ABSTRACT

WEIGEL, ANNA MARIE. Effects of Soil Physicochemical Properties on Phosphorus Sorption and Availability in North Carolina. (Under the direction of Dr. Luke Gatiboni).

Critical soil test values (CSTV) in soil fertility refer to a concentration of a nutrient that indicates a lack of a numeric or economically significant increase in yield with applied nutrients. Studies to evaluate and amend CSTVs should be conducted often, as changes in management practice, crop, and soil will impact these values. Although CSTV studies for phosphorus (P) were conducted in North Carolina (NC) often from 1950 – 1980, these studies were conducted using Mehlich 1 soil test methods, which differ from the current standard, the Mehlich 3 soil test. Additionally, P fertilizer requirements are influenced by soil P buffering capacity (PBC), which describes the ability of a soil to adsorb P from soil solution to non-labile forms. However, tests to determine PBC are labor and time intensive, and therefore not included in routine soil analyses. As soils in NC often test high for P, there may be shortcomings of the fertilizer recommendation system that are leading to higher costs for farmers and increased risk to environments. The objectives of this study were to compare CSTVs for corn (*Zea mays*) on 10 NC soils cultivated in greenhouse conditions and to develop a model to classify PBC of NC soils using routine soil fertility analysis parameters. In the greenhouse study, P was applied to 10 soils at rates of 0, 56, 112, 168, and 224 kg P_2O_5 ha^{-1}. Plants were grown for a period of 49 days and evaluated for plant height, dry matter, and P uptake. The P CSTVs observed averaged from 26 to 72 mg kg^{-1} for Piedmont soils and 66 to 85 mg kg^{-1} for Coastal Plain soils. Additionally, 423 NC soils were analyzed for PBC, texture, and routine soil testing parameters. Strong relationships were observed between PBC and clay, aluminum (Al), weight to volume ratio (W/V), sulfur (S), and soil test P. The PBC of soils can be separated by clay in three groups: < 21%, 21-47%, and > 47% of clay for soils with low, medium, and high PBC, respectively. The equation *23.100 –*

$19.304*W/V - 0.0404*P + 0.01395*Al + 0.3247*S$ can be used to estimate the PBC with an R^2 of 0.657. Incorporating these equations into P fertilizer recommendation methods can allow for the consideration of PBC without the associated cost and labor of physically conducting PBC analysis. These improvements have the potential to enhance farm profitability, protect water quality, and ensure the conservation of finite resources.

Effects of Soil Physicochemical Properties on Phosphorus Sorption and Availability in North Carolina

by
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DEDICATION

To those I worked with in Idaho, who taught me that the most exhausting and rewarding experiences can be found in a field, and who helped to develop my passion for agriculture.

And to my husband Bryan, whose love, support, and belief in my abilities has allowed me to create a career and life I otherwise could not have.

BIOGRAPHY

Anna Marie Weigel was born in Sacramento, California in April of 1997. She grew up in the nearby rural town of Wilton, where she was introduced to the joys of agriculture: riding horses, raising goats and steers, and being an active member of her local 4-H and FFA chapters. Upon graduation from high school, Anna moved to Idaho to pursue a bachelor's degree in Agronomy, Crop and Soil Science. She spent two of her years in Idaho working for the Research and Business Development Center as first a Research Assistant, and later an Assistant Manager, where she was introduced to agricultural research and field trials. She worked on fertilizer, seed, and pesticide trials on alfalfa, wheat, barley, and (of course) potato.

Also during her time in Idaho, Anna met and married her husband Bryan, and expanded the family by adding a golden retriever named Russet. Upon graduation, Bryan received orders to Fort Bragg, North Carolina, where they moved in November of 2019. Shortly after, Anna continued her education in pursuit of a Master of Science in Soil Science degree and a Graduate Certificate in Geographic Information Systems from North Carolina State University. Near the end of her studies, she began her position as the Agronomist and GIS Analyst for Aerial Vantage, a drone service and analytics provider.

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CHAPTER 1: REVIEW OF LITERATURE

PHOSPHORUS IN AGRICULTURE

Phosphorus (P) is an essential macronutrient for plant production, with requirements of up to 67 kg ha^{-1} for optimum yields, depending on crop and field conditions (The N.C. PLAT Committee, 2005). Critical to several physiological processes, adequate P contributes to nitrogen (N) fixation capability, storage and transfer of energy, and root exploration (Havlin et al., 2016; Sawyer et al., 2000). Increased root production further influences the plant's ability to absorb available nutrients by increasing explored soil volume. Furthermore, P can help protect crops from damage incurred during the growing season by reducing time to maturity and decreasing risk to pest and disease damage (Sawyer et al., 2000). Limited availability of P can stunt plant growth and limit optimum yield, so it is important to understand the supply mechanisms by which P reaches the crop, as well as the factors that affect nutrient availability in the soil and conditions conducive to P loss from the field. Proper management of soil P enhances farm profitability, protects water quality, and ensures the conservation of finite resources.

Phosphorus Cycle

Soil P comes from a variety of sources. Initially, soil P originates from the parent material that forms a specific soil. As soils are cultivated, P is added through fertilizer applications and organic residues. While total soil P can range from 900 to 1800 kg ha^{-1}, it is estimated that 80% of total P is immobile and unavailable for plant uptake (Mullins, 2009; Prasad & Chakraborty, 2019).

Soil P is present in two primary forms: inorganic and organic. The organic portion comprises 35-70% of total soil P and inorganic forms comprise 30-65% of total P (Prasad & Chakraborty, 2019). Although there are many forms of P storage in the soil, plants can only absorb P in solution in the form of $H_2PO_4^{1-}$ and HPO_4^{2-}. The prominent form of plant available P is dependent on pH, with $H_2PO_4^{1-}$ being the dominant form when pH is below 7.2, HPO_4^{2-} when pH is above 7.2, and relatively even concentrations when pH is approximately 7.2 (Sims & Sharpley, 2007; Mullins, 2009). In acidic soils like those in North Carolina (NC), the most prevalent forms of inorganic P are represented by P bound to iron (Fe) and aluminum (Al) oxides, whereas alkaline soils tend to bind P in calcium (Ca) phosphates (Havlin et al., 2016).

To achieve equilibrium within the soil between solution and bound P, increases in solution P concentration are counteracted by adsorption to clay and mineral surfaces, precipitation, and immobilization to organic P forms or microbial P (Havlin et al., 2016) (Figure 1.1). When plant available P is depleted from the soil solution, soluble P must then be replenished by the weathering/dissolution of soil minerals, desorption from clay particles, microbial degradation, and organic matter decomposition (Sawyer et al., 2000; Mullins, 2009). Phosphorus buffering capacity (PBC) describes the soil's ability to buffer these changes in solution. As soil P is bound to soil particles in a process known as P fixation, the amount of P in solution and the amount of fertilizer needed to increase plant available P is affected. Additionally, although diffusion is the primary mechanism for P movement within soil, P does not travel far by this method, so a well-developed root system is important for plants to have sufficient access to available P (Corey, 1987).

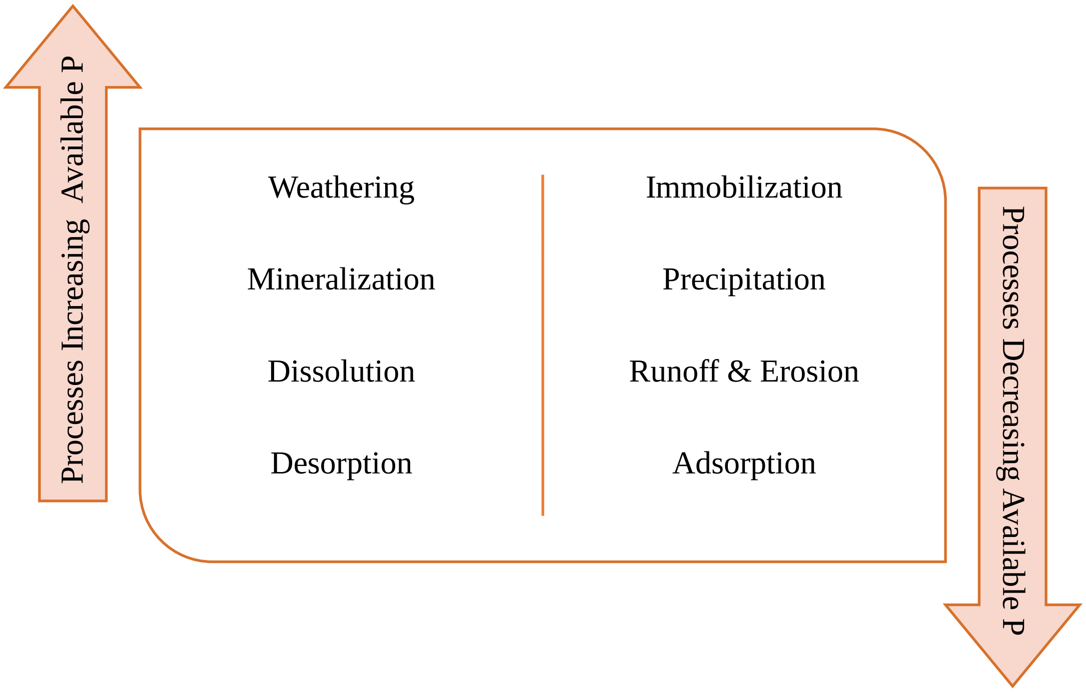

Figure 1.1. Soil processes affecting quantity of plant available P. Adapted from Prasad & Chakraborty, 2019.

Removal of P from the soil occurs primarily through crop uptake, surface runoff, or leaching (Sims & Sharpley, 2007). Surface water can remove P from fields in forms of soluble P and particulate P through erosion, with P saturated soils having a higher risk for leaching (The N.C. PLAT Committee, 2005).

Impacts on Soil and Environment

Soil testing has become a valuable tool for addressing not only the needs of a crop, but also the potential environmental impacts of farming. In NC, based on soil test data from samples submitted for routine analysis, an increase in soil test P levels has been observed in recent decades, raising environmental concerns. In 2003, over 70% of NC counties were found to have median Mehlich 3 P (M3P) levels above 120 kg ha^{-1}, which suggests no response to added P would be observed on these soils (Johnson et al.; 2005, Dell'Olio et al., 2008). Furthermore, from 2017 to 2019, the average M3P level was 329 kg ha^{-1}, once again above the critical soil test values set for the state (Kulesza, 2020).

Adding to this issue, confined swine and poultry operations produce waste that is often used to fertilize crops in nearby fields. In swine production, only 14% of P in corn and 31% of P in soybean meal is digested, leaving the remaining P in feed to be excreted as waste (Sawyer et al., 2000). This leads to swine manure that is high in P being applied to fields. However, nutrient management plans using animal waste typically determine rates based on N, which leads to over application of P by up to five times the crop requirement (The N.C. PLAT Committee, 2005). These inefficient methods of fertilization contribute to imbalances among nutrients in the soil, often creating a buildup of P, among other nutrients, such as zinc.

Although P is a valuable resource for agricultural production, it has proven to be a significant pollutant of NC bodies of water. The Neuse and Tar-Pamlico River basins and Jordan Lake, High Rock Lake, and Falls Lake watersheds suffer from nutrient impairment (North Carolina Department of Environmental Quality, 2021). Increased M3P levels, as can be found where repeated P applications are made, heighten the risk of P loss through runoff and leaching (Line et al., 2019). Excess fertilizer applications are not only an unnecessary cost to farmers, but in the case of P, also pose a threat to natural resources. Applied P is recovered in crops at a rate of only 30% or less (The N.C. PLAT Committee, 2005), suggesting that excess P is either stored in the soil or lost to the environment. Phosphorus loss from agricultural land contributes to accelerated eutrophication of local bodies of water, where phytoplankton and algae experience excessive growth. The effects of this accelerated growth include altering the aquatic ecosystem causing the death of fish, diminishing the recreational value of the water, and polluting sources of drinking water (Jarvie et al., 2017).

Phosphorus as a Global Resource

Just as P is essential for plant growth, it is also a limited and finite resource with 85% of the world reserves concentrated in Morocco (Cordell & White, 2011). While supply is currently maintaining pace with demand, it is estimated that some reserves may run out shortly. For example, if China, the second largest P reserve location at 5% of world reserves, were to maintain their current P mining rate for the foreseeable future, it is estimated that their reserves would be depleted in only 35 years (Misachi, 2018). Total world reserves are estimated to last between 60 and 400 years at current mining rates (Cordell & White, 2011). However, mining of P can be impacted by future availability, increased demand for P fertilizers, alternative fertilizer sources, and legislation. Avoiding over-use of this nutrient can prolong the availability of P for agricultural purposes.

METHODS FOR SOIL PHOSPHORUS ANALYSIS

Soil testing methods were developed to measure plant available nutrients and identify soils requiring fertilization. In the US, there are 5 primary soil extractants for P: Bray 1, Olsen, Morgan, Mehlich 1, and Mehlich 3. In 1945, Bray and Kurtz developed a P soil test extractant that would specifically react with acidic forms of P, such as Fe and Al bound P, by using HCl and NH_4F. Following this method in 1953, Mehlich developed an alternative method known as Mehlich 1, using HCl and H_2SO_4, which was especially useful for soils in the southern region of the United States. The benefits of this test include removal of Fe and Al bound P, similar to the Bray method above, but also removal of P bound to clay particles. One year later Olsen (1954) published their method for P extraction using a 0.5 M sodium bicarbonate solution for calcareous, alkaline, and neutral soils. While this method is useful for other states, the acidic NC soils do not primarily bind Ca-phosphates, so this method is not used. In NC, the Mehlich 1 method was used until the early 1980s, when the Mehlich 3 (M3P) method was adopted for widespread use (Hardy et al., 2014). This was a favorable test as it is a multi-nutrient extractant to include P, K, Ca, Mg, Na, S, and micronutrients Mn, Zn, and Cu. North Carolina labs use the M3P method to evaluate extractable P but using this measurement does not provide an accurate representation of P availability, uptake by the crop, and transformations occurring in the soil.

SOIL TEST CORRELATION AND CALIBRATION

Soil test correlation and calibration studies serve a key role in the agricultural industry as they address the constantly evolving conditions of farming. Differences in crop, climate, inputs, and farm management practices impact how soil tests are interpreted, and these relationships must be evaluated periodically. Correlation and calibration studies consider soil test nutrient levels, yield response to the added nutrient, and fertilizer requirements to raise soil test levels. In the case of P, as we learn more about nutrient interactions and the influence of decades of farming, further correlation and calibration studies are needed.

Correlation

Correlation studies aim to evaluate the relationship between soil test P, plant uptake, and yield response. This is a useful tool for determining which extractant most accurately represents plant available P, with the main objective of correlation studies being to determine the critical soil test value (CSTV) for a given soil test method. Therefore, correlation studies are conducted to evaluate at what soil test value a crop does not respond to fertilizer, and at which values an increase in yield or quality will occur with added nutrient (Hochmuth et al., 2014). The relationships observed in greenhouse trials serve as a basis for field trials which more accurately assess crop responses to added nutrients in conditions farmers encounter. Greenhouse trials cannot calculate a true CSTV, as the plant roots are growing in a confined environment. However, greenhouse studies are valuable to group similar soils, thereby reducing the number of field sites necessary for correlation studies. The relationships between soil test values and plant parameters are quantified using a variety of models that consider the impacts of crop and soil characteristics on the uptake of nutrients (Corey, 1987). When correlation studies determine that an increase in yield or quality would be obtained, the next step is the calibration studies to determine the amount of applied nutrient that is appropriate for farm objectives (Hochmuth et al., 2014).

Calibration

Accurate nutrient recommendation programs are dependent on calibration studies that consider regional variations in mineralogy, texture, and primary crops cultivated. Permanent soil characteristics and environmental impacts represent the majority of variation among agricultural sites in the state and must be represented accordingly in calibration studies (Nelson, 1987; Evans, 1987). Calibration studies are conducted to determine the optimum rate of nutrients needed to reach the CSTV for major crops. In other words, calibration studies determine the nutrient requirement of a crop beyond what the soil can supply. These studies are best conducted in field trials by growing crops in soils with varying soil test levels of the specified nutrient to observe growth and yield responses to added nutrients (Hochmuth et al., 2014). An effective calibration study will reduce the input of excess nutrients, better ensuring farm profitability and protecting environments from excessive field runoff.

Calibration studies are often evaluated in terms of yield data or relative yield. Relative yield is a useful metric for eliminating the effect of site when many calibration studies are conducted (Evans, 1987). Relative yield is calculated by dividing the yield from a particular test plot by the yield of the maximum treatment plot from each location. Additionally, calibration studies produce a crop response curve that demonstrates the rate of response to varying soil test levels. There are several models that can be used to map the response of soils and crops to added nutrients, but the models that typically provide a best fit for P are the linear plateau and quadratic plateau models, which observe an initial steep response to added nutrients, followed by a plateau (Nelson, 1987). At the point where there is no response to added fertilizer, no nutrient recommendations are made at or above that soil test value. All yields below this value, known as the critical level or critical soil test value (CSTV), would determine how much added fertilizer produced a significant response in crop growth. Critical soil test values are crop, soil, and nutrient dependent. Another influencing factor in field studies evaluating P CSTVs is weather. In years with limited rainfall, for example, higher P will be required to reach plant roots with limited capability for diffusion (Gatiboni et al., 2021).

Fertilizer Recommendation Methods

Several nutrient recommendation methods are commonly used across the country: build-maintain, sufficiency, or a combination of these, termed hybrid. The sufficiency recommendation approach for P is designed to supply enough nutrients for only the current year's crop, dependent on yield goal and crop requirement, whereas the build-maintain approach aims to raise soil test values to the determined CSTV and maintain that level throughout later years (Macnack et al., 2017). Using the build-maintain approach, fertilizer is recommended at high soil test levels for the purpose of replenishing nutrients expected to be removed by the crop (Olsen et al., 1987). However, P availability to crops is independent of yield goal, and more reliant on the concentration of available P near the root surface (Macnack et al., 2017). For this reason, yield goals should not be taken into consideration when determining P rates.

When making fertilizer recommendations, PBC can have a significant impact. As P added to the soil may be adsorbed to soil particles and unavailable for plant uptake, this factor should be considered. Refining fertilizer recommendation methods and using a sufficiency approach for immobile nutrients versus the hybrid approach that is currently being used would be a useful strategy to increase the efficient use of P in the state.

FACTORS AFFECTING PHOSPHORUS SORPTION

While soil testing is a valuable resource for improving yields, extractable nutrients are not the only descriptor of plant available P. To fully understand P reserves in the soil, factors affecting sorption, or PBC, need to be understood and accounted for when making fertilizer recommendations.

Texture

It has been demonstrated that PBC would increase with increasing kaolinitic clay content, as the edges of clays can provide additional binding sites for P. Clay soils also have a higher ability to supply P because of increased diffusion rates affected by water holding capacity (Gatiboni et al., 2021). In a 1990 study by Cox & Espejo, P sorption correlated linearly with clay content, with variation increasing as soil texture increased. Cox (1994) found that the increase in M3P after fertilization decreased exponentially with increasing clay content. Mumbach et al. (2020) also found that extractable P was sensitive to clay content. However, soil textural determination is not a practical approach to apply to routine samples due to the increased time and labor necessary to conduct this analysis when compared to other routine soil test analyses. Evaluating parallel indicators for soil texture can be useful to incorporate textural influences on PBC without performing textural analysis.

Sample Density

Sample density, or weight to volume ratio (W/V), can be a useful indicator for clay content within a soil, and is regularly measured in routine soil analysis. In a study conducted by Cox & Espejo (1990), clay content and sample density were related with an R^2 of 0.43. As sample density increased, clay content also increased. Because the positive relationship between clay content and PBC has already been observed, an increase in sample density may be representative of an increase in PBC.

Fe/Al Oxides

An additional soil characteristic that may be indicative of PBC is Fe/Al oxide content. These oxides, present as coating on soil particles, represent a large portion of precipitated P in acidic soils, which are dominant in NC. The -OH and OH_2^+ groups on the surface of Fe and Al oxides interact with P ions to adsorb to the mineral surface of these oxides (Havlin et al., 2016). These Fe and Al oxides are typically strongly sorbed to clay particles in the soil (Thomas & Peaslee, 1973; Wild, 1950).

In an evaluation of P sorption characteristics in highly weathered soils, Espejo & Cox (1992) found that exchangeable Al, Fe, and clay represented 85% of the variation in P sorption. In that study, Al had the highest correlation with P sorption. In another study, Al oxides were found to strongly correlate (R^2= 0.86) with PBC (Kang et al., 2009). Several studies have shown varying degrees of Fe oxides influence on PBC, so further evaluation would be necessary to determine how these characteristics behave in NC soils. The lack of significant relationship between Fe and PBC in some studies may be because Mehlich 3 is not very efficient at removing Fe (Kang et al., 2009). Some studies have shown that P bound to Al is more labile than when it is bound to Fe (Hingston et al., 1974). Phosphorus bound to Fe oxides is considered one of the least soluble forms of soil P (Fixen & Grove, 1990). In soils of the piedmont and mountain regions of NC, P bound to Fe accounts for approximately 67% of soil P (Shelton and Coleman, 1968). In the coastal plains region, 25% of soil P is present as Fe bound P (Novais and Kamprath, 1978).

Humic Matter

Humic matter (HM) is a routinely measured soil characteristic that may be indicative of PBC. Humic matter represents the portion of organic matter in the soil that has decomposed and is now chemically reactive (Hardy et al., 2014). Additionally, organic molecules will compete with P adsorbed within the soil, causing some P to be released (Prasad & Chakraborty, 2019). Increases in HM relate to an increase in cation exchange capacity (CEC), but this does not always translate into increased PBC. This may be due to sorption of humic acid to Fe and Al binding sites, explaining the lack of increase in P sorption when an increase in HM was observed (Dell'Olio et al., 2008). In organic soils, PBC was negatively correlated to organic matter (Dell'Olio et al., 2008). However, there have been mixed observations of the relationship between HM and PBC, so evaluation on a local scale is needed to determine how individual soils behave.

Soil pH

As pH increases, P fixation is less likely due to the increase in negative charges near the oxide surfaces (Fixen & Grove, 1990). However, in alkaline soils, the formation of calcium phosphates is favored (Prasad & Chakraborty, 2019). Additionally, at low pH levels, similar to those in NC, the amount of Al and Fe oxides in solution increases, increasing sorption sites for P (Kang et al., 2009; Prasad & Chakraborty, 2019).

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CHAPTER TWO: CRITICAL SOIL TEST VALUES OF PHOSPHORUS FOR CORN DURING EARLY VEGETATIVE STAGES IN TEN NORTH CAROLINA SOILS CULTIVATED IN A GREENHOUSE

INTRODUCTION

In general, North Carolina (NC) soils are naturally acidic with low levels of plant available phosphorus (P). Soil testing methods are used to predict the response of plants to fertilization and to assist in the recommendation of P fertilizers for optimum crop growth. Soil test correlation procedures are used to define the soil test critical soil test value (CSTV) for a crop in a given environment (soil type, climate, crop management, etc.) and require evaluation of crop yield increase in response to applied nutrient rates (Slaton et al., 2021).

Soil test correlation and calibration studies were conducted often in NC between 1950 and 1980 to determine the CSTV of P and the appropriate rates of fertilizer for significant agricultural soils in the state (Gatiboni et al., 2021). Most of those studies were conducted using the Mehlich 1 soil test extractant. Few correlation studies were conducted between 1980 and 2015, after the adoption of Mehlich 3 as the official soil test P method in NC. Additionally, Gatiboni et al. (2021) shows that few soil types were used to determine the CSTV in NC, suggesting further studies are needed to refine this information. Critical soil test values need to be constantly evaluated, as they differ according to crop, soil, climate, and the model used to determine the CSTV (Cox, 1992).

Among the many soil and environmental factors contributing to the variation in P CSTVs, texture has a significant impact. As P adsorbs to clay particles, particularly in kaolinite and iron oxides, a negative relationship between clay content and the CSTV is observed (Cox & Espejo, 1990). Clay soils adsorb more P with greater binding strength when compared to coarse-textured soils, resulting in an increased PBC which can be further enhanced by greater microporosity, facilitating the P diffusion process (Gatiboni et al., 2021). These factors explain the variation in CSTVs in studies conducted across different soil types of NC.

Critical soil test values vary for nutrients with low mobility, such as P, because higher concentrations are necessary to intersect with the minimal root volume of seedlings at early growth stages. For example, Romer and Schilling (1986) observed that wheat grown in greenhouse conditions presented a P uptake of 14 µg P m^{-1} day^{-1} and a root density of 0.27 cm cm^{-3} during the first two weeks of development. During the 7th and 8th week of development, the P uptake declined to 3.4 µg P m^{-1} day^{-1} and root density increased to 3.88 cm cm^{-3}, indicating that the CSTV of P could be much lower at later growth stages.

In general, greenhouse experiments have plant growth restrictions due to pot size, limiting corn to early growth stages. For this reason, the CSTVs obtained in greenhouse experiments are typically very different from those in field trials. Additionally, if plants are grown to later stages in pots, the root system will over-explore the soil volume, and the CSTV will decrease unrealistically as plants access more P per unit of soil volume than in field conditions. For these reasons, greenhouse trials are not useful to define P CSTVs. Despite this, greenhouse trials are useful to compare the PBC of different soils and to group similar soils to reduce the number of field trials required for soil test correlation and calibration.

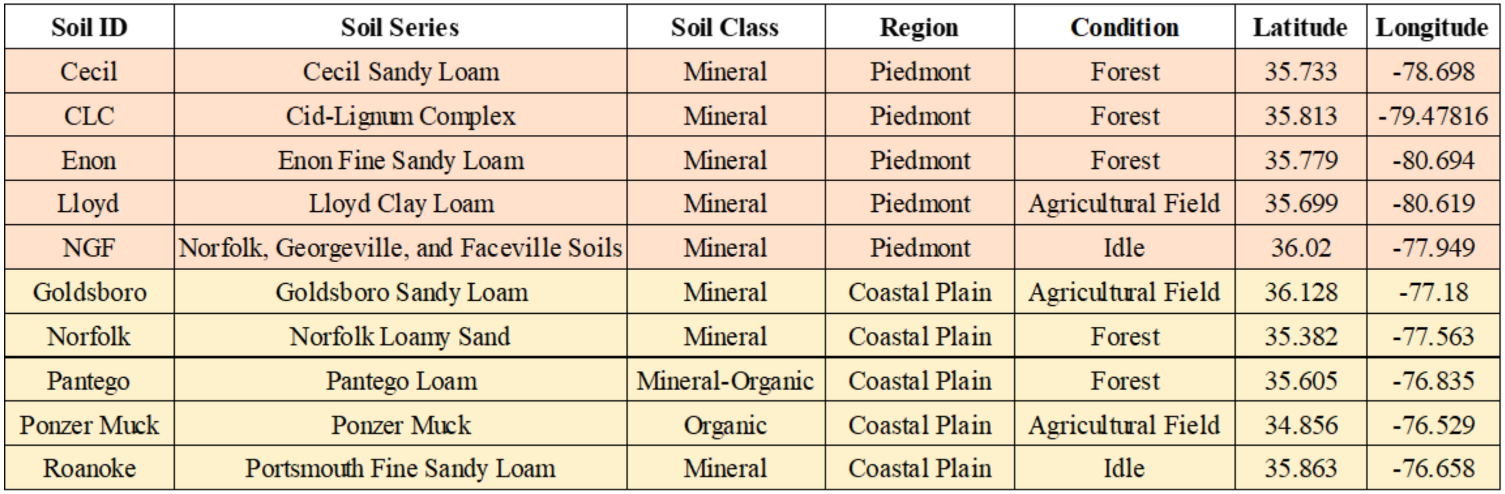
The objective of this study was to determine the range of P CSTVs for corn grown in greenhouse conditions in 10 NC soils with diverse characteristics. These results will serve as a guide for later occurring field trials to refine the CSTV for NC.

MATERIALS AND METHODS

Soil Collection

Ten soil series were selected to provide a variety representative of agricultural land in NC. Soils were collected from forested or idle areas, or in an agricultural field with no known recent fertilizer applications. These soils included mineral, mineral-organic, and organic soils from the piedmont and coastal plain regions of NC (Table 2.1) (Figure 2.1). Soil series were determined using soil maps accessed through Web Soil Survey and verified by collection of a soil core to assess texture by the “feel” method and color using the Munsell soil color chart. Approximately 100 kg of each soil was collected to a depth of 0.2 m, excluding major plant residue or other impurities. Following collection, soils were air dried and screened through a 4 mm mesh. Granules larger than 4 mm were ground to pass through the mesh. After thorough mixing of samples by hand, four subsamples from each soil were sent to the North Carolina Department of Agriculture & Consumer Services (NCDA&CS) Soil Testing Laboratory for analysis (Table 2.2).

Table 2.1. Characteristics of ten North Carolina soil series collected for use in a greenhouse trial.



Soil ID	Soil Series	Soil Class	Region	Condition	Latitude	Longitude
Cecil	Cecil Sandy Loam	Mineral	Piedmont	Forest	35.733	-78.698
CLC	Cid-Lignum Complex	Mineral	Piedmont	Forest	35.813	-79.47816
Enon	Enon Fine Sandy Loam	Mineral	Piedmont	Forest	35.779	-80.694
Lloyd	Lloyd Clay Loam	Mineral	Piedmont	Agricultural Field	35.699	-80.619
NGF	Norfolk, Georgeville, and Faceville Soils	Mineral	Piedmont	Idle	36.02	-77.949
Goldsboro	Goldsboro Sandy Loam	Mineral	Coastal Plain	Agricultural Field	36.128	-77.18
Norfolk	Norfolk Loamy Sand	Mineral	Coastal Plain	Forest	35.382	-77.563
Pantego	Pantego Loam	Mineral-Organic	Coastal Plain	Forest	35.605	-76.835
Ponzer Muck	Ponzer Muck	Organic	Coastal Plain	Agricultural Field	34.856	-76.529
Roanoke	Portsmouth Fine Sandy Loam	Mineral	Coastal Plain	Idle	35.863	-76.658

Figure 2.1. Locations and soil series of 10 North Carolina soil samples collected for use in a greenhouse trial. The solid line represents the boundary between the mountain (left) and piedmont (center) regions. The dotted line represents the boundary between the piedmont (center) and coastal plain (right) regions.

Table 2.2. Soil test results for soils collected from ten North Carolina soil series for use in a greenhouse trial.

Soil ID	Region	HM	W/V	CEC	BS	Ac	pH	P	K	Ca	Mg	S	Mn	Zn	Cu	Na
		g 100cc^{-1}		meq 100cc^{-1}	%	meq 100cc^{-1}		mg dm^{-3}								meq 100cc^{-1}
Cecil	Piedmont	0.79	79.3	6.65	54	3	4.875	18	151	379.5	172	24.3	65.6	3.8	1.3	0.075
CLC	Piedmont	0.4	108	3.375	49	1.7	5.075	9.5	23	246.5	48.5	17.5	133	1.2	0.4	0
Enon	Piedmont	0.12	110	12.25	87	1.625	5.45	7.5	45.8	1419	416	10.5	93.7	1.2	1.2	0.1
Lloyd	Piedmont	0.13	109	6.15	82	1.1	6.25	6.8	70.5	631.8	206	23.3	376	8.7	3	0
NGF	Coastal Plain	0.13	137	4.025	84	0.625	6.25	15	128	400.3	127	33.5	10.7	1	0.3	0
Goldsboro	Coastal Plain	1.11	122	6	74	1.6	5.65	24	60.8	695.5	95.5	12.5	8.4	2.1	1.7	0
Norfolk	Coastal Plain	0.77	110	5.05	29	3.6	4.25	44	67.3	183.8	42.8	24	6.2	2.4	0.3	0.05
Pantego	Coastal Plain	4.51	109	6.875	6.8	6.4	3.725	21	21.3	51.5	21	16.5	0.3	1.2	0.1	0.025
Ponzer Muck	Coastal Plain	7.93	49.5	26.675	77	6.075	4.9	19	68.5	3035	640	17.8	8.68	6.6	0.7	0.2
Roanoke	Coastal Plain	1.79	111	8.275	79	1.775	5.6	56	93.5	986	163	13.8	5.63	2	1.4	0.025

Description of Soils

Cecil Sandy Loam (Fine, Kaolinitic, Thermic Typic Kanhapludults)

The Cecil soil was collected near a North Carolina State University facility on Midpines Road in Raleigh, NC. It was collected in forest soil 50 feet from a road and agricultural field. This soil series is a well-drained sandy loam found on the slopes and ridges of the piedmont, with slopes from 0 to 25 percent. Cecil soil is a kaolinitic mineral soil found in forested sites (National Cooperative Soil Survey, 2007).

Cid Silt Loam (Fine, Mixed, Semiactive, Thermic Aquic Hapludults) – Lignum Silt Loam (Fine, Mixed, Semiactive, Thermic Aquic Hapludults) Complex (CLC)

The CLC soil was collected from a forested area in Pittsboro, NC. This soil series is a moderately to poorly drained silt loam formed in the Carolina Slate Belt and piedmont uplands, with slopes from 0 to 15 percent. Cid Lignum Complex soil is a mineral soil found in forested sites (National Cooperative Soil Survey, 2003; National Cooperative Soil Survey, 2010).

Enon Fine Sandy Loam (Fine, Mixed, Active, Thermic Ultic Hapludalfs)

The Enon soil was collected from a forested site in Rowan County, NC. This soil series is a well-drained fine sandy loam found on the slopes and ridges of the piedmont, with slopes from 2 to 45 percent. Enon soil is a mineral soil found in forested sites (National Cooperative Soil Survey, 2021).

Lloyd Loam (Fine, Kaolinitic, Thermic Rhodic Kanhapludults)

The Lloyd soil was collected on the border of long-term trials at the Piedmont Research Station near Salisbury, NC. This soil series is a well-drained loam found in the southern piedmont, with slopes from 2 to 10 percent. Lloyd soil is a kaolinitic mineral soil (National Cooperative Soil Survey, 2006).

Norfolk Loamy Sand (Fine-Loamy, Kaolinitic, Thermic Typic Kandiudults) – Georgeville Silt Loam (Fine, Kaolinitic, Thermic Typic Kanhapludults) – Faceville Fine Sandy Loam (Fine, Kaolinitic, Thermic Typic Kandiudults) Complex (NGF)

The NGF soil was collected from an idle soil site in Nash County, NC. This soil is a well-drained sandy loam found in the transition between piedmont and upper coastal plain, with slopes from 0 to 1 percent. This soil is a kaolinitic mineral soil (National Cooperative Soil Survey, 2013).

Goldsboro Loamy Sand (Fine-Loamy, Siliceous, Subactive, Thermic Aquic Paleudults)

The Goldsboro soil was collected on the border of long-term trials conducted at Peanut Belt Research Station. This soil series is a moderately well-drained loamy sand found in the lower to upper coastal plains, with slopes from 0 to 10 percent. Goldsboro soil is a mineral soil found in cultivated sites (National Cooperative Soil Survey, 2005).

Norfolk Loamy Sand (Fine-Loamy, Kaolinitic, Thermic Typic Kandiudults)

The Norfolk soil was collected from a forested site bordering agricultural land in Kinston, NC. This soil series is a well-drained loamy sand found in the coastal plain, with slopes from 0 to 10 percent. Norfolk soil is a kaolinitic mineral soil found in cultivated sites (National Cooperative Soil Survey, 2005).

Pantego Loam (Fine-Loamy, Siliceous, Semiactive, Thermic Umbric Paleaquults)

The Pantego soil was collected in a forested soil in Pinetown, NC. This soil series is a very poorly drained loam found on the southern coastal plain and Atlantic Coast Flatwoods with slopes from 0 to 2 percent. Pantego soil is a mineral-organic soil found in cultivated sites (National Cooperative Soil Survey, 1999).

Ponzer Muck (Loamy, Mixed, Dysic, Thermic Terric Haplosaprists)

The Ponzer Muck soil was collected in Carteret County, NC. This soil series is a very poorly drained muck loam found in flats and depressions in the coastal plain with slopes from 0 to 2 percent. Ponzer Muck soil is an organic soil found in cultivated sites (National Cooperative Soil Survey, 2010).

Roanoke Silt Loam (Fine, Mixed, Semiactive, Thermic Typic Endoaquults)

The Roanoke soil was collected from an idle soil on the border of long-term trials at Tidewater Research Station. This soil series is a poorly drained silt loam, with slopes from 0 to 2 percent. Roanoke soil is a mineral soil found in pasture sites (National Cooperative Soil Survey, 2006).

Soil Analysis

Water holding capacity was estimated by filling an aluminum tinfoil tube with soil, cinching the end, and adding water until drainage occurred through the soil. Tubes were stored upright for approximately 24 hours, whereafter a sample was collected from the middle of the tube and dried in an oven at 50 degrees Celsius for 48 hours. Sample weights were collected before and after drying (Table 2.3) (Cook et al., 2021). Equation 1 was used to calculate water held at field capacity:

$$\text{Water Holding Capacity} = (\text{Wet Weight} - \text{Dry Weight}) / \text{Dry Weight}$$

(Equation 1)

Table 2.3. Data collected from ten North Carolina soils to determine water holding capacity.

Soil ID	**Wet Weight**	**Dry Weight**	**Water Holding Capacity**
	g	**g**	**$g\ g^{-1}$**
Cecil	20.97	13.13	0.60
CLC	43.19	29.61	0.46
Enon	36.35	26.02	0.40
Lloyd	41.03	30.52	0.34
NGF	43.03	33.93	0.27
Goldsboro	38.42	29.46	0.30
Norfolk	40.38	28.89	0.40
Pantego	36.72	25.76	0.43
Ponzer Muck	24.75	11.02	1.25
Roanoke	31.88	24.19	0.32

Soil Testing Analysis by NCDA&CS Soil Testing Lab

Soil samples were dried at 49^{o} C for 48 hours and screened through a 2-mm sieve. Elements (P, K, Ca, Mg, S, Na, Mn, Cu, and Zn) were extracted on a 1:1 volume basis (2.5 cc soil:25 mL extractant) using Mehlich-3 and analyzed using inductively coupled argon plasma emission spectroscopy, which is the standard method of the Agronomic Division, NCDA&CS (Mehlich, 1984). Cation exchange capacity (CEC) was determined by summation of basic cations (excluding Na) and buffer acidity (Mehlich, 1976). Base saturation was estimated by sum of Ca, Mg, and K in relation to CEC. Soil pH was determined on a 1:1 soil/water volume ratio in 0.01 M $CaCl_2$ and reported as a water pH by addition of 0.6 pH units. Humic matter determination was made using a NaOH digestion with colorimetric determination (Mehlich, 1984). Soil density was determined gravimetrically by weighing 10 mL of dried, sieved soil. (David Hardy, Personal Correspondence).

Soil Preparation

Dependent on analysis from NCDA&CS, lime applications were determined to aim for a target pH of 6.0 for mineral soils, 5.5 for mineral-organic soils, and 5.0 for organic soils. After determination of soil class, $CaCO_3$ rates were calculated using Equation 2 (Hardy et al., 2014).

Lime Requirement (tons per acre) = Exchangeable Acidity x (Target pH – Initial pH) / (6.6 x Initial pH)

(Equation 2)

The average lime requirement for the four samples collected from each soil series were calculated and used for application (Table 2.4). Calculation of rate was made by converting tons per acre furrow slice to the pot volume. Soils were weighed, moistened to approximately 90% water holding capacity, mixed with $CaCO_3$, and incubated at room temperature (~25 degrees C) for four weeks. After incubation, four samples were collected from each soil and sent to NCDA&CS for analysis (Table 2.4). Soils were air-dried and stored for use during the greenhouse experiment.

Table 2.4. Soil test data for ten North Carolina soils used to determine and evaluate liming rates.

Soil ID	**Ac**	**pH**	**Target pH**	**Lime Rate**	**pH**
	meq 100cc^{-1}	**Pre-Lime**		**kg ha^{-1}**	**Post-Lime**
Cecil	3	4.9	6	4483	6.1
CLC	1.7	5.1	6	2242	6.6
Enon	1.6	5.5	6	1793	6.8
Lloyd	1.1	6.3	6	0	6.4
NGF	0.6	6.3	6	0	6.4
Goldsboro	1.6	5.7	6	1345	6.1
Norfolk	3.6	4.3	6	6053	6.4
Pantego	6.4	3.7	5.5	8967	5.5
Ponzer Muck	6.1	4.9	5	897	4.9
Roanoke	1.8	5.6	6	1569	6

Experimental Design and Implementation

The greenhouse trial was conducted at the North Carolina State University Method Road Greenhouse Facility from October to November 2021. Treatments consisted of 10 soils (Table 2.1) and five rates of P at 0, 56, 112, 168, and 224 kg P_2O_5 ha^{-1}. The crop was corn (*Zea mays*, Dyna-Gro, Variety 01075500). The treatments were arranged in a randomized complete block design with four replications in 3.7-liter pots.

Pots were filled with the equivalent of 3.7 dm^{-3} of soil, using a specified weight for each soil type based on the W/V ratio (Table 2.2). Nutrients (excluding P) were dissolved in water, sprayed, and mixed in each soil before planting (Table 2.5). On September 15, 2021, triple superphosphate was ground using mortar and pestle and applied to soil at the treatment rates. Fertilizer granules were ground to ensure even distribution throughout the soil in each pot.

Table 2.5. Fertilizer rates applied to all soils in a greenhouse trial.

Nutrient	**Rate**	**Source**	**Placement**	**Time**
	kg ha^{-1}			
Nitrogen	168	UAN (28% N)	Soil	At Planting
Potassium	168	KCl (52.48% K)	Soil	At Planting
Sulfur	34	$MgSO_4.7H_2O$ (9.86% Mg, 13% S)	Soil	At Planting
Manganese	2	$MnCl_2$ (27.8% Mn)	Soil	At Planting
Copper	2	$CuCl_2$ (37.28% Cu)	Soil	At Planting
Zinc	2	$ZnSO_4 \bullet 7H_2O$ (22.7% Zn)	Soil	At Planting
Boron	0.28	H_3BO_3 (17.5% B)	Soil	At Planting
Manganese	0.28	$MnCl_2$ (27.8% Mn)	Foliar	30 DAP[1]
Copper	0.28	$CuCl_2$ (37.28% Cu)	Foliar	30 DAP
Zinc	0.28	$ZnCl_2$ (48% Zn)	Foliar	30 DAP
Nitrogen	32	Liquid Urea (45% N)	Soil	35 DAP
Manganese	0.28	$MnCl_2$ (27.8% Mn)	Foliar	35 DAP
Copper	0.28	$CuCl_2$ (37.28% Cu)	Foliar	35 DAP
Zinc	0.28	$ZnCl_2$ (48% Zn)	Foliar	35 DAP

[1] DAP = days after planting

Three corn seeds were planted in each pot approximately 2.5 cm below the soil line on September 29, 2021. Seeds were placed close to the center of the pot, leaving sufficient space between plants to ensure lack of root disturbance when thinning. After plants reached 5 cm in height (~7 days after planting), the seedling displaying the most vigor was chosen and the other two seedlings were removed in whole, including roots.

Plants were hand watered with the assistance of drip irrigation for several weeks in the middle of the study. Due to difficulty in calibration of drip irrigation, hand watering became the primary method of watering for the majority of the study. During the period of attempted irrigation calibration, several pots experienced both over- and under- watering. The Ponzer Muck, Goldsboro, and Lloyd had significant difficulties with irrigation calibration, although all soil types suffered during this period.

Plants were grown for a 49-day period (Figure 2.2). Plant height was measured at 15, 31, and 49 days after planting by measuring from the soil line to the height of the flag leaf. Micronutrient deficiencies were observed midway through the study (most prevalent in the Ponzer Muck soil, most likely due to chelation) and were addressed by foliar applications of manganese, copper, and zinc to all plants on October 29 and November 3, 2021 (Table 2.5) (Figure 2.3). At the second micronutrient foliar application, nitrogen was also supplied at 32 kg nitrogen ha^{-1} (Table 2.5).

Figure 2.2. Corn grown for the greenhouse trial, 35 days after planting.

Figure 2.3. Nutrient deficiency observed at 30 days after planting in corn grown in the Ponzer Muck soil. Less severe deficiency symptoms were also observed in corn grown in other soils.

Harvest date was determined after evaluating pots for over-exploration of soil by roots and to avoid further nutrient deficiency. Corn plants were cut at the soil line, placed in paper bags, and dried in an oven at 50 degrees C. Roots were separated from the soil, washed to remove remaining soil and debris, placed in paper bags, and dried in an oven at 50 degrees C. After approximately 10 days in the oven, corn stalks and roots were weighed to determine dry matter and sent to NCDA&CS for analysis of P content. After removal of roots, the soil volume from each pot was mixed and a sample was collected for analysis at NCDA&CS.

Data Analysis

Statistical analysis was conducted using SAS Studio software (SAS Institute, Cary, NC). Data was analyzed by conducting analysis of variance (ANOVA) using Tukey's Honest Significant Difference test, chosen to evaluate the difference among sample means between groups of the same sample size (SAS Institute Inc., 2018). A linear plateau model was fitted to each parameter using soil test P measured at the end of the study to determine CSTVs (SAS Institute Inc., 2018). The linear plateau model was chosen to reflect one of the two main models typically used in soil CSTV studies conducted in NC.

RESULTS AND DISCUSSION

Plant Height

Plant height was not significant for any soils at 15 days after planting (DAP) (Figure 2.4; Figure 2.5), due to the limited nutrient requirement of early-stage growth and the nutrients supplied by the seed.

At 30 DAP, corn height in most piedmont soils began to show P rate treatment effects. The Enon soil did not show an increase in plant height with increasing P rate. Only one of the coastal plain soils, the Norfolk soil, showed a significant difference in height with increasing applied P at 30 DAP. This may be a result of the kaolinitic soil, as opposed to other coastal plain soils included in the study. It is of interest that corn grown in coastal plain and piedmont soils had a similar height range at 30 DAP (40-80 cm in height).

At 49 DAP, similar trends are observed in corn height in most piedmont and coastal plain soils, with no significant differences were observed beyond the 56 kg ha^{-1} rate. The exceptions were in the CLC and Lloyd soils, where significant corn height increases ceased at 112 kg ha^{-1} applied P. These two soils had a higher clay content than other soils within the study and had low initial levels of P, 7 and 10 mg P dm^{-3}, respectively.

The Ponzer Muck soil did not show any significant differences among height collected at 15, 30, or 49 DAP. This organic soil behaved very differently than all other soils collected in this study. This soil posed a difficulty during the study, as it was difficult to maintain proper moisture.

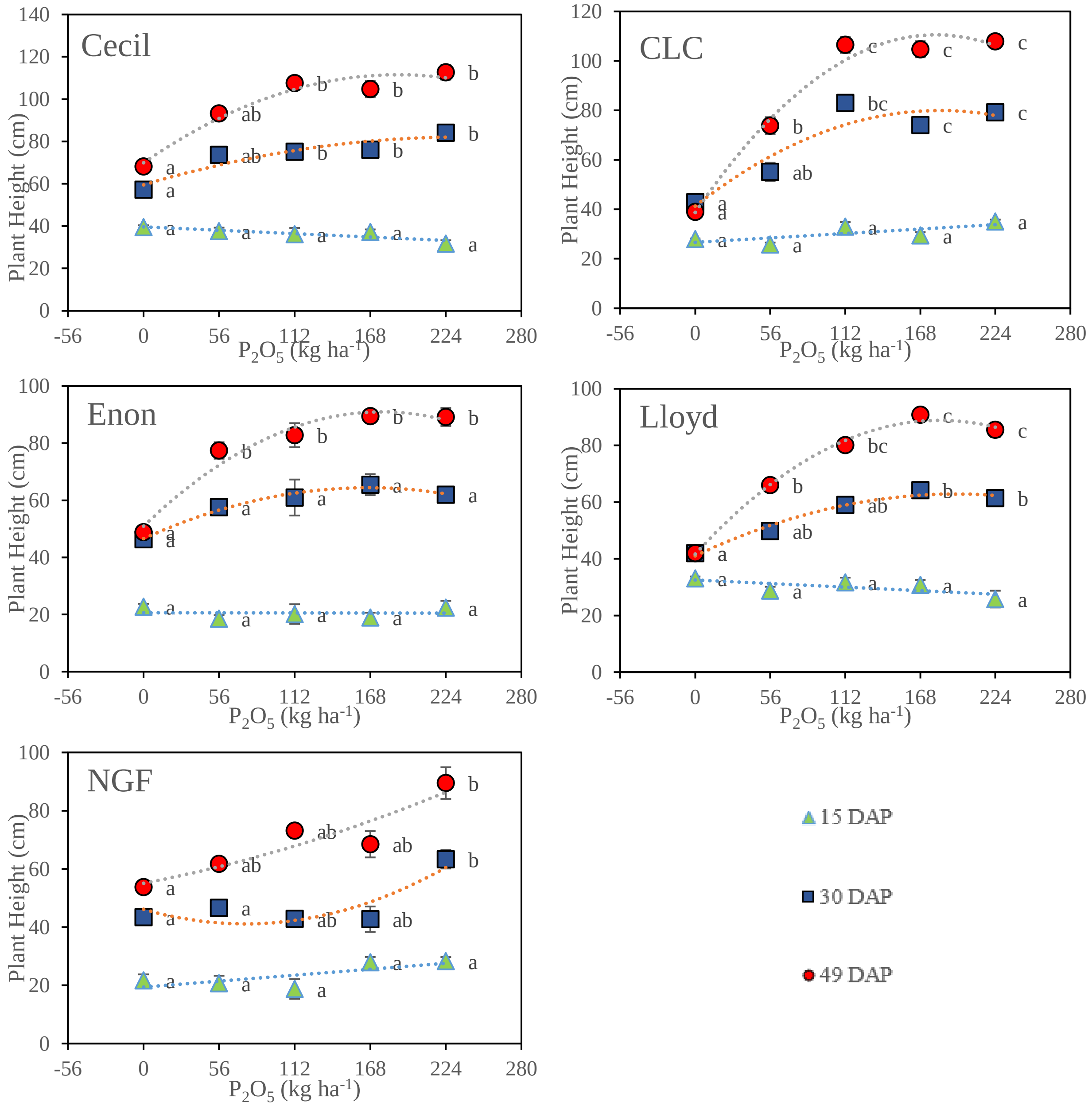


Figure 2.4. Greenhouse trial height measurements collected at 15, 30, and 49 DAP on corn grown in NC piedmont soils treated with varying rates of P fertilizer. Letters of significance (P = 0.05) refer to each sampling date.

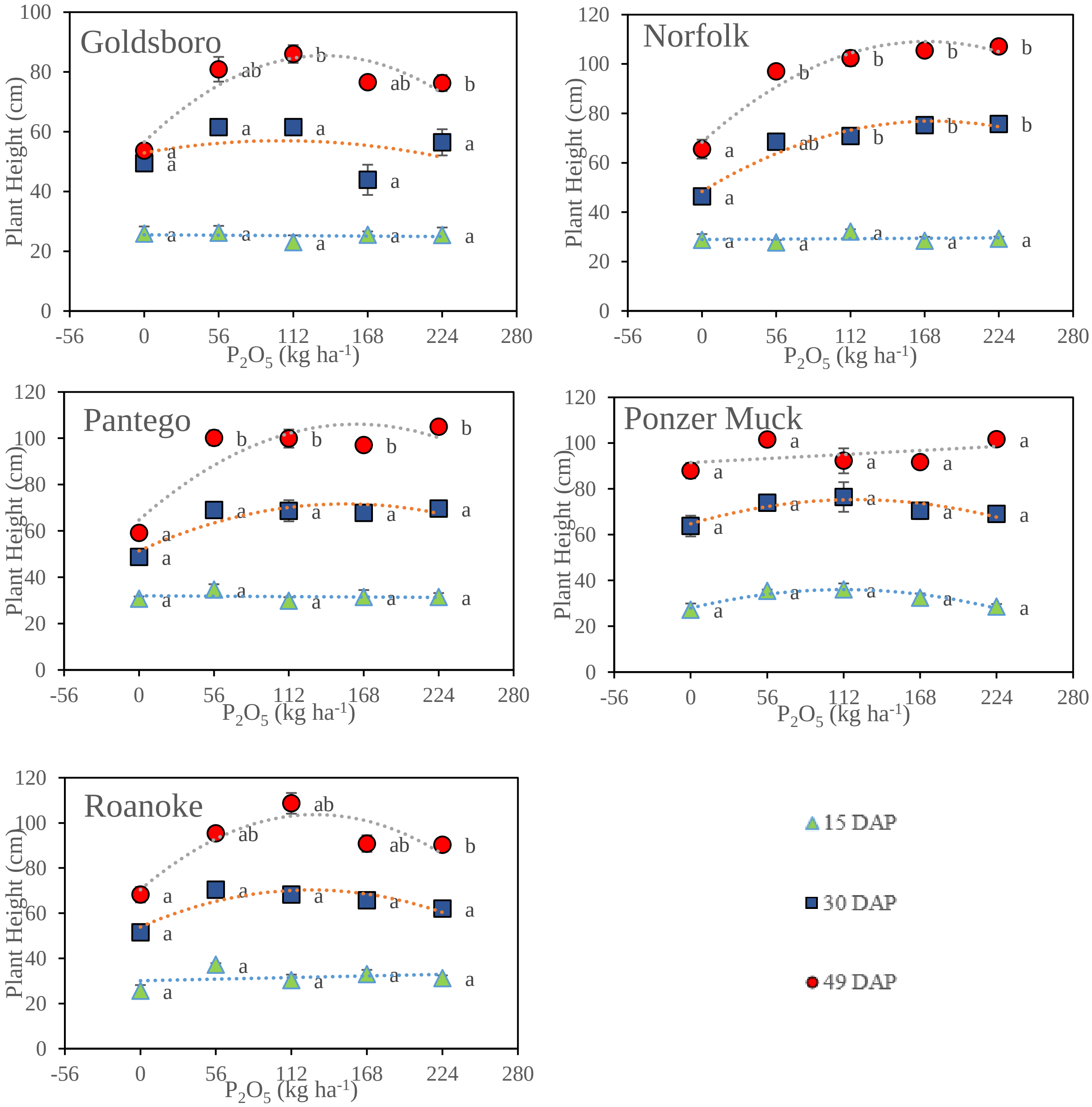


Figure 2.5. Greenhouse trial height measurements collected at 15, 30, and 49 DAP on corn grown in NC coastal plain soils treated with varying rates of P fertilizer. Letters of significance ($P = 0.05$) refer to each sampling date.

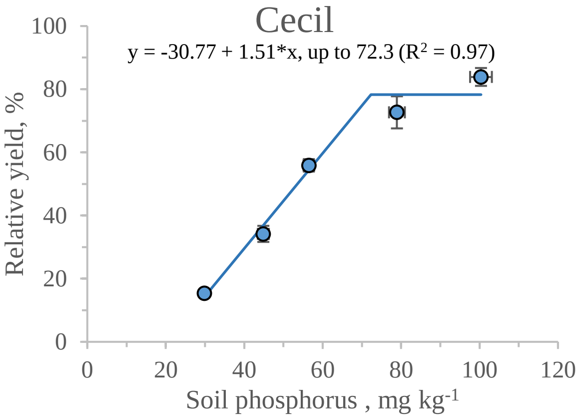
Relative Yield

Initial soil test P levels and the rates of P applied in the greenhouse experiment were high enough to observe a plateau in the dry matter response (Figure 2.6; Figure 2.7). For the piedmont soils, the CSTVs ranged from 26 to 72 mg kg^{-1} P. Clearly, Enon and Lloyd soils, collected at western piedmont (Rowan County), presented lower CSTVs than the eastern piedmont soils, indicating that these soils have a higher PBC. Results from Table 2.2 show that these soils have low HM content but relatively high CEC, indicating soils with higher clay content and, consequently, higher PBC. For the Piedmont soils, the breakpoint of the linear plateau model occurred between the 3rd and 5th P rate, indicating that a high rate of P is necessary to reach the CSTV.

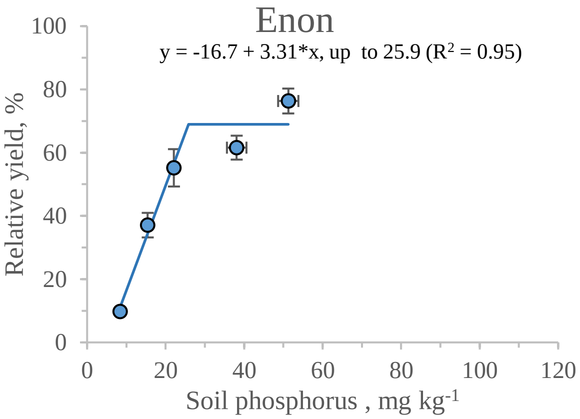
For the coastal plain soils, except the Ponzer Muck (organic soil), the CSTVs were higher than for piedmont soils, ranging from 66 to 85 mg kg^{-1}. For these soils, the breakpoint occurred between the 2nd and 4th P rate, indicating less P fertilizer is necessary to reach the CSTV. The organic soil (Ponzer Muck) presented a behavior completely different from others, with a CSTV of 32 mg kg^{-1} and the breakpoint close to the first P rate, indicating that this soil has very low PBC. Also, this soil presented high variability among replications and high error. Because of the low soil density and little presence of clay, these organic soils are assumed to have a low P retention capacity and, consequently, low PBC (NC PLAT Committee, 2005). It is important to highlight that some organic soils divert form this common pattern, as those soils identified by Dell'Olio et al. (2005), which have high content of Mehlich-3 Al concentrations and higher P retention capacity. During the greenhouse experiment, the Ponzer Muck was the most challenging soil during the irrigation process because of low density and soil volume.

Soil test calibration research in NC has been primarily focused in the coastal plain region, where the majority of corn production occurs. However, piedmont regions of the state have significantly higher clay content and should thus be studied more thoroughly, as piedmont soils in NC tend to have low plant available P and high PBC (Kamprath, 1967). In our study, all 10 soils were grouped into three groups: piedmont, coastal plain, and organic. The CSTVs were recalculated for piedmont and coastal plain soils (Figure 2.8). The average CSTV for piedmont was 55 mg kg^{-1} and for coastal plain it was 90 mg kg^{-1}. In a similar study conducted by Kamprath and Miller (1958), CSTVs for P in soybeans cultivated in coastal plain soils in a greenhouse was 51 mg kg^{-1}. It is important to recognize that greenhouse trials cannot be compared directly, as many factors have an impact- soil types, crop, size of pots, and duration of study. The current CSTV values are much higher than those obtained in NC field trials by others: In sandy coastal plain soils the mean CSTV was 36 mg kg^{-1} (Cox & Lins, 1984; Cox, 1992; Cox, 1996; Cox & Barnes, 2002; Crozier et al., 2004) and 14 mg kg^{-1} in piedmont soils (Shelton et al., 1961; Cox & Lins, 1984; Kamprath, 1999). Despite these differences, P CSTVs were never adjusted for soil type or region in NC, and a single CSTV (Hardy et al. 2014) was established, which is significantly higher than those observed in field trials. This has surely contributed to the fact that in 2015, only 29% of soil samples in North Carolina tested below the CSTV for P (IPNI, 2015).

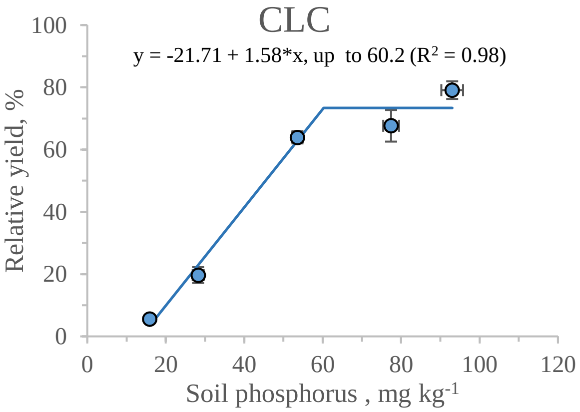
Figure 2.6. Dry matter relative yield of corn obtained with different soil test P levels in soils from the piedmont of NC during a greenhouse experiment. The linear plateau model was adjusted to the data and the breakpoint represents the CSTV. The bars represent the standard error.


Cecil

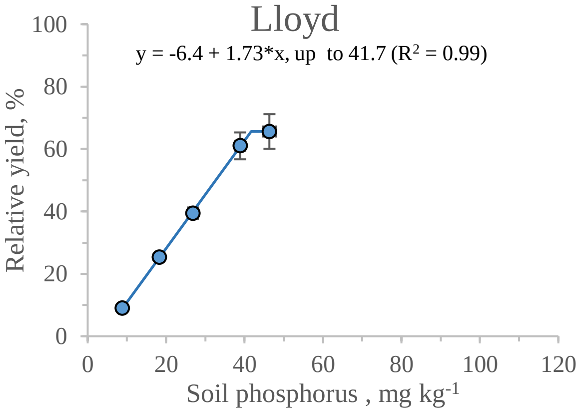
y = -30.77 + 1.51*x, up to 72.3 (R^2 = 0.97)


Enon

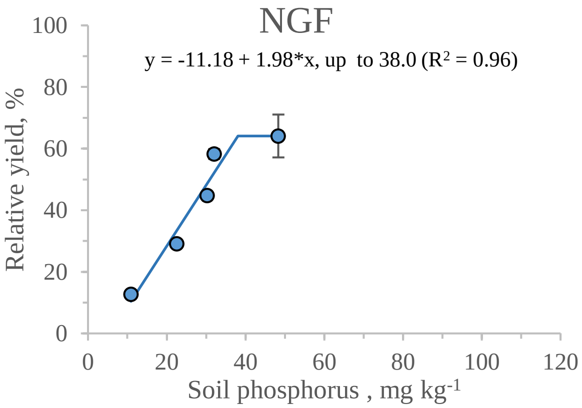
y = -16.7 + 3.31*x, up to 25.9 (R^2 = 0.95)


CLC

y = -21.71 + 1.58*x, up to 60.2 (R^2 = 0.98)

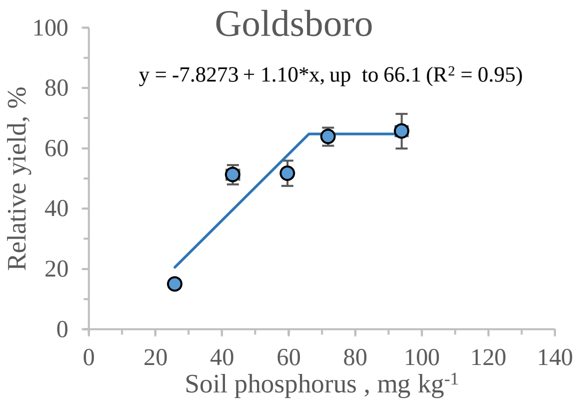

Lloyd

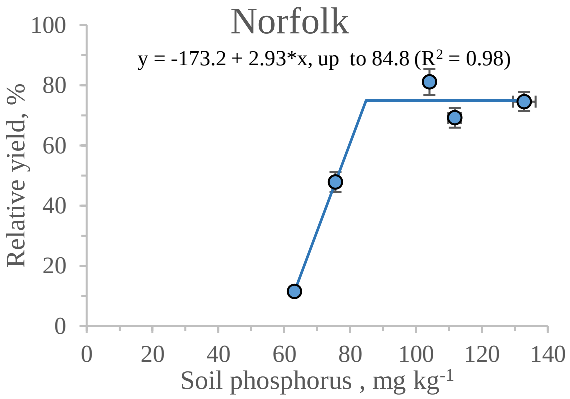
y = -6.4 + 1.73*x, up to 41.7 (R^2 = 0.99)

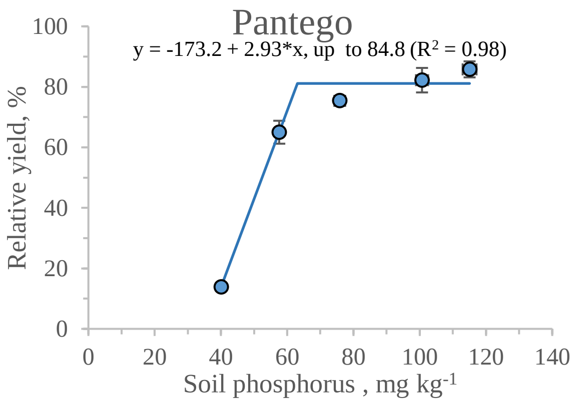

NGF

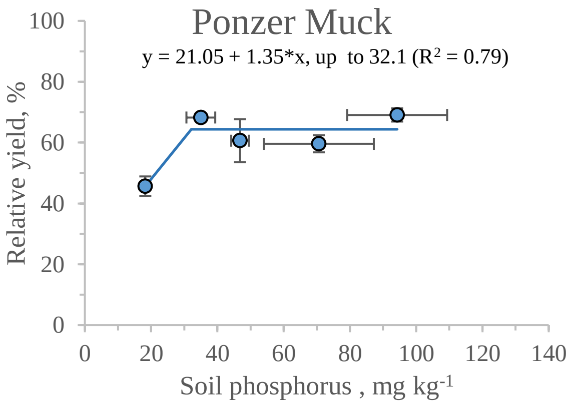
y = -11.18 + 1.98*x, up to 38.0 (R^2 = 0.96)

Figure 2.7. Dry matter relative yield of corn obtained with different soil test P levels in soils from the coastal plain of NC during a greenhouse experiment. The linear plateau model was adjusted to the data and the breakpoint represents the CSTV. The bars represent the standard error.


Goldsboro
y = -7.8273 + 1.10*x, up to 66.1 (R² = 0.95)
Relative yield, %
0
20
40
60
80
100
0
20
40
60
80
100
120
140
Soil phosphorus , mg kg-1


Norfolk
y = -173.2 + 2.93*x, up to 84.8 (R² = 0.98)
Relative yield, %
0
20
40
60
80
100
0
20
40
60
80
100
120
140
Soil phosphorus , mg kg-1


Pantego
y = -173.2 + 2.93*x, up to 84.8 (R² = 0.98)
Relative yield, %
0
20
40
60
80
100
0
20
40
60
80
100
120
140
Soil phosphorus , mg kg-1


Ponzer Muck
y = 21.05 + 1.35*x, up to 32.1 (R² = 0.79)
Relative yield, %
0
20
40
60
80
100
0
20
40
60
80
100
120
140
Soil phosphorus , mg kg-1

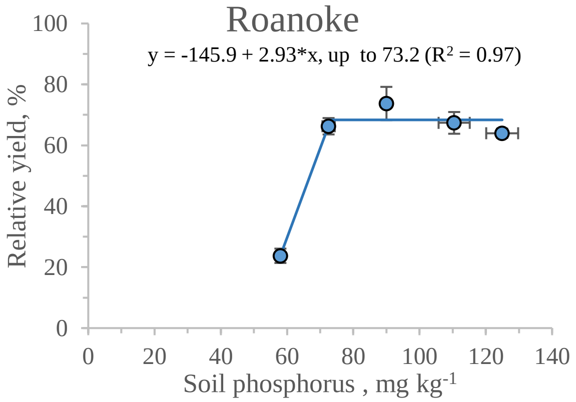
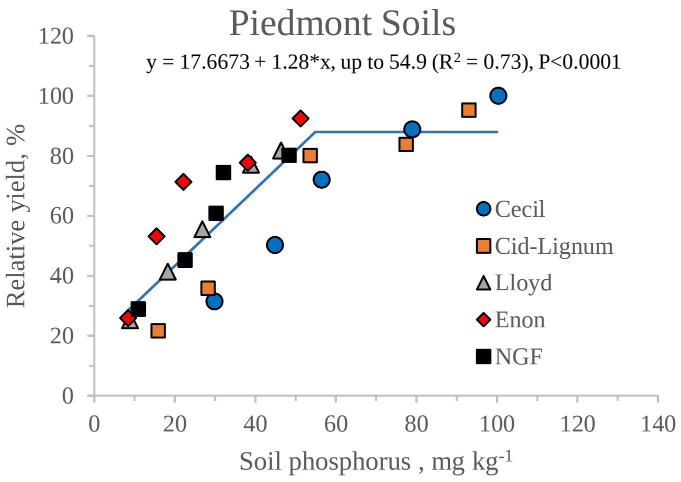
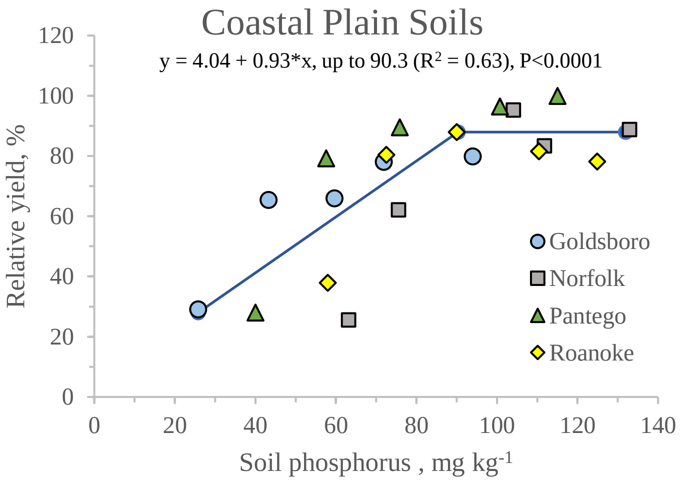
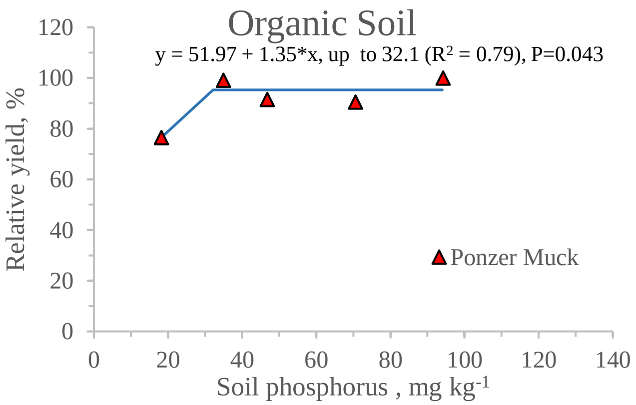

Roanoke
y = -145.9 + 2.93*x, up to 73.2 (R² = 0.97)
Relative yield, %
0
20
40
60
80
100
0
20
40
60
80
100
120
140
Soil phosphorus , mg kg-1

Figure 2.8. Dry matter relative yield of corn obtained with different soil test P levels in three distinct groups: piedmont soils, coastal plain soils, and organic soil. The linear plateau model was adjusted to the data and the breakpoint represents the CSTV.


Piedmont Soils
y = 17.6673 + 1.28*x, up to 54.9 (R² = 0.73), P<0.0001
Relative yield, %
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
Soil phosphorus , mg kg-1
Cecil
Cid-Lignum
Lloyd
Enon
NGF


Coastal Plain Soils
y = 4.04 + 0.93*x, up to 90.3 (R² = 0.63), P<0.0001
Relative yield, %
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
Soil phosphorus , mg kg-1
Goldsboro
Norfolk
Pantego
Roanoke


Organic Soil
y = 51.97 + 1.35*x, up to 32.1 (R² = 0.79), P=0.043
Relative yield, %
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
Soil phosphorus , mg kg-1
Ponzer Muck

Phosphorus Uptake

The relationship between dry matter relative yield and P concentration in corn tissue is presented in Table 2.6 and Figure 2.9. For seven soils, the linear plateau model was significant, for one soil (Lloyd) the linear model was significant, and for two soils (NGF and Roanoke) no significant relationship was observed. For the soils following a linear plateau relationship, the Ponzer Muck presented a plant tissue critical value (PTCV) of 0.51%, while for the other soils (Cecil, Enon, CLC, Goldsboro, Norfolk, and Pantego) the PTCV ranged from 0.11 to 0.15%. These values are below 0.25%, the sufficiency level recommended by Campbell (2000) as the optimal for corn in the southern United States. Conversely, the concentration of P in plants grown in the organic soil was much higher, which may indicate a luxury consumption of P in that soil with low P retention capacity.

Table 2.6. Dry mass and P uptake of aerial and root portions of corn grown in the greenhouse. Letters of significance refer to the individual soil and type of measurement recorded across P rates.

Soil	**P Rate**	**Dry matter (g pot^{-1})**			**P uptake (mg pot^{-1})**		
	(kg ha^{-1})	**Aerial Tissue**	**Roots**	**Total**	**Aerial Tissue**	**Roots**	**Total**

Table 2.6 (Continued).

Cecil	0	1.94 a	1.03 a	2.97 a	2.57 a	0.83 a	3.40 a
	56	4.31 ab	2.31 ab	6.61 ab	3.88 a	1.43 a	5.30 a
	112	7.04 bc	3.30 ab	10.34 bc	7.15 ab	2.68 a	9.84 ab
	168	9.16 c	4.26 ab	13.42 c	10.95 ab	3.03 a	13.98 ab
	224	10.57 c	3.78 b	14.35 c	18.92 b	3.17 a	22.09 b
	CV (%)	28.33	46.05	30.70	61.12	47.40	53.02
	P	0.0009	0.1106	0.0034	0.0199	0.0690	0.0160
CLC	0	0.55 a	0.21 a	0.76 a	1.00 a	0.12 a	1.11 ab
	56	1.93 a	0.72 ab	2.65 a	1.84 a	0.43 b	2.26 ab
	112	6.27 b	1.85 bc	8.12 b	6.76 b	1.34 c	8.10 bc
	168	6.63 b	2.33 c	8.96 b	7.53 bc	1.90 c	9.43 bc
	224	7.75 b	1.76 c	9.52 b	11.83 c	1.66 c	13.48 c
	CV (%)	31.48	35.60	32.19	35.31	35.58	29.67
	P	0.0002	0.0010	0.0003	0.0001	0.0053	0.0011
Enon	0	0.79 a	0.34 a	1.13 a	0.67 a	0.24 a	0.91 a
	56	2.99 ab	0.90 b	3.90 ab	3.70 ab	0.63 ab	4.33 a
	112	4.46 bc	0.93 b	5.39 bc	5.57 abc	0.75 ab	6.32 a
	168	4.97 bc	0.97 b	5.94 bc	9.27 bc	1.24 b	10.51 ab
	224	6.16 c	1.52 c	7.68 c	12.46 c	2.03 c	14.49 b
	CV (%)	30.16	17.80	26.96	49.22	26.67	43.48
	P	0.0006	<0.0001	0.0003	0.0041	0.0002	0.0110

Table 2.6 (Continued).

Lloyd	0	0.65 a	0.26 a	0.91 a	0.55 a	0.15 a	0.70 a
	56	1.82 ab	1.82 ab	2.60 ab	2.04 a	0.56 ab	2.60 a
	112	2.83 bc	1.02 bc	3.85 bc	3.58 ab	0.96 bc	4.54 ab
	168	4.38 c	1.54 cd	5.91 cd	5.32 b	1.32 c	6.64 b
	224	4.71 c	1.74 d	6.54 d	6.23 b	1.44 c	7.67 b
	CV (%)	30.70	22.41	24.57	39.08	27.46	33.62
	P	0.0003	<0.0001	<0.0001	0.0010	0.0032	0.0042
NGF	0	0.96 a	0.49 a	1.45 a	1.47 a	0.39 a	1.86 a
	56	2.19 ab	0.74 a	2.93 ab	4.87 ab	0.77 ab	5.64 ab
	112	2.86 ab	1.12 a	3.97 ab	5.45 ab	1.35 ab	6.80 ab
	168	2.84 ab	0.89 a	3.73 ab	4.10 ab	1.01 b	5.11 ab
	224	4.82 b	1.20 a	6.02 b	10.07 b	1.55 b	11.62 b
	CV (%)	51.40	36.03	46.44	56.59	38.77	50.34
	P	0.0560	0.0857	0.0581	0.0321	0.0283	0.0229
Goldsboro	0	0.94 a	0.38 a	1.32 a	1.14 a	0.40 a	1.54 a
	56	3.21 ab	1.77 a	4.99 ab	4.16 ab	1.48 a	5.63 a
	112	3.24 ab	1.12 a	4.36 ab	4.86 b	1.21 a	6.08 ab
	168	4.00 b	1.66 a	5.66 b	5.79 b	1.92 a	7.71 b
	224	4.12 b	1.32 a	5.44 b	7.10 b	1.68 a	8.78 b
	CV (%)	33.15	63.12	40.43	33.70	58.55	34.94
	P	0.0139	0.2963	0.0733	0.0019	0.3970	0.0146

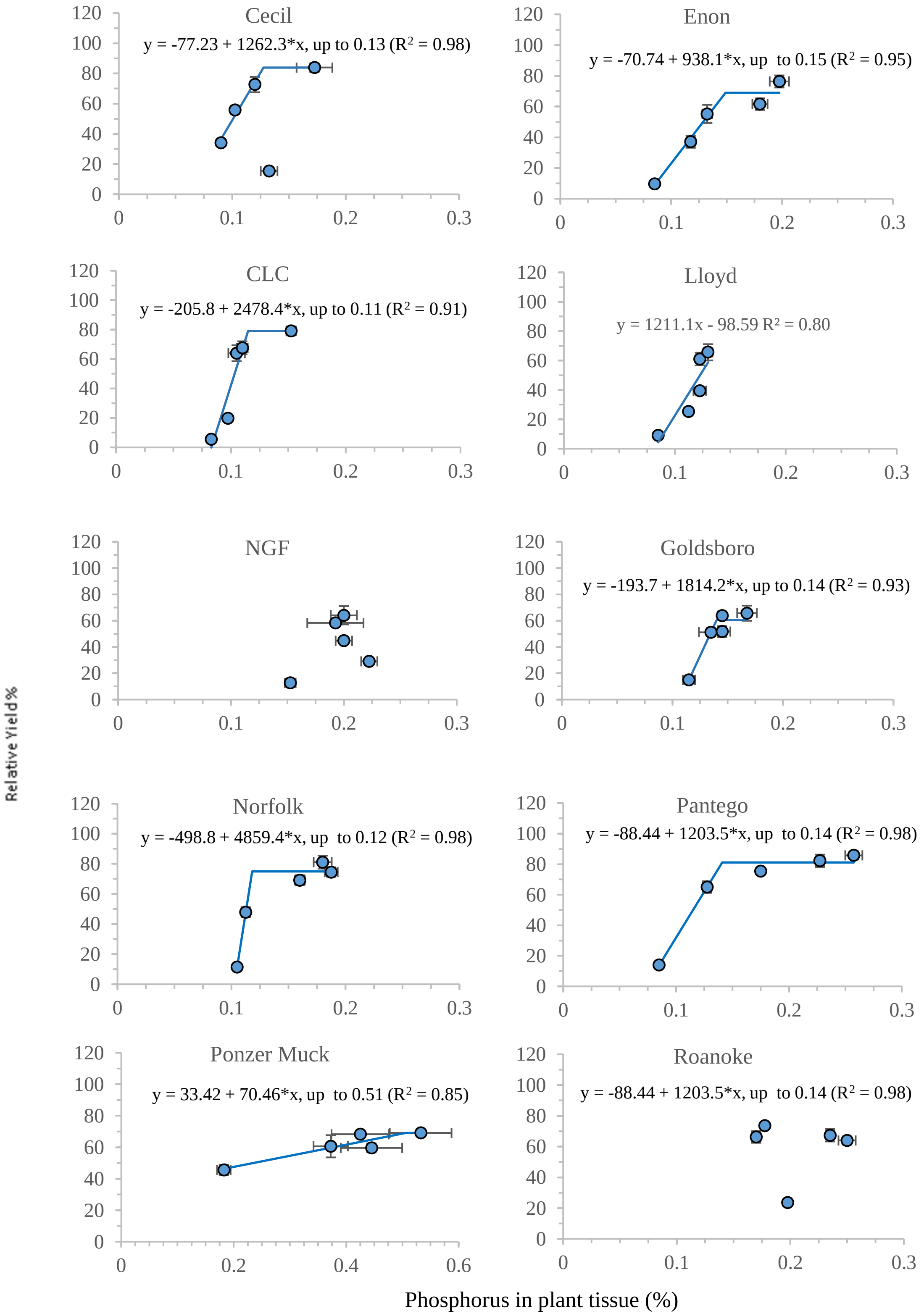
Table 2.6 (Continued).

Norfolk	0	1.52 a	0.47 a	1.99 a	1.53 a	0.38 a	1.91 a
	56	6.36 b	2.64 ab	9.00 b	7.17 ab	1.80 ab	8.97 a
	112	10.78 bc	3.44 ab	14.21 b	19.35 bc	3.54 ab	22.89 b
	168	9.19 bc	4.22 b	13.40 b	14.92 c	4.39 ab	19.30 b
	224	9.90 c	3.95 b	13.85 b	18.87 c	4.86 b	23.73 b
	CV (%)	26.62	50.33	28.39	34.88	55.76	35.51
	P	0.0003	0.0298	0.0011	0.0010	0.0453	0.0043
Pantego	0	1.84 a	0.50 a	2.34 a	1.59 a	0.38 a	1.97 a
	56	8.63 b	2.13 ab	10.77 b	11.16 ab	1.73 a	12.89 a
	112	7.61 b	2.41 ab	10.02 b	13.28 b	2.51 b	15.79 b
	168	10.92 b	2.89 b	13.81 b	25.03 c	3.36 b	28.39 b
	224	11.39 b	3.34 b	14.73 b	28.99 c	4.93 b	33.91 b
	CV (%)	27.60	41.80	27.50	28.47	51.41	28.23
	P	0.0018	0.0304	0.0018	<0.0001	0.0416	0.0004
Ponzer Muck	0	6.25 a	2.13 a	8.38 a	11.97 a	2.66 a	14.63 a
	56	9.34 a	3.34 a	12.68 a	39.05 ab	7.35 ab	46.40 ab
	112	8.29 a	2.78 a	11.07 a	32.51 ab	6.00 ab	38.51 ab
	168	8.15 a	3.55 a	11.70 a	39.15 ab	7.42 ab	46.57 ab
	224	9.45 a	3.98 a	13.43 a	50.40 b	10.93 b	61.33 b
	CV (%)	27.10	31.95	27.77	48.28	48.67	47.82
	P	0.2399	0.2128	0.4257	0.0199	0.0876	0.0272

Table 2.6 (Continued).

Roanoke	0	2.53 a	0.76 a	3.28 a	4.84 a	1.03 a	5.86 a
	56	7.06 b	1.95 a	9.01 b	12.02 b	2.28 ab	14.30 b
	112	7.85 b	2.44 a	10.30 b	14.17 b	3.06 b	17.23 b
	168	7.18 b	2.10 a	9.27 b	16.37 b	2.98 b	19.35 b
	224	6.81 b	2.46 a	9.27 b	17.05 b	3.61 b	20.66 b
	CV (%)	24.51	43.63	25.28	24.36	33.16	21.91
	P	0.0064	0.0739	0.0087	0.0026	0.0196	0.0011

Figure 2.9. Dry matter relative yield and concentration of P in corn tissue in 10 NC soils cultivated in the greenhouse. The linear or linear plateau model was adjusted to the data and the breakpoint represents the PTCV.


Relative Yield %
Cecil
y = -77.23 + 1262.3*x, up to 0.13 (R² = 0.98)
Enon
y = -70.74 + 938.1*x, up to 0.15 (R² = 0.95)
CLC
y = -205.8 + 2478.4*x, up to 0.11 (R² = 0.91)
Lloyd
y = 1211.1x - 98.59 R² = 0.80
NGF
Goldsboro
y = -193.7 + 1814.2*x, up to 0.14 (R² = 0.93)
Norfolk
y = -498.8 + 4859.4*x, up to 0.12 (R² = 0.98)
Pantego
y = -88.44 + 1203.5*x, up to 0.14 (R² = 0.98)
Ponzer Muck
y = 33.42 + 70.46*x, up to 0.51 (R² = 0.85)
Roanoke
y = -88.44 + 1203.5*x, up to 0.14 (R² = 0.98)
0
20
40
60
80
100
120
0
0.1
0.2
0.3
0.4
0.6
Phosphorus in plant tissue (%)

SOIL TEST PHOSPHORUS

Increases in soil test P varied notably be region (Figure 2.10, Figure 2.11). The average rate of increase (Mehlich 3 P mg kg^{-1} per P_2O_5 kg ha^{-1}) with added P was 0.24 mg kg^{-1} in piedmont soils and 0.32 mg kg^{-1} in coastal plain soils, with a range among all soils of 0.15 to 0.36 mg kg^{-1}. As expected, the red soils of the piedmont region require greater rates of P to increase soil test P levels. This may be explained by higher clay content of soils in the region, which generally have greater PBC. A portion of the added P is sorbed to clay particles and is unavailable for plant uptake. These relationships should be studied further for incorporation into fertilizer recommendation methods. Phosphorus rate requirements of some clayey soils of NC may require significantly heavier applications of fertilizer to raise soil test P in satisfying a fixation requirement. Using a universal fertilizer recommendation method may recommend too high of rates in the coastal plain regions, increasing the cost of inputs and the potential for nutrient leaching, while simultaneously failing to recommend adequate P in piedmont soils.

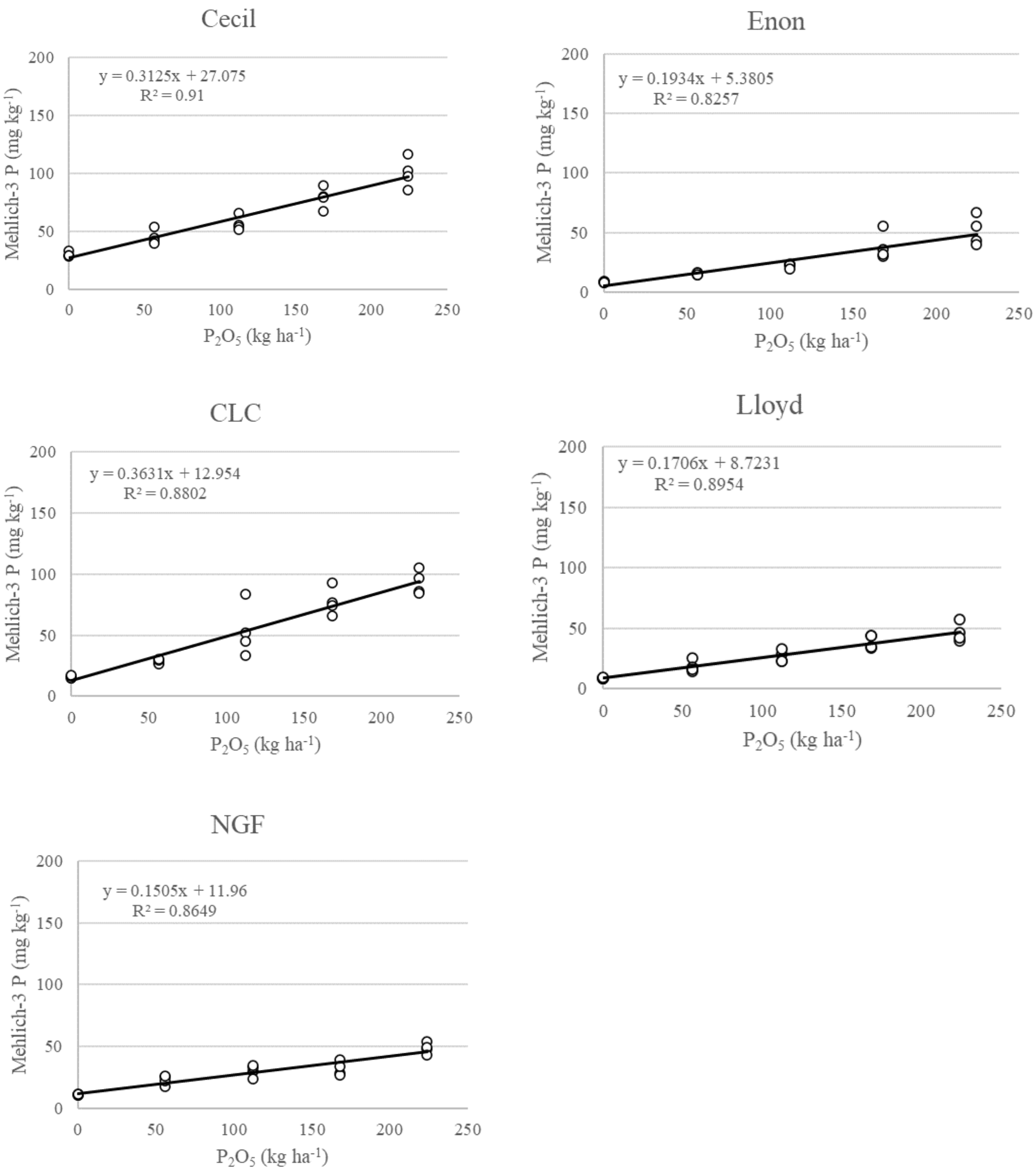


Figure 2.10. Soil test P of soils from the Piedmont of NC amended with P fertilizer during a greenhouse experiment.

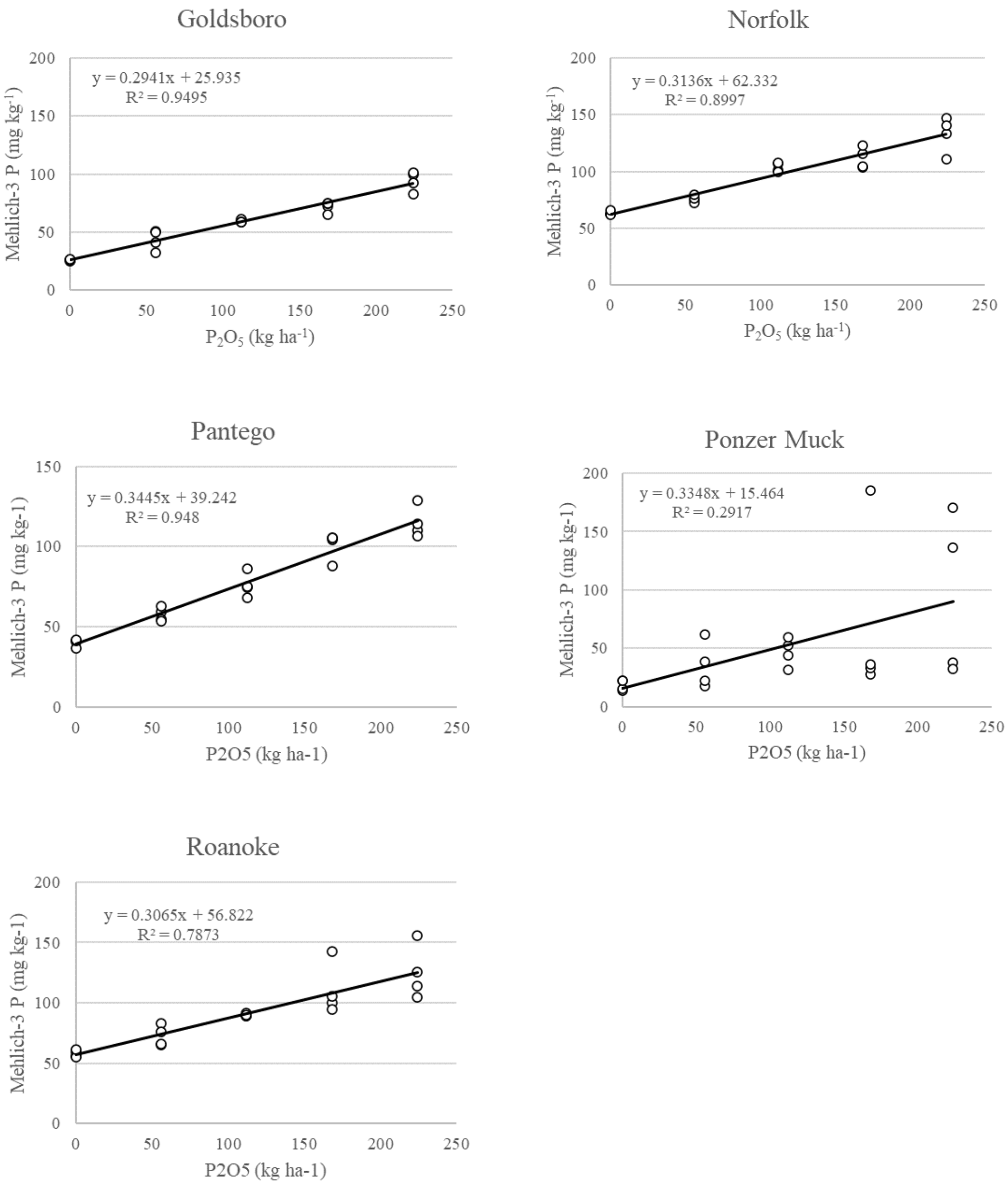


Figure 2.11. Soil test P of soils from the Coastal Plain of NC amended with P fertilizer during a greenhouse experiment.

CONCLUSIONS

For the Piedmont soils, the breakpoint of the linear plateau model occurred between the 112 mg kg^{-1} and 224 mg kg^{-1} P rate for relative yield. For Coastal Plain soils, the breakpoint occurred between the 56 mg kg^{-1} and 168 mg kg^{-1} P rate, indicating less P fertilizer is necessary to reach the CSTV than for the Piedmont soils. The average CSTV for Piedmont was 55 mg kg^{-1} and for Coastal Plain it was 90 mg kg^{-1}. The average rate of increase in soil test P with added P was 0.24 mg kg^{-1} P per kg ha^{-1} P_2O_5 in Piedmont soils and 0.32 mg kg^{-1} ^{1} P per kg ha^{-1} P_2O_5 in Coastal Plain soils, with a range among all soils of 0.15 to 0.36 mg kg^{-1} P per kg ha^{-1} P_2O_5.

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CHAPTER THREE: ESTIMATION OF PHOSPHORUS BUFFERING CAPACITY USING ROUTINE SOIL FERTILITY ANALYSES

INTRODUCTION

Current fertilizer recommendation methods in North Carolina (NC) are based on Mehlich 3 soil test phosphorus (P), which does not accurately account for all factors affecting P uptake, specifically P sorption. Phosphorus buffering capacity (PBC) compensates for some of the shortcomings of routine P soil testing but is too time consuming, and therefore expensive, for soil testing labs to measure regularly. However, soil characteristics such as sample density via a weight per volume (W/V), iron (Fe) and aluminum (Al) oxides, humic matter (HM), and soil pH can affect P availability, sorption, and fertilizer requirements, and are measured in routine soil fertility analysis. Sample density can be indicative of soil texture, and more importantly, clay content, of a soil (Cox & Espejo, 1990). While clay content increases, PBC commonly increases. Therefore, W/V may be used as a parallel indicator for clay content and PBC. Additionally, at low pH levels, similar to those in NC, the amount of reactive Al and Fe oxides increases, increasing sorption sites for P (Kang et al., 2009; Prasad & Chakraborty, 2019). In an evaluation of P sorption characteristics in highly weathered soils, Espejo & Cox (1992) found that exchangeable Al, Fe, and clay represented 85% of the variation in P sorption.

For this reason, it would be beneficial to classify PBC via a mathematical model to consider how soil characteristics influence PBC, and, ultimately, P availability. A relationship between several sorption-affecting factors that are currently analyzed by the North Carolina Department of Agriculture & Consumer Services (NCDA&CS) Soil Testing Laboratory in routine analysis can be used to classify PBC of soils throughout the state. This classification could be used to improve the correlation between soil test P and plant uptake and serve to refine the recommendations of P fertilizers for NC soils (Corey, 1987). Ultimately, this classification would be beneficial to predict and identify which NC soils should have different critical soil test values.

The objective of this study was to determine the PBC of selected soils from NC and correlate with select soil fertility parameters routinely measured by NCDA&CS soil tests.

MATERIALS AND METHODS

Sample Collection and Analyses

A collection of 423 soil samples were used for this study (Figure 3.1). These samples were collected in part by Chandler Fulmer in 2020 (Fulmer, 2021; personal communication) as a representative sample of NC soils for a thesis study at North Carolina State University. Many sites have two samples: a 0-10 cm and a 10-20 cm depth. Additional soils were sampled to provide better representation of the red soils of the piedmont region which historically have high PBC, and to include soils used in Chapter Two: Critical Soil Test Values of Phosphorus for Corn During Early Vegetative Stages in Ten North Carolina Soils Cultivated in a Greenhouse. Soil samples were sent to NCDA&CS for analysis (Table 3.1).

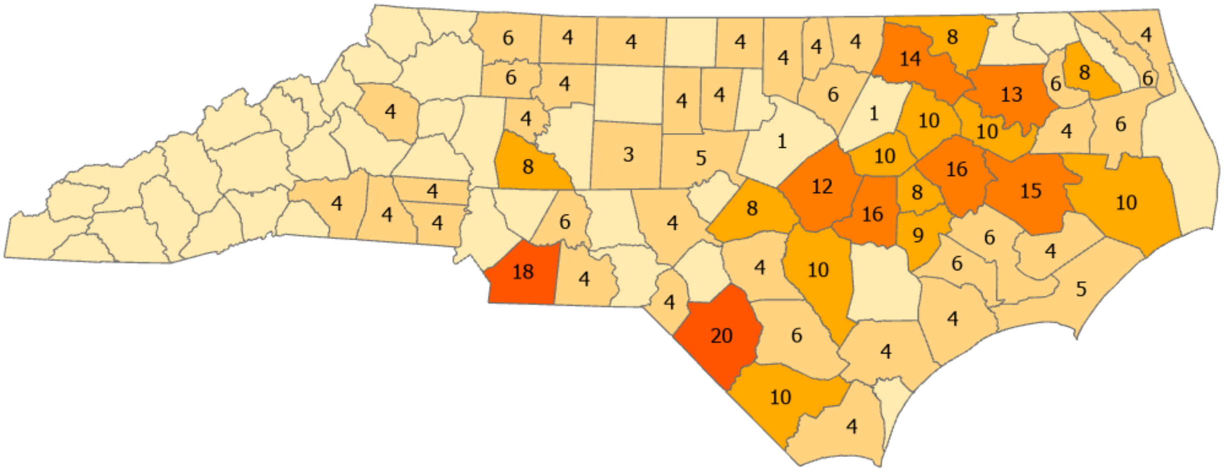


Figure 3.1. Location and number of soil samples per county used for analysis. Samples were acquired from 63 counties. Counties that were not sampled for the purpose of this study do not display a number. Darker colors represent counties with a higher number of samples included in the study.

Table 3.1. Descriptive statistics of soil samples collected for use in this study.

	Minimum	Maximum	Mean	Median	Standard Deviation
HM *%*	0.04	10	1.1	0.51	1.78
W/V *g* cm^{-1}	0.50	1.61	1.2	1.24	0.18
CEC *meq 100* cm^{-3}	2.2	36.7	6.6	5.9	3.32
BS *%*	6.75	98	72.1	73	12.20
Ac *meq 100* cm^{-3}	0.2	7.6	1.7	1.5	0.94
pH	3.7	7.2	5.7	5.6	0.50
P *mg* dm^{-3}	2	803	139.7	114	108.21
K *mg* dm^{-3}	10	390	106.1	94	60.24
Ca *mg* dm^{-3}	51.5	4878	720.4	625	478.74
Mg *mg* dm^{-3}	14	639.8	130.1	111	86.98
S *mg* dm^{-3}	4	120	22.0	19	11.24
Mn *mg* dm^{-3}	0.3	529.4	40.1	14.3	72.28
Zn *mg* dm^{-3}	0.4	45.4	6.2	4.1	7.02
Cu *mg* dm^{-3}	0.13	27.4	2.9	1.6	3.41
Na *meq 100* cm^{-3}	0	1.7	0.1	0	0.12
Al *ppm*	157	1891	914.9	838	289.82
Fe *ppm*	49	591	206.08	198	83.81
Sand *%*	4.11	83.72	52.0	56.05	20.16
Silt *%*	1.59	74.15	25.6	22.78	15.54
Clay *%*	10.76	56.42	22.4	20	8.31
PBC *%*	-0.08	0.68	0.1	0.11148	0.13

Soil texture in terms of percent sand, silt, and clay was determined using the hydrometer methods detailed in Gavlack et al., 2005. Samples were prepared by weighing 40 g of soil ground to pass through a 2 mm sieve. Samples were mixed with 100 mL of a 5% sodium hexametaphosphate dispersing solution and stored for approximately 16 hours. Samples were mixed again for 5 minutes and transferred to a graduated cylinder, where room temperature deionized water was added to bring the total volume to 1 L. The contents of the cylinder were mixed thoroughly with a plunger and the hydrometer was placed in the cylinder. Two readings were taken at 40 seconds and 6 hours, respectively. At each time of collection, a hydrometer and temperature reading were taken from a control solution. The following equations were used to calculate percentages of sand, silt, and clay:

$$\% \text{ Sand} = (\text{Oven Dry Soil Mass} - (\text{40 Second Reading} - \text{Control})) / (\text{Oven Dry Soil Mass}) \times 100$$

(Equation 3)

$$\% \text{ Clay} = (\text{6 Hour Reading} - \text{Control}) / (\text{Oven Dry Soil Mass}) \times 100$$

(Equation 4)

$$\% \text{ Silt} = 100 - \% \text{ Sand} - \% \text{ Clay}$$

(Equation 5)

Phosphorus buffering capacity was determined using a P stock solution of 60 mg P L^{-1} created by dissolving and diluting potassium phosphate monobasic (KH_2PO_4) in deionized water. A 50 ml aliquot of the P stock solution was applied to 5 cm^3 of ground soil and agitated on a reciprocating shaker at 180 oscillations $minute^{-1}$ for 1 hour. Samples were centrifuged at 9770 relative centrifugal force for 15 minutes. The supernatant was filtered through a Whatman No. 42 filter and collected for P analysis at EATS lab at North Carolina State University. Phosphorus buffering capacity was reported in terms of percent of added P adsorbed (Figure 3.2).

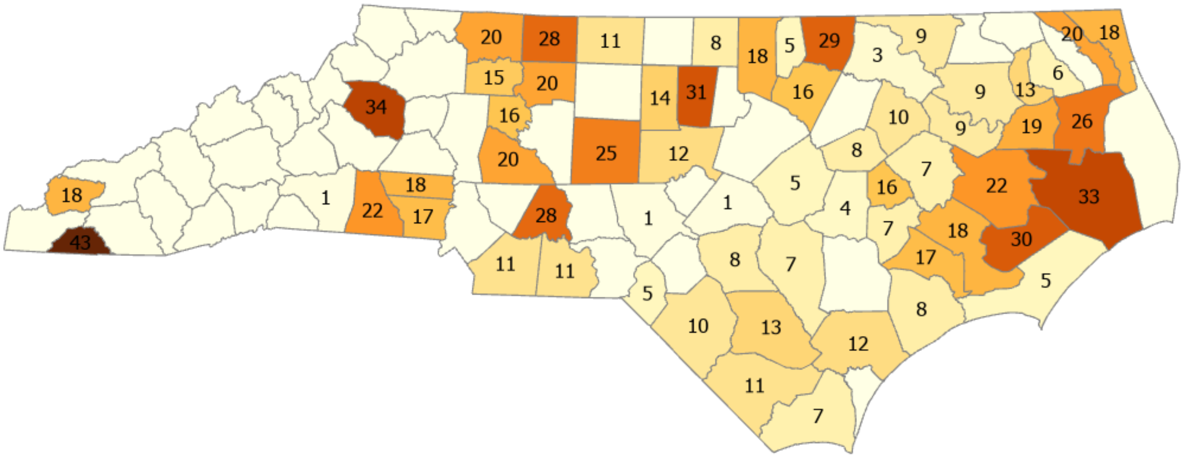


Figure 3.2. Average PBC percentage recorded among soils collected from 63 NC counties. Counties that were not sampled for the purpose of this study do not display a number. Darker colors represent a higher average PBC for the county.

Statistical Analysis

Statistical analysis was conducted using JMP software (SAS institute, 2015). Data was analyzed by conducting a Pearson correlation analysis, stepwise multiple linear regression, and decision tree analysis for soil test parameters in relation to PBC. Pearson correlation analysis was chosen to determine soil characteristics with a significant relationship with PBC to use in further analysis. These parameters were then used in a stepwise multiple linear regression to create a usable model for estimation of PBC using significant parameters. Decision tree analysis was chosen to clearly dictate the upper and lower boundaries of soil characteristics as they relate to PBC. Breakpoints in the decision tree were determined by JMP software as a statistically significant division point for a parameter.

RESULTS AND DISCUSSION

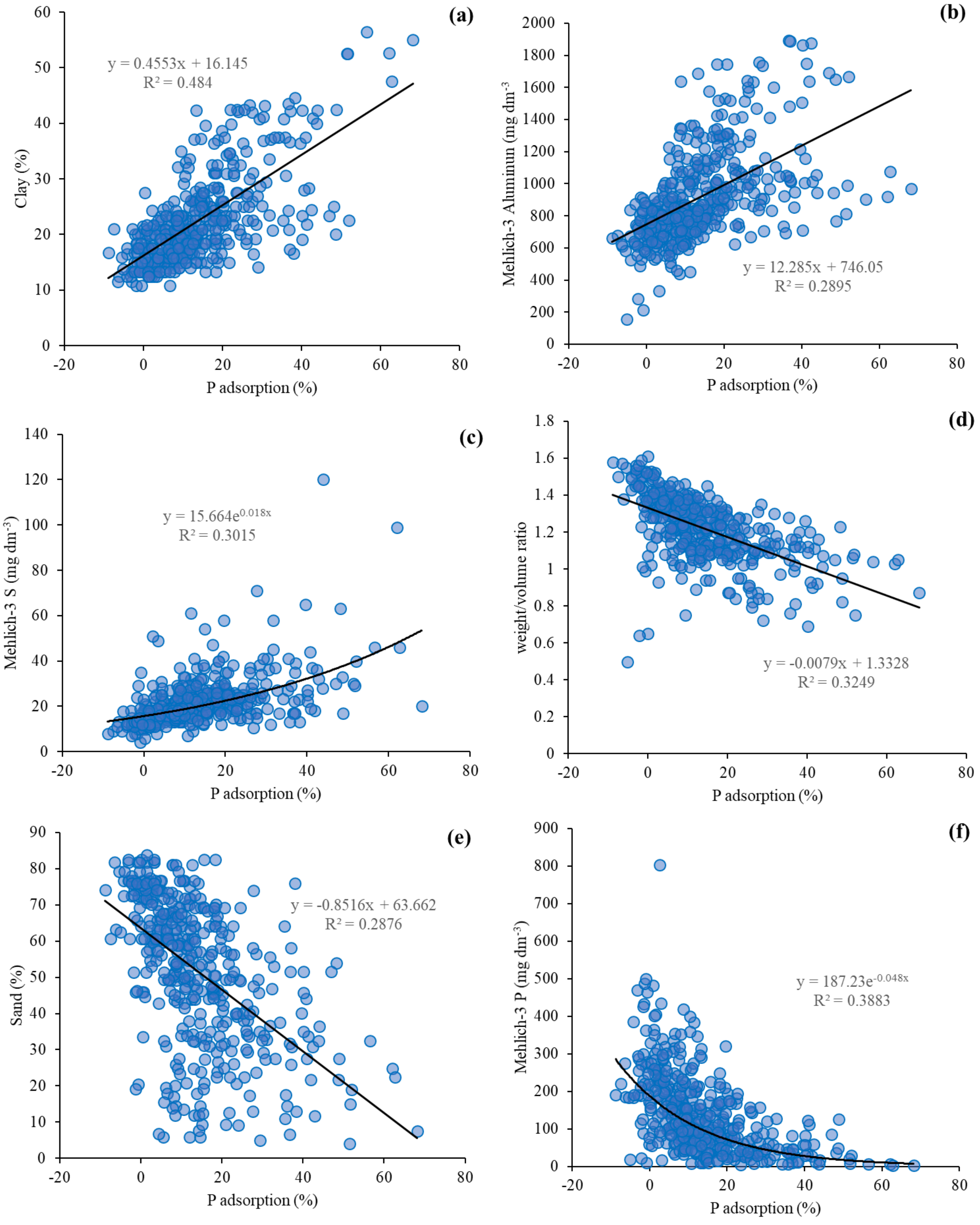
Pearson Correlation Analysis for Strongest Predictors of Phosphorus Sorption

All soil testing parameters included in the study were significantly correlated with PBC ($P < 0.05$), excluding CEC and pH (Table 3.2). Clay content provided the most significant positive relationship (0.70) with PBC, followed by Al (0.54) and S (0.52) (Table 3.2; Figure 3.2). Highly significant negative correlations were observed between PBC and W/V (-0.57), sand content (-0.54) and Mehlich 3 P (M3P) (-0.53). These results followed expected trends and suggested that many soil characteristics may be useful in modelling PBC.

Table 3.2. Pearson correlation coefficients between P adsorption and soil testing parameters (n=423).

Soil Parameter	**Pearson Correlation**	**Probability**
HM	0.2065	0.0408
W/V	-0.5700	0.0328
CEC	0.2107	0.0837
Base saturation	0.1242	0.0105
Acidity	0.1592	0.001
pH	0.0896	0.0653
P	-0.5337	<0.0001
K	0.1263	0.0092
Ca	0.1161	0.0168
Mg	0.3529	<0.0001
S	0.5187	<0.0001
Mn	0.2910	<0.0001
Zn	-0.2308	<0.0001
Cu	-0.1405	0.0037
Na	0.1486	0.0021
Sand	-0.5362	<0.0001
Silt	0.3236	<0.0001
Clay	0.6956	<0.0001
Al	0.538	<0.0001
Fe	-0.3767	<0.0001

Figure 3.3. Relationship between P adsorption and clay content (a), Mehlich-3 Al (b), Mehlich-3 S (c), weight/volume ratio (d), sand content (d), and Mehlich-3 P (f).


(a)
Clay (%)
0
10
20
30
40
50
60
-20
0
20
40
60
80
P adsorption (%)
y = 0.4553x + 16.145
R² = 0.484
(b)
Mehlich-3 Aluminum (mg dm⁻³)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
-20
0
20
40
60
80
P adsorption (%)
y = 12.285x + 746.05
R² = 0.2895
(c)
Mehlich-3 S (mg dm⁻³)
0
20
40
60
80
100
120
140
-20
0
20
40
60
80
P adsorption (%)
y = 15.664e^0.018x
R² = 0.3015
(d)
weight/volume ratio
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
-20
0
20
40
60
80
P adsorption (%)
y = -0.0079x + 1.3328
R² = 0.3249
(e)
Sand (%)
0
10
20
30
40
50
60
70
80
90
-20
0
20
40
60
80
P adsorption (%)
y = -0.8516x + 63.662
R² = 0.2876
(f)
Mehlich-3 P (mg dm⁻³)
0
100
200
300
400
500
600
700
800
900
-20
0
20
40
60
80
P adsorption (%)
y = 187.23e^-0.048x
R² = 0.3883

Decision Tree Analysis to Classify Phosphorus Adsorption Classes

The decision tree analysis aims to define the strongest predictors of a single characteristic, in this case the PBC. This method is a predictive modeling that uses divisions to separate the population into subgroups. During modeling, successive splits are added to the model, increasing the R^2, and it is expected that after some splits the R^2 will not increase because the last splits are adding non-significant parameters. Using the entire dataset, all parameters were included in this analysis. The most significant predictor of PBC was clay content, followed by Al and W/V, resulting in a model with an R^2 of 0.668 (Figure 3.4). Including further parameters did not significantly improve the accuracy of the model. Soil with clay content < 21.76% had an average P sorption of 7.82%, while soils with clay content above 21.76% had an average P sorption rate of 22.64%. A secondary split among soils with high clay content, and therefore high sorption rate, showed that soils with less than 47.5% clay adsorbed less P than soils with clay content above this threshold. Above this threshold is the highest class of P sorption recorded in this study at 58.78% P sorption rate. Those soils with low PBC had clay contents below 21.76% and are separated further into groups impacted by Al and W/V content. Soils with lower Al content recorded lower PBC, which is a result of less binding sites for P on Al oxides within soil. Additionally, lower W/V correlated to a higher PBC, which relates to texture again. This is a redundancy because clay was already included in the model, but these values are still indicative of a trend related to the impacts of soil clay content as a source for P binding sites.

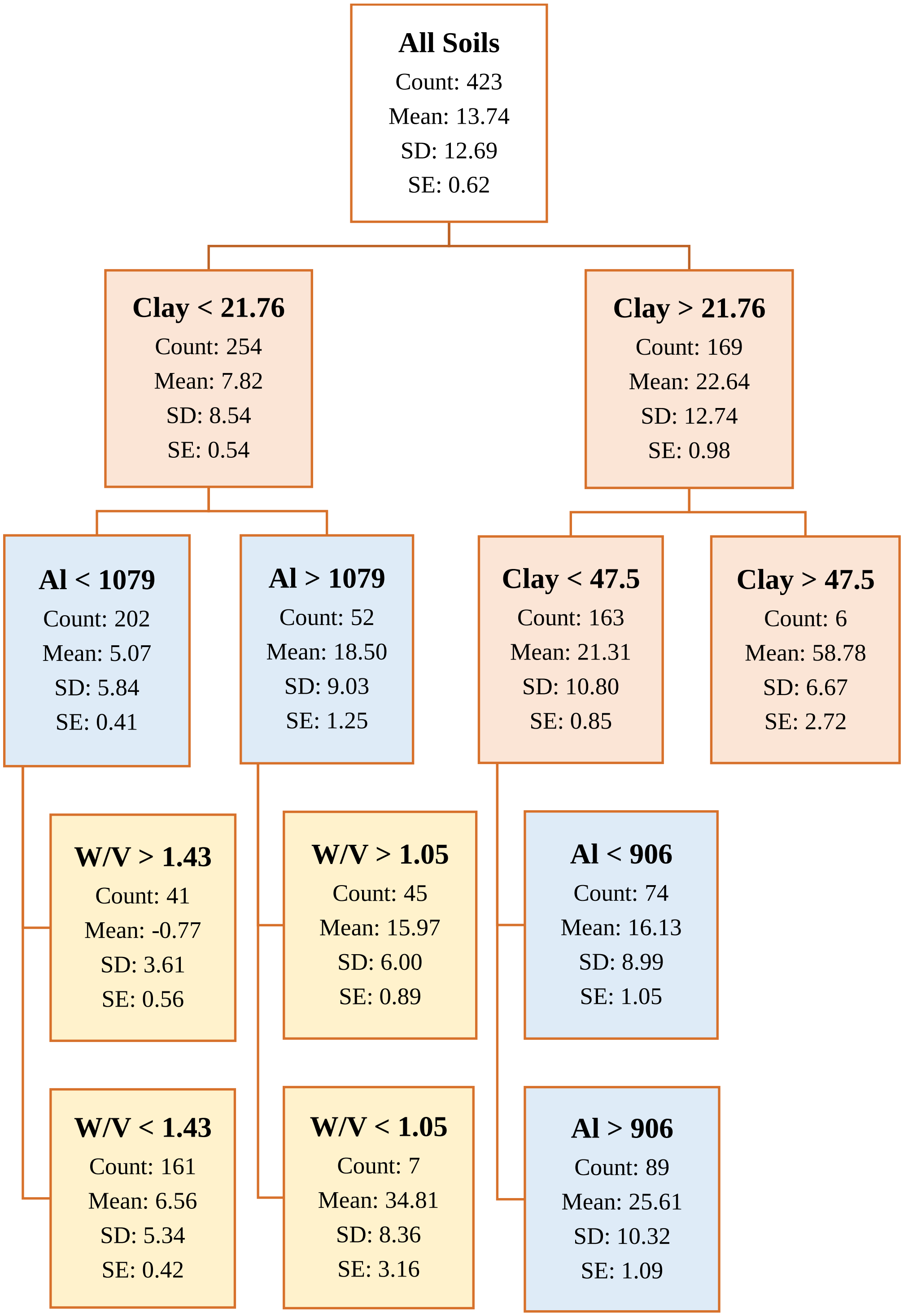


Figure 3.4. Decision tree showing the strongest predictors of P adsorption, including clay as a predictor. (n=423, R^2=0.668).

While clay does play an important role in determination of PBC, it is not measured in routine analysis at the NCDA&CS Soil Testing Laboratory. To provide a good opportunity for adaptation of P fertilizer recommendation systems to include PBC, a model must be developed using soil testing parameters that are already being routinely measured. For this reason, the decision tree analysis was conducted with only NCDA&CS measured soil parameters (Figure 3.5). When clay was not included in the model, Al, W/V, and M3P were the most significant predictors of PBC, with an R^2 of 0.553. These results align with the trends observed through the Pearson Correlation Analysis (Table 3.2). Including additional parameters did not significantly increase the reliability of the model. Aluminum had the most significant influence on PBC, with high values of Al > 899 having increased PBC. This may be in relation to clay content, as Al content is increased with increasing clay content, and the Pearson correlation displayed an increase in PBC with increasing clay content (Cox & Espejo, 1990). Soils with W/V above 1.34 showed decreased PBC, which is again most likely a reflection of soil texture. Soils with higher W/V typically represent an increased sand percentage. The third most significant predictor of PBC is M3P. Soils with lower M3P showed an increase in PBC. As M3P increases, the soil becomes closer to P saturation and P sorption rate decreases as sorption sites are filled. The PBC was separated even further in soils with higher P, by separating Al values above or below 1402 ppm. This indicates that Al has a significant impact on PBC as concentrations continue to increase.

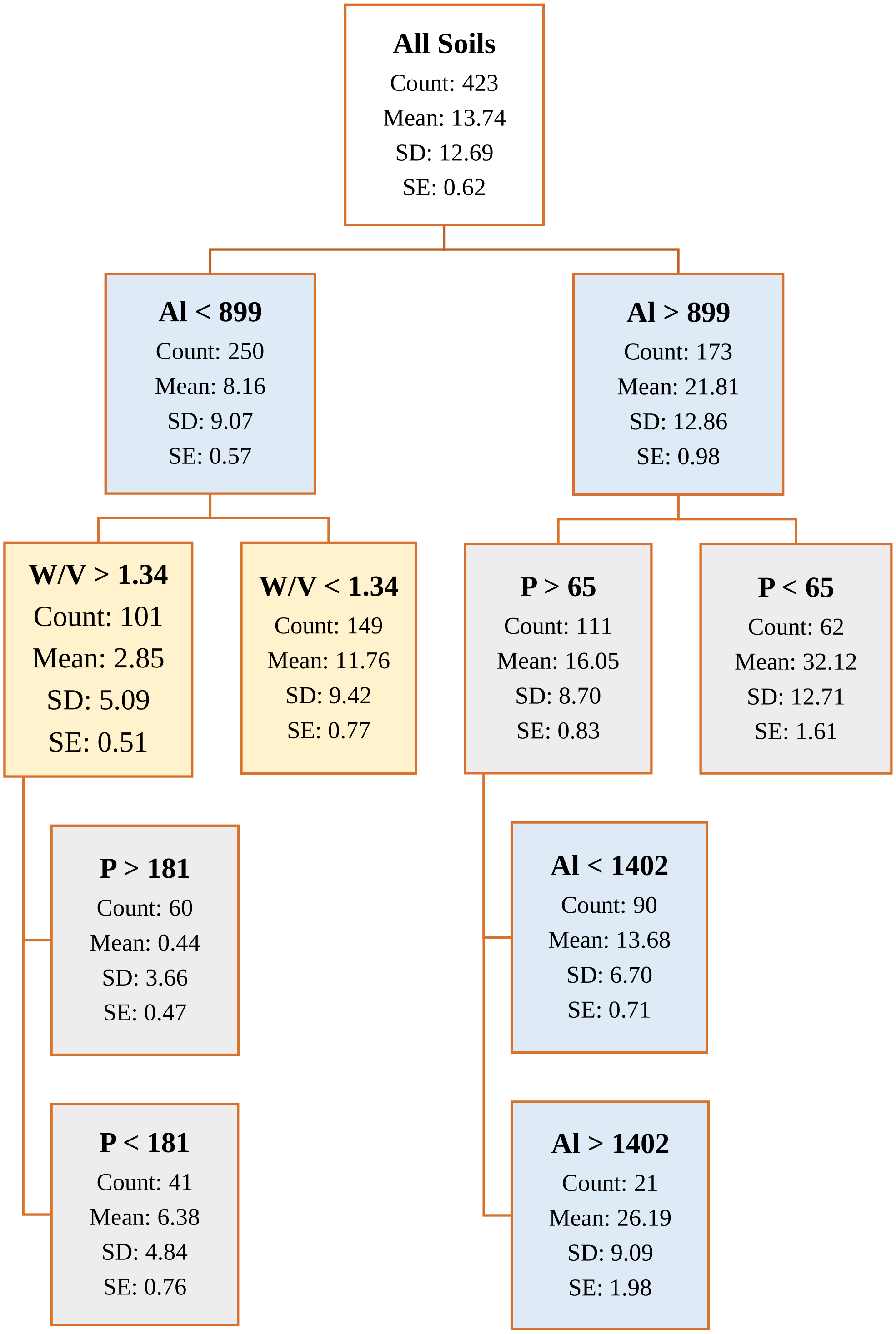


Figure 3.5. Decision tree showing the strongest predictors of P adsorption, excluding clay as a predictor (n=423, R^2=0.553).

Stepwise Multiple Linear Regression for Estimation of Phosphorus Adsorption

Another statistical approach to modeling the PBC is using multiple linear regression models. The multiple linear regression models developed using NCDA&CS soil testing parameters and soil textural analysis were in agreement with the Pearson analysis described above (Equation 6; Table 3.3; Table 3.4). One significant parameter of interest is S. Sulfur is adsorbed to the same adsorption sites as P and is mobile in sandy soils, increasing leaching potential. A soil containing more S represents increased sorption sites and, by extension, increased PBC. However, S is leachable and may not be a good indicator in coastal plain soils. Additionally, S is not considered as a fixed soil characteristic, but instead as an added nutrient, and will be strongly affected by farm management. The model displayed good fit with an R^2 of 0.77, suggesting that this multiple linear regression is useful for estimating PBC using these parameters (Figure 3.5).

$$P\ adsorption\ (\%) = -8.088 - 6.687*W/V - 0.0285*P + 0.0162*Al + 0.191*S + 0.669*Clay$$

(Equation 6)

Table 3.3. Analysis of variance of a multiple linear regression model including NCDA&CS soil test parameters and soil texture.

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**R^2**
Model	5	52645.964	10529.2	286.1815	0.7743
Error	417	15342.270	36.8	**Prob > F**	
C. Total	422	67988.234		<.0001*	

Table 3.4. Parameter estimates using stepwise multiple linear regression including all NCDA&CS soil test parameters and soil texture. Non-significant parameters are not included.

Term	**Estimate**	**Std Error**	**Prob>|t|**
Intercept	-8.089	3.51	0.0217*
W/V	-6.69	2.08	0.0014*
P mg kg^{-1}	-0.03	0.00	<.0001*
AL PPM	0.02	0.00	<.0001*
S mg kg^{-1}	0.19	0.03	<.0001*
Clay %	0.67	0.05	<.0001*

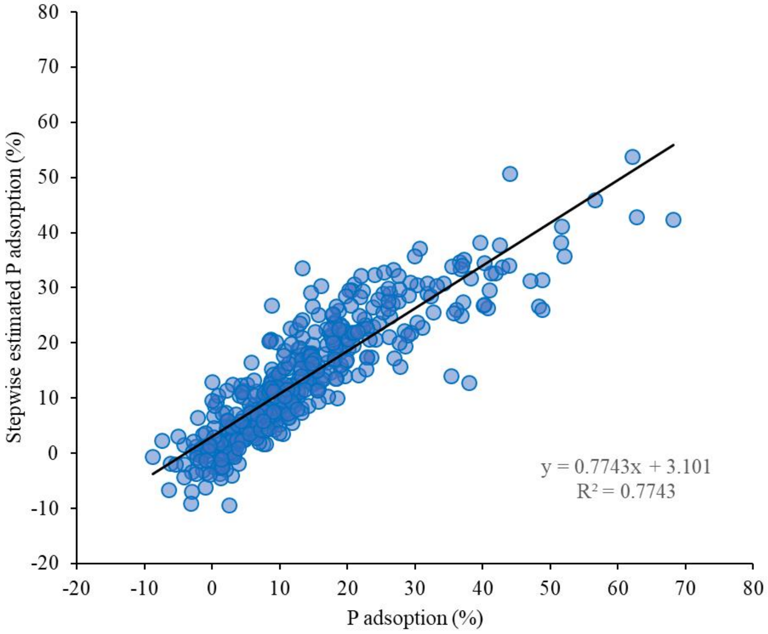


Figure 3.6. Relationship between measured PBC and the PBC estimated by the stepwise multiple linear regression model including texture.

When soil texture was excluded from the model, the R^2 decreased from 0.77 to 0.66, which is still a good model fit and a reliable method for classification of PBC (Equation 7; Figure 3.6). Significant parameters are in agreement with the Pearson analysis detailed above, with W/V, P, Al, and S having the most influence over PBC (Table 3.5; Table 3.6). Including additional parameters did not increase the accuracy of the model.

$$P\ adsorption\ (\%) = 23.100 - 19.304*W/V - 0.0404*P + 0.01395*Al + 0.3247*S \quad \text{(Equation 7)}$$

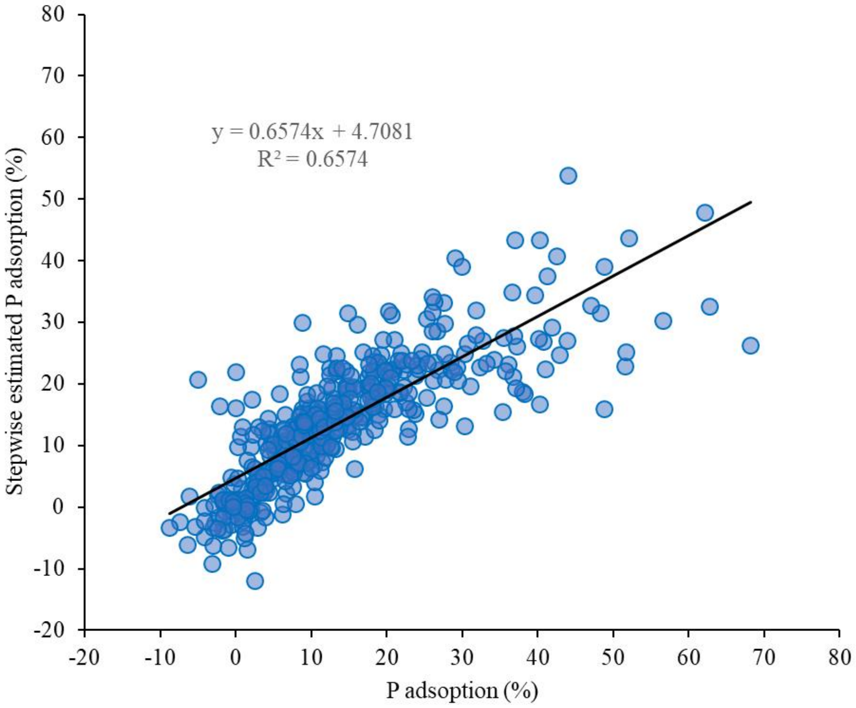


Figure 3.7. Relationship between measured PBC and the PBC estimated by the stepwise multiple linear regression model excluding texture.

Table 3.5. Analysis of variance of a multiple linear regression model including NCDA&CS soil test parameters, excluding soil texture.

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**R^2**
Model	4	44695.142	11173.8	200.52	0.657
Error	418	23293.092	55.7	**Prob > F**	
C. Total	422	67988.234		<.0001*	

Table 3.6. Parameter estimates using stepwise multiple linear regression including all NCDA&CS soil test parameters, excluding soil texture. Non-significant parameters are not included.

Term	Estimate	Std Error	Prob>|t|
Intercept	23.10	3.44	<.0001*
W/V	-19.30	2.33	<.0001*
P mg kg^{-1}	-0.04	0.00	<.0001*
AL PPM	0.01	0.00	<.0001*
S mg kg^{-1}	0.32	0.03	<.0001*

ESTIMATING CLAY CONTENT USING MULTIPLE LINEAR REGRESSION

As clay has a significant impact on PBC, it would be useful to be able to predict clay content without conducting textural analysis. Clay content can be estimated by using equation 8 with an R^2 of 0.57 (Table 3.7; Table 3.8). This model adjusted well to measured clay content (Figure 3.8).

Using *equation 8* to estimate clay and using it in *equation 6* to estimate P adsorption capacity, it was possible to predict the P adsorption with an R^2 of 0.76 (Figure 3.9).

$$Clay\ (\%) = 64.62 + 2.543*HM + 30.8749*W/V + 0.00539*Al - 0.03144*Fe \quad \text{(Equation 8)}$$

Table 3.7. Analysis of variance of a multiple linear regression including all parameters from the NCDA&CS soil test report to estimate soil clay content.

Source	DF	Sum of Squares	Mean Square	F Ratio	R^2
Model	4	16500.643	4125.16	136.69	0.566
Error	418	12614.517	30.18	**Prob > F**	
C. Total	422	29115.160		<.0001*	

Table 3.8. Parameter estimates using stepwise multiple linear regression including all parameters from the NCDA&CS soil test report to estimate soil clay content. Non-significant parameters are not included.

Term	**Estimate**	**Std Error**	**Prob>|t|**
Intercept	64.63	2.50	<.0001*
HM %	-2.54	0.20	<.0001*
W/V	-30.87	1.74	<.0001*
AL PPM	0.01	0.00	<.0001*
FE PPM	-0.03	0.00	<.0001*

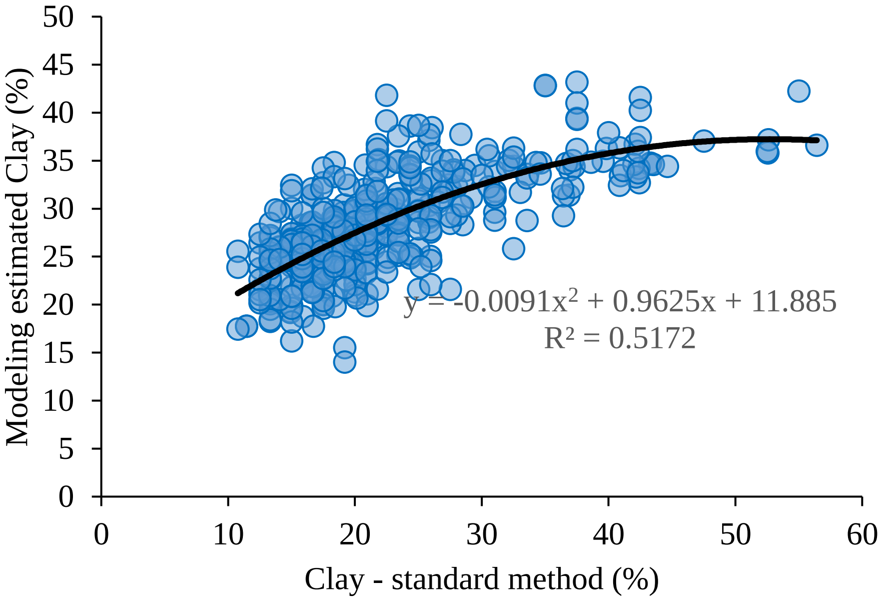


Figure 3.8. Relationship between estimated and measured soil clay content.

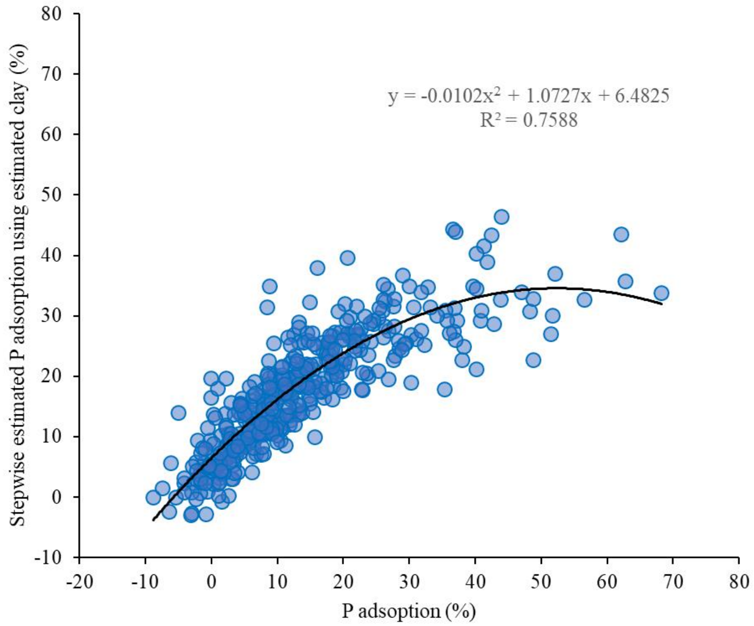


Figure 3.9. Relationship between soil P adsorption and the P adsorption estimated by stepwise multiple linear regression, including soil clay content estimated.

CONCLUSIONS

The P adsorption capacity of soils can be separated by clay in three groups: <21%, 21-47%, and > 47% of clay, for soil with low, medium, and high P sorption capacity. Mehlich 3 aluminum can be used to separate PBC. The equation "*23.100 – 19.304*W/V - 0.0404*P + 0.01395*Al + 0.3247*S*" can be utilized to estimate the P sorption capacity using existing parameters from soil test reports analyzed in North Carolina by NCDA&CS Agronomic Services Laboratory. Additionally, clay may be estimated using soil testing parameters and the result used for modeling PCB, However, it may be more useful to use an estimation of PBC using only parameters aready present in the soil test reports. Using an estimation of clay with the model detailed above, and including this value in the model to estimate PBC provides an opportunity for increased error. The model that directly estimates PBC without clay content would be a better use for incorporating PBC into the P fertilizer recommendation system.

Modelling PBC using soil testing parameters measured in routine NCDA&CS analysis can be a useful tool for incorporating influences of PBC on P availability within the soil. Developing models separated by Coastal Plain and Piedmont regions may improve accuracy of models due to differences in parent material. Additionally, separating soils by organic, mineral-organic, and mineral classes may improve reliability of the model. While we know that PBC affects the rate of required fertilizer, further studies to evaluate incorporation of PBC in fertilizer recommendations are needed.

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