Southwestern Pecan Orchard Soil Standards

Honors Thesis

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ABSTRACT

The Rio Grande Basin in southern New Mexico and western Texas has become a large source of commercially produced pecans over the past few decades, yet agronomic research specific to soil management and fertilization in this region has not yet been fully developed. This project aims to review the currently published optimal soil analysis ranges as well as to identify significant relationships between soil characteristics and yield which merit further investigation. During the 2012 growing period, 106 production blocks in Dona Ana County, NM, were observed. Soil analysis was conducted on each block prior to budbreak and after harvest to determine soil changes over the full growth cycle; yield and tree counts were also collected. Due to alternate bearing in pecans, yield was analyzed in four population groupings: "ON" blocks only, "OFF" blocks only, all blocks using a two year yield average, and all blocks using a dummy variable to isolate the alternate bearing yield differences. Mixed regression models were used to identify optimal levels and significant relationships within all four groupings. Of the production blocks observed, the soil analysis results fell within only 22% of the published optimal ranges, which are not crop specific. boron, bulk density, copper, iron, magnesium, manganese, and zinc were all identified as exhibiting significant, largely negative, relationships with yield, suggesting that these variables may be inhibiting production. The observed relationships merit further investigation and optimal soil analysis ranges must be developed in order to ensure accurate interpretation of results and subsequent soil management practices.

INTRODUCTION

The pecan industry in the United States is comprised of two distinct methods of production: orchards with a high density of commercial varieties and orchards with increased spacing of native varieties. While Georgia has historically been the center of production, western Texas and southern New Mexico have become focal points for commercial pecan production, producing approximately 40% of the national production and exhibiting the highest production efficiencies in the country (Blain, 2003). However, studies on optimal soil conditions and overall fertilization of pecans in this region are lacking. Smith et al. (2012) thoroughly discussed nutritional sufficiency ranges from and appropriate fertilization of pecans in Oklahoma, yet their focus was on native variety, low density orchards and relied upon mid-season leaf tissue analysis. While leaf tissue analysis has been found to be the most accurate method of determining the nutritional status of pecans, soil amendments should begin at a minimum of four months prior to the appropriate leaf sampling time (Smith et al., 2012; Herrera, 2000). Therefore, leaf tissue analysis, while critical to the determination of mid- to late season fertilization, may not be an effective test in the winter to determine the appropriate soil amendments needed in the first half of the production cycle, due largely to the lack of leaves at this point in time. Additionally, leaf tissue may not reflect nutrient availability and deficiencies within one growth cycle; Worley (1990) found that pecans trees exposed to different nitrogen levels took up to six years to reflect the differences in application rates. As discussed by Weinbaum et al., (1992), over-fertilization, especially of nitrogen, can have many undesirable effects on orchards, including excessive leaf growth leading to overshading. Soil sampling should therefore be carried out prior to commencement of fertilization for the season as a method of assessing current nutrient availability, as opposed to nutrient uptake, as a way of properly adjusting fertilizer application rates.

Often occurring in December or January, soil sample analysis is a common practice used to determine appropriate soil amendments and assess whether soil nutrients are deficient or excessive. However, very little research has been published addressing optimal soil nutrient levels for commercial pecan production, and that which has been published typically concerns orchards located in the southeastern United States. Additionally, cooperative extension services in the southwest provide interpretations of soil analysis according to standards that are not crop specific, a practice which is followed by soil analysis laboratories as well (Self, 2010; McWilliams, 2003; AgSource, 2013; Flynn, 2012). Extension publications from Texas A&M suggest that soils for commercial pecan trees ‘should be deep and well drained to hold water, air, and nutrients’ but do not further specify optimal soil nutrient qualities (McEachern et al., 1997). This view is shared by the cooperative extension services at New Mexico State University (“NMSUCES”) and University of Arkansas (Herrera, 1999; Turner, 2006). To this end, our study investigated optimal soil nutrient ranges for pecan production in the Rio Grande Basin area.

In addition to a lack of regionally appropriate soil standards, fertilization guidelines for this production area have not been fully developed. Pecan trees require very intensive nutrient management through fertilization, especially of trace elements such as zinc and manganese, which may be applied to foliage approximately three times per growing season (Hererra, 2000). It is possible that there are other nutrients that would increase pecan yields that have not yet been identified due to a lack of thorough investigation. NMSUCES’ guidelines for fertilization solely address nitrogen, zinc, potassium, phosphorous, and iron, yet acknowledge that other elements are necessary for plant health (Herrera, 2005). Broad information on general fertilization practices is also available from other sources, but none address the entire spectrum of 16 nutrients required for plant growth (Herrera and Lindeman, 1999; McCraw et al.; Wells and Harrison, 2010; Mitchem & Parker, 2005; Herrera, 2005). Research has assessed effective application amounts and uptake of individual nutrients such as Zn, and has identified slight yet insignificant yield differences among test groups (Nunez-Moreno, et.al, 2009). Nunez-Moreno concluded that Zn levels may have already been sufficient for optimal production, suggesting that relative to trees with insufficient zinc, significant yield differences may exist. Today, foliar Zn applications are utilized across the entire industry. Foliar boron applications have also been reviewed, but only resulted in increased leaf necrosis with no effect on yields (Khalil et al., 2011).

While niche research of tracing individual elements may improve academic understanding of nutrient uptake, commercial producers are not able to control uptake on a per tree basis; however, they are able to ensure sufficient *availability* of critical nutrients through fertilizer applications and assessment of bioavailable nutrients in the soil. Thus, providing producers with relevant information to improve nutrient management could be useful to improving current production methods. Utilizing the soil analysis data gathered to establish standard soil nutrient ranges, this study will also attempt to identify which, if any, nutrients found in the soil have the potential to impact yield and require further investigation.

MATERIALS AND METHODS

Data Collection

To determine optimal soil nutrient levels, a database including both soil properties and yield information was created. Starting in January 2012, five commercially operated farms within an 80.5 km stretch of the Lower Rio Grande Irrigation District in New Mexico were studied for the 2012 production year. These five farms were cumulatively comprised of 124 production blocks of varying acreage, of which sufficient yield data were available to assess only 106 blocks. The blocks observed were a mix of ‘Western Schley’, ‘Wichita’, and ‘Bradley’ pecan varieties, averaging 35 years of age. The soil in each block was largely calcareous, with the most common textures being loam or sandy-loam. All five farms followed cultural and irrigation practices as recommended by extension services (Herrera, 2000; Herrera and Sammis, 2000).

Soil sampling of each block occurred before bud break and after harvest. The soil samples were 0.9 cm diameter plugs taken from the top 30.5 cm of soil. To assess the entirety of each block, the tested samples were an aggregate of at least 7 plugs taken within the trees’ dripline, according to a randomized pattern within the block. Fourteen soil components (Soluble Salts (“Salts”), pH, Organic Material (“OM”), Na, P, NO3, K, Mg, Ca, S, Zn, Mn, Cu, Fe, B) were assessed, in addition to an analysis of soil texture (%Clay, %Sand, %Silt) and Bulk Density (“Bulk”). All nutrients were assessed in parts per million (ppm), and select nutrients were also assessed as a percentage (%K, %Mg, %Ca, %Na), along with an examination of cation-exchange capacity (“CEC”). The elements being analyzed were tested only for bioavailability; see Table 1 for test type and units.

The yield data were collected as kilograms of nuts in shell for each block, as assessed at commercial cleaning plants once debris was removed. Yield was calculated on a per tree basis, using aerial tree counts and yield data for each block, resulting in the final unit of kilograms in shell per tree (“kg/t”). This method was employed to minimize per hectare harvest variations that may arise from differences in orchard planting patterns. As pecans have alternate bearing production, in which there is one “On” year followed by one “Off” year, the production blocks were assessed according to their cycle. In addition to evaluating the blocks according to their two-year yield average, which may be the most reliable estimate of a tree’s productivity (Wells and Wood, 2007), the blocks were grouped by cycle phase for further assessment. Sufficient yield data were available to assess 91 blocks on a two-year average (“AVG”), 70 production blocks at “Off” year levels (“OFF”), and 36 production blocks at “On” year levels (“ON”). Univariate descriptive statistics were reviewed for all variables within each grouping (Table 2).

Optimal Ranges

To establish optimal ranges, yield was assessed as both a linear and quadratic function of each variable according to a mixed bivariate regression in which random effect due to farm differences was controlled. Due to the observational nature of this study, the level of significance accepted was ~15%, using the JMP statistics software. These regressions were conducted on all three previously mentioned variable groupings, as well as on the entire data collection (n=106) (“ALL”), in which a dummy variable was utilized to control for the production cycle phase. If a significant relationship was not present, or the significance occurred only within a linear function, ranges were not recommended. If a significant relationship was present within a quadratic function, the maximum of the quadratic function was proposed as the “optimal” level. Following the establishment of these ranges within the scope of this study, the “optimal” values were compared with the ranges suggested by publications from NMSUCES and the University of Georgia (UGA) (McWilliams, 2003; Flynn, 2012; Herrera, 2000; Kissel and Sonon, 2008; Wells, 2009; Wells, 2013).

Production Function

To identify soil characteristics and nutrients which should be further investigated, the variables previously identified and showing a significant relationship to yield were compiled into a mixed multivariate regression model, controlling for the random effect due to farm differences. This method may frame the variables as having an additive effect rather than minimizing covariance between independent variables. Following the establishment of the best fitting model, those variables which continued to demonstrate significance were further reviewed. If the variable was a fixed characteristic, such as soil texture, related literature was discussed. If the variable is not fixed, such as nutrient levels, the correlation between observed change in soil characteristic levels during the 2012 production cycle and yield was presented. Related literature was reviewed and recommendations proposed for further investigation into the variables identified.

RESULTS AND DISCUSSION

All variables were normally distributed or slightly skewed, with very few outliers (were Table 2). Within yield distributions, the data were minimally left skewed within ON and OFF cycles, while AVG exhibited a slight right skew. ON ranged from 11.2 – 65.4 kg/t, with a mean of 36.7 kg/t ± SD = 11.7 kg/t. OFF ranged from 7.2 – 40.6 kg/t, with a mean of 22.4 kg/t ± SD = 7.5 kg/t. AVG ranged from 10.6 – 52.5 kg/t, with a mean of 28 kg/t ± SD = 8.6 kg/t. Correlations between yield data and initial soil characteristic values as presented in Table 3. Overall, correlations were much higher within ON, which is reflected by the increased number of significant variables present when mixed bivariate regression models were run on the ON data, relative to OFF data. This suggests that responsiveness to soil fertility decreases during the low productivity phase.

Production Function

Variable significance found in the mixed bivariate regression models can be seen in Table 4. %Mg was the only significant variable for OFF yields, and was also prevalent in ON, AVG, and ALL. Mg(ppm) was identified as significant in some regressions as well, but for the purposes of formulating the multivariate regressions, only %Mg will be used, as this measurement of Mg had a higher statistical significance. Other significant variables identified include B, Bulk, Ca, %Ca, CEC, Cu, Fe, and Mn. Based on the findings of the mixed bivariate regressions, four mixed multivariate regressions were formulated to reflect the significant variables within each population clustering:

OFF: $\mathbf{lbs/t = a + b(\%Mg)^2 + c(\%Mg) + \varepsilon}$

ON: $\mathbf{lbs/t = a + b(NO3)^2 + c(NO3) + d(Zn)^2 + e(Zn) + f(Cu)^2 + g(Cu) + h(B)^2 + i(B) + j(\%Mg)^2 + k(\%Mg) + l(\%Na)^2 + m(\%Na) + n(Mn) + \varepsilon}$

AVG: $\mathbf{lbs/t = a + b(Bulk)^2 + c(Bulk) + d(\%Ca)^2 + e(Ca) + f(CEC)^2 + g(CEC) + h(\%K)^2 + i(\%K) + j(\%Mg)^2 + k(\%Mg) + \varepsilon}$

ALL: $\mathbf{lbs/t = a + b(\%Sand)^2 + c(\%Sand) + d(\%Silt)^2 + e(\%Silt) + f(Zn)^2 + g(Zn) + h(Mn)^2 + i(Mn) + j(Cu)^2 + k(Cu) + l(Fe)^2 + m(Fe) + n(B)^2 + o(B) + p(\%Mg)^2 + q(\%Mg) + r(pH) + s(OM) + t(K) + u(Ca) + v(Bulk) + w(CEC) + \varepsilon}$

The fit of each model, along with significant variables, for all population groupings are presented in Table 5; the ALL model has the best fit across all population groupings. The variables which merit further discussion are B, Bulk, Cu, Fe, %Mg, Mn, and Zn; Table 6 contains the correlation coefficient for yield and the observed change of these variables for 2012.

Optimal Ranges

For significant variables, the “optimal” levels are presented in Table 7, and compared with recommended ranges. The β estimate for B within a quadratic fit is positive for OFF, ON, and ALL, yet research has identified the danger of B toxicity, which is reflected by the negative β estimate for B within linear fits for OFF, ON, ALL, and AVG. These observations suggest that B has a negative impact on yield, which is likely best represented by the linear relationship and/or the decreasing portion of the quadratic relationship ($B \leq \sim 1.19$ppm). This conclusion is strengthened by research identifying B presence in irrigation water and orchard floors in the Rio Grande Basin as a potential limiting factor for pecan production (Picchioni et al., 2000). Boron has been used to increase total yield in other orchard crops in more humid regions, but foliar applications of B on southwestern pecans have not resulted in the desired effect (Khalil et al., 2011; Wojcik et al., 2008). Further research into the appropriate range for B should be pursued, especially in light of the increasing B concentrations observed over the 2012 growing season.

A similar situation can be seen for bulk density, in which a positive β estimate for a quadratic fit is seen in AVG, but a negative β estimate was found for a linear fit in ALL. Due to the nature of the variable as a cumulative representation of soil compaction and density, however, these conflicting observations may be interpreted as quantifying the negative impact of clay and compaction on pecan production, suggesting that increased bulk density may cause decreased yields. In the setting observed, this relationship may be attributable to poor drainage, resulting from the bulk density. This interpretation is further supported by the significance of %Silt and %Sand in the mixed bivariate regression models run on ALL yields; the quadratic fit of both used a positive β estimate. The curve presented for %Sand shows increased yield as a function of %Sand where $\%Sand \geq 49.7$, whereas the curve presented for %Silt shows increased yield as a function of %Silt where %Silt $\geq$ 33.8. As %Silt + %Sand + % Clay = 100%, the Bulk observations in combination with the bivariate regressions from %Sand and %Silt support the conclusion that fields with a lower percentage of clay are more likely to exhibit higher yields. This is almost certainly due to the increased permeability of soils with a lower clay percentage, which benefit from decreased waterlogging and soil hardness as well as increased aeration (Myamoto and Storey, 1995).

Cu, unlike B and Bulk, demonstrates a positive relationship with yield within the range of the values collected. The mixed bivariate regression for Cu revealed a positive β estimate within a quadratic function for both ON and ALL populations. Increasing yield is a function of increasing Cu when Cu $\geq$ 1.4. While this value is outside of the NMSUCES recommended range, 1.4ppm Cu is only in the third quartile of the values observed, suggesting that 1.4 ppm Cu is either the maximum or minimum of the “optimal” range. Isolating the blocks which were observed with Cu $\geq$ 1.4 and running a mixed linear model results in a significant positive linear relationship ($p = 0.07$), suggesting that 1.4ppm Cu is likely a potential minimum, rather than maximum, for the optimal range for pecans in the Rio Grande Basin. UGA publications suggest that Cu is indeed a part of pecan plant uptake throughout the growing season (Sparks, 2002), but the observed ΔCu in the soil is positive on average. Foliar Cu applications are not typical of the industry, and have not shown any positive effects when tested in research units (Wagle et al., 2011)—therefore it is unlikely that the increase in soil Cu was a result of foliar applications, and no Cu soil amendments were reported for the observed period. Additional publications suggest the use of Cu as a fungicide for pecans, (Arnold and Crocker, 1998), indicating that the significance of Cu identified may be indirectly related to yield by suppressing potential fungal pests, rather than directly related to increasing yield.

Within ALL data, a mixed bivariate regression produced a positive β estimate for Fe within a quadratic function. For the range of Fe observed, the quadratic function shows a negative relationship between Fe and yield. For pecans and other orchard crops, Fe deficiency is common, especially in calcareous soils (Rombola and Tagliavini, 2001; 2006; Chen and Barak, 1982), yet the blocks observed all had an excess of Fe according to the ranges proposed by both NMSUCES and UGA. The relationship observed suggests that such high levels may actually reduce yield, an area which has not yet been researched.

Another component which has not been thoroughly investigated is the relationship between %Mg and yield. Of the significant variables, %Mg was the most prominent; all four data groupings revealed a significant, negative β estimate within a quadratic function and a negative β estimate for a linear function was also significant within ON and ALL data. The linear and quadratic estimations complement one another, as the linear function reveals a negative relationship between %Mg and yield which is very similar to that of the quadratic function when %Mg ≥ 9.4. The literature available addresses Mg deficiency in sandy soils, yet there has not been a toxicity threshold identified for orchard crops. The relationship between %Mg and yield in the observed blocks suggests that after reaching the maximum end of the "optimal" range (9.4%Mg in this study), increased Mg may actually result in decreasing and negative marginal returns.

Manganese, unlike Mg, has been identified as a potentially damaging element present in orchards in the Rio Grande Basin (Hereema, 2009). While Mn is not typically bioavailable in basic, calcareous soils, but the widespread use of flood irrigation in combination with poor soil drainage has the potential to create an anaerobic environment in which Mn may become bioavailable. If Mn is readily bioavailable, the trees will rapidly absorb Mn as there is no regulatory mechanism in trees to moderate uptake. Delayed budbreak and shoot dieback observed as a direct result of Mn toxicity in other studies (Nunez-Moreno et al., 2012) is the main cause of yield decreases associated with Mn. Data from the observed blocks support the existing literature, with a significant positive β estimate from a mixed bivariate model for ALL data and a negative β estimate for a mixed univariate model for ON data. The linear function supports the decreasing portion of the quadratic function (Mn ≤ 3.52), and the 90% of the blocks observed fall within that section of the model as well, confirming that a negative relationship exists between Mn and yield. To further clarify soil analysis interpretation, a maximum Mn threshold should be established.

The final significant variable observed is Zn; mixed bivariate models exhibited a negative β estimate for a quadratic function within ON and ALL data. Orchard use of Zn has been widely studied and foliar application is widely practiced in the industry. The levels of Zn observed in the soil samples were likely residual Zn from foliar applications the previous season, as Zn is not readily bioavailable in calcareous soils. As such, a Zn "optimal" level has not been proposed for soil analysis interpretation.

CONCLUSIONS

Of the blocks observed and the variables tested, a majority of the blocks fell within the NMSUCES recommended ranges for only 6 variables. This once again highlights the need to develop pecan crop-specific soil analysis optimal ranges, as well as soil management practices to optimize soil fertility and production. It is acknowledged that any relationships identified between the observed soil characteristics and yield data is subject to further verification, as a study covering such a wide range of interrelated variables has a high likelihood of drawing false conclusions. The difference in yield response between the ON and OFF year also highlights the potential benefit of developing specific cultural practices for soil management for the two different phases of the production cycle. Cu was the only element identified which may have a significant positive impact on yield, and appropriate ranges and applications should be further investigated. Additionally, the relationship identified between Bulk and yield supported published literature and should continue to be emphasized as a critical aspect of orchard site selection, as well as the development of better drainage methodology. More importantly, significant relationships were identified between B, Fe, Mn, and Mg in which these nutrients may have a negative impact on yield. These relationships merit further investigation to establish toxicity thresholds and to develop methods for reducing soil concentrations.

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TABLE 1 – Soil Analysis Test Methods and Units

Soil Analysis	**Units**	**Description**
Soil pH	n/a	1:1 Soil/Water Slurry
Soluble Salt	mmhos/cm	1:1 Soil/Water Slurry
Cations (Ca, K, Mg, Na)	ppm	Ammonium Acetate Extraction
Phosphorus	ppm	Olson extraction
Traces (Zn, Mn, Cu, Fe)	ppm	DTPA extraction
Sulfur	ppm	Phosphate extraction
Boron	ppm	DTPA/Sorbitol
Nitrate Nitrogen	ppm	Cadmium reduction
Particle Size Analysis	%	Hydrometer measurement

TABLE 2 – Univariate Descriptors of Variables, part 1: *an overview of the variables observed and their statistical distributions, following the separation of blocks into different yield groupings to control for alternate bearing. "ALL" utilizes a dummy variable to control for alternate bearing, "ON" and "OFF" are separated for the phase of the cycle, and "AVG" uses the two-year average yield to measure production.*

	ALL (n=106)				ON (n=36)			
Variable	**Range**	**Median**	**Mean**	**Standard Deviation**	**Range**	**Median**	**Mean**	**Standard Deviation**
Yield (kg/tree)	7.2 – 65.4	25.6	27.3	11.4	11.2 – 65.4	35.2	36.7	11.7
Clay(%)	0.4 - 34.8	16.8	16.4	6.2	2.4 - 34.8	17.4	17.4	6.6
Sand(%)	23.2 - 83.2	50.8	50.8	13.9	23.2 - 77.2	45.2	46.3	15.4
Silt(%)	3.6 - 54.0	32.0	32.9	10.1	14.4 - 54.0	35.6	36.3	11.8
pH	7.5 - 8.7	8.3	8.2	0.2	8.0 - 8.6	8.3	8.3	0.1
Soluble Salts (mmhos/cm)	0.3 - 2.3	0.5	0.6	0.3	0.3 - 1.8	0.6	0.7	0.3
Na(ppm)	63 - 680	170	191.4	107	96 - 680	210.5	226.6	108.3
Org Mat(%)	0.6 - 2.1	1.5	1.5	0.3	0.6 - 2.0	1.4	1.4	0.3
NO3(ppm)	2.1 - 86.6	3.7	6.0	9.9	2.5 - 14.6	3.4	4.4	2.5
P(ppm)	5.0 - 34.0	13.0	14.8	6.5	5.0 - 27.0	11.0	11.3	4.4
K(ppm)	93 - 598	316.0	324.8	98.0	162 - 476	311.0	324.7	80.5
Mg(ppm)	135 - 597	303.5	313.1	84.5	174 - 597	306.5	323.2	97.0
Ca(ppm)	2432 - 5837	3974	3946.9	654.6	2682 - 5837	4075.0	4046.2	741.8
S(ppm)	11 - 506	35.0	57.8	68.2	17 - 362	40.5	69.0	68.7
Zn(ppm)	0.5 - 11.9	3.7	4.4	2.6	0.8 - 7.4	3.0	3.0	1.4
Mn(ppm)	1.2 - 5.5	2.4	2.5	0.7	1.2 - 3.4	2.4	2.4	0.5
Cu(ppm)	0.5 - 2.5	1.2	1.3	0.4	0.6 - 2.5	1.3	1.4	0.5
Fe(ppm)	3.2 - 93.4	8.7	10.5	11.0	3.3 - 20.2	8.3	8.5	2.9
B(ppm)	0.3 - 2.2	1.0	1.1	0.3	0.3 - 1.9	1.1	1.1	0.4
Bulk Density	1.2 - 1.5	1.3	1.3	0.05	1.3 - 1.5	1.3	1.3	0.05
K(%)	1.7 - 6.0	3.3	3.4	0.7	2.6 - 4.6	3.3	3.3	0.4
Mg(%)	8.1 - 14.0	10.8	10.7	1.3	8.5 - 14.0	10.7	10.8	1.4
Ca(%)	74.7 - 88.1	82.5	82.4	2.2	74.7 - 85.6	82.3	82.0	2.1
Na(%)	1.5 - 10.1	3.2	3.4	1.5	2.2 - 8.2	3.7	3.9	1.2
CEC	13.8 - 36.4	23.9	24.0	4.4	15.7 - 36.4	24.7	24.7	5.0

TABLE 2 – Univariate Descriptors of Variables, part 2: *an overview of the variables observed and their statistical distributions, following the separation of blocks into different yield groupings to control for alternate bearing. "ALL" utilizes a dummy variable to control for alternate bearing, "ON" and "OFF" are separated for the phase of the cycle, and "AVG" uses the two-year average yield to measure production.*

	OFF (n=70)				AVG (n=91)			
Variable	**Range**	**Median**	**Mean**	**Standard Deviation**	**Range**	**Median**	**Mean**	**Standard Deviation**
Yield (kg/tree)	7.2 – 40.6	46.8	22.4	7.5	10.6 – 52.5	26.9	28	8.6
Clay(%)	0.4 - 30.4	15.6	15.9	6.0	0.4 - 34.8	16.8	16.4	6.2
Sand(%)	26.8 - 83.2	52.8	53.0	12.5	23.2 - 83.2	50.8	50.8	13.9
Silt(%)	3.6 - 54.0	30.4	31.1	8.7	3.6 - 54.0	32.0	32.9	10.1
pH	7.5 - 8.7	8.2	8.2	0.3	7.5 - 8.7	8.3	8.2	0.2
Soluble Salts (mmhos/cm)	0.3 - 2.3	0.5	0.6	0.3	0.3 - 2.3	0.5	0.6	0.3
Na(ppm)	63 - 624	151.5	173.3	102.5	63 - 680	170	191.4	107
Org Mat(%)	0.6 - 2.1	1.6	1.5	0.3	0.6 - 2.1	1.5	1.5	0.3
NO3(ppm)	2.1 - 86.6	3.8	6.8	12.0	2.1 - 86.6	3.7	6.0	9.9
P(ppm)	6.0 - 34.0	15.0	16.5	6.8	5.0 - 34.0	13.0	14.8	6.5
K(ppm)	93 - 598	317.0	324.9	106.4	93 - 598	316.0	324.8	98.0
Mg(ppm)	135 - 551	301.5	307.9	77.5	135 - 597	303.5	313.1	84.5
Ca(ppm)	2432 - 5613	3927	3895.9	604.3	2432 - 5837	3974	3946.9	654.6
S(ppm)	11 - 506	33.0	52.0	67.7	11 - 506	35.0	57.8	68.2
Zn(ppm)	0.5 - 11.9	4.6	5.0	2.8	0.5 - 11.9	3.7	4.4	2.6
Mn(ppm)	1.7 - 5.5	2.4	2.6	0.8	1.2 - 5.5	2.4	2.5	0.7
Cu(ppm)	0.5 - 1.9	1.2	1.2	0.3	0.5 - 2.5	1.2	1.3	0.4
Fe(ppm)	3.2 - 93.4	8.8	11.6	13.2	3.2 - 93.4	8.7	10.5	11.0
B(ppm)	0.4 - 2.2	1.0	1.0	0.3	0.3 - 2.2	1.0	1.1	0.3
Bulk Density	1.2 - 1.5	1.4	1.4	0.05	1.2 - 1.5	1.3	1.3	0.05
K(%)	1.7 - 6.0	3.4	3.5	0.8	1.7 - 6.0	3.3	3.4	0.7
Mg(%)	8.1 - 13.1	10.8	10.7	1.2	8.1 - 14.0	10.8	10.7	1.3
Ca(%)	76.5 - 88.1	83.2	82.6	2.3	74.7 - 88.1	82.5	82.4	2.2
Na(%)	1.5 - 10.1	2.5	3.2	1.6	1.5 - 10.1	3.2	3.4	1.5
CEC	13.8 - 36.3	23.4	23.6	4.0	13.8 - 36.4	23.9	24.0	4.4

TABLE 3 – Correlation Coefficient between Yield and X-variables: *a review of the degree to which changes in soil characteristic values and yield are related, split into yield groupings "ALL", "ON", "OFF", and "AVG"*

Variable	POPULATION GROUPING			
	ALL	ON	OFF	AVG
Clay(%)	0.07	0.07	-0.07	-0.06
Sand(%)	-0.21	-0.32	0.13	0.05
Silt(%)	0.25	0.38	-0.13	0.00
pH	0.23	0.08	0.19	0.15
Soluble Salts (mmhos/cm)	0.14	0.25	-0.06	-0.10
Na(ppm)	0.20	0.14	0.03	0.00
Org Mat(%)	-0.20	-0.17	-0.16	-0.08
NO3(ppm)	-0.12	0.15	-0.11	-0.16
P(ppm)	-0.28	-0.06	-0.10	-0.16
K(ppm)	-0.15	-0.16	-0.21	-0.11
Mg(ppm)	-0.14	-0.29	-0.19	-0.11
Ca(ppm)	0.00	-0.03	-0.15	-0.07
S(ppm)	0.16	0.32	-0.04	-0.08
Zn(ppm)	-0.33	-0.02	-0.22	-0.18
Mn(ppm)	-0.15	-0.19	-0.06	-0.10
Cu(ppm)	0.18	0.37	-0.27	-0.14
Fe(ppm)	-0.08	-0.20	0.04	-0.12
B(ppm)	0.01	0.02	-0.09	-0.10
Bulk Density	-0.27	-0.47	-0.16	-0.11
K(%)	-0.19	-0.20	-0.19	-0.08
Mg(%)	-0.26	-0.51	-0.16	-0.08
Ca(%)	0.04	0.23	0.09	0.03
Na(%)	0.25	0.27	0.08	0.06
CEC	-0.01	-0.06	-0.15	-0.08

TABLE 4 – Variable Significance in Mixed Bivariate and Univariate Regression Models: *a review of the significance of regressions run between individual soil characteristics and yield. Significance level = 15%. If a significant relationship was identified, the population grouping in which the relationship was identified has been listed.*

	Mixed Bivariate Model				Mixed Univariate Model			
	Population	**β estimate**	**Std Error**	**p-value**	**Population**	**β estimate**	**Std Error**	**p-value**
Clay(%)		---	---	---		---	---	---
Sand(%)	ALL	0.0154559	0.009142	0.0941		---	---	---
Silt(%)	ALL	0.0307567	0.014433	0.0356		---	---	---
pH		---	---	---	ALL	13.471243	9.289954	0.1501
Soluble Salts (mmhos/cm)		---	---	---		---	---	---
Na(ppm)		---	---	---		---	---	---
Org Mat(%)		---	---	---	ALL	-10.03107	7.083655	0.1598
NO3(ppm)	ON	-0.836206	0.516133	0.1185		---	---	---
P(ppm)		---	---	---		---	---	---
K(ppm)	AVG	-0.00037	0.000137	0.0083	ALL	-0.035867	0.019902	0.0745
Mg(ppm)	ALL	-0.000306	0.000185	0.1009	ALL	-0.05488	0.02313	0.0195
	AVG	-0.000523	0.000188	0.0064	ON	-0.066117	0.038619	0.0962
Ca(ppm)		---	---	---	ALL	-0.005225	0.002909	0.0254
S(ppm)		---	---	---				---
Zn(ppm)	ALL	-0.569698	0.224867	0.0128		---	---	---
	ON	-2.880151	1.162111	0.0187				
Mn(ppm)	ALL	3.4803129	2.137297	0.1066	ON	-11.61562	7.454655	0.1291
Cu(ppm)	ALL	27.243376	9.522333	0.0051		---	---	---
	ON	27.843823	14.12748	0.0577				
Fe(ppm)	ALL	0.0160584	0.007642	0.0381		---	---	---
B(ppm)	ALL	24.204841	11.71559	0.0414		---	---	---
	ON	66.543639	21.33832	0.0041				
Bulk Density	AVG	1045.0252	524.5405	0.0495	ALL	-51.22538	36.64925	0.1652
K(%)	AVG	-6.529314	2.338429	0.0064		---	---	---
Mg(%)	ALL	-3.683571	0.909228	0.0001	ALL	-3.961839	1.800824	0.0304
	OFF	-2.403039	1.436399	0.1140	ON	-6.268714	3.223969	0.0612
	ON	-3.798632	1.722936	0.0346				
	AVG	-2.7878	0.951602	0.0043				
Ca(%)	AVG	-0.502598	0.260255	0.0567		---	---	---
Na(%)	ON	-2.995931	1.810261	0.1095		---	---	---
CEC	AVG	-0.110904	0.074526	0.1403	ALL	-0.804504	0.437403	0.0688

TABLE 5 – Multivariate Model Fit and Significant Variables: *a review for each population grouping of the fit of the models proposed based on individual variable significance, along with a listing of all variables identified as being significant within these models for any given population group. Level of significance = 15%*

	ALL Population	**OFF Population**	**ON Population**	**AVG Population**
ALL Model	r^2 =0.713	r^2 =0.420	r^2 =0.927	r^2 =0.299
	B^2 (p-value=0.0277) %Mg^2 (p-value=<0.0001) Bulk (p-value=0.0420)	%Mg^2 (p-value=0.0041) Fe^2 (p-value=0.1528) Zn (p-value=0.0925) Fe (p-value=0.1526) Bulk (p-value=0.1759)	Cu^2 (p-value=0.1944) B^2 (p-value=0.1594) Mg^2 (p-value=0.2976)	%Mg^2 (p-value=0.0053)
OFF Model	r^2 =0.555	r^2 =0.083	r^2 =0.506	r^2 =0.197
	%Mg^2 (p-value=0.0001)	%Mg^2 (p-value=0.1140)	%Mg^2 (p-value=0.0346)	%Mg^2 (p-value=0.0043)
ON Model	r^2 =0.626	r^2 =0.256	r^2 =0.831	r^2 =0.274
	%Mg^2 (p-value=<0.0001) B (p-value=0.0559)	No significant variables	Zn^2 (p-value=0.0430) B^2 (p-value=0.0402) %Mg^2 (p-value=0.0304) Mn (p-value=0.0716)	%Mg^2 (p-value=0.0131)
AVG Model	r^2 =0.592	r^2 =0.204	r^2 =0.563	r^2 =0.306
	%Mg^2 (p-value=0.0004)	%Mg^2 (p-value=0.0154) Bulk^2 (p-value=0.1328)	No significant variables	%Mg (p-value=0.0686) %K (p-value=0.0602)

TABLE 6 – Correlations between Yield and ΔX-var: *a review of the relationship between changes in yield and significant individual soil characteristics, as well as between changes in yield and the observed change in significant individual soil variables over the 2012 growing season.*

	Population			
X-var	**ALL**	**ON**	**OFF**	**AVG**
B	0.01	0.02	-0.09	-0.10
ΔB	0.25	0.37	-0.12	-0.02
Bulk	-0.27	-0.47	-0.16	-0.11
Cu	0.18	0.37	-0.27	-0.14
ΔCu	0.25	0.19	-0.04	0.13
Fe	-0.08	-0.20	0.04	-0.12
ΔFe	0.06	0.01	-0.09	0.12
%Mg	-0.26	-0.51	-0.16	-0.08
Δ%Mg	0.34	-0.55	-0.02	0.17
Mn	-0.15	-0.19	-0.06	-0.10
ΔMn	-0.20	-0.44	-0.27	-0.17
Zn	-0.33	-0.02	-0.21	-0.19
ΔZn	0.30	0.30	-0.05	-0.05

TABLE 7 – Optimal Levels and Recommended Ranges: *a comparison of currently published extension recommended ranges for soil characteristics in pecan orchards and the observed ranges and optimal levels of soil characteristics for the 2012 growing period.*

Variable (units)	Actual Range	% Blocks Observed within NMSUCES Recommended Range	Optimal Level Observed	NMSUCES Recommended Range*	UGA Recommended Range*
Clay(%)	0.4 - 34.8	--	--	--	--
Sand(%)	23.2 - 83.2	--	≥ 49.7	--	--
Silt(%)	3.6 - 54	--	≥ 33.8	--	--
pH	7.5 - 8.7	17.92%	--	6.5 - 8.0	6.5 - 7.0
Soluble Salts (mmhos/cm)	0.28 - 2.3	0.90%	--	2 - 4	0.51 - 1.25
Na(ppm)	63 - 680	--	--	--	--
Org Mat(%)	0.6 - 2.1	5.70%	--	2 - 3	--
NO3(ppm)	2.1 - 86.6	4.70%	7.35	10 - 50	--
P(ppm)	5 - 34	38.68%	--	15 - 30	7.5 - 15
K(ppm)	93 - 598	0.00%	338	31 - 60	15 – 38
Mg(ppm)	135 - 597	--	342	--	22 – 25
Ca(ppm)	2432 - 5837	0.00%	--	100 - 250	100 - 225
S(ppm)	11 - 506	91.51%	--	12.5 - 125	2.5 - 12.5
Zn(ppm)	0.48 - 11.9	65.09%	--	0.75 - 5	3.75 - 5
Mn(ppm)	1.2 - 5.5	20.75%	≤ 3.52	2.75 - 5	3.75 - 10
Cu(ppm)	0.5 - 2.5	29.25%	≥ 1.4	0.3 - 1	0.1 - 0.4
Fe(ppm)	3.2 - 93.4	100%	≤ 42.6	> 2.5	3 - 6.25
B(ppm)	0.3 - 2.2	1.89%	≤ 1.19	0.1 - 0.5	0.1 - 0.3
Bulk Density	1.2 - 1.5	--	≤ 1.37	--	--
K(%)	1.7 - 6	98.11%	3.72	2 - 5	--
Mg(%)	8.1 - 14	84.91%	9.4	6 - 12	--
Ca(%)	74.7 - 88.1	90.57%	81.1	65 - 85	--
Na(%)	1.5 - 10.1	0.94%	5.22	<10	--
CEC	13.8 - 36.4	--	21.7	--	--

* Many units converted from ppa to ppm