Comparison of Soil Health and Soil Fertility Progression in Organically Grown Pecans

Sean Day, Samuel Rathke, James Walworth, and Joseph Blankinship
(College of Agriculture and Life Sciences
University of Arizona, Tucson 85721)

Abstract

In recent decades, there has been an increased demand for organic food production systems that do not use synthetic pesticides, fertilizers, and other amendments. Current trends suggest that organic farming practices will continue to be adopted at an increasing rate. Therefore, it is crucial that soil health and soil fertility indicators be assessed to determine if such practices are sustainable. By focusing on soil health, soil fertility, and marketable yields of United States Department of Agriculture (USDA) Organic Wichita/Western pecans, the objectives of our field study are to: (1) determine whether USDA Organic practices increase soil health, soil fertility, and marketable yields over time; and (2) evaluate the effects of flood irrigation on the variability of soil health and soil fertility within an orchard row. Effects of organic farm practices on the progression of soil health, soil fertility, and marketable yield will be evaluated in four USDA Certified Organic pecan orchards (31.959333, -110.950932) that were converted from conventional practices in 2002, 2006, 2008, and 2013. Studied blocks in each orchard are flood irrigated with sandy loam soils. Well-established Wichita (protognynous) and Western (protandrous) pecan (*Carya illinoinensis*) varieties occupy all blocks in similar ratios. A soil health assessment at depths of 0-10 cm, 10-20 cm, and 20-30 cm will be measured at eight evenly divided locations down a single row within each of the four blocks. The rows within each block will be compared to analyze differences in soil health and fertility metrics. Soil health measurements will include aggregate stability, bulk density, soil organic matter, water-holding capacity, water infiltration, and soil microbial activity. We will also analyze irrigation water for pH, EC, and nitrate at each block. Soil fertility at depths of 30 cm, 60 cm, 90 cm and 120 cm will be measured at eight evenly divided locations down a single row within each of the four blocks. Zinc, Total N, EC, and pH will comprise the soil fertility measurements. This will be done during dormancy, before first zinc spray, after last zinc spray, and before harvest. Similarly, leaf tissue analysis will be tested for nitrates and zinc content. We will create a complete N budget—including organic and inorganic forms—to determine fertilizer efficiency and whether pecan orchards with organic practices are progressively becoming N-limited. In addition, historical records of marketable yields since the time of planting from the four blocks will be examined to determine quantitative relationships between soil health and crop health and yield.

What is Organic?

USDA Organic can be generally defined as the federal guidelines by which farmers must abide by to produce agricultural products as set forth in *The Organic Foods Production Act of 1990*. While most synthetic fertilizers, amendments, and pesticides are unlawful to have been used within the last three years on certified blocks, some synthetic substances can still be used. However, any methods or substances that are amended to this act which are intended to improve crop health and mitigate weed, pest and disease problems must be proven to promote the balance of the ecosystem, encourage ecological conservation, and foster biodiversity. In some instances, we will be referring to compounds and substances as organic or inorganic using the organic chemistry definition used in agronomy. In other instances, we will denote approved USDA Organic inputs and practices as such to avoid any semantic confusion. We will be avoiding the organic definition coined by Walter Northbourne and developed by Sir Albert Howard (1873-1947) which was an agricultural system "having a complex but necessary interrelationship of parts, similar to that in living things"[2].

No Genetically Modified Organisms (GMO) can be used ever in USDA Organic but the definition remains vague. No legal definition of GMO exists in the United States as the date of this paper. Biotechnology is however defined in the *United States (U.S.) Code of Federal Regulations* which states any product engineered using DNA recombination technology. The *European Unio*n (*EU*) definition is the strictest and thus relevant if farmers are exporting products globally [3]. *EU* legislation defines GMO as "...an organism, except for human beings, in which the genetic material has been altered in a way that does not occur naturally by mating and/or natural selection."

What is Soil Health?

Over the last decade soil health, soil quality, and soil tilth have been acknowledged substantially in the scientific and agricultural community [6]. Many authors and organizations have tried to isolate the definitions but we will use soil health and soil quality interchangeably and avoiding the older term soil tilth. The National Resource Conservation Service (USDA-NRCS) and Agricultural Research Service (USDA-ARS) defines soil quality or health as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health” [7]. While this definition may seem ambiguous it is precise in that there is no universally healthy soil for any one crop. For instance, marketable yields in potatoes (*Solanum tuberosum*) are not affected by alkaline soil pH at the same rate as pecans *(Carya illinoinensis)* [8,9]. Therefore, vice having a rigid soil standard, several measures are used to evaluate soil health which address biological, physical and chemical parameters. These soil health indices are interpreted within in their natural or anthropogenic environmental context to which the samples are derived from [23].

Although the definition of soil health is not confined to certain quantitative measures, soil carbon (C) and soil organic matter (SOM) have been intimately associated with soil health. They are linked with improving soil aggregate stability, erosion potential, water holding capacity, and controlled nutrient release [10]. Soil health deterioration, SOM decline, and agricultural management practices have been correlated with one another extensively [11]. And though yields often decline in USDA Organic systems when compared to conventional systems, SOM has been proven to increase even in systems that have off-farm-inputs that near zero [11].

Many indicators exist to measure soil health and continue to change as more research is conducted but we have chosen just a few due to time and funding constraints. We will be collecting data on aggregate stability, available water holding capacity (AWHC), bulk density, water infiltration, soil organic matter (SOM), and soil microbial activity via Tea Bag Index. Below in figure 1 is a more complete list of soil health indicators that the USDA-NRCS is currently promoting [23].

Soil Health/Soil Quality Indicators		
Physical Properties	**Chemical Properties**	**Biological Properties**
Aggregate Stability/Slaking		Earthworms
Available Water Capacity	Reactive Carbon	Particulate Organic Matter
Bulk Density	Soil Electrical Conductivity	Potentially Mineralizable Nitrogen
Infiltration	Soil Nitrate	Soil Enzymes
Soil Crusts	Soil pH	Soil Respiration
Soil Structure and Macropores		Total Organic Carbon

Figure 1. *USDA-NRCS soil health and soil quality indicators* [23].

Aggregate Stability

Soil aggregates can be defined as soil particle groups that adhere to each other more tightly than neighboring particles. The ability of the soil to protect these aggregates is referred to as aggregate stability. As plants senescence, the soil microbiome utilizes the carbon rich plant materials as a food source and make exudates as it degrades the roots, shoots, fruits, seeds, and leaves. Plants also pump carbon into the soil to form symbiotic relationships with other organisms [23]. These exudates act as glue and protect the soil from erosion and dust bowl conditions. Moreover, these aggregates are linked to other processes, functions and properties of the ecosystem such as water infiltration and actively cycled soil organic matter. Excessive tillage, unwarranted foot and vehicle traffic, leaving fields fallow, and reduced carbon inputs are just some of the activities that can degrade these aggregates. Since macro-aggregates are strongly correlated with actively cycled SOM and have relatively elevated cycling rates they are responsive to agricultural management practices [17].

Available Water-Holding Capacity

The maximum amount of water a soil can hold is called water holding capacity (WHC) and the amount that is available to plants is referred to as the available water holding capacity (AWHC). The latter is often defined as the difference between field capacity and the permanent wilting point. AWHC is inherently controlled by the soil texture, rock abundance, soil horizonation, and soil depth. Coarse sandy soils have the lowest AWHC while silty loams have the highest. These innate soil characteristics are not generally dynamic. SOM, bulk density, and EC are dynamic however and can affect the AWHC. SOM affects AWHC directly by increasing the (porosity) surface area of the soil. It indirectly improves WHC by improving soil structure and increasing pore size. Many of the same agricultural practices that reduce aggregate stability and SOM will therefore decrease WHC [23].

Bulk Density

Soil compaction is often referred to as bulk density (soil oven dry weight/volume). Soil texture inherently affects the bulk density. Sandier soils generally have higher bulk densities due to lower porosity than more clayey soils with higher porosities. Rocks usually have a bulk density of 2.65 g/cm^3 and for reference loamy soils have bulk density of 1.33 g/cm^3. Soils rich in SOM generally have lower bulk densities as do soils with finer textures due to higher porosity than more coarse soils. Since SOM and land management practices can greatly affect bulk density, it is considered a dynamic soil health indicator. Again, the same factors that can change aggregate stability and WHC can affect bulk density as well. The sustainability question is unclear though because deep tillage can reduce bulk density but can also increase it if done too often or under less than ideal conditions such as when the soil is saturated [23].

Soil Texture	Bulk densities most conducive for plant growth (g/cm^3)	Bulk densities that hinder plant growth (g/cm^3)
Sandy	<1.60	>1.80
Silty	<1.40	>1.65
Clayey	<1.10	>1.47

Figure 2. *Summarizes relationship between soil texture and bulk density* [23].

Increased bulk densities not only restrict root growth of plants as summarized in figure 2 but they also deprive them of oxygen [23]. Pecans, like other C3 photosynthetic plants, rely on respiration to produce sugars when conditions for photosynthesis are not ideal. In oxygen rich environments 38 mol of ATP can be made with 1 mol of glucose. In anaerobic conditions, only 2 mol of ATP are synthesized from 1 mol of glucose. Toxic metabolites like lactate, H_2O_2, and ethanol can also build up in plant cells under hypoxic conditions causing more damage [20].

Consequently, if soil bulk densities are too high pecans can't obtain enough oxygen and thus energy to carry out biological functions to sustain their health [23].

Water Infiltration

The vertical entry of water into the soil is called water infiltration. The infiltration rate generally is conveyed as inches per hour. Soil texture is a key inherent factor in predicting infiltration rates. Water will have faster vertical rates in a coarser soil and more lateral movement in more fine grained soils. However, some clayey (2:1) soils have high shrink capacities that can creates cracks and act as conduits for faster vertical infiltration rates. While texture can't be managed on large scales, SOM and management practices can. These factors impact infiltration rates tremendously because they directly affect pore size. Larger pores allow for greater infiltration rates which prevent soil erosion and surface run-off of amendments and nutrients. But if infiltration is too high leaching of key nutrients such as nitrate can occur and conveying water down rows in flood irrigated systems becomes a challenge. Below in figure 3 is a summary of infiltration rates of three soil textures for reference [23].

Soil Texture	Infiltration Rate (in/hr)
Sands	<0.8
Loamy	0.2-0.4
Clays	0.04-0.2

Figure 3. *Universal soil texture and steady state infiltration rates relationship summary* [23].

Soil Organic Matter (SOM)

The carbon cycle is a fundamental part of life on earth. The amount of carbon stored in the soil is a component of soil organic matter. Organic carbon in the soil is the basis of soil fertility. Carbon is a buffer against harmful pests, assists in releasing nutrients for plant growth, promotes improved structure, and enhances biological and physical health of soil. Organic material is manufactured by plants using carbon dioxide from the air and water. Plants and animals die and return to the soil where they are decomposed and recycled. Minerals are released into the soil and carbon dioxide is released into the atmosphere where it undergoes reduction reactions and gains electrons. It then returns to the soil where microbes strip CO_2 of its electrons in a process called oxidation thus completing the carbon cycle. The electrons are vital for producing enzymes that lower the activation energy requirements to decompose organic matter. Plants require carbon dioxide for photosynthesis and having more living things in the localized region will result in more carbon for crops [5].

One of the solid portions of the soil is called organic matter. Plant and animal residues in various stages of decomposition, monosaccharides, polysaccharides, amino acids, proteins, fats, waxes, and lignin that comprise cells and tissues, all are considered organic matter. Once the organic matter has been broken down it forms a dark brown and black unstructured and heterogeneous substance referred to as humus. The main reasons for adding organic matter to soil are; to discard of any organic waste that is not useable, introduce nutrients needed for plants, and to prepare seed beds by increasing the workability of the soil. The addition of organic matter has other benefits such as; better water holding capacity, improved aeration, decrease soil erosion, better soil structure, and increased cation exchange capacity [4].

Microbial Activity

Microbial activity and decomposition rates promote recycling and storage of nutrients within the soil biome and hence soil health. Saprotrophic organisms decompose organic material and release gasses such as CO^2. Carbon dioxide evolution is often used as a proxy for microbial activity and decomposition rates but is highly variable due to various abiotic and biotic conditions. Traditionally mesh bags filled with native litter were buried, recovered, and weighed to evaluate decomposition rates over a two or more-year period to capture the variability and inaccuracies of other methods that attempt to quantify microbial activity. This method though prevents comparisons between sites because leaf litter used can greatly impact decomposition rates independent of other state factors. The Tea Bag Index (TBI) uses uniform tea bags that are accessible worldwide in both brick-and-mortar-stores and online stores. Green tea is used because it is more biodegradable while rooibos tea is used because it is less labile. In only 90 days this test produces a decomposition rate constant k_{TBI} that can be compared across different agro-ecosystems [18].

USDA Organic growers have less pesticides to choose from and sometimes resort to other practices that are not conducive to microbial health. Few USDA Organic herbicides exist to combat weeds and growers are thus driven to eradicate weeds with increased tillage practices and flame weeding in many cases. Flame weeding has been proven to only increase the temperature by 4°C at 5 mm so the threat to the soil microbiome and SOM will likely not threaten soil health [12]. However increasing evidence has shown that reduced tillage and no tillage systems have improved soil health [13]. But these systems often depend on conventional herbicides to control weeds so no clear connections can be made from such conflicting data. Even more confusion arises because many conventional pesticides are not broad spectrum and only kill specific families or orders of pests preserving more of the biodiversity than their USDA Organic counterparts. Some conventional pesticides even biodegrade faster than there USDA Organic pesticide registered for the same crop and pest. Other USDA Organic pesticides are broad spectrum and may cause more damage to the soil microbiome and thus soil health and fertility.

In some cases, they may not even kill insect pests but may instead drive them to neighboring fields increasing pesticide use.

What is Soil Fertility?

While similar to soil health, soil fertility, according the USDA-NRCS, focuses more on plant health and is defined by the soil's ability to deliver physical, chemical, and biological necessities for plant growth, plant reproduction, and plant efficiency. This framework is studied in relation to human and animal welfare for crops that are used for food, fuel, and/or clothing. Further connections are additionally made between plant quality and soil fertility as they pertain to plant species, soil morphology (including past and present climatic constraints and parent material), and land classification (primarily land use) [15]. For the purposes of this paper we have decided to measure total N, pH, EC, and zinc as a metric of soil fertility since they are often cited specifically as affecting pecan health in the Sonoran Desert.

Zinc and Soil pH Relationship

Pecan trees are native to the Mississippi where soils are more acidic. Pecans were brought to the Sonoran Desert to escape pest pressure but suffered from nutrition deficiencies because of the inherently alkaline soils present in the South West. They especially continue to suffer from zinc deficiency which necessitates foliar applications three to four times throughout the growing season. With every 1-unit of increase in soil pH, zinc becomes 100 times less available to the plant. Due to economic reasons and soils being highly buffered with calcium carbonate ($CaCO_3$) growers struggle to reduce the pH to pecan's native conditions. Worse, USDA Organic growers can't use many fertilizers that are acidifying or other amendments that have proven to be effective against "rosetting" caused by zinc deficiency [19].

Soil Electrical Conductivity (EC)

EC is often utilized as an indirect measure of salts dissolved in soil water and can be used to measure soil moisture and depth articulated in deciSiemens per meter (dS/m). Soil pore size and soil porosity are heavily influenced by soil texture and minerology. Higher porosity generally increasing EC. They are inherent characteristics of the soil that alter EC, independent of salts present in the soil. High CEC clay soils such as smectite will have an elevated EC and conversely low CEC clay minerals such as kaolinite will have reduced EC readings. Marine shales when compared to granites have higher EC. Alluvial deposits generally have lower EC than clay lacustrine deposits. EC while not a direct measure can be utilized as a link to dynamic quantities of anions (SO_4^{2-}, Cl^-, NO_3^-, and HCO_3^-) and cations (Ca_2^+, Mg_2^+, K^+, and Na^+) [23].

In arid regions like the Sonoran Desert, EC is often elevated on farms due to salts collecting in the soil that are derived from deep ground water wells and high ET. In addition, USDA Organic and conventional fertilizers and amendments can both increase EC in agricultural systems. While soil water EC does not usually directly inhibit plant growth it is linked with reduced crop growth, development, and yield. This occurs for several reasons; it can inhibit microbial activity, increase water tension mimicking droughty signs and symptoms, interfere with nitrification by microbes and disrupt respiration of crops. However, this can be highly variable in flood irrigated systems such as the one in this study that can leach salts thus lowering the EC in the soil root profile [23].

EC (dS/m)	Salinity Class
0-2	Non-Saline
2-4	Very Slightly Saline
4-8	Slightly Saline
8-16	Moderately Saline
>16	Strongly Saline

Figure 4. *NRCS Soil Survey Handbook classes of salinity [23].*

Nitrogen Uptake Curve

Pecan orchards and groves (natural "orchards") like most other crops, requires intensive nitrogen management for successful plant growth, optimization of health, prevention of economic losses, and avoidance of environmental contamination. While pecans need this essential element more than any other nutrient, much of it is needed during a narrow window within a growing season for development of dry matter accumulation [22]. Despite the atmosphere being 78% nitrogen, it is largely unavailable to non-leguminous crops like pecans and is only introduced into the soil naturally in sparse amounts not substantial enough for agricultural purposes [24]. Split applications are required as result of these circumstances which requires more labor costs to the grower [22]. Moreover, not all sources of nitrogen applied are plant available. Sources that are more bioavailable, have a higher potential for leaching into surface and ground water. This is rare in these vast amounts in almost all other crop nutrients. To make matters more difficult, leaching is exacerbated in more course soil textures and is compounded in more hot arid regions such as the Sonoran Desert because pecans require longer irrigation sets that drive nitrates into rivers and streams poisoning both wildlife and livestock at a higher rate [23, 24, 25]. These unique characteristics of nitrogen require crop advisors to manage nitrogen more closely than any other plant nutrient. Growers must therefore apply nitrogen to the soil at the right time, using the right source, at the right rate, and at the right place to maximize yields and profits while simultaneously doing so in an environmentally sustainable way [30,29].

The most efficient way of delivering nitrogen at the right time and place is via drip line fertigation and injected via differential pressure injectors. Not only will this method prevent leaching it will also reduce the risk of the nitrogen turning into ammonia gas or nitric oxide (greenhouse gas) termed volatilization because excessive amounts won't be sitting idle in the soil. Denitrification occurs when nitrate-nitrogen is converted into nitrogen gas by bacteria [26]. However, few liquid nitrogen rich fertilizers exist for USDA Organic growers that are economical on larger scales such as the 7,000-acre pecan orchard in this study. Moreover, converting from flood to drip for many pecan growers in the region in not feasible financially because of narrow profit margins [22].

Choosing the right rate at which to apply nitrogen fertilizer is directly influenced by the source and the source will also dictate at what rate to apply. Pecans can only absorb nitrogen as ammonium or nitrate but often prefers the nitrate form even though it must reduce it thus getting less energy than from ammonium. Here in lies the fundamental complication of choosing the best quantity and type of nitrogen fertilizer; soil particles being an anion will more easily hold onto cationic ammonium thus preventing leaching [31, 32]. However, nitrates being anionic will repel the soil particles and be leached out of the root zone and into water supplies more easily if not used by the plant. For instance, if soil nitrogen analysis prescribes the need for 50 pounds/acre of nitrogen and the source is primarily ammonium, the crop may not be able to absorb enough nitrogen and show signs of chlorosis. An inexperienced farm manager may then apply too much the following application if not aware "Quick Nitrate Soil Tests" often used, are not testing for ammonium and not cognizant a crop can still show signs of deficiency regardless of ample nitrogen being in the soil profile [31]. This ammonium may then convert over to nitrates too quickly, leach, volatilize, nitrify, and/or cause toxicity symptoms due to high EC. If timed correctly though, could result in less split applications reducing labor costs because the ammonium could convert over to nitrate when its most needed if precise planning is conducted. Choosing an ammonium source may also cause the pH of the soil to become too acidic causing toxicity and deficiency symptoms in other nutrients [26]. This may or may not benefit pecan growers in arid regions dealing with zinc issues and alkaline soils [19]. Water nitrate levels also should be checked but often aren't as they will serve as a credit to the nitrogen budget and influence the rate of fertilization [24]. Choosing the right rate and source are very complex decisions that can have antagonist effects but if done correctly can have additive or even synergistic effects if managed properly. It should be noted though that quantitative soil tests do not always reflect soil fertility because the plant cannot sometimes access the nutrients so it is vital that soil tests be coupled with soil tissue analysis [31].

The decomposition of organic matter by microorganisms is vital for plant nitrogen uptake. Microbes have an important task in this regard which is called mineralization where they consume free nitrates, create enzymes, and decompose organic nitrogen held within organic matter and transform it into inorganic plant bioavailable nitrogen. The process peaks at a rate that is affected by several environmental factors to include the nitrogen content. This comes at a temporary cost however, because the nitrogen needed by plants becomes temporarily unavailable when it is first absorbed into the tissues and cells of the organisms consuming the organic matter, termed immobilization [24]. Since the organic matter lacks enough readily available nitrogen for microbes, they consume nitrogen in the soil to initiate the decomposition process of the organic matter. Immobilization creates a temporary nitrogen depression where plant growth is reduced. When the microbes consume all the nitrogen in the soil they die and then release nitrogen [27]. This nitrogen then goes through a process called nitrification and ammonium ions are oxidized to nitrate ions. This whole process called the nitrogen cycle results in a net gain in total bioavailable nitrogen for plant consumption. If the organic matter has a low C:N ratio then the immobilization phase will be shorter and the net gain in inorganic nitrogen will be higher. On the contrary, the immobilization phase will be longer if the C:N ratio is higher resulting in a net gain in inorganic nitrogen but to a lesser extent of the former on a mass by mass basis [28, 31, 26].

If USDA Organic fertilizers are applied as ammonium and it's not converting over to nitrate at the correct time in the pecan trees lifecycle the tree will be unhealthy and suffer from reduce foliar brix content making it more susceptible to pest damage such as black aphid infestations. This can then cascade into other disease issues necessitating the need for even more pesticides. Worse could lead to increased leaching if ammonium is converted to nitrate when nitrogen uptake is reduced in the pecan lifecycle. If the nitrogen becomes more bioavailable via "slow release" fertilizers at the wrong time this can lead to excessive foliar growth late in the season which could reduce foliar drop and lead to permanent cold damage [16]. Due to labor increases, USDA Organic growers often avoid split application of N and do so all at once expecting the "slow release" fertilizers will be timed with plant needs. This is not always the case [21,22].

More Research Needed

In recent decades, there has been an increased demand for organic food production systems that do not use synthetic pesticides, fertilizers, and other amendments. Current trends suggest that organic farming practices will continue to be adopted at an increasing rate [1]. Therefore, it is crucial that soil health and soil fertility indicators be assessed to determine if such practices are sustainable. While many organic systems exist with their own set of accepted and prohibited practices, we will be focusing on USDA Organic practices and their impact on sustainability. It is widely accepted that soil health and fertility are greatly affected by agricultural practices but it's still unclear if conventional practices are superior to USDA Organic practices [4, 5]. Many meta-analyses have confirmed that USDA Organic systems do not improve soil health. This likely stems from the fact that many conventional farmers still adopt many of the same practices that build soil health that USDA Organic farmers utilize. Some key contributors to improving soil health are dependence on heavy crop rotations, cover crops, reduced tillage, and inputs with a lower carbon to nitrogen ratio (C:N). Other reasons for this disparity are the unknown connections between conventional and USDA Organic pesticide use and soil health. For example, in areas like the San Joaquin Valley, record yields have been reported despite soil health declining [13]. And even more unclear is the effects of GMOs on soil health since many genetically modified crops are more resistant to abiotic and biotic stress thus needing less inputs in some instances [15]. However, due to energy prices rising, more government labor regulations, human population booms, and climate change, the traditional agrarian ambition to increase yields must be combined with doing so in an environmentally and economically sustainable way [14].

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