A Soil Quality Index for Alabama

By

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Abstract

Soil quality is how well soil performs the functions expected of it. Many of Alabama's agricultural soils are considered poor quality due to compaction, excessive runoff, a history of severe erosion, low soil organic matter, and lack of cover crops. Routine soil testing does a good job of evaluating the status of plant nutrients in the soil but it does not provide farmers with the overall quality or health of their soil. There has been some research on using a soil quality index (SQI) but defining the parameters to use has been difficult. Most studies agree that a SQI must be determined on a regional basis due to differences in soils and their uses. The objective of this study was to determine a SQI for Alabama soils by measuring soil parameters that are inherently associated with soil quality in a soil testing lab and make such service available for farmers and gardeners. Paired samples from fields with similar soils and landscapes, but different yields, were taken from farms in Alabama and Georgia. Long-term fertility experiments were also sampled in Alabama. The samples were then analyzed for soil organic matter (SOM), potentially mineralizable N, pH, P, K, Ca, Mg, micronutrients, electrical conductivity, CEC, aggregate stability, and respiration. Each of the parameters were assigned a predetermined weight. Weights for each parameter were summed up to determine a SQI based on 100 for each soil. The final SQI includes selected chemical, physical and biological indicators that are easily and inexpensively measured in a routine soil testing laboratory. Through a process of correlations and iterations, the final parameter weights for SQI are proposed for Alabama. The SQI was significantly related to yield for the long-term research samples but not the farmer samples.

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Introduction

Air and water quality are well defined, and parameters are in place for testing their quality. While equally important, soil quality has not received the same focus as air and water quality. Soil quality should be considered even more important since it does not recycle itself the way air and water do. Three centimeters of mineral soil may take 200 yrs to form (Friend, 1992). Once soil is lost, by either erosion or urbanization, it will take a long time to replace it, and the soil that is not completely destroyed is degraded in quality (Brady and Weil, 2008). The demand for food in the twenty first century is expected to double its current level, which will place an even greater demand on our soils (Doran et al., 2002).

Soil quality refers to the soil's ability to perform the functions expected of it (Karlen et al., 1994). The terms soil quality and soil health are often considered to be the same. Soil health is a broader term related to the overall condition of the soil, while soil quality is more confined term focused on the chemical, physical, and biological properties (Doran and Zeiss, 2000). Soil is a home for microbes, is responsible for water supply and purification, and for recycling of nutrients. Alabama has a history of poor soil quality due to severe erosion, steep slopes, soil borne diseases, and low productivity (Charles Mitchell, personal communication, August 7, 2014).

Interest in soil quality increased in the early 1990's but the first few years were spent trying to define soil quality (Smith et al., 1993). A definition of soil quality did exist; however, there were no established methods to test the quality of the soil. With the interest in soil quality increasing, the NRCS created a website, http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/, with information and resources related to soil quality. However, with numerous measures of soil quality, it is difficult to evaluate soils for overall quality. A soil quality index could establish a set of parameters that give numerical evidence of the soils ability to carry out its expected functions (Acton, 1994). While there may be some universal indices listed, the weight of the indices will have to be determined on a regional level due to the different geography and cropping systems (Smith et al., 1993).

History of Soil Quality

Even though soils are important to almost all land uses they have not previously been considered in management decisions (Herrick, 2000). Interest in soil quality began due to the improvement in agricultural technologies, new methods of land evaluation, and an increased focus on agricultural problems (Lewandowski and Zumwinkle, 1999). When the soil quality concept was first introduced it focused mainly on problems with erosion. Not until the late 1980s did the focus shift from erosion to sustainable agriculture (Wienhold et al., 2004). The Soil Science Society of America (SSSA) defines “sustainability” as “managing soil and crop cultural practices so as not to degrade or impair environmental quality on or off site, and without eventually reducing yield potential as a result of the chosen practice through exhaustion or either on-site resources or non-renewable inputs” (SSSA, 1997). The soil quality focus was a nice fit with efforts of agricultural sustainability.

The concept of soil quality was first suggested by Warkentin and Fletcher 1977). While Warkentin and Fletcher started the discussion, it did not become a real focal point until the early 1990s. In 1990, the U.S Forest Service and Soil Science Society of America sponsored a Soil Quality symposium with the purpose of opening a discussion into soil quality. Larson and Pierce (1991) came up with a working definition of soil quality and suggested that soil quality is a combination of chemical, physical and biological properties. These three properties work together to maintain plant growth, regulate water flow, and act as an environmental buffer.

Harris et al. (1996) and, Romig et al. (1996) began assessing soil quality using score cards. These score cards were used mainly as a way to show the importance of soils and as a means to record what was being done to improve them (Karlen et al., 2008). When considering soil quality for agriculture, the farmer's need for profits and soil conservation need to be taken into account (Gomez et al., 1996).

Although soil quality was fully recognized in the early 1990's, very little research was done to create a way to measure soil quality until early to mid-2000. In 1999, the USDA released a Soil Quality Test kit. This kit is comprised of 12 tests that can be done on site. Unfortunately, some of the tests may need more than one day to complete. It was also comprised of tests that are subjective to the person performing the test. The studies that can be found in the literature are using soil quality indices to study the effect of one management decision on soil and were not trying to create an index that could be more broadly used. The majority of the studies were conducted in Europe or China. Larson and Pierce (1991), one of the most frequently cited studies, was performed in Thailand.

Soil Quality Indices

Soil quality indices are a way to incorporate multiple points of information into one tool that can be used for decision making (Karlen and Scott, 1994). This tool has the potential to show farmers what they can do to improve their soil and yield beyond basic fertilizer application. A soil quality index will be most useful when the goal is sustainability as well as yield (Andrews et al., 2001).

Larson and Pierce (1991) suggested that a minimum data set needed to be accepted when measuring the quality of soils and that a standard set of methodologies needed to be instituted. Most of the indicators that are used to create soil quality indices have procedures established well before the soil quality interest became dominant. Wienhold et al. (2004) noted that measuring these factors together and producing an index will help improve the sustainability of the land.

When choosing parameters for the minimum data set, the reason soil quality is being measured needs to be remembered (Andrews et al., 2004). Since soil quality can be site-specific, different tests may need to be performed for different agro-ecosystems (Shukla et al., 2006). A farmer in Alabama would not need the same recommendations as a potato farmer from Idaho. The parameters chosen should provide numerical data that show the ability of the soil to perform its expected functions (Acton, 1994).

Gomez et al. (1996) stated that there are two methods for measuring the sustainability of agriculture. In the first method, the indicators are chosen based on the location of each individual farm taking into account what that farm needs. This means that a farm in steep lands with problems with erosion would be assigned a different set of indicators than those of a lowland farm where erosion is not a concern. The second method states that the same indicators should be used despite the differing situations of the farms. Most studies looking into soil quality use a variety of indicators based solely on the study they are currently performing. The indices that are currently being used are not readily available to all producers. According to Herrick (2000), soil quality indices will be more readily adopted if the measurements are simplified, the costs are reduced, and the time between sampling and computation of analysis is shortened. Soil quality measurements need to be easily performed, incorporated into management decisions, and made widely available to land managers (Shukla et al., 2006).

Soil Quality Indicators

When selecting indicators, natural and anthropogenic changes should be measured (Wienhold et al., 2004). The indicators chosen should be easy to measure and able to show any existing problems in the soil (Schloter et al., 2003). A survey of farmers found that farmers use yield, profit, and crop failure as field indicators of sustainability (Gomez et al., 1996). Farmers will find measuring their soil's quality more advantageous if the number of indicators deemed necessary are kept at a minimum (Franzluebbers et al., 2000). Some of the most common indicators to assess soil quality used in research are pH, aggregate stability, SOM, and those relating to microbial activity (Bastida et al., 2008). Other indicators include electrical conductivity, soil respiration, CEC, and metal contamination. Many of these indicators have been found to be strongly correlated with each other (Arshad and Martin, 2002).

Soil texture is related to CEC and can be relatively easy to determine in a routine soil testing lab. While the Auburn University soil testing lab does not actually measure soil texture, it does calculate an estimated CEC (ECEC) based upon Mehlich-1 extractable cations (K, Ca, Mg) and exchange acidity using a modified Adams-Evans buffer solution (Huluka, 2005). Based upon the ECEC and sometimes the region of the state from which the soil originated, all soils are placed into one of four "soil groups" (Mitchell and Huluka, 2012):

Group 1. Sandy soils with an ECEC<4.6 cmol kg^{-1}

Group 2. Loams and light clays with an 4.6<ECEC<9.0 cmol kg $^{-1}$

Group 3. Clays and soil high in organic matter with ECEC 9.0+ cmol kg $^{-1}$

Group 4. Clays of the Alabama Blackland Prairie region with ECEC 9.0+ cmol kg $^{-1}$

SOM has been found to be one of the most important soil quality indicators. When studying the correlation between indicators, SOM is correlated or has an effect on almost all other indicators (Arshad and Martin, 2002). It is related to better soil fertility, nutrient retention, and plant available water (Friedman et al., 2001). Although it is an important soil quality component, a 2001 survey of central Alabama cotton fields indicated that 50 % of the soils had less than 0.4% SOM (Mitchell et al., 2002).

Aggregate stability measures how well the soil can withstand disruptive forces, such as tillage and rainfall. Unfortunately for producers, aggregate stability is degraded by land cultivation (Celik 2005). The deterioration of soil aggregates is one of the major factors in the degradation of soils (Groenevelt, 1991). SOM helps hold aggregates together, and free SOM on the surface helps protect the aggregates from disturbance (Tisdall and Oades, 1982). Disruptive forces that affect aggregate stability include erosion due to both wind (Kempler and Rosenau, 1986). While erosion is disruptive to aggregate stability, Barthes and Roose (2002) found that high aggregate stability helped reduce the amount of runoff and erosion. Aggregate stability is important due to its effect on porosity, bulk density, and hydraulic conductivity (Cerda, 1996).

Soil respiration measures the release of carbon dioxide from dry soil as it is rewetted. Soil respiration can be used as an indicator of soil fertility (Staben et al., 1997). Soil respiration may also be used to help predict the amount of N that can be mineralized (Haney et al., 2012). It is most widely used as in indicator of the level of microbial activity (Haney et al., 2008). Franzluebbers et al. (1996), found that the flush of CO_2 released during the first 24 h following rewetting was highly correlated with carbon mineralization, soil microbial biomass, and nitrogen mineralization. As a biological parameter, soil respiration is important for soil quality. Biological parameter may have a more rapid response to changes in management decisions (Staben et al., 1997).

Electrical conductivity is frequently used to express the salinity of the soil (Malick and Walczak, 1999). It describes the concentration of soluble salts found in the soil (Rhoades, 1982). Plants often uptake nutrients as soluble cations and anions, but if the concentration are too high then the plants may be harmed (Bernstein, 1964). If a soil is exposed to high sodium levels where sodium replaces other cations, to fill 15 % of the exchangeable sites, the soil structure becomes less stable, and the breakdown of aggregates become more restrictive to yield than the sodium itself (Bernstein, 1964). As the electrical conductivity in the soil increases, ammonia volatilization and nitrification inhibition increases (McClung and Frankenberger, 1985). Electrical conductivity an important indicator since it can have an impact on management decisions of producers. The effect of salinity on crops and suggested categories for interpretation are given by Lorenz and Maynard (1980), and by Donohue (1983).

Soil Quality Indices in American Agriculture

Karlen et al. (1994), studied the effects of different residue applications on soil quality in soils from Illinois, Wisconsin, Minnesota, and Iowa. This study was one of the first attempts to develop a multiparametric index of soil quality. Aggregate stability, porosity, worms, microbial biomass, respiration, total C, total N, bulk density, available water, pH, and electrical conductivity were used as indicators. The index was weighted based on Eq. [1].

$$\text{Soil Quality} = qwe\,(wt) + qwma\,(wt) + qrd\,(wt) + qfqp\,(wt). \qquad [1]$$

Where wt was a weight assigned to each function and qwe was how well the soil could accommodate water; qwma was how well the soil could transfer water; qrd was how well the soil could withstand degradation; and qfqp was how well the soil supported plant growth. The weights were subjectively assigned a value between zero and one. There was no mathematical or statistical backing; the number was based on what the researcher felt was the more important factor for the function being studied.

Hussian et al. (1999) studied aggregate stability, organic C, crop residues, porosity, exchangeable K, and pH as indicators of soil quality. The objective of the study was to adjust soil quality indices to determine the effect of three differing tillage treatments on soil in south Illinois. They used the equation:

$$\text{Index} = f\,(y\ \text{nutrient} + y\ \text{water} + y\ \text{rooting}) \qquad [2]$$

where y was the weight assigned to each function. Six indexes were created with this equation and compared using analysis of variance and general linear modeling. The purpose of this study was to determine which tillage system scored the highest. The eight years no-till treatment scored the highest on all indices used compared to more intensive tillage practices. The study also found that when the index thresholds were adjusted to the local conditions, it became more sensitive to the management practices they were evaluating.

Glover et al. (2000) conducted a study using aggregate stability, porosity, worms, organic C, microbial biomass C and N, cationic exchange capacity, pH, total N, and nitrate-N as indicators of soil quality. The effects of conventional, organic, and integrated apple productions in the state of Washington were compared. Integrated apple production employ methods from both conventional and organic methods. This study used the same weighting system as Karlen et al. (1994), where the weights for all the soil functions had to add up to one. Integrated apple production ranked higher than both conventional and organic methods individually.

Liebig et al. (2001) studied the effects of conventional and alternative agricultural systems using a performance based index. Seed yield, N content of seed, pH, organic C, and soil nitrates were used as indicators of soil quality. The index was created by grouping data, calculating averages, ranking treatments, and summing the scores across the agroecosystems. The overall equation was:

$$\text{Agroecosystem performance} = f\,[(\text{food production} \times W_{fp}), (\text{raw materials production} \times W_{rmp}), (\text{nutrient cycling} \times W_{nc}), (\text{greenhouse gas regulation} \times W_{ggr})\qquad [3]$$

Where W_x was the weight assigned to each function. The weight was 0.25 for each, but could be adjusted if one function had more factors in it than another.

Andrews et al. (2002) were the first to compare methods of indicator selection. Indicators selected by expert opinion were compared with those selected by statistical methods. Principle component analysis was used to determine which indicators should be selected for the function they wanted to measure. Expert opinion chose soluble phosphorus, pH, electrical conductivity, sodium absorption ratio, and soil organic matter as indicators. Principle component selected soluble phosphorus, pH, calcium, sodium and total nitrogen. Both types of indices were found to be equally representative of soil quality, but principle component analysis would not work with a study of low observation that was missing crop rotation data.

Shukle et al. (2006) used water stable aggregates, mean weight diameter of aggregates, geometric mean weight diameter of aggregates, particle size, electrical conductivity, pH, total C, total N, water infiltration, crop biomass, and grain yield as indicators. The purpose of this study was to use factor analysis to determine indicators between five corn treatments. Indicators in correlation or in pairs of attributes such as biomass with total C were studied. Factor and discriminant analysis were then used to determine which factors were dominant in discriminating among the treatments being studied. Total C was the dominant attribute for every factor.

Cornell University is one of the first public soil testing laboratories to use a Soil Quality Index for the purpose of making it available to the public. Cornell's indicators were selected from 39 potential soil health indicators (Idowu et. al, 2008; Gugino et al., 2009). Cornell's Soil Quality Index requires submission of penetrometer readings with soil sample collections (Gugino et al., 2009). They offer multiple packages, the most basic including soil texture, wet aggregate stability, available water capacity, surface/sub-surface hardness, organic matter, and active carbon in addition to standard fertility tests and recommendations.

Objectives

A soil testing program began in Alabama in 1953 when the Alabama Agricultural Experiment Station initiated soil testing at Alabama Polytechnic Institute, now Auburn University (Wilson, 1954). The AU Soil Testing lab has focused primarily on testing routine soil samples for pH and extractable nutrients for the purposes of making lime and fertilizer recommendations for crops (Mitchell and Huluka, 2012). Many of the components of soil quality indexes are part of the routine soil testing service, and some of the non-routine analyses can also be performed by the lab. The objective of this study was to help Alabama producers improve the quality/health of their soils through the use of a prototype soil quality index (SQI). To accomplish this, we used five premises in developing a SQI.

1) The SQI should make farmers and gardeners aware of soil quality/soil health.
2) The SQI should suggest ways of improving soil quality/soil health.
3) The SQI must be adaptable to existing soil test methodologies.
4) The SQI must be relatively inexpensive to run on traditional soil samples.

5) The SQI must provide information in a simple and easy to understand manner.

Materials and Methods

Calculation of Soil Quality Index

The first iteration of a SQI was modeled after the Cornell Soil Health Assessment (CSHA) which integrates measurements of several soil attributes (Idowu et al., 2009). However, our approach varied considerably due to the difference in the premises we used in our objectives. This was the first attempt, to our knowledge, to quantify soil quality parameters for the highly weathered, generally acid, low CEC soils of the Southeastern U.S. We took the approach of listing tests we could do through our routine soil testing laboratory at Auburn University. A weight was assigned to each factor based upon the best judgment of several experienced extension and research scientists. The first iteration is presented in Table 1. We then proceeded to try and validate the selection of theses parameters.

Soil Samples

Two hundred and forty-nine soil samples were collected from farms and Long-term research projects throughout Alabama, and 47 soil samples were collected from Georgia. At least two soil samples were taken from each farm, one sample from a low yield area and the other from an area of high yield, supposedly from the same soil mapping unit or at least the same soil series. Samples were taken by farmers, extension agents, and researchers. Samples were brought to the Auburn University Soil Testing lab and dried at 65 ˚C overnight. The samples were ground and passed through a 2-mm sieve. Then the soils were analyzed following procedures used by AU Soil Testing lab (Hue and Evans, 1986).

Crop Yields

Crop yield was considered an indicator of soil quality with the assumption that a high quality soil would result in a higher crop yield. The concept of soil quality/soil health involves more than just crop yield, but we needed a parameter that was easily available and could be measured. Farmers were asked for an estimated or relative yield for all samples submitted, regardless of crop. Some producers kept detailed records and had yield monitors while others just estimated yield. When paired soil samples were submitted, one of the samples represented 100 % relative yield and the other samples came from an area in the same field with lower production. For the purposes of this study, the crop was recorded but not included in any analysis. Samples that came from research plots had recorded crop yields associated with them. A relative yield was calculated and compared to a treatment that received optimum fertilization and liming. On-going soil fertility experiments were sampled from the Tennessee Valley Research and Extension Center in Belle Mina, AL (Decatur silt loam, fine, kaolinitic thermic Rhodic Paleudults), Sand Mountain Research and Extension Center, Crossiville, AL (Hartsells fine sandy loam, fine-loamy, siliceous, subactive, themic Typic Hapludults), Prattville Research Unity, Prattville, AL (Lucedale fine sandy loam, fine-loamy, siliceous, subactive, thermic Rhodic Paleudults), and Brewton Research Unit, Brewton, AL (Benndale loamy sand, coarse-loamy, siliceous, semiactive, thermic Typic Paleudults). These samples came from long-term, soil fertility experiments known as the “Two - Year Rotation” (circa 1929) (Cope, 1984). A similar experiment at Auburn, AL, known as the “Cullars Rotation” (circa 1911) on a Marvyn loamy sand (fine-loamy, kaolinitic, thermic Typic Kanhapludults) was also sampled (Mitchell et al., 2011). The “Old Rotation” experiment (circa 1986) at Auburn, AL, on a Pacolet fine sandy loam (fine, kaolinitic, thermic, Typic Kanhapludults), which is the world’s oldest cotton experiment and also includes cover crops and crop rotations was also sampled (Mitchell et al., 2008).

Soil pH

Ten cm^3 of soil was mixed with 10 mL of water and equilibrated for at least 30 min. The pH of the solution was measured with a Labfit AS-3000 Dual pH meter (Labfit, Ltd, Burswood, West Australia), after appropriate calibrations. A buffer pH was determined after adding 10 cm^3 of modified Adam's Evans buffer solution to the soil-water solution (Huluka, 2005). This resulted in a 1:1:1 soil: water: buffer ratio.

Elemental Analysis

Five grams of soil sample was weighed and added to an Erlenmeyer flask for Mehlich I extractable elements. Twenty mL of Mehlich I solution was added, and samples were then shaken for 5 min. After filtering, the solution was analyzed for P, K, Mg, Ca, Zn, Mn, Cu, Pb, Cr, Cd, and Ni by inductively coupled plasma (ICP) (Varian Vista-MPX, ICP-OES, Ltd, Victoria, Australia). Interpretation for extractable P, K, and micronutrients e.g., low medium, high, very high and extremely high, were based on classifications defined by Mitchell and Huluka (2012).

Carbon by Dry Combustion

Carbon was measured on selected samples using Elementar vario Macro C, H, N, and S analyzer (Elementar Ltd, Mt. Laurel, NJ) by burning 0.16 to 0.20 g of dried and finely ground soil at 960 °C in pure O_2 gas. The result from dry combustion was reported as total soil carbon. Soil organic matter contains more than 50% soil organic carbon (Baldock and Nelson, 2000). The conversion factor between soil organic carbon and SOM varies from 1.724 to 2.5 (Nelson and Sommers, 1996). We used a conversion factor of 1.7 to convert total soil carbon readings to SOM.

Soil Organic Matter by Loss on Ignition

SOM was determined by loss on ignition according to Ball (1964). This method was selected based upon an evaluation of the cost and relative accuracy of several methods of determining SOM in soils from the southeastern U.S. (Ou, 2014). This method required all soil samples to be the same moisture level and temperature. To insure this, all samples were dried overnight at 105 ˚C in a weighed crucible (weight 1). The crucible was then removed and cooled in a desiccator for 10 min before being weighed again (weight 2). The samples were then placed in a muffle furnace at 375 ˚C for 16 h for ignition. After ignition, the samples were cooled in a desiccator for 45 min, reweighed (weight 3). The percent SOM was then calculated by Eq. [4].

$$\text{SOM \%} = (\text{weight 2} - \text{weight 3}) / (\text{weight 2} - \text{weight 1}) \qquad [4]$$

Soil Respiration and Potential N mineralization

Soil respiration was measured using the Solvita method established by Woods End Laboratories (Mt Vernon, ME). This method requires oven dried soil to be passed through a 2-mm sieve. Forty grams of soil sample was placed over a glass microfiber filter in a small plastic beaker. The beaker was placed in a glass jar and 25 mL of water was added. A Solvita® paddle was added and the jar was completely closed. After 24 h of incubation at 25 ˚C, the paddle was removed and read with the Digital Color Reader for CO_2 levels (Haney and Haney, 2010). Based on the CO_2 reading from the Digital Color Reader for respiration, a range of potential N mineralization was assigned to each sample. There is a relationship between aerobic microbial respiration and ammonification and nitrification as related to water-filled pores space in soils (Linn and Doran, 1984). This relationship was used by USDA-NRCS to create categories for soil respiration and potential N mineralization (http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051573.pdf.) These are given in Table 2 and were the basis of the categories we used in our SQI.

Electrical Conductivity

Twenty cm^3 of soil sample was mixed with 40 mL of water (1:2 soil water ratio) in a plastic Erlenmeyer flask. The sample was shaken for 15 min and allowed to settle for 1 h. Once the suspension settled the sample was filtered through a number 42 Whatman filter paper. The electrical conductivity of the filtrate were measured with a YSI Model 31 Conductivity Bridge (Yellow Springs, Ohio).

Wet Aggregate Stability

Aggregate stability was measured on selected samples according to Kemper and Rosenau (1986). The soil samples were removed before being dried overnight at 65 ˚C. Four grams of unground, air dried samples were placed into sieves. In order to bring the soil samples to the desired moisture level with minimum disruption, a modified humidifier was used. If the aggregates were wet too quickly, they could become weakened and cause errors. Once the samples were wetted, the sieving apparatus was used to dip the sieves first in tins with 80 mL deionized water and then in tins with 100 mL dispersing solution made with sodium hexametaphosphate. The tins were then placed in an oven at 110 ˚C so the water could evaporate. The amount of soil lost in the water and in the dispersing solution was then used to calculate the stability of the aggregate of each soil.

Slaking Method

Aggregate stability was also tested using a slaking method from the USDA Soil Quality test kit. The soil quality test kit can be found on the NRCS website: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/nedc/training/soil/?cid=nrcs142p2_053873

A 1 cm, air dried, aggregate was placed into a sieve. The sieve was placed in 2 cm of deionized water for 5 min. If the aggregate did not destabilize after 5 min it was lifted in and out of the water 5 times. Stability was estimated based on the percentage of aggregate remaining on the sieve at the end of this process.

Estimated Cation Exchange Capacity

Estimated cation exchange capacity (ECEC) was calculated by the summation of K, Mg, and Ca extracted by Mehlich-1 and the exchangeable acidity determined from the modified Adams-Evans buffer (Huluka, 2005).

The calculation were made using Eq. [5-8].

$$\text{Extractable } Ca^{2+} \text{ (cmolc/kg)} = \text{Mehlich-1 Ca (lb/A)}/400.8 \quad [5]$$

$$\text{Extractable } Mg^{2+} \text{ (cmolc/kg)} = \text{Mehlich-1 Mg (lb/A)}/243 \quad [6]$$

$$\text{Extractable } K^{+} \text{ (cmolc/kg)} = \text{Mehlich-1 K (lb/A)}/782 \quad [7]$$

$$\text{Soil } H^{+} \text{ (cmolc/kg)} = 8 \text{ x } (8\text{-buffer pH}) \quad [8]$$

Soils were placed into one of 4 “soil groups” based upon the ECEC and region of the state from which they originated (Mitchell and Huluka, 2012).

Base Saturation

Percent base saturation was calculated by dividing sum of bases by ECEC and then multiplying by 100. The result was the percentage of base saturation.

Statistical Analysis

SAS (SAS Institute Inc., Cary, NC, USA) was used for most of the data analysis. PROC MEANS was used to determine summary statistics. PROC CORR was used to determine correlation coefficients, and PROC REG was used for the regression models. Microsoft Excel 2010 frequency function was used to determine the distribution of the samples. JMP Pro 12 (SAS Institute Inc., Cary, NC, USA) and Microsoft Excel 2010 were also used for generating figures and corresponding regression equations.

Results and Discussion

Soil organic matter methodology

Soil organic matter was measured by both dry combustion and loss on ignition. Dry combustion is considered a faster and more accurate way of measuring soil organic carbon, but it is also more expensive. Since loss on ignition was reported as SOM and dry combustion was reported as total carbon, the results from dry combustion were converted to SOM by multiplying the total C by 1.7 for comparison. We found that results from loss on ignition and those from dry combustion were highly correlated (Fig.1). Since one of our objectives was to create an affordable index, we decided to use loss on ignition for all samples instead of dry combustion. This decision was also based on the research of Ou (2014) who found a high correlation between loss on ignition and dry combustion. She also found loss on ignition to be the least expensive method and had less environmental impacts.

Aggregate stability methodology.

Two methods for measuring aggregate stability were compared. The first method was measured according to Kemper and Rosenau (1986). The second method was the slaking method from the USDA Soil Quality test kit. The wet aggregate method requires specialized equipment and reagents while the slaking method requires simple sieves and deionized water. The wet aggregate method is also more time consuming than the slaking method. The wet aggregate method requires 20 min preparation, 45 min in the cycle, and then all samples must be dried overnight in the oven. The slaking method requires 5 min preparation and 10 min for each sample. The ease of interpretation is much easier for the slaking method. While the wet aggregate method requires weighing and calculations to determine the aggregate stability, the slaking method requires simple visualization. Based on a table provided by the USDA Soil Quality kit, aggregate stability was assigned by how much the soil destabilizes in water (Table

3). Aggregate stability measurements on samples from the Old Rotation experiment at Auburn Alabama were compared by both methods (Fig. 2). Since slaking is more efficient and cost effective test, it is the recommended for determining aggregate stability.

Metals and Micronutrients

Several authors have suggested that a SQI should recognize contaminated soils as having poor quality or health (Bastida et al., 2008; Chen et al., 2005; Taylor et al., 2010). The most common source of contamination is the over-application of metals, either in the form of fertilizer micronutrients, or contaminated animal manures, sludges, or by-products. The Mehlich-I soil extractant is not recognized for its correlation with plant response to micronutrients or its use to predict micronutrient deficiencies. The Mehlich-III extractant is generally used if micronutrient predictability is a goal of a soil testing program (Zhang et al., 2014). However, some commercial soil testing laboratories do use the Mehlich-I for Zn, Cu, Fe, Mn and B (Charles Mitchell, personal communications, July 17, 2015). The reliability of these interpretations is questionable. However, it has been our experience that when unusually high levels of Mehlich-I extractable metals are present in an extract, the soil has been contaminated from some source. For example, Davis and Rhoads (1994) recommended that if soil pH<6.0 and Mehlich-I extractable Zn is above 10 mg kg^{-1}, Zn toxicity in peanuts could be a problem. Although Mn availability, like Zn, is highly pH dependent, they suggested that Mn toxicities could occur above a Mehlich-I extractable Mn concentration of 10 mg Mn kg^{-1}. Davis and Rhoads (1994) also suggested critical values for hot water extractable B (0.2 mg kg^{-1}) and Mehlich-I extractable Zn (0.25 mg kg^{-1})

Mitchell and Huluka (2012) established critical values for interpreting Mehlich-I extractable Zn, Cu, Mn and B, for all Alabama soils (Table 4). Because micronutrient deficiencies are not common, the table was designed so that most extractable micronutrients would fall in the “High” category suggesting that they are adequate for most crops. The “Very High” category suggests possible soil contamination. These are the levels we used to flag contaminated soils in our SQI. Mehlich-I concentrations of other metals that may be analyzed on soil extracts include Cd, Cr, Pb, and Ni. Because all the soils in this study had relatively low levels of these metals, specific concentrations that would flag these samples were not established.

Comparison of Samples

The AU Soil Laboratory analyses about 24,000 routine soil samples a year from farmers and gardeners throughout Alabama. To determine if our samples were comparable to the samples run by the AU Soil Laboratory in 2014, we compared the percentage of the soil groups, pH ranges, phosphorus, and potassium (Fig. 3-6). The AU Soil Laboratory categorizes four soil groups based on ECEC and location within the state. We used the same soil groups to compare our soils. Our soil represented similar percentages of sandy soils (ECEC < 4.6 cmol kg^{-1}), loams and light clays (4.6 < ECEC< 9.0 cmol kg^{-1}), and heavy clays (ECEC >9.0 cmol kg^{-1}) with very few Blackbelt clays (ECEC >9.0 cmol kg^{-1}) from the Blackland Prairie region in central Alabama. Our soils were mainly comprised of heavy clays and sandy soils (Fig. 3). This difference could be due to the fact that all of our samples were taken from farmer’s fields, primarily in the Lower Coastal Plain and Tennessee Valley regions, while the AU Soil Laboratory receives samples from row crop farmers, home owners and gardeners throughout the state. The Long-term soil fertility research samples were from the Tennessee Valley and Coastal Plain regions. The range in soil pH of our samples was similar to those tested by the AU Soil Laboratory in 2014 (Fig. 4).

Our samples had a higher percentage of high and very high values of phosphorus than those run by the AU Soil Laboratory (Fig. 5). Our samples also showed a lower percentage of very low values. We suspect that this is because most of our samples were from farmers who have done a very good job of fertilizing their crops over the years. Some may have over-fertilized resulting in a larger percentage of “High” and “Very High” samples.

Our samples also had a higher percentage of very low and medium values of K than those run by the AU Soil Laboratory (Fig. 6). They had a lower percentage of high and very high values than those run by the soil lab. We had many samples from long-term fertility studies with K variables comprising a major component of these tests.

Sample Distribution

In the first iteration of our SQI, the indicators were divided into categories. The categories were assigned values based on expert opinion in an attempt to include all three of the basic components of soil quality, chemical, physical, and biological (Table 1). Most initial categories were those already in use by the AU Soil Laboratory (e.g., soil group / ECEC, pH, P, K, and micronutrients). Some categories were assigned based upon general knowledge of what we expected to find in Alabama soils (e.g., SOM, respiration, mineralizable N, and aggregate stability). To determine if our samples would fall into the different categories of each predetermined parameter, we ran a simple distribution analysis. Most variables fell within our expected range, the categories assigned in our initial index. Other variables, such as SOM and EC, did not fit into the categories originally assigned (Fig. 7-9).

Base saturation is an example of a variable that exhibited the categories we expected. The ideal base saturation is 50-75%. As we expected, the majority of our samples fell within this range (Fig. 7). The next largest number of samples had a base saturation of >75%, suggesting that our farmers had done a very good job of liming their soils.

SOM did not fit the expected distribution pattern. According to a survey of Central Alabama cotton fields in 2000, most Alabama soils had less than 0.5% SOM (Mitchell et al., 2002). We had no samples with less than 0.6% SOM, with many of our samples having 1.1-2.0% (Fig. 8). We believe this is due to a difference in sampling depths and tillage. Previous SOM studies were sampled to a depth of 15 cm under conventional tillage while most of our samples were only taken to 7 cm. Our samples were also mostly taken from fields that practiced conservation tillage. Since the majority of SOM is at the surface, this would result in our samples having a higher percentage. Based on these data, the categories in our initial assigned value (Table 1) were shifted in order to get a better separation of the distribution of SOM in Alabama soils.

Electrical conductivity was skewed more to the left indicating that there is little salt problem in Alabama. The majority of the samples, 265 out of 294, had a value of 0.4 mmhos cm^{-1} or less (Fig. 9). Based on these data we determined the first EC category, 0-0.4 mmhos cm^{-1}, should be split into smaller categories and the higher categories combined.

Regression Models

Originally plans were to use relative crop yield was to be used indicator of soil quality assuming soil quality is related to yield. This assumption may or may not be true because soil quality/soil health does involve more than just yield or yield potential. Admittedly, our SQI is largely intended for farmers with a focus on agronomic crops. However, the yield values from farmers' samples were estimates by the producers. This may explain why there was little or no correlation to yield (Table 5). The yield values from Experiment Stations and Long-term soil fertility experiments were actual, measured yields. We separated these values from farmers' samples to determine if these were contributing to the low correlation. When the samples from known experiments only were analyzed, better correlations were observed (Table 6).

Since the yield data for farmers' samples were arbitrary, we focused on data from the research samples. A linear regression model using stepwise variable selection yielded the model:

$$SQI= 0.0567*P + 0.16373 * K + 30.57827*\log EC + 14.32960*pH. \quad [9]$$

The parameter estimates of this equation are given in Table 7. This model had an R^2 of 0.87. We also tested a quadratic regression model:

$$SQI=-609+0.0377*P+0.5538*K+361410*\log EC+222.8106*pH-0.0013*K^2-17.9127pH^2 \quad [10]$$

The parameter estimates of this equation are given in Table 8. This model had an R^2 of 0.43. The regression models were not surprising considering that the data used to develop them included experiments with P, K, and pH variables. The linear model was determined to be the best fit and could have been justified for SQI determination. In that case, we could have just called our model a “Soil Nutrient Index”. These models do not include the physical and biological components of soil quality that are necessary based upon the definition of soil quality/soil health.

We also compared linear and quadratic modeling for the individual variables (Table 9). Individually, the variables had a better fit with quadratic instead of linear which was better for the combination of all variables as a whole. The relationship between K and yield was quadratic (Fig. 10), similar to a familiar soil test calibration curve (Cope and Rouse, 1973; Evans, 1987; Mitchell, 2010). This was true for many essential macro nutrients. Electrical Conductivity was also quadratic (Fig. 11). As EC increased above 0.6 mmhos cm^{-1}, yield decreased but we have very few samples from Alabama with an EC that high. Phosphorus (Fig. 12) and pH (Fig. 13) both had higher R^2 values and fit well to quadratic models. These were expected since P and pH, as other essential nutrients, affect yield. Phosphorus deficiencies affect plant growth and reduce yields. Very high P may contribute to eutrophication, but doesn’t proportionally increase yield. This is why “extremely high” soil test P (5 times the critical soil test P value) was assigned a SQI value of 0 in our model. At very low pH, Mn and/or Al may be toxic to some crops. Also, many plants have ideal pH ranges for optimum growth; yield will be affected if soil pH is too low or high. High soil pH can also limit the availability of many micronutrients needed by plants.

Determining Weights

We initially assigned a large weight to SOM based on previous studies and on data taken from the Old Rotation study in Auburn, AL (Mitchell and Entry, 1998). These data showed a reasonably good correlation between SOM and yield (Fig. 14). The cited study was a crop rotation study with and without cover crops resulting in some dramatic differences in SOM. We took samples from the Old Rotation and found the same correlation, but with higher percentages of SOM (Fig. 15). The increase in SOM, we think is due to conservation tillage and sampling depth. Mitchell and Entry (1998) study was from plow layer samples taken when the experiment was in conventional tillage. In 1997, the experiment was converted to conservation tillage and has had no soil inversion or conventional tillage for 18 years. Our samples were also taken from the upper 7 cm of the soil. When all data were compared to yield, it had a lower correlation than expected at $r^2= 0.28$. When known experiments were separated from farmers' samples the correlation to yield increased to $r^2= 0.35$. This is not as high as the correlations seen in the previous study, but we believe this is due to difference in soils. SOM did not show up as a significant independent variable when all 247 soils were used because of the different soils, different tillage practices, and many different factors affecting crop yield. The study from Old Rotation only accounted for one soil while our samples came from many different soils.

While the linear regression model could be used as a nutrient index, we wanted to create an index that was reasonably comprehensive and easy to read and understand. We also wanted to remain close to our original assumptions. The regression model only represents the "chemical/mineral" component of soil quality. However, the concept of soil quality also includes the "biological" component, represented by SOM, respiration and potential N mineralization, and the “physical” represented by soil aggregate stability. We initially hoped these would be related to yield but other than samples from the Old Rotation experiment, our statistical analysis showed very weak correlation.

In order to retain a statistically sound index, we correlated our SQI to that of the linear regression model. Our initial SQI had a correlation of r^2=0.71 to the linear regression model, and it also exhibited a reasonably good fit to the model (Fig. 16). In order to increase the correlation, we adjusted our weights based on the indicators determined to be critical by the regression model. The maximum values were adjusted as shown in Table 10. Many iterations were attempted, but most adjustments caused a decrease in correlation to both the model and yield. For example, when the weight of SOM was dropped below 20% of the total index, the correlation also dropped. While SQI 12 had a slightly better correlation to yield, SQI 10 had a higher correlation to the model. When the correlations were added SQI 10 summed to 1.2604, while SQI 12 only summed to 1.2557. Soil Quality Index 10 was determined to be the final choice with a correlation $r^2 = 0.74$ to the linear regression model (Table 11). The final SQI also exhibited a slightly better fit when modeled with both the linear regression model and yield (Fig. 17, 18).

Suggestions for Interpretation and Practical Recommendations

The second premise behind developing a SQI, was to “suggest ways of improving soil quality/ soil health.” In order to do this, we first must interpret the SQI for producers sending samples to our soil testing lab. We expect most Alabama soils to fall within the range of a SQI of 40 to 80. Recommendations/comments will be given for best management practices that can be used to improve each component of the SQI (Table 12). Web links to USDA-NRCS best management practices will have to be attached to the SQI report to farmers and gardeners.

Linking Index to Conservation Practices.

A critical part of the SQI is incorporating it in existing conservation practices that can be used to improve soil quality. Practices will be based on existing USDA-NRCS-AL recommended practices that are available on the web. There will be two sets of practices recommended to improve soil quality. The first set of recommendations will be primary practices that would be recommended in all situations (Table 13). The second set would be supporting practices that would be recommended depending upon specific site, situations, and conditions (soil, slope, operation goals, and needs) (Table 14).

Implementing the SQI

Most producers should be able to use the SQI without additional help or assistance as long as they are able to gain access to USDA-NRCS web sites where the best management practices are listed. At some point, these may be included on the AU Soil Laboratory website along with training material. Cooperative Extension agents, NRCS Conservationists, consultants and Certified Crops Advisors (CCAs) will be a valuable asset in incorporating field observations and field measurements into the SQI.

Summary and Conclusion

Soil quality is defined as the ability of soil to perform its intended functions on a sustainable basis. Unfortunately, soil quality can be degraded naturally and anthropogenically. Soils are a vital part of our ecosystem, yet little focus has been paid into measuring and maintaining their quality. Although practices such as conservation tillage and reduced use of agro-chemicals have been implemented, there is still a lack of protocol to quantify soil quality for practitioners. Determination of a soil quality index that is a product of soil factors that impact the soil's ability to perform its expected functions is necessary. With years of literature to support the importance of soil quality/soil health, addition of soil quality indices to regular fertilizer recommendations may help producers improve the sustainability of their soils. In order for soils to be sustainable, farmers need to be aware of soil quality and what they can do to improve it. Just adding lime and fertilizer based on a soil test will not be the answer. The objective of this study was to determine a SQI for Alabama soils by measuring soil parameters that are inherently associated with soil quality in a soil testing lab and make such service available for clienteles. Paired samples from fields with similar soils and landscapes, but different yields, were taken from farms throughout the state of Alabama. The samples were then analyzed for SOM, potentially mineralizable N, pH, P, K, Ca, Mg, micronutrients, EC, ECEC, aggregate stability, and respiration. Each of the parameters were assigned a predetermined weight accordingly. Weights for each parameter were summed up to determine SQI of each soil. We varied the contribution weight of each parameter and selected the linear regression model that was significantly correlated to SQI and yield.

Our samples had similar distribution percentages for the major factors we measured with the bulk samples that came to the AU Soil Laboratory from Alabama in 2014. Except for SOM and EC, our samples had fairly similar frequency distribution. The major soil parameters such as P, K, SOM, and pH were significantly correlated to yield for samples that came from research stations and Long-term experimental plots but not for all 297 samples from throughout Alabama.

Arguments can be made that our final iteration of a SQI inherently assigns a higher index to certain regions of the state because of inherent soil properties such as a higher CEC or more organic matter. The Tennessee Valley or Black Belt region of the State would indeed have an inherently higher SQI than a sandy, eroded Coastal Plain soil. These soils also produce higher average yields than a sandy, eroded Coastal Plain soils. By the same argument, Midwestern U.S.

soils would inherently have a higher SQI than most Alabama soils. Our SQI is a first attempt to regionalize a SQI for the soils of Alabama (Smith et al., 1993). With experience, we would hope that the SQI could be refined to reflect differences in physiographic regions and at least, allow producers to compare their soils quality with other soils in their region. Regardless, recommended best management practices should encourage producers from all regions to implement practices to improve all soils.

Soil testing labs that have traditionally focused only on the chemical aspects of a soil by making lime and fertilizer recommendations can now help practitioners look at practices that enhance, protect, and make our soils more sustainable for future uses. Soil quality index value should be a focal point of each soil test report so that the health of our soils are frequently examined and all necessary inputs are made so that its uses are preserved for generations to come. Soil is an invaluable natural resource that society cannot afford to ignore. The soil quality index can be used as a starting point to enhance soil health, fitness, and its indefinite use.

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Table 1. First iteration of proposed soil quality index for Alabama Soils

Factors	Values					Max. value
Soil CEC/soil group	<4.6 (Grp 1)	4.7-9.0 (Grp2)	9.0- 15.0 (Grp.3)	>15,0 (Grp 4)		
	2	4	5	5		5
Soil pH	<5.0	5.1-5.8	5.9-7.0	7.0-8.0	>8.0	
	0	10	15	10	5	15
P RATING	VL/LOW	MEDIUM	HIGH	VERY HIGH	EXTREMELY HIGH	
	0	5	10	5	0	10
K RATING	VL/LOW	MEDIUM	HIGH	VERY HIGH	EXTREMELY HIGH	
	0	3	5	3	2	5
Base saturation	<10%	11-25%	26-50%	50-75%	>75%	
	0	3	6	10	8	10
SOM (%)	<0.5	0.6-1.0	1.1-2.0	2.1-3.0	>3.0	
	0	5	15	20	25	25
N mineralized (lb/a)	<10	11-20	21-40	41-80	>80	
	0	1	2	3	5	5
Soil respiration	Very Low	Low	Moderate	High	Very High	
	0	1	2	3	5	5
Aggregate stability	No aggregates	Weak	Moderate	Good	Very strong aggregates	
	0	2	4	6	8	8
EC (1:2)	<0.40	0.40-0.80	0.81-1.60	1.61-3.20	>3.20	
Mmhos cm^{-1}	3	5	3	2	0	5
Metals	Two or more metals "very high"		One metal is "very high"		All metals optimum	
	-10		-5		7	7
TOTAL SOIL QUALITY INDEX						100

Table 2. USDA-NRCS categories for soil respiration and potential N mineralization using the Solvita™ procedure.

Color/ Colorimetric Number				
0-1 Blue-Grey	1.0-2.5 Gray-Green	2.5-3.5 Green	3.5-4.0 Green-Yellow	4-5 Yellow
Soil Respiration Activity				
Very Low Soil Activity	Moderately Low Soil Activity	Medium Soil Activity	Ideal Soil Activity	Unusually High Soil Activity
Associated with dry sandy soils, and little or no organic matter	Soil is marginal in terms of biological activity and organic matter	Soil is in a moderately balanced condition and has been receiving organic matter additions	Soil is well supplied with organic matter and has an active population of microorganisms	High/Excessive organic matter additions
Approximate Level of CO_2 Respiration				
< 300 mg CO2/kg soil/wk	300-500 mg CO_2/kg soil/wk	500-1000 mg CO_2/kg soil/wk	1,000-2,000 mg CO_2/kg soil/wk	>2,000 mg CO_2/kg soil/wk
< 9.5 lbs CO_2-C/acre-3"/d	9.5-16 lbs CO_2-C/acre-3"/d	16-32 lbs CO_2-C/acre-3"/d	32-64 lbs CO_2-C/acre-3"/d	>64 lbs CO_2-C/acre-3"/d
Approximate quantity of nitrogen (N) release per year (average climate)				
<10 lbs/acre	10-20 lbs/acre	20-40 lbs/acre	40-80 lbs/acre	80->160 lbs/acre

Table 3. USDA aggregate stability standard characterization from the USDA Soil Quality test kit.

Stability Class	Criteria for assignment to stability class (for Standard Characterization)
0	Soil too unstable to sample (falls through sieve)
1	50 % of structural integrity lost within 5 seconds of insertion in water
2	50 % of structural integrity lost within 5-30 seconds of insertion
3	50 % of structural integrity lost within 30-300 seconds of insertion or <10 % of soil remains on the sieve after 5 dipping cycles
4	10-25% of soil remains on the sieve after 5 dipping cycles
5	25-75% of soil remains on the sieve after 5 dipping cycles
6	75-100% of soil remains on the sieve after 5 dipping cycles

Table 4. Ratings used for Mehlich-1 extractable micronutrients for all soils and crops* (from Mitchell and Huluka 2012)

Rating	Zinc	Copper	Manganese	Boron
	———————lb/A or pp2m———————			
Low	0-0.8	<0.1	0-20	0-1.0
Medium	0.9-1.6	0.2-2.0	21-40	1.1-2.0
High	1.7-20	2.0-100	41-600	2.0-100
Very High	21+	101+	601+	101+

*This table is based upon observations and very limited soil test calibration research. Plant availability and potential toxicity of micronutrients are affected by many soil factors especially soil pH. Mehlich-1 is not very effective at removing these micronutrients in all soils.

Table 5. Correlation between variables and relative yield of all soil samples with correlation probability of no correlation.

Variable	Relative Yield
Relative Yield	1
Soil Group	0.1461
Correlation Probability	0.0141
pH	0.0668
Corr. Probability	0.2635
Phosphorus	0.1177
Corr. Probability	0.0484
Potential N	0.2103
Corr. Probability	0.0004
Potassium	0.2733
Corr. Probability	<.0001
ECEC	0.09
Corr. Probability	0.1316
CO2(ppm)	0.1531
Corr. Probability	0.0100
EC(mmhos cm-1)	0.1181
Corr. Probability	0.0475
OM (%)	0.1439
Corr. Probability	0.0156
Base Sat (%)	0.1774
Corr. Probability	0.0028
Initial SQI	0.4133
Corr. Probability	<0.0001

Table 6. Correlation between first proposed Soil Quality Index and relative yield with variables of research soil samples with correlation probability of no correlation.

Variable	Initial SQI	Relative Yield
BaseSat	0.73937	0.29287
Correlation Probability	<.0001	0.0001
ECEC	0.58153	0.22533
Corr. Probability	<.0001	0.0037
CO2	0.56522	0.20732
Corr. Probability	<.0001	0.0077
Potential N	0.57006	0.18887
Corr. Probability	<.0001	0.0154
Phosphorus	-0.03004	0.12711
Corr. Probability	0.7026	0.1048
Potassium	0.57079	0.41585
Corr. Probability	<.0001	<.0001
Soil Group	0.71579	0.28244
Corr. Probability	<.0001	0.0002
Initial SQI	1.00000	0.50638
Corr. Probability		<.0001
Relative Yield	0.50638	1.00000
	<.0001	
EC	0.11196	0.28824
Corr. Probability	0.1535	0.0002
OM	0.75077	0.35144
Corr. Probability	<.0001	<.0001
pH	0.44544	0.19996
Corr. Probability	<.0001	0.0103

Table 7. Linear Regression model parameter estimates of research soil samples.

Parameter Estimates					
Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr >t**
Phosphorus	1	0.05760	0.02263	2.54	0.0119
Potassium	1	0.16373	0.02853	5.74	<.0001
logEC	1	30.57827	7.66796	3.99	0.0001
pH	1	14.32960	1.79197	8.00	<.0001

Table 8. Quadratic regression model parameter estimates of research soil samples.

Parameter Estimates					
Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	1	-609.45383	155.48117	-3.92	0.0001
Phosphorus	1	0.03771	0.02131	1.77	0.0787
Potassium	1	0.55379	0.11467	4.83	<.0001
logEC	1	36.14097	8.79390	4.11	<.0001
pH	1	222.81063	52.86460	4.21	<.0001
Phosphorus^2	1	-0.00134	0.00035088	-3.83	0.0002
pH^2	1	-17.91266	4.41976	-4.05	<.0001

Table 9. Linear and quadratic models of independent variables from research soil samples.

	Linear			Quadratic		
Source	**R^2**	**Pr >F**	**model**	**R^2**	**Pr >F**	**model**
Potassium	0.24	<.0001	y=1.0922K+ 22.648	0.36	<.0001	y=-0.0549K^2+5.0459K-33.378
Phosphorus	0.54	>0.1048	y=3.0655+39.962	0.57	>.1135	y=-0.1375P^2+6.69P+24.261
logEC	0.16	<.0001	y=54.235EC+139.57	0.18	<.0001	y=-23.343EC^2+9.1091EC+121.07
pH	0.04	0.0103	y=11.7504pH+1.6223	0.12	<.0001	y=-20.05pH^2+251.4pH-707.38

Table 10. Soil quality indices tested for different weights of factors.

	Soil Quality Index (SQI) iterations											
Factors	SQI 1	SQI 2	SQI 3	SQI 4	SQI 5	SQI 6	SQI7	SQI 8	SQI 9	SQI 10	SQI 11	SQI 12
CEC	5	5	5	5	5	5	5	5	5	5	5	5
pH	15	15	10	10	10	10	10	15	15	15	10	10
P	10	10	10	15	10	5	10	10	10	10	10	10
K	5	20	20	20	25	25	25	25	5	10	15	20
BS	10	5	5	5	5	5	5	5	10	10	10	10
OM	25	15	20	15	15	25	25	10	25	20	20	15
N	5	5	5	5	5	5	0	5	5	5	5	5
CO2	5	5	5	5	5	5	5	5	5	5	5	5
Ag	8	5	5	5	5	5	5	5	8	8	8	8
EC	5	10	10	10	10	10	10	10	5	5	5	5
Metals	7	5	5	5	5	5	5	5	7	7	7	7
Total SQI	100	100	100	100	100	100	100	100	100	100	100	100
r^2 to Model	0.7061	0.6615	0.6659	0.5962	0.6041	0.6555	0.6247	0.6006	0.6914	0.7373	0.7354	0.732
r^2 to Yield	0.5064	0.5083	0.5051	0.4816	0.4572	0.466	0.4765	0.4868	0.484	0.5231	0.5223	0.5237
Sum	1.2125	1.1698	1.171	1.0778	1.0613	1.1215	1.1012	1.0874	1.1754	1.2604	1.2577	1.2557

Table 11. Final iteration of Soil Quality Index for Alabama Soils

Factors	**Values**					**Max. value**
Soil CEC/soil group	<4.6 (Grp 1)	4.7-9.0 (Grp2)	9.0- 15.0 (Grp.3)	>15,0 (Grp 4)		
	2	4	5	5		5
Soil pH	<5.0	5.1-5.8	5.9-7.0	7.0-8.0	>8.0	
	0	10	15	10	5	15
P RATING	VL/LOW	MEDIUM	HIGH	VERY HIGH	EXTREMELY HIGH	
	0	5	10	5	0	10
K RATING	VL/LOW	MEDIUM	HIGH	VERY HIGH	EXTREMELY HIGH	
	0	5	10	8	5	10
Base saturation	<10%	11-25%	26-50%	50-75%	>75%	
	0	3	6	10	8	10
Soil O.M.(%)	<1.0	1.1-2.0	2.1-3.0	23.1-4.0	>4.0	
	0	4	12	16	20	20
N mineralized (lb/a)	<10	11-20	21-40	41-80	>80	
	0	1	2	3	5	5
Soil respiration	VeryLow	Low	Moderate	High	Very High	
	0	1	2	3	5	5
Aggregate stability	No aggregates	Weak	Moderate	Good	Very strong aggregates	
	0	2	4	6	8	8
EC (1:2) **Mmhos cm^{-1}**	<0.20	0.21-0.40	0.41-0.80	0.81-1.6	>1.6	
	3	5	3	2	0	5
Metals	Two or more metals "very high"		One metal is "very high"		All metals optimum	
	-10		-5		7	7
TOTAL SOIL QUALITY INDEX						100

Table 12. Interpretation and recommendations suggested for implementation with Soil Quality Index for Alabama soils.

Factor	Comment on report	NRCS practice
If SQI>80	Soil Quality Index is high. Continue with existing practices	
If pH<5.8	Add Ag. lime at recommended rates	
If P=EH	P is excessive and additional P in fertilizers or manures should be avoided.	
If P value = VL or L	Consider using animal manures to build soil P (PP4)	PP4
If K = VL, L or M		See soil test K recommendations
If SOM= <1.0%	Consider residue and tillage management and cover crops	PP2, PP3, SP3, SP7
If N mineralized > 50 lb/a	Consider reducing commercial N applied by 30 to 50 lb. N/acre	
If aggregate stability is moderate or less	Soil compaction and runoff is a hazard. Consider reduced or no-till, high residue management, use of cover crops, and mulching. Consider in-row subsoiling or strip tillage.	PP1, PP2, PP3, SP7, SP2
If N mineralized <20 lb N/acre	Building soil organic matter will help increase mineralizable N.	
If respiration is VL or L	Building soil organic matter will help improve soil respiration.	
If EC>1.60	WARNING. . . SALT BUILDUP COULD DMAGE CROPS.	
If one metal is VH	**CAUTION. Zn, Cu, Cd, Pb, or Cr** is very high. This could be an indication of contamination from micronutrient fertilizers, manures or some other application. Metals cannot be removed from the soil. Keep soil pH above 6.0 to reduce metal uptake by plants.	
If 2 or more metals are VH	**WARNING.** This soil has been contaminated from excessive metal application either from fertilizers or some other application. Metals cannot be removed from the soil. Keep soil pH above 6.0 to reduce metal uptake by plants.	
If 50<SQI<80	Soil could use improvement. Consider implementing one or more of the above practices.	See BMPs above.
If SQI< 50	Your total soil quality index is low. Use one or more of the following primary practices to help improve the soil quality index. Re-test your soil in 3 years to determine if the practices are helping. You may be eligible for assistance from your local Soil and Water Conservation District Office or USDA-NRCS office.	(list of NRCS Primary and Secondary practices)

Table 13. Web links to USDA-NRCS-AL primary practice recommendations to be included with Soil Quality Index for producers.

Primary Practice	Web Link
PP1. Conservation Crop Rotation (328)	http://efotg.sc.egov.usda.gov/references/public/AL/tg328.pdf
PP2. Residue and Tillage Management (329)	http://efotg.sc.egov.usda.gov/references/public/AL/tg329.pdf
PP3. Cover Crops (340)	http://efotg.sc.egov.usda.gov/references/public/AL/tg340.pdf
PP4. Nutrient Management (590)	http://efotg.sc.egov.usda.gov/references/public/AL/tg590.pdf
PP5. Integrated Pest Management (595)	http://efotg.sc.egov.usda.gov/references/public/AL/tg595.pdf

Table 14. USDA-NRCS-AL secondary practice recommendations for producers.

Secondary Practice	Web Link
SP1. Contour Farming (330)	http://efotg.sc.egov.usda.gov/references/public/AL/tg330.pdf
SP2. Deep Tillage (324)	http://efotg.sc.egov.usda.gov/references/public/AL/tg324.pdf
SP3. Forage and Biomass Planting (512)	http://efotg.sc.egov.usda.gov/references/public/AL/tg512.pdf
SP4. Irrigation Water Management (449)	http://efotg.sc.egov.usda.gov/references/public/AL/tg449.pdf
SP5. Contour Buffer Strips (332)	http://efotg.sc.egov.usda.gov/references/public/AL/tg332.pdf
SP6. Filter Strips (393)	http://efotg.sc.egov.usda.gov/references/public/AL/tg393.pdf
SP7. Mulching (345)	http://efotg.sc.egov.usda.gov/references/public/AL/tg484.pdf
SP8. Terrace (600)	http://efotg.sc.egov.usda.gov/references/public/AL/tg600.pdf

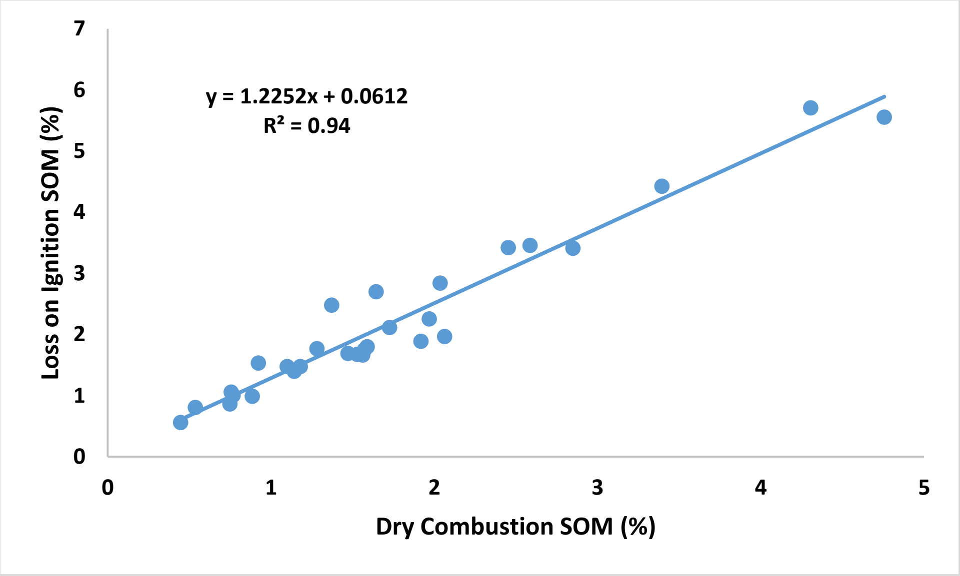

Figure 1. Relationship between dry combustion soil organic matter converted by conversion factor 1.7 and Loss on Ignition soil organic matter of soil samples.

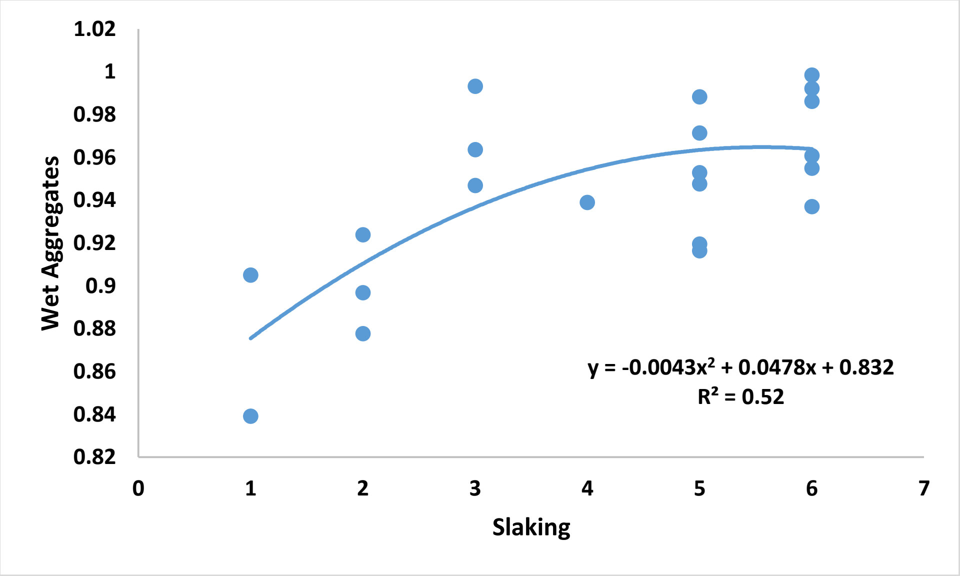

Figure 2. Relationship between aggregate stability methods wet aggregate stability and USDA soil quality test kit slaking method in soil samples.

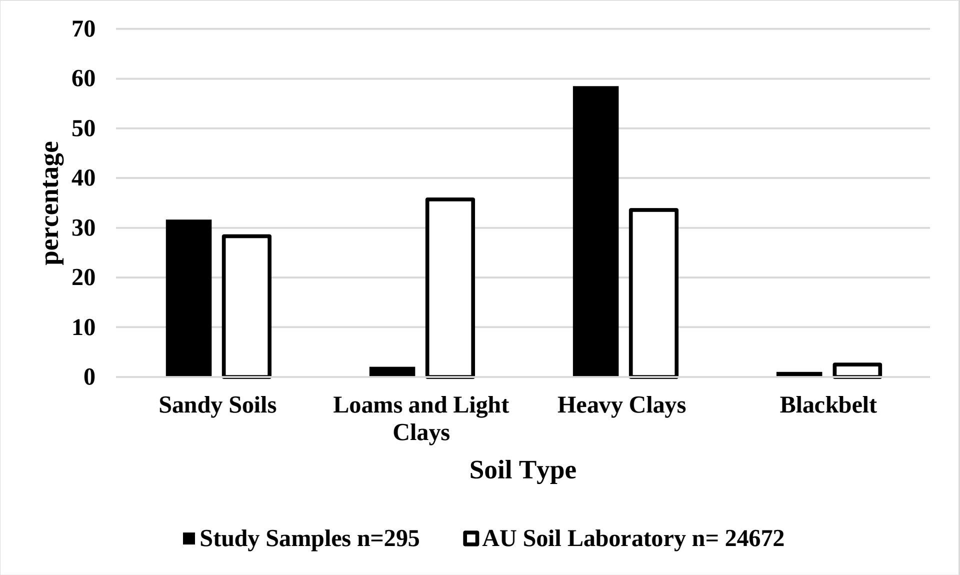

Figure 3. Percentage of soil groups analyzed by this study compared to those analyzed by AU soil lab.

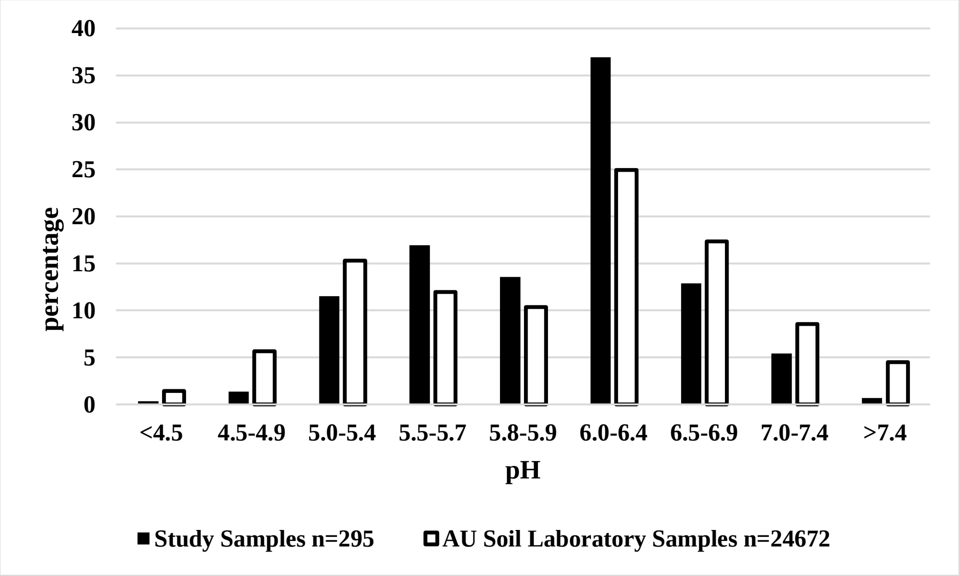

Figure 4. Percentage of soil pH ranges analyzed by this study compared to those analyzed by AU Soil Laboratory.

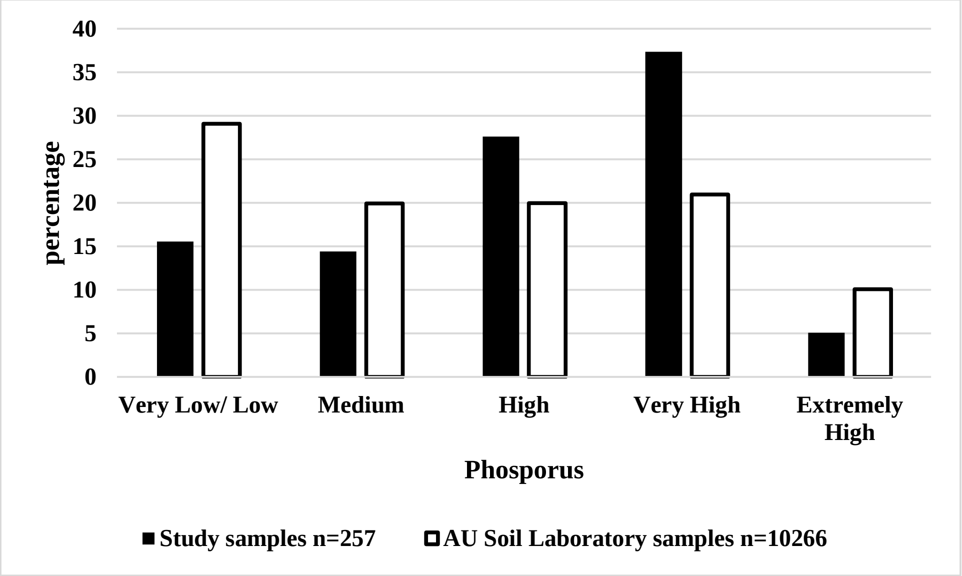

Figure 5. Soil test rating for phosphorus analyzed in this study compared to those analyzed by AU Soil Testing Lab.

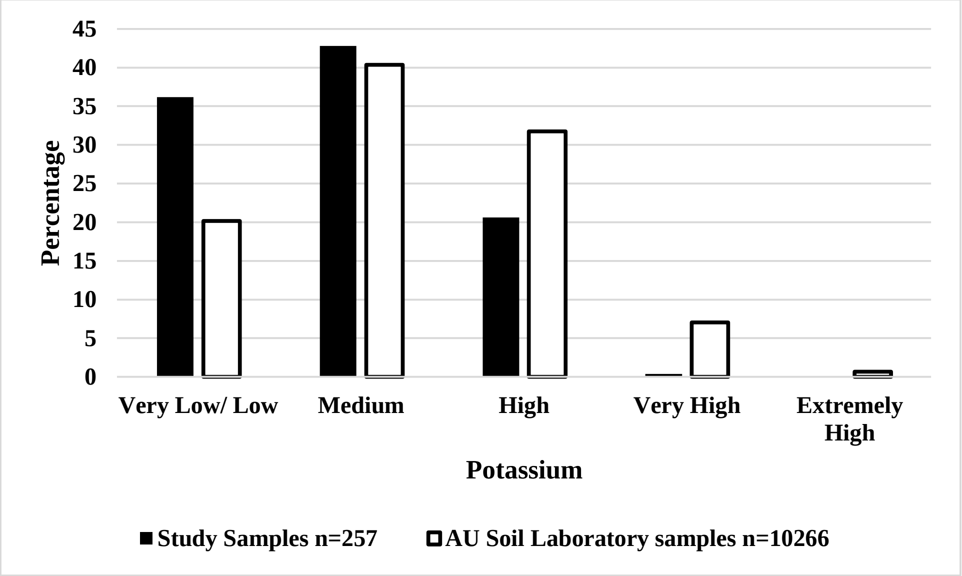

Figure 6. Soil test rating for potassium analyzed in this study compared to those analyzed by AU Soil Testing Lab.

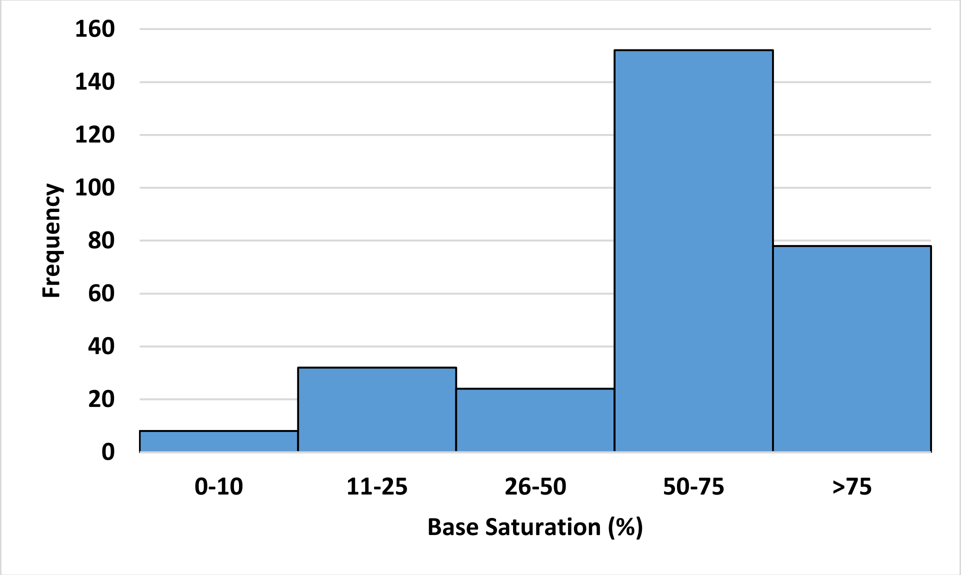

Figure 7. Distribution of base saturation in 273 Alabama soils.

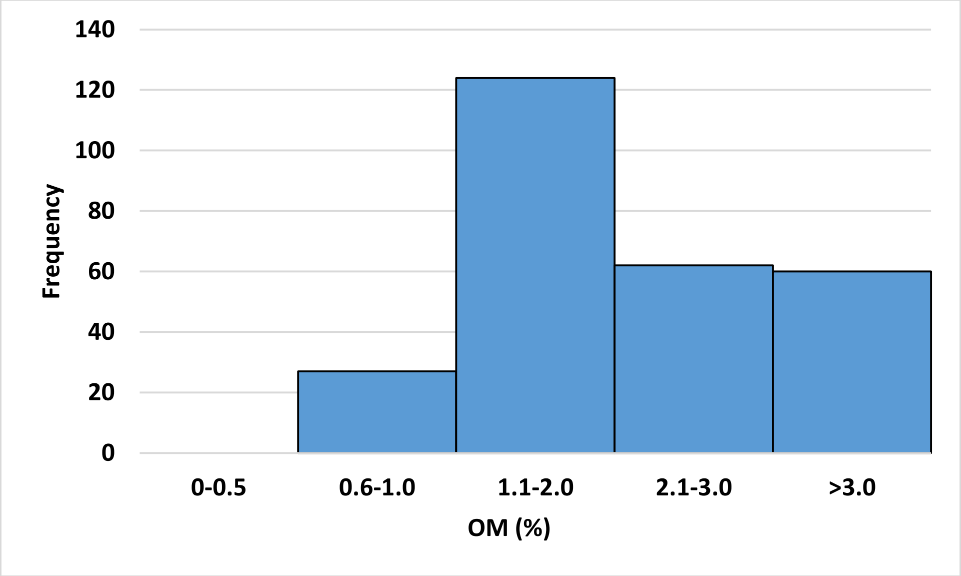

Figure 8. Distribution of Organic Matter in 273 Alabama soils.

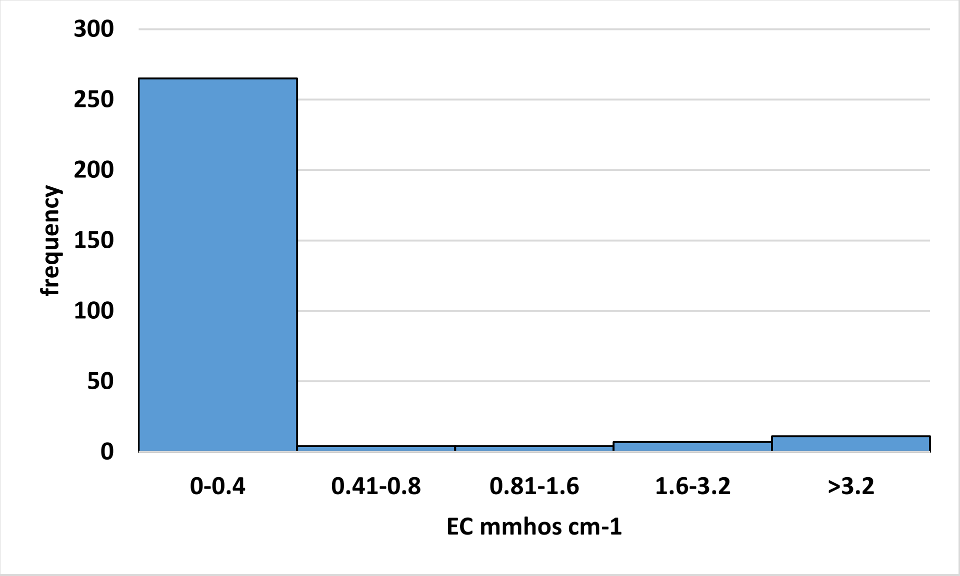

Figure 9. Distribution of electrical conductivity (EC) in 273 Alabama soils.

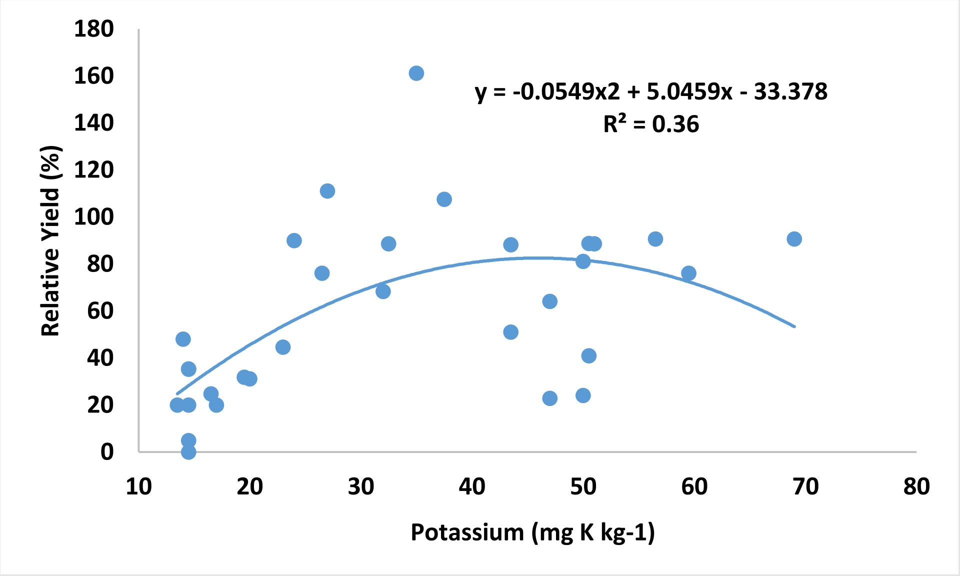

Figure 10. Relationship between relative yield and M-1 extractable potassium of soil samples with correct yield data.

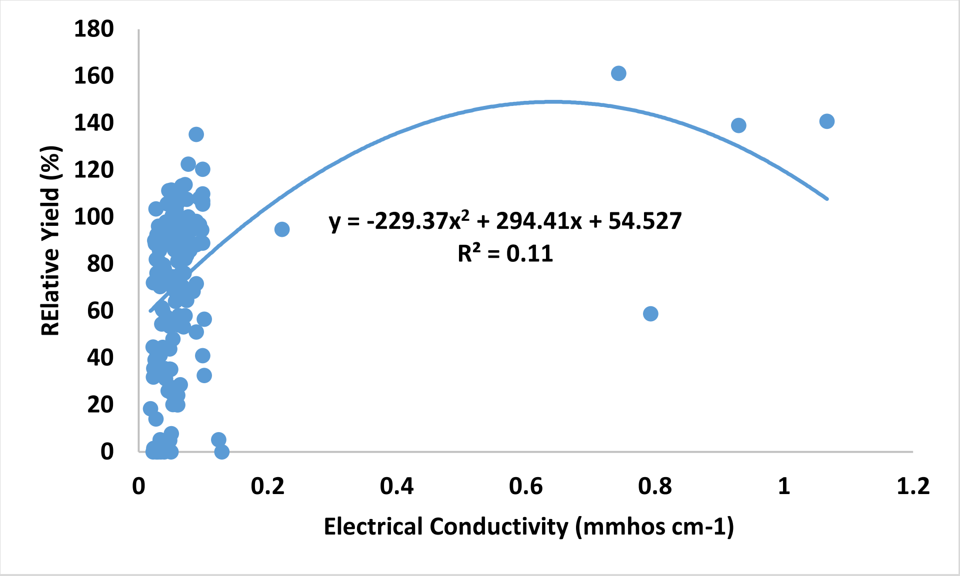

Figure 11. Relationship between relative yield and electrical conductivity of soil samples with correct yield data

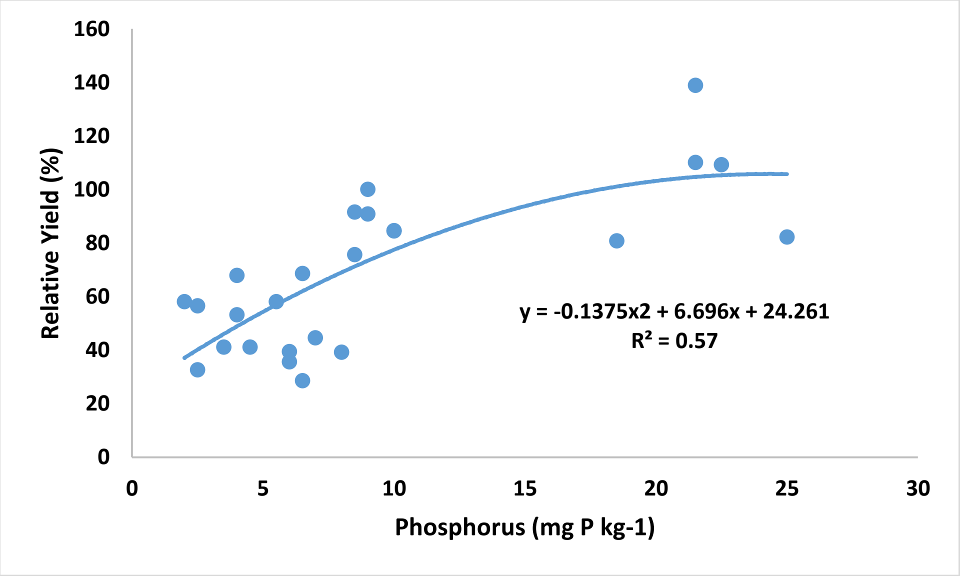

Figure 12. Relationship between relative yield and M-1 extractable phosphorus of soil samples with correct yield data.

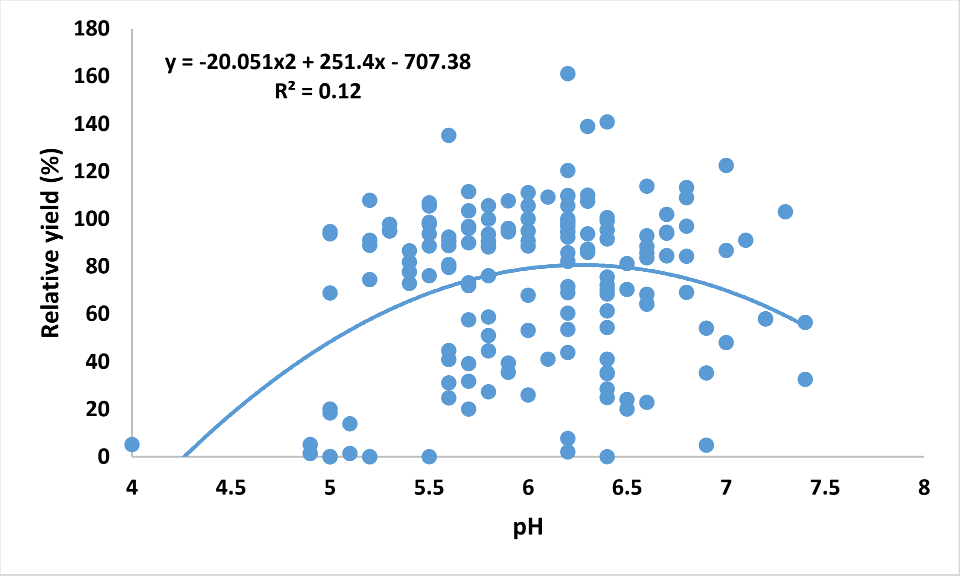

Figure 13. Relationship between relative yield and pH of soil samples with correct yield data.

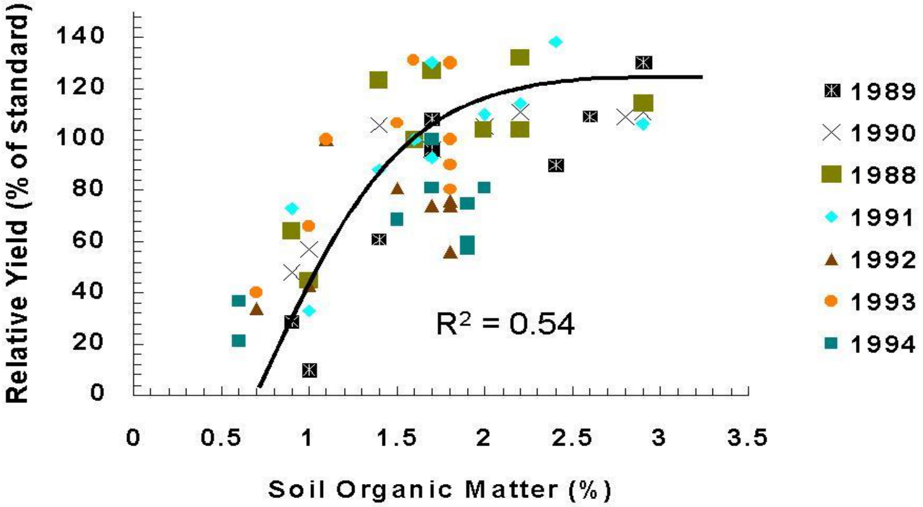

Figure 14. Relationship between relative yield and soil organic matter (from Mitchell and Entry, 1998).

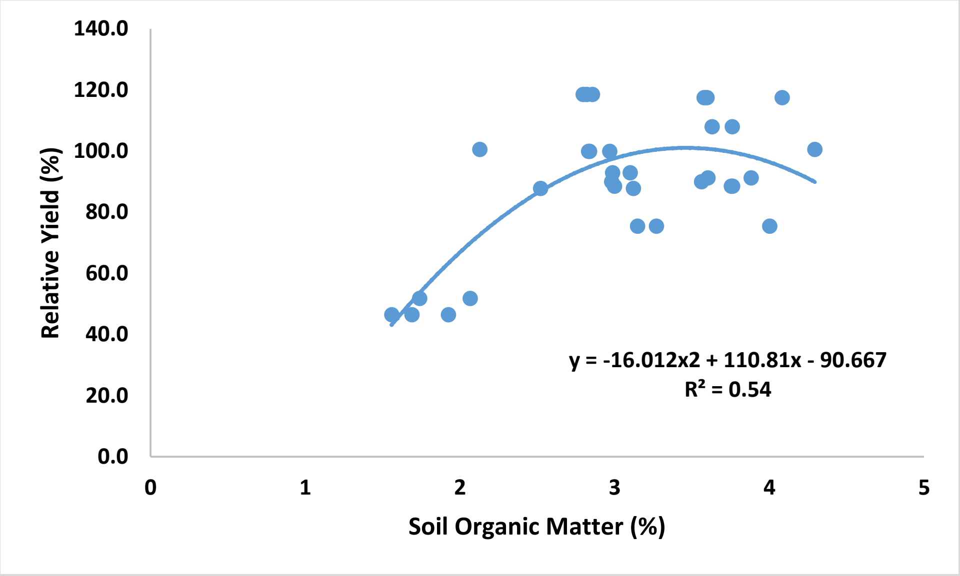

Figure 15. Relationship of relative yield and soil organic matter from Old Rotation soil samples.

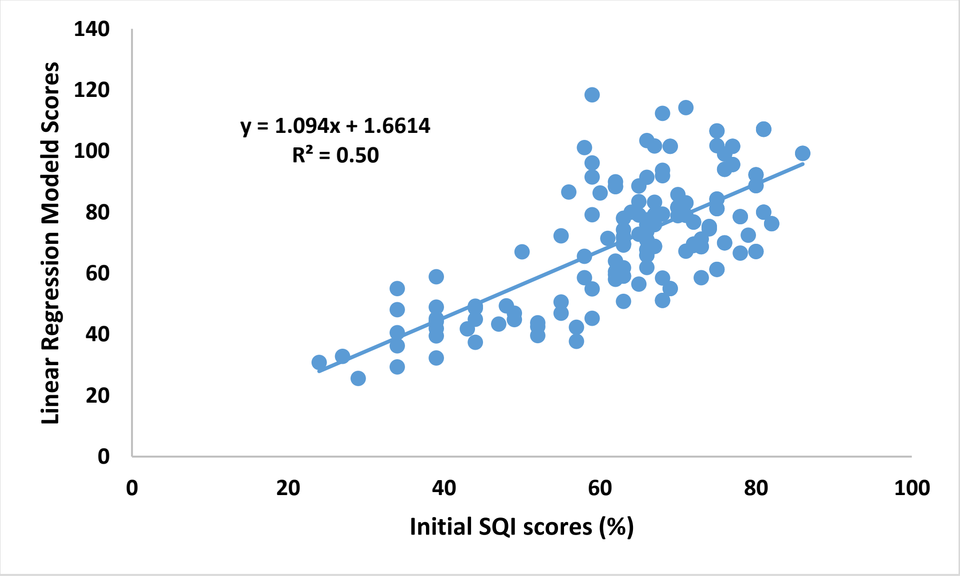

Figure 16. Relationship between first iteration of the Soil Quality Index (SQI) to scores from linear regression model.

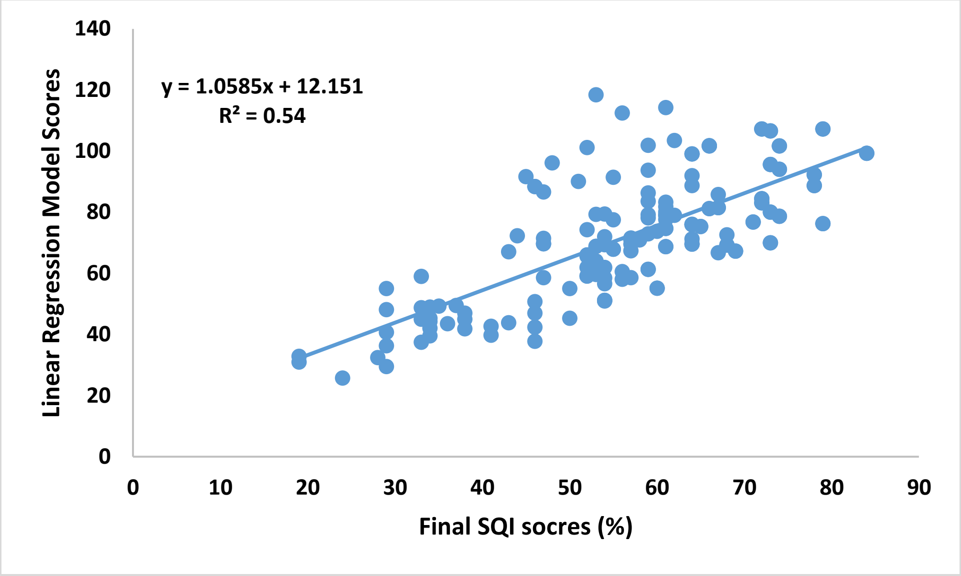

Figure 17. Relationship between final iteration of Soil Quality Index (SQI) to scores from linear regression model.

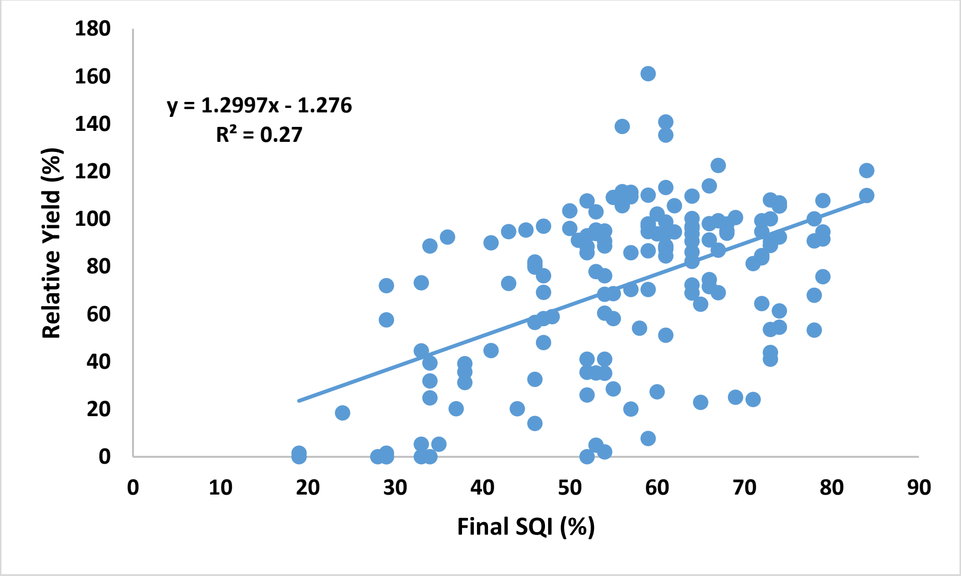

Figure 18. Relationship between relative yield and scores from the final iteration of the Soil Quality Index (SQI).