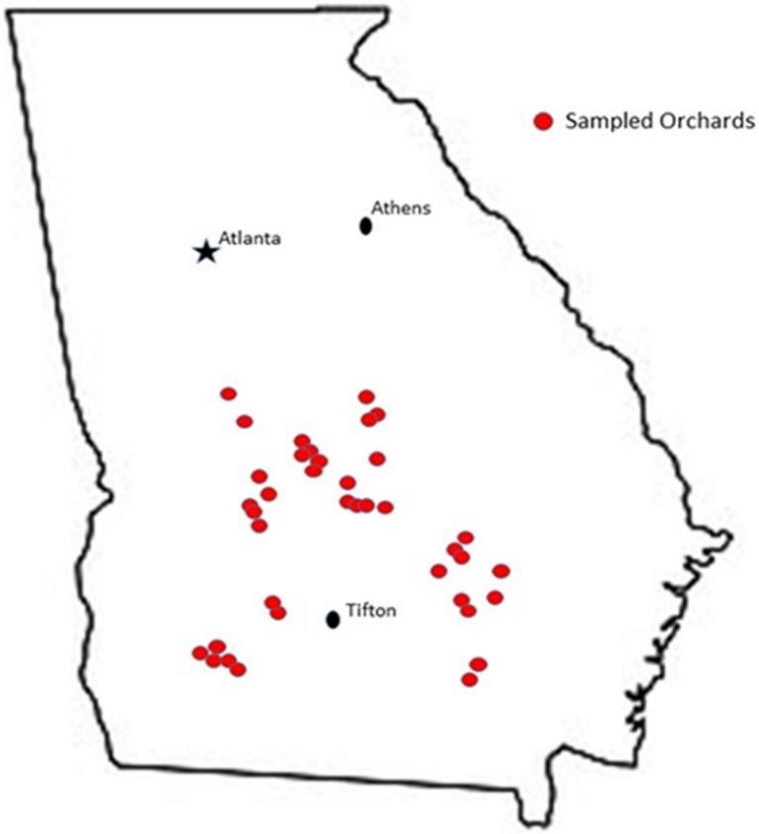

Figure 3.1. Map of commercial pecan orchards sampled in 2020 and 2021.

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CHAPTER 4

PERFORMANCE OF THREE DISEASE RESISTANT PECAN CULTIVARS IN THE SOUTHEASTERN UNITED STATES [1]

[1] Slade H., Wells L. To be submitted to *HortScience*.

Abstract

Pecan scab (*Fusicladium effusum*) is the most destructive disease of pecan (*Carya illinoinensis*) in the southeastern United States. In commercial orchards, scab is most often managed with multiple fungicide applications applied throughout the growing season. Fungicides used to control pecan scab can be expensive for commercial operations. Many producers in the Southeast are seeking more resistant cultivars due to the difficulty and expense of managing high-input commercial cultivars such as ‘Desirable’. The objectives of this study were to evaluate scab incidence, yield, and quality of the scab resistant cultivars, ‘Lakota’, ‘McMillan’, and ‘Excel’, compared to that of highly susceptible ‘Desirable’, and to assess the efficacy of managing pecan scab in ‘Excel’ with a minimal fungicide program. All resistant cultivars exhibited high levels of scab resistance, as no nut scab incidence or severity was observed in 2020 or 2021. Average yields of each low-input cultivar were greater than that of fully-sprayed ‘Desirable’ in 2020. ‘Desirable’ yields were not collected in 2021 due to disease severity. ‘Excel’ trees that received the minimal fungicide program exhibited no scab incidence or severity throughout the course of this study. Results from this study indicate that these three scab resistant cultivars may help producers increase profits in this region by eliminating the need for an extensive fungicide schedule throughout the growing season.

Introduction

The southeastern Coastal Plain accounts for almost 45% of the United States commercial pecan production (Wells 2009). Georgia's location falls in the southeastern pecan growing region. Pecans are one of Georgia's most valuable horticultural crops, generating $187 million in 2020 (USDA 2021). This region is known to have long growing seasons that consist of hot summers with frequent rainfall (Conner 2014). Annual precipitation throughout this region of the southeastern United States averages 127 cm or more (Wells 2015).

Due to the high level of rainfall and humidity in this region, pecan scab [*Venturia effusa* (G. Winter) Rossman & W. C. Allen (basyonym *Fusicladium effusum*)] is prevalent. Pecan scab is the most detrimental pecan disease in the southeastern United States (Gottwald and Bertrand 1983; Bock et al. 2016). With increasing scab susceptibility and fungicide resistance, ten or more fungicide applications may be required throughout the growing season on scab susceptible cultivars in this region (Wells 2014). As a result, the cost of production has increased rapidly over the last few years. Fungicides used to control scab can account for more than 12% of variable production cost (Wells 2021). More fungicide applications result in more fuel, equipment and labor, all of which further increases the cost of production.

Pecan cultivars in this region must possess some level of resistance to scab in order to be successfully managed with fungicides (Conner 2014). Proper cultivar selection is one of the most important decisions a grower can face when establishing a new orchard. The 'Desirable' cultivar has been considered the standard for nut quality in the southeast for many years and is the most widely established variety in Georgia (Wells and Conner 2015). However, 'Desirable' is now one of the most susceptible cultivars to pecan scab and is no longer recommended for planting in southern Georgia (Wells and Conner 2015; Conner 2022). Many growers in the southeast now opt to plant more resistant cultivars due to the difficulty and expense of managing ‘Desirable’ trees (Conner 2014). Cultivars with high levels of resistance to scab may help growers increase net profits by requiring fewer fungicide sprays. Therefore, the objectives of this study were two-fold. We wanted to evaluate scab incidence and yield of resistant cultivars ‘Lakota’, ‘McMillan’, and ‘Excel’ and compare these resistant cultivars to that of highly susceptible ‘Desirable’ trees. We also wanted to implement and assess a minimal fungicide program for resistant cultivars using ‘Excel’ as a representative cultivar.

Materials and Methods

Studies were conducted in 2020 and 2021 at the University of Georgia Ponder Research Farm located near Tifton, GA. The orchard was located at 31º51’ N latitude and -83º64’ W longitude. Orchard soils consisted of Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults). Trees were planted in 2008 and are spaced at 12.2 m x 12.2 m throughout the orchard. The orchard was managed under commercial conditions in accordance with the University of Georgia Cooperative Extension recommendations (Wells 2017a). Vegetation-free strips 3.7 m wide were maintained along each tree row using the herbicide glyphosate. Row middles consisted of bermudagrass (*Cynodon dactylon* L.) sod. All trees were irrigated with micro-sprinklers at a rate of 56.8 L/h^{-1}. Micro-sprinklers were placed ≈0.3 m from the tree trunk in alignment with the tree row.

Experiment 1.

Four trees each of ‘Lakota’, ‘McMillan’, and ‘Excel’ pecan within the low-input block of the UGA Ponder Research farm were evaluated. Trees of each cultivar are arranged randomly within each tree row. With the exception of four individual trees used for Experiment 2, no trees planted in this orchard block have ever received fungicide applications.

'Desirable' trees planted in 2007 were grown in a separate adjacent orchard block, which received a standard fungicide program of 9 fungicide applications in 2020 and 10 fungicide applications in 2021 ('Desirable FS'). Cultivars in this block are arranged by rows with 10 consecutive rows of 'Desirable'. All trees in this block consistently receive a full fungicide program annually based on UGA Extension Commercial Spray Guide (Wells et al. 2022). The sprayed block is 46 meters from the non-sprayed, low-input block. Four 'Desirable' trees from the center of the 8th row of the sprayed block were chosen randomly for sampling.

Treatments were arranged in a randomized complete block design using four blocks, with each cultivar represented once per block. Single-tree plots were used with guard trees between treated trees. Individual trees received the same treatments from one year to the next throughout the course of the study.

Disease ratings of pecan nuts were conducted from 7 Sept. to 11 Sept., 2020 and from 6 Sept. to 10 Sept., 2021 after pecan shell hardening and completion of all foliar sprays. Disease severity rating followed the nearest percent estimate (NPE) method as described by Bock et al. (2013). Ten random fruiting terminals per tree were rated for incidence and severity of pecan scab and powdery mildew (*Microsphaera penicillata*). Incidence is defined as the percentage of nuts with at least one pecan scab lesion or powdery mildew infection. Severity is defined as the percentage of the pecan shuck surface covered by pecan scab or powdery mildew. At harvest, nuts were shaken from the trees onto a tarp under each tree. All nuts were hand-harvested and weighed to determine yield. Yield data were calculated for each cultivar by averaging all single-tree plots for each cultivar each year. 'Desirable' nuts were not harvested in 2021 due to disease loss. A 50-nut sample was collected from each tree for analysis of individual nut weight and percent kernel. Nuts were shelled and percentage of edible kernel was calculated by dividing the kernel weight for the 50-nut sample by total nut weight. Rainfall data were obtained from a University of Georgia weather station located near the study site (UGA 2020).

Analysis of variance (ANOVA) was used to determine differences between cultivars. All statistical analyses were performed using SigmaPlot 14 statistical software. All pairwise multiple comparison procedures were performed using Tukey's Test ($p < 0.05$).

Experiment 2.

For the second experiment; four 'Excel' trees in the Ponder Farm low-input pecan orchard block were randomly selected to receive 3 fungicide applications at scheduled intervals in 2020 and 2021 ('Excel 3S'). Fungicides included were Phostrol (Mono- and dibasic sodium, potassium, and ammonium phosphites; Nufarm Americas Inc., Alsip, IL), applied at a rate of 4.68 liter/ha^{-1} and Absolute 500SC (tebuconazole + trifloxystrobin; Bayer CropScience LP, St. Louis, MO), applied at a rate of 0.56 liter/ha^{-1}. Phostrol was applied in the middle of April and August each year, respectively. Absolute was applied in the middle of June each year. Sprayed 'Excel' trees were compared to non-sprayed 'Excel'. In addition, four 'Desirable' trees from the center of the 2nd row in the sprayed block described above were selected to only receive the same 3 fungicide applications as 'Excel' to compare the effects of the minimal fungicide program on 'Desirable' ('Desirable 3S'). Four 'Desirable' trees receiving a full spray program as described for Experiment 1 were used to compare differences in scab incidence and severity of 'Desirable' in a full fungicide program with non-sprayed and minimally sprayed 'Excel' and 'Desirable' trees that only received 3 fungicide applications. All fungicide applications were made with a commercial air blast sprayer delivering 935 L per ha^{-1}.

Sampling methods, data collection, and statistical methods were the same as for Experiment 1 above.

Results

Experiment 1.

'Lakota', 'McMillan', and 'Excel' exhibited significant resistance to pecan scab in 2020 and 2021. In the absence of fungicide applications, we observed no scab incidence on any of these cultivars throughout the trial (Table 4.1). In comparison, 'Desirable' exhibited a significant amount of scab incidence (98.99%) in 2020. Scab severity of 'Desirable' was 26.11% after receiving 9 fungicide applications in 2020 (Table 4.1). In 2021, with 10 fungicide applications, similar incidence levels were observed; however, nearly half (49.55%) of the nut surface from 'Desirable' exhibited pecan scab lesions in September (Table 4.1). Powdery mildew infections were evident on 'Desirable' and on all scab resistant cultivars, 'Lakota', 'McMillan', and 'Excel' in 2020. Incidence and severity of powdery mildew was significantly higher ($p < 0.001$) on 'McMillan' than on any other cultivar in 2020 (Table 4.1). In 2021, we found powdery mildew on all cultivars; however, we observed no significant differences in incidence or severity between cultivars (Table 4.1). The study site received 67 cm of rainfall from April 1 to Sept. 30 in 2020 (Fig. 4.1). However, the study site received 83 cm of rainfall during the same time period in 2021, facilitating conditions conducive to intense scab pressure (Fig. 4.2). The higher levels of scab observed throughout fully sprayed 'Desirable' in 2021 are likely attributed to the increase in the frequency of rainfall during the growing season, making scab control difficult on this scab susceptible cultivar even with 10 fungicide applications.

Yields of ‘Lakota’, ‘McMillan’, and ‘Excel’ averaged 72.17 kg, 25.59 kg, and 50.29 kg, respectively, in 2020 (Table 4.2). Yields obtained from ‘Desirable’ averaged 22.46 kg in 2020. ‘Lakota’ exhibited the highest average yield (72.17 kg), which was significantly higher ($p < 0.001$) than that of ‘McMillan’ and ‘Desirable’. Nuts from ‘Lakota’ and ‘McMillan’ averaged 54% kernel in 2020, significantly greater than that of ‘Excel’ (46%) and ‘Desirable’ (46%) (Table 4.2). Mean nut weight of ‘Lakota’, ‘McMillan’, and ‘Excel’ measured 7.23 g, 8.14 g, and 9.65 g, respectively, in 2020 (Table 4.2). Nut weight obtained from ‘Desirable’ averaged 9.55 g in 2020. Nut weight of ‘Excel’ and ‘Desirable’ was significantly greater ($p < 0.05$) than that of ‘Lakota’ and ‘McMillan’ (Table 4.2). In 2021, yields from ‘Lakota’, ‘McMillan’, and ‘Excel’ averaged 38.33 kg, 41.49 kg, and 33.10 kg, respectively. ‘Desirable’ yield was not recorded due to disease loss. ‘Lakota’ nuts averaged 60% kernel, which was significantly higher ($p < 0.001$) than any other cultivar in 2021 (Table 4.2). Nut weight of ‘Lakota’, ‘McMillan’, and ‘Excel’ averaged 8.82 g, 7.63 g, and 10.07 g, respectively. Thompson et al. (2008) found ‘Lakota’ to be more alternate bearing. Our data agrees with this as yields from 2020 were significantly higher ($p < 0.05$) than from 2021 (Table 4.2). Fruit thinning of ‘Lakota’ may help to reduce its alternate bearing tendencies (Wells, unpublished data). ‘McMillan’ and ‘Excel’ exhibited lower levels of alternate bearing crop yields between both years of this study. Conner (2014) and Wells et al. (2018) noted that the alternate bearing tendencies of ‘McMillan’ and ‘Excel’ begin to show at a fairly young age.

Experiment 2.

We observed no scab incidence on ‘Excel’ trees that received the minimal fungicide program nor on non-sprayed ‘Excel’ trees in 2020 (Table 4.3). In comparison, ‘Desirable’ trees that received only 3 fungicide applications exhibited a significant incidence of scab (100%).

‘Desirable’ receiving 3 fungicide applications exhibited significantly higher ($p < 0.001$) levels of scab severity than that of ‘Desirable’ trees managed with a full spray program and both ‘Excel’ groups (Table 4.3). Powdery mildew infection was observed on both ‘Excel’ treatments. ‘Desirable’ exhibited a similar degree of powdery mildew infection to that of ‘Excel’ under both treatments (Table 4.3). In 2021, ‘Excel’ continued to show high resistance to pecan scab as we observed no scab incidence or severity on trees that received the minimal fungicide program nor on the ‘Excel’ trees that did not receive fungicides (Table 4.3). ‘Desirable’ trees under both fungicide programs had a high incidence and severity of scab in 2021 (Table 4.3). Powdery mildew infection was seen on all treatments in 2021; however, we observed no significant differences between cultivars and fungicide programs for powdery mildew incidence or severity.

Discussion

The goals of this study were to evaluate scab incidence and yield of resistant cultivars ‘Lakota’, ‘McMillan’, and ‘Excel’ and to compare these disease resistant cultivars to that of highly susceptible ‘Desirable’ trees. We also wanted to explore the efficacy of managing pecan scab and other minor diseases on ‘Excel’ with a minimal fungicide program. ‘Lakota’, ‘McMillan’, and ‘Excel’ each exhibited high levels of scab resistance, as no scab incidence or severity was observed in 2020 or 2021. These cultivars produced significant yields each year in the absence of fungicides, demonstrating their potential as economically viable cultivars. ‘Desirable’ trees that received full fungicide programs each year contained significant levels of scab with nut scab severity almost doubling from 2020 to 2021. As mentioned previously, the 2021 growing season experienced greater and more frequent rainfall than that of 2020. Rainfall during the summer months likely contributed to this increase in nut scab severity as the study site received 52 cm over 54 rainfall events from June 1 to August 31 in 2021 (Fig. 4.2), compared to

31 cm over 42 rainfall events during the same time period in 2020 (Fig. 4.1). Several studies have indicated that the timing of rainfall events relative to fungicide applications can have a considerable effect on fungicide efficacy (Reynolds et al. 1994; Hunsche et al. 2007; Standish et al. 2018; Granados and Zambolim 2019). Results from this study demonstrate the difficulty of managing scab on ‘Desirable’ throughout this region even when trees receive a full fungicide program.

Average yields from each low-input cultivar were greater than that of fully-sprayed ‘Desirable’ in 2020 (Table 4.2). Fully-sprayed ‘Desirable’ contained high levels of nut scab which likely reduced the average yield and nut weight. In 2021, ‘Desirable’ yield was a complete loss, primarily as a result of pecan scab. Conner (2014) found yields of ‘Desirable’ to be negatively affected by severe nut scab in wet years. ‘Excel’ exhibited the highest average nut weight in both years of the study (Table 4.2). Percent kernel data of ‘Lakota’, ‘McMillan’, and ‘Excel’ observed in this study was similar to trial data from Wells and Conner (2015). The results from this study suggest that these low-input cultivars have the potential to increase returns by substantially reducing the need for fungicide applications. However, there are tradeoffs with these scab resistant cultivars. ‘Lakota’ has shown some variability in nut size and alternate bearing tendencies (Wells and Conner 2015). Its variability in nut size is likely from over-production during heavy crop years. Another quality issue of ‘Lakota’ is its darker kernel color. Wells (2021) found the kernel of ‘Lakota’ to turn considerably dark if not harvested in a timely manner. ‘McMillan’ produces nuts that are only of mediocre quality. As a result, it has been regarded as a cultivar that is only recommended for low input operations where scab resistance is of paramount importance (Conner 2014). ‘Excel’ produces a large nut similar in size to ‘Desirable’. However, it has a thick shell, and this factor negatively affects its’ percent kernel, which is a primary measure of nut quality (Wells and Conner 2015). This can limit its profitability in the absence of an in-shell pecan market.

‘Excel’ trees in this study were highly resistant to scab. Non-sprayed ‘Excel’ did not exhibit any scab incidence or severity. Similarly, ‘Excel’ trees that received the minimal fungicide program also exhibited no sign of scab incidence or severity. Therefore, we observed no significant difference in scab incidence or severity between ‘Excel’ treatments. However, powdery mildew was observed on ‘Excel’ each year. Brenneman et al. (1988) found that severe powdery mildew infection significantly reduced the kernel weight of non-sprayed nuts. Powdery mildew incidence did not seem to affect yield or nut quality in this study. However, worsening infections of powdery mildew and other minor foliar diseases could possibly develop in non-sprayed trees. Trees that receive a minimal fungicide program are less likely to exhibit high levels of minor foliar diseases because many are controlled as a by-product from fungicides applied for pecan scab. In addition, implementing a minimal fungicide program on scab resistant cultivars would aid in scab prevention and could possibly prolong the resistance exhibited by that cultivar (Staub 1991).

Conclusion

This study suggests that there are currently cultivars which can be successfully grown in the humid, relatively high rainfall conditions of the southeastern United States without fungicides or with minimal fungicide applications. Results from this study indicate that ‘Lakota’, ‘McMillan’, and ‘Excel’ may help growers maximize yields and mitigate expenses by having a significantly reduced fungicide program throughout the growing season. Although scab resistant cultivars are available, pecan scab has the ability to persist and adapt to new cultivars over time (Conner 2002). Regardless, planting resistant cultivars is still the most desirable practice for controlling scab (Bock et al. 2016). Integrating such approaches to pecan production can lower costs for producers throughout the growing season, thus allowing for a larger profit margin while also providing a more sustainable means of production.

Table 4.1. Mean incidence and severity of pecan scab and powdery mildew on pecan nuts of low-input cultivars 'Lakota', 'McMillan', and 'Excel' compared to that of 'Desirable' in 2020 and 2021.

		Pecan Nut Disease Ratings			
Year	Treatment[y]	Scab Inc. %	Scab Severity %	Powdery Mildew Inc. %	Powdery Mildew Severity %
2020	Lakota	0.00 b[z]	0.00 b	22.49 b	5.24 b
	McMillan	0.00 b	0.00 b	65.79 a	17.31 a
	Excel	0.00 b	0.00 b	14.29 b	1.59 b
	Desirable FS	98.99 a	26.11 a	6.06 b	1.17 b
2021	Lakota	0.00 b	0.00 b	19.15 a	2.60 a
	McMillan	0.00 b	0.00 b	19.08 a	2.79 a
	Excel	0.00 b	0.00 b	7.21 a	0.77 a
	Desirable FS	97.30 a	49.55 a	17.57 a	7.08 a

[y] 'Lakota', 'McMillan', and 'Excel' received no fungicide applications in 2020 or 2021; 'Desirable FS' received full fungicide program each year, 9 and 10 applications in 2020 and 2021, respectively.

[z] Means followed by the same letter within each year are not statistically different according to Tukey's Test ($P < 0.05$).

Table 4.2. Mean pecan nut % kernel, nut weight (g) and yield (kg) of low-input cultivars 'Lakota', 'McMillan', and 'Excel' compared to that of 'Desirable' in 2020 and 2021.

		Yield Data		
Year	Treatment	% Kernel	Nut Wt. (g)	Yield (kg)
2020	Lakota	54 a[x]	7.23 b	72.17 a
	McMillan	54 a	8.14 b	25.59 b
	Excel	46 b	9.65 a	50.29 ab
	Desirable FS	46 b	9.55 a	22.46 b
2021	Lakota	60 a	8.82 b	38.33 a
	McMillan	50 b	7.63 c	41.49 a
	Excel	51 b	10.07 a	33.10 a
	Desirable FS[z]	-	-	-

[x] Means followed by the same letter within each year are not statistically different according to Tukey's Test ($P < 0.05$).
[z] 'Desirable' nuts were not harvested in 2021 due to disease loss.

Table 4.3. Mean incidence and severity of pecan scab and powdery mildew on pecan nuts from a minimal fungicide program applied to 'Excel' and 'Desirable' in 2020 and 2021, including results from 'Excel' that did not receive any fungicide applications and 'Desirable' that received a full fungicide program.

		Pecan Nut Disease Ratings			
Year	Treatment[y]	Scab Inc. %	Scab Severity %	Powdery Mildew Inc. %	Powdery Mildew Severity %
2020	Excel	0.00 b[z]	0.00 c	14.29 a	1.59 a
	Excel 3S	0.00 b	0.00 c	1.44 a	0.06 a
	Desirable 3S	100 a	63.19 a	13.13 a	2.19 a
	Desirable FS	98.99 a	26.11 b	6.06 a	1.17 a
2021	Excel	0.00 b	0.00 c	7.21 a	0.77 a
	Excel 3S	0.00 b	0.00 c	18.62 a	6.73 a
	Desirable 3S	100 a	73.16 a	3.92 a	1.84 a
	Desirable FS	97.30 a	49.55 b	17.57 a	7.08 a

[y] 'Excel' received zero fungicide applications; 'Excel 3S' received the minimal fungicide program each year; 'Desirable 3S' received the minimal fungicide program each year; 'Desirable FS' received a full fungicide program each year, 9 and 10 applications in 2020 and 2021, respectively.
[z] Means followed by the same letter within each year are not statistically different according to Tukey's Test ($P < 0.05$).

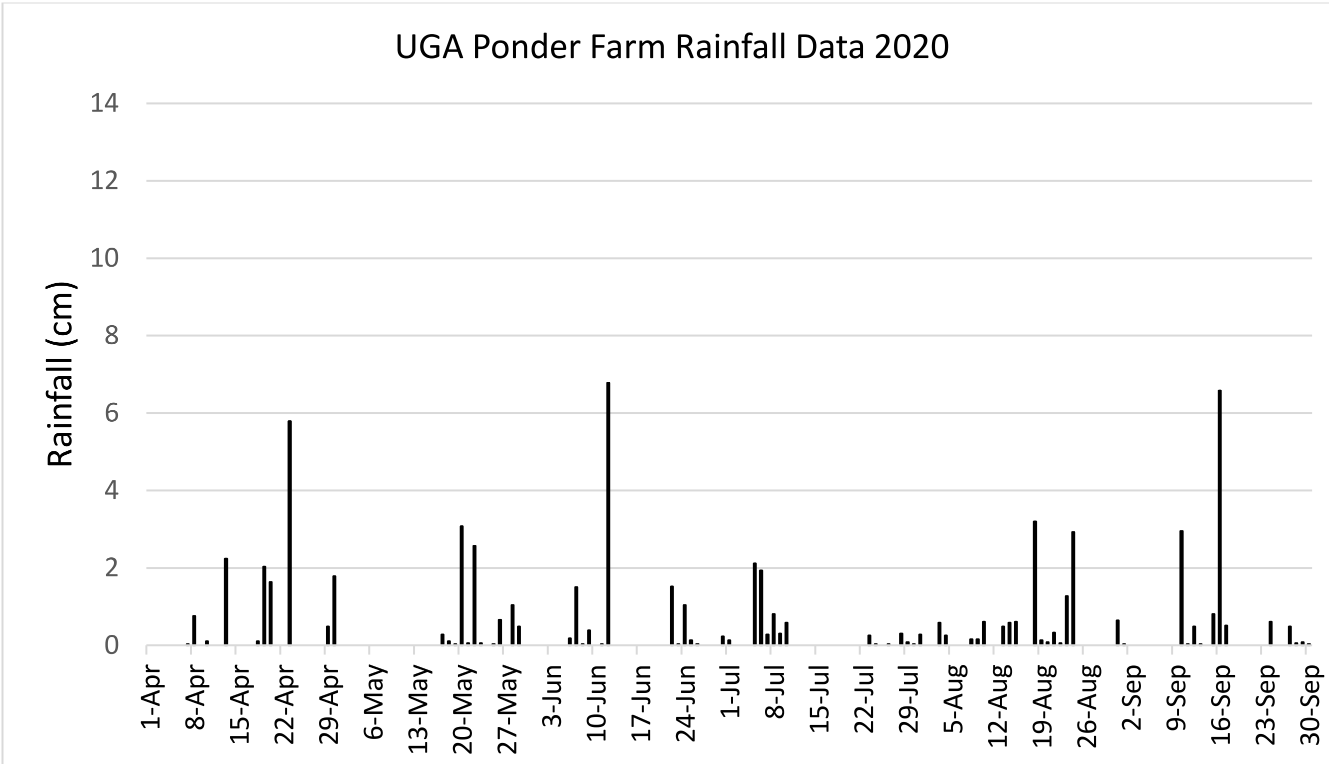

Figure 4.1. Rainfall data from the University of Georgia Ponder Research Farm for the 2020 growing season. Cumulative rainfall from April 1 to September 30, 2020 was 67 cm.

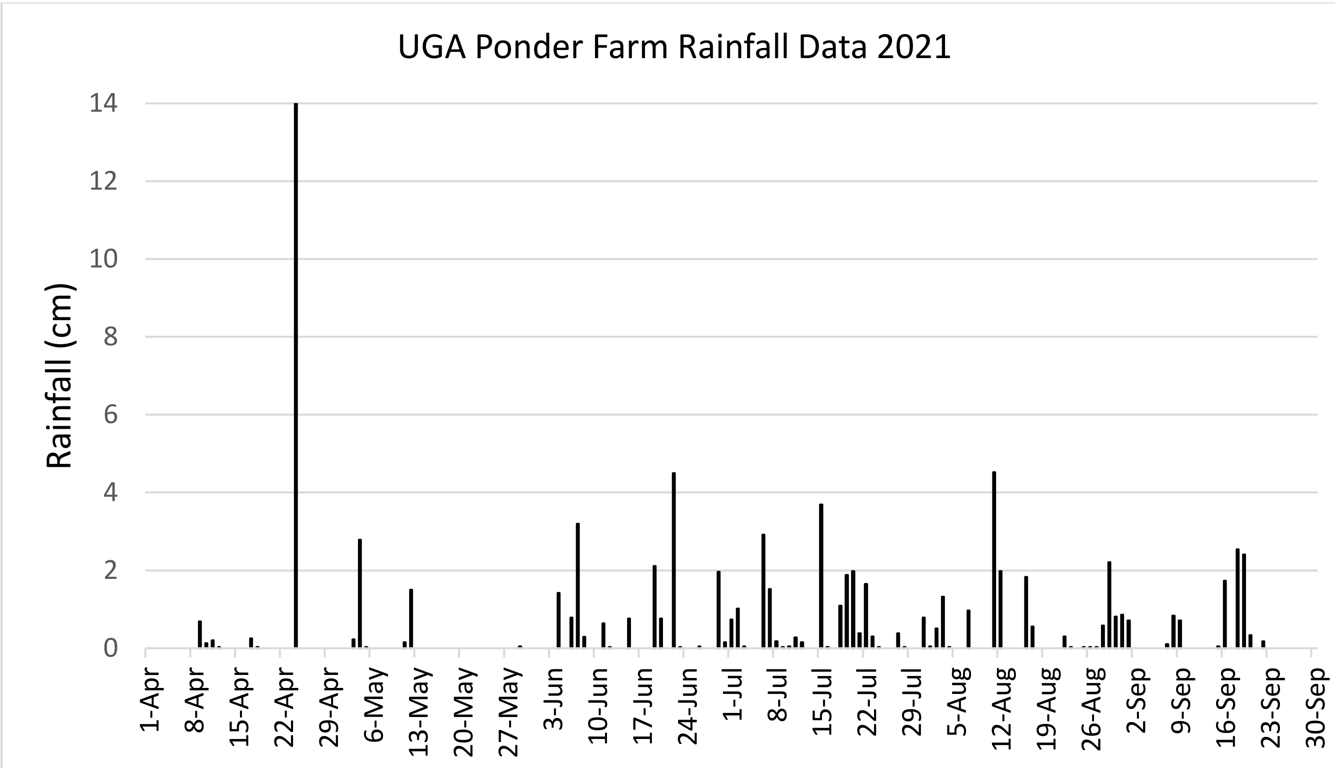

Figure 4.2. Rainfall data from the University of Georgia Ponder Research Farm for the 2021 growing season. Cumulative rainfall from April 1 to September 30, 2021 was 83 cm.

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