Validation of Soil Test Based Phosphorus and Potassium Fertilizer Recommendations for Soybean in West Tennessee

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Sydney L. Logwood

December 2024

DEDICATION

I'd like to dedicate this work to my family and friends. To my family, thank you for your love, support, and guidance. To my friends, thank you for being my Knoxville family.

I'd also like to give a special dedication to my Meemaw, who has been with me every step of the way. Love you more.

.

ACKNOWLEDGEMENTS

I'd like to start by acknowledging my Advisors, Dr. Nutifafa Adotey and Dr. Lori Duncan. Thank you for the opportunity and the guidance you have provided over the last two years. I'd also like to acknowledge the BESS Department at the University of Tennessee for providing funding and support for my research. A big thank you to the research team at the West TN AgResearch and Education Center for helping to ensure my research went smoothly. Finally, I'd like to acknowledge the TN Soybean Promotion Board for funding this project.

ABSTRACT

Soil tests provide accurate information about nutrient availability. Several soil test extractants, commonly Mehlich 1 (M1) and Mehlich 3 (M3), are used in the Southeastern United States. Differences in soil test reports and fertilizer recommendations arise when laboratories use different extractants, leading to frustration for producers who rely on M3 results from commercial labs but prefer or must use M1 recommendations from Land Grant Universities such as the University of Tennessee. This study's first objective is to evaluate the relationship between M1 and M3 extractants for phosphorus (P) and potassium (K) and to develop conversion equations between the extractants for these nutrients. A total of 520 samples were collected over 11 site years at five locations in West Tennessee. Samples were analyzed for M1P, M3P, M1K, M3K, and pH. Linear regression analysis revealed strong correlations between the extractants for both P and K. Two equations for converting M1P to M3P were developed based on soil pH, which affected the amount of extractable P: for pH < 6, M3P = 2*M1P; for pH ≥ 6, M3P = 1.7*M1P. The equation developed for converting M1K to M3K is M3K = 1.33*M1K + 33.62. Additionally, the study aimed to validate current soil test-based fertility recommendations for soybean in West Tennessee. Changes in soybean varieties, management practices, and demonstrated producer interest have created a need for validation of current recommendations, which have not been updated since 2009. Soybean response trials were conducted at three locations over four site years, with three sites receiving six P and K application rates and one site receiving five rates. The GLIMMIX procedure in SAS version 9.4 was used to analyze yield responses. No significant crop response to P fertilization was observed; however, K fertilization showed a response at two of four site years, with maximum yields at the 140 lb. K2O/A rate.

These results suggest that the University of Tennessee’s P recommendations are adequate, while K recommendations may need to be increased.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 : INTRODUCTION AND LITERATURE REVIEW

Soybean Production in Tennessee

Overview

Soybeans are an important row crop in Tennessee. Nearly 1.65 million acres of soybean (Glycine max (L.) Merr.) are harvested annually in Tennessee, with an average yield of 46 bushels per acre over the last 10 years. Roughly 65 percent of soybean production in Tennessee occurs in West Tennessee (McClure, 2022b). According to the USDA's 2023 State Agriculture Overview, the economic value derived from soybean production in Tennessee was $1 billion from approximately 1.6 million acres with an average yield of 51 bu/A. This made soybean the highest valued crop in Tennessee production, above corn, cotton, and wheat in 2023 (USDA/NASS, 2023).

Higher acreage of soybean production in Tennessee compared to corn and cotton can be partially attributed to the ability of soybean to grow in a wide range of soil conditions and various planting dates (Egli and Cornelius, 2009). In addition, soybean plants are an excellent alternative to other row crops, such as corn and cotton, where soils are less productive or spring planting dates are postponed due to factors outside of producer control (McClure, 2022b). Furthermore, input costs associated with soybean are lower than other row crops, which protects producer profit in lower yielding environments (Smith and Bowling, 2024).

Average soybean yield and harvest data in Tennessee from 1990-2021 is shown in **figure 1.1** (McClure, 2022b). Since the early 2000s, there has been a noticeable increase in average yields due to producers' implementation of technologies such as early maturing varieties, improved

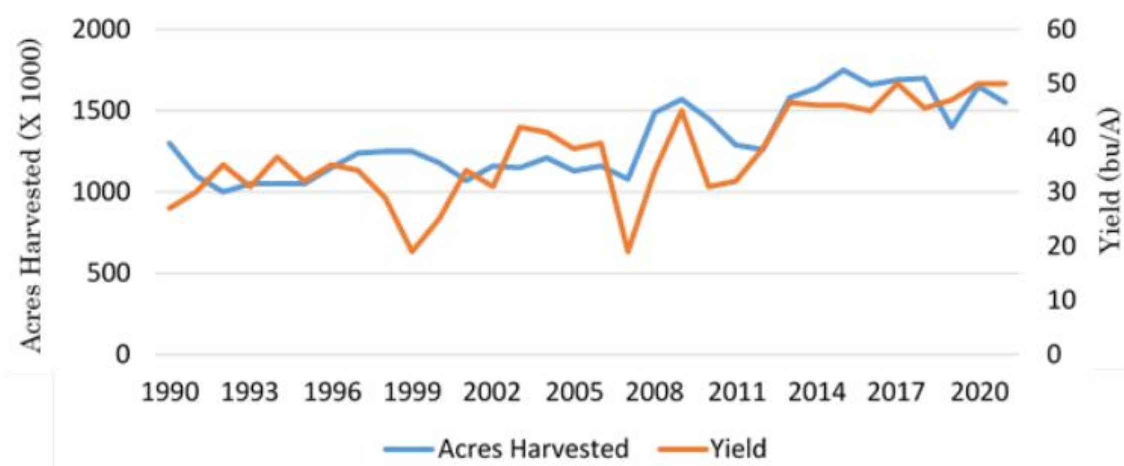

Figure 1.1 Average soybean yield and harvested area in Tennessee from 1990-2021 Source: U.S. Department of Agriculture National Agricultural Statistics Service (McClure, 2022b).

traits for herbicide resistance, and the development of various seed treatments and foliar fungicides that protect seed against diseases and pests (McClure, 2022b).

Soybean Cropping Systems in Tennessee

The majority of soybeans in Tennessee are grown in rotation with a corn crop, and roughly 20% of Tennessee's soybeans are grown as double crop soybeans after a wheat crop (USDA/NASS, 2018). Growing soybeans in crop rotation is a cultural practice that provides several key benefits to agricultural systems. One of crop rotation include soil health benefits, such as reduced soil degradation and improvements in soil fertility and structure. Disruption of pest life cycles and reduced disease buildup of soil borne pathogens that target specific plants helps to control pests and diseases in crop rotations (Bullock, 1992). A final benefit of growing crops in rotation is weed control, due to the ability of some crops to outcompete weeds which reduces the need for herbicides and improves the overall ecosystem of the site (Bullock, 1992; Steckel, 2022).

In Tennessee, planting dates for soybean fall between the months of April and June depending on maturity group (MG), however, the optimal planting date for the commonly used maturity group in Tennessee, MGIV, is late April to mid-May (McClure et al., 2016). In the past, determinate MGV varieties were the predominate variety used in Tennessee soybean production. Since the 2000s, a shift to earlier maturing indeterminate MGIV varieties occurred following success seen with the Early Soybean Production System (EPS). Currently, around 70% of the soybeans planted in Tennessee are the MGIV variety, and the remainder are planted as MGIII or MGV varieties (McClure, 2022a). Most Tennessee producers rely on rainfall for irrigation and to meet target yields. In some instances, in years with low rainfall, soybeans may be irrigated at the early R5 growth stage if soil moisture is not high enough to support developing seeds after pod formation (McClure, 2022b).

Due to the high susceptibility of Tennessee soils to erosion and soil loss (**figure 1.2**), a majority of Tennessee's soybean production has been managed under no-tillage or reduced tillage systems in the past three decades (USDA/NASS, 2018). No-till practices minimize soil disturbances caused by tillage and mechanical cultivation of the land; hence reducing compaction and erosion, improving water infiltration, water retention, and promoting the build-up of soil organic matter as well as biodiversity (USDA/NASS, 2018). These benefits lead to improved nutrient management through reduced nutrient runoff and improved nutrient retention in the soil, thereby minimizing environmental hazards associated with runoff.

A 2018 report from the USDA National Agricultural Statistics Service (NASS) reported Tennessee's no-till usage for major crops to be at the highest level recorded, with 85.1% of producers using no-till practices for soybean production. Conservation tillage practices, or practices that include tillage before planting but maintain a minimum of 30 percent ground cover following planting, made up 12.6% of the state's soybean production in 2018. This leaves only 2.3% of Tennessee's soybean production in conventional tillage practices as of 2018 (USDA, 2018). According to a 2022 report from The Nature Conservancy, Tennessee is the leading state in no-till agricultural systems in the United States (**figure 1.3**), with these systems being employed most heavily in the Western part of the state (**figure 1.4**) (The Nature Conservancy, 2022).

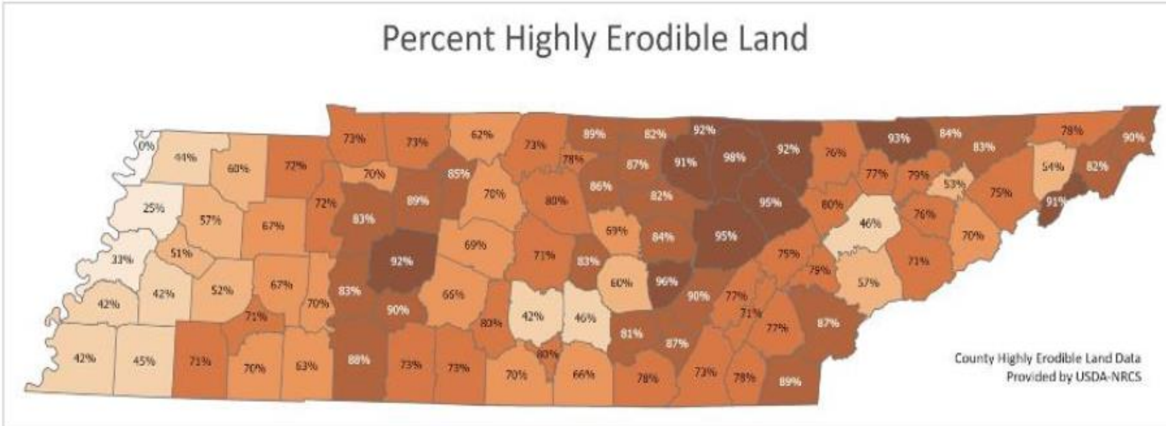

Figure 1.2 Percent highly erodible soils for each county in Tennessee (USDA/NASS, 2018)

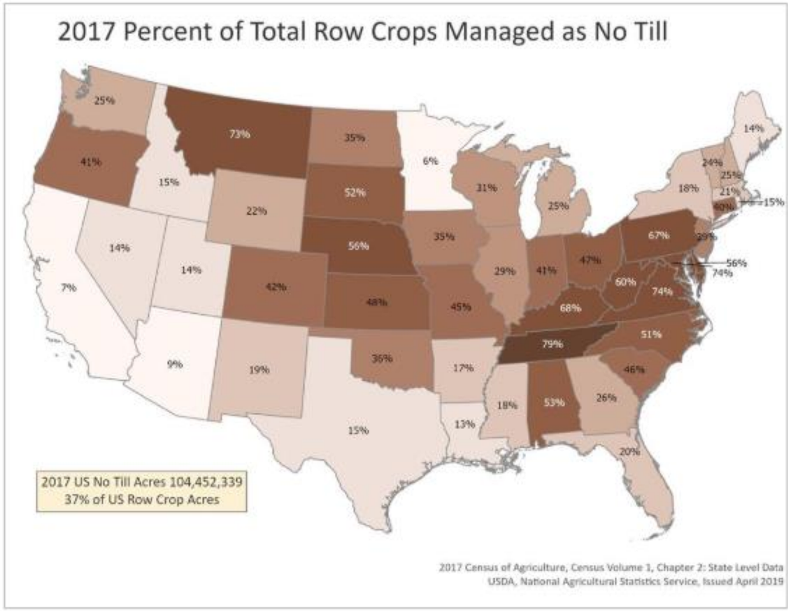

Figure 1.3 Percent of total crops managed in no-till production systems by States in the US. (USDA/NASS, 2018)

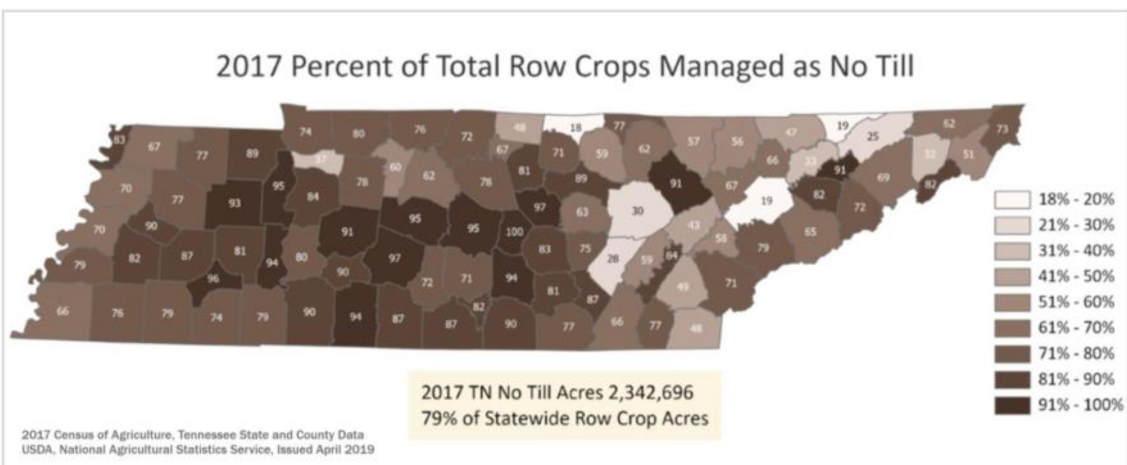

Figure 1.4 Percent of total row crops managed as no-till by county in Tennessee (USDA/NASS, 2018)

Soybean Soil Fertility

In soybean production, soil pH and nutrients are instrumental in obtaining optimal yield. The appropriate means to access the soil pH and nutrient needs of the soybean plant is via a soil test. One reason soil pH is important specifically to soybean productivity is because of the effect pH has on the availability of molybdenum (Mo) (Adotey, 2022). Molybdenum is a cofactor in the nitrogenase and nitrate reductase enzyme which are required for biological nitrogen (N) fixation. Soybean production is best suited to a pH range of 6.2 to 6.8, and Mo can often be deficient due to its low availability in acidic or low pH soil. In soils with a pH of less than 6, liming is prescribed based on soil test results (Adotey, 2022).

Appropriate fertilizer application is imperative to optimal soybean yield, especially for nutrients such as phosphorus (P), potassium (K), and sulfur (S). Using appropriate rates eliminates excessive fertilizer expenses and minimizes nutrient losses to the environment. To ensure appropriate rates are used, soil tests are performed to determine the nutrient status of the soil. Recommendations for fertilizer use are made based on soil test levels, also referred to as rankings or categories. The University of Tennessee uses four rankings: Low, Medium, High, and Very High (Duncan et al., 2015). These rankings correspond with the amount of available nutrient in the soil and report the likelihood of observing yield increases with additional fertilizer application. Crop response in low testing soils is assured, in medium testing soils is possible, in high testing soils is marginal, and in very high testing soils is considered unlikely. Since crop response in high and very high testing soils are considered marginal and unlikely, respectively, fertilizer additions to these soils are not recommended. Current soil test-based P and K recommendations for Tennessee soybean for each soil test ranking are listed in **tables 1.1 and 1.2**, respectively (Duncan et al., 2015).

Table 1.1 University of Tennessee's Soil Test Based P Fertility Recommendations for Soybeans (adapted from Duncan et al., 2015)

Ranking	M1 Soil Test P (lb P A^{-1})values	Application Rate(lb P_2O_5 A^{-1})
Low	0-18	40
Medium	19-30	20
High	31-119	0
Very High	≥ 120	0

Table 1.2 University of Tennessee's Soil Test Based K Fertility Recommendations for Soybeans (adapted from Duncan et al., 2015)

Ranking	M1 Soil Test K (lb K A^{-1}) Values	Application Rate (lb K_2O A^{-1})
Low	0-90	80
Medium	91- 160	40
High	161- 319	0
Very High	≥ 320	0

Nutrients and Fertilizer Products

Phosphorus

Phosphorus is a macronutrient that is needed in large quantities for soybean growth and development. Soybean growth and development is limited in soils that are low in P. In this case, visual deficiencies can occur that require fertilization for prevention or remediation. The amount of P available to plants is a fraction of total soil P.

Phosphorus Forms

Several forms of P are present in the soil environment either as inorganic or organic with varying degrees of availability for plant uptake. The most readily available form of P exists as inorganic P in the soil solution as orthophosphates (Havlin et al., 2020). These orthophosphates are present as dihydrogen phosphate ($H_2PO_4^-$) or hydrogen phosphate (HPO_4^{2}-) (Adotey, 2022). The availability of phosphates for plant uptake from soil solution depends on soil pH, where $H_2PO_4^-$ predominates in acidic soils while HPO_4^{2-} predominates in neutral to alkaline conditions. Phosphates occur in less available forms when they interact with minerals such as aluminum and iron in acidic soils and calcium in neutral to alkaline conditions. These interactions form P minerals which must go through a dissolution process to become plant available. Inorganic phosphates can also exist in various compounds as they are adsorbed to clay and other mineral surfaces, making them unavailable for plant uptake until desorption processes occur. Organic P compounds also exist in the soil in plant and animal residues, which must be processed by microbial communities to become soil organic matter or stable humus which can then be mineralized by microbes to become inorganic soil solution P that is available for plant uptake over time (Havlin et al., 2020).

Phosphorus Functions

Nearly all metabolic processes in soybeans require some form of phosphate, making P deficiency a major limiting factor to plant growth and development. Once taken up by soybeans, P plays a key role in soybean growth and development, especially in early stages of growth. One of the most essential roles of P in plants is energy storage and transfer (Hawkesford et al., 2011). Phosphorus is a constituent of adenosine diphosphate (ADP) and adenosine triphosphate (ATP), which are involved in energy transfer reactions (Raghothama, 2005). The energy produced by photosynthesis and the metabolisms of carbohydrates is stored in phosphate compounds for later use in growth and reproduction. Photosynthesis is another function in which P plays a vital role. Low P in plants leads to lower ATP production and decreased activity of several enzymes involved in the Calvin cycle, which decreases the rate of photosynthesis (Fredeen, et al. 1990). Growth and development of reproductive parts of soybeans, i.e. seeds, is dependent on P as well. Phosphorus is a constituent of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), which are required for protein synthesis. These proteins are responsible for the production of other compounds necessary for soybean structure, yield, and genetic transfer. Root development is also an important function of P in soybeans (Liu, 2021).

Phosphorus Deficiencies

Phosphorus is redistributed from older tissue to developing tissue when supply to the plant is interrupted; as a result, visual deficiency symptoms will occur first in older leaves (Adotey et al. 2021). Spindly plants with stunted growth are a visual indicator plants are P deficient. In some cases, plants will turn a dark or blueish-green color, and in severe cases necrosis of older leaves occurs. Nodulation is also reduced in plants deficient in P, impeding soybeans ability to fix nitrogen (Taliman et al., 2019). **Figure 1.5** depicts P deficient soybeans (Adotey, 2022).

Phosphorus Fertilizers

According to the latest report from the USDA NASS, 76% of Tennessee soybean acreage was fertilized with P fertilizers in 2018 (USDA/NASS, 2019). Synthetic P fertilizers are manufactured primarily from rock phosphate (Havlin et al., 2020). Common P fertilizers are monoammonium phosphate, diammonium phosphate, triple super phosphate, and ammonium polyphosphate (IPNI, 2019).

Monoammonium Phosphate (MAP)

Monoammonium phosphate (MAP) is one of several ammonium phosphate fertilizers available. Monoammonium phosphate is produced by reacting a 1:1 ratio of ammonia with phosphoric acid. A slurry is produced which is then solidified in a granulator. A second method using a cross-pipe reactor and heat from the reaction of ammonia and phosphoric acid evaporates water during the reaction to create a solid product. The production of MAP is favorable because it uses phosphoric acid of lower quality compared to other P fertilizer sources. The most common grade of available MAP is 11-52-0, while P_2O_5 content can range from 48-61% depending on the purity of the phosphoric acid used. Monoammonium phosphate is water soluble and can dissolve rapidly in soils where soil moisture is adequate. When dissolved, MAP releases both NH_4^+ and $H_2PO_4^-$ into the soil. Monoammonium phosphate fertilizers are slightly acidic, thus preventing loss of NH_3 to the air. This fertilizer is commonly applied as concentrated bands on the surface or in soil near developing root tissue. In soybean production under tillage, MAP is commonly spread over the soil surface and incorporated into soil by tilling.

Figure 1.5 Phosphorus deficient soybeans (Nebraska institute of Agriculture and Natural Resources, 2020)

Diammonium Phosphate (DAP)

Diammonium phosphate is another ammonium phosphate fertilizer product. The standard fertilizer grade of DAP is 18-46-0. Diammonium phosphate is created by reacting a 2:1 ratio of ammonia to phosphoric acid and forming a slurry, which is then cooled and sieved. Diammonium phosphate is highly soluble which enables it to dissolve quickly and deliver NH_4^+ and $H_2PO_4^-$ to plants rapidly. When DAP granules dissolve, alkaline conditions are created around the granule. This presents conditions favorable to volatilization of ammonia which can be harmful to seedlings and plant roots. Care should be taken not to apply DAP too closely to germinating seeds for this reason. The alkaline conditions created by dissolving DAP granules is temporary, as N from DAP will be converted to nitrate by soil bacteria which will reduce soil pH.

Triple Super Phosphate (TSP)

In the 20th century, triple super phosphate was one of the first widely used high analysis P fertilizers for agricultural production. Standard grade TSP has a fertilizer analysis of 0-45-0. Since the introduction of other P sources, use of TSP has declined due to higher P amounts found in ammonium phosphates as well as their lower cost of production. Triple super phosphate is produced in granular as well as nongranular forms. Nongranular TSP is made when finely ground rock phosphate is reacted with liquid phosphoric acid. Granular TSP is made in a similar fashion, but the resulting mixture is then used to coat small particles in several layers to build TSP granules to a specific size. The reaction of rock phosphate with liquid phosphoric acid is slow, so the resulting products are cured for several weeks to allow for complete reaction. Phosphate rock properties will determine the chemistry and process of these reactions. Rapid availability of P from this TSP makes it a popular source, as 90% of the total P is soluble. Triple super phosphate also contains 15% calcium, which provides additional plant nutrition.

Ammonium Polyphosphate (APP)

Ammonium polyphosphate (APP) is a liquid fertilizer source that contains 10-15% N and 34-37% P_2O_5. Roughly 75% of P is polyphosphates and 25% is present as orthophosphates. The orthophosphate component of APP is immediately available for plant uptake, while the polyphosphate components are required to be broken down or hydrolyzed by enzymes from microbes into the orthophosphate form (IPNI, 2019). Some of this breakdown occurs without the presence of microbial enzymes. Temperature, moisture, soil carbon (C), pH, and conditions increasing root growth and microbial activity will also increase phosphatase activity and polyphosphate hydrolysis (Havlin et al., 2020). About half of the polyphosphate compounds in APP will be broken down in 1-2 weeks. Ammonium polyphosphate is commonly mixed with other fertilizers, such as urea ammonium nitrate (UAN), to maximize nutrient application.

Potassium

Potassium is another nutrient imperative to soybean growth and development which is required in large quantities. Potassium exists in soils in the ion form, in soil solution or bound to soil minerals. Like P, K is important for the growth and development of soybean and can also be a major limiting factor in production. Fertilization with synthetic fertilizers is often employed to prevent yield losses in K deficient soils.

Potassium Forms

Potassium exists in soils in several forms, including exchangeable K, nonexchangeable K, fixed or mineral K, and soluble K in soil solution (Havlin et al, 2020). Soybeans take up soluble K from solution as the K+ ion. Soluble soil K is available for immediate plant uptake and is the most plant available form of K in the soil. Exchangeable K is found loosely bound to exchange sites of soil colloids where it is easily accessed by roots and becomes plant available. Nonexchangeable K is more tightly bound to soil particles, especially in clay minerals and other mineral or structural K forms, such as feldspar, a type of soil mineral high in K (Havlin et al., 2020). This form of potassium is not immediately available to plants but may become plant-available over time through weathering and the breakdown of soil minerals

Potassium Functions

Potassium does not exist as a component of biological compounds in plants, but rather exists in plants in solution (such as cytoplasm) or bound to the tissue surface by negative charges. Because of this, $K+$ functions are dependent on solution ionic strength within plant cells. One of the primary functions of K in soybeans is regulating stomatal functions, which is important in controlling water loss and optimizing photosynthesis. Potassium is also needed for improved enzyme activation. Enzyme activation is imperative to the transfer of energy and the metabolism of carbohydrates, both of which play a substantial role in plant growth and vigor.

Potassium Deficiencies

Potassium deficiencies in soybean are diagnosed when tissue K concentration is less than 1.5% at flowering (Adotey, 2022). Symptoms will appear first in older leaves, as K is mobile and will be transported to new growth in deficient conditions. Visual K deficiencies appear as yellowing of the leaf along the leaf margin that will eventually turn into browning as the veins of the leaves remain green, also called interveinal chlorosis. Eventually, interveinal chlorosis will develop into necrosis, which occurs when the leaf becomes brown and dies. **Figure 1.6** shows an example of soybeans deficient in K (Adotey, 2022).

Figure 1.6 Potassium deficient soybeans (Nebraska institute of Agriculture and Natural Resources, 2020)

Potassium Fertilizers

Fertilization of Tennessee soybeans with K fertilizers was reported by the USDA NASS in 2018 for 72% of soybean acreage (USDA/NASS, 2019). Common sources of K fertilizers include muriate of potash or potassium chloride, potassium magnesium sulfate, potassium nitrate, and potassium sulfate.

Muriate of Potash

Muriate of potash (MOP) is also commonly referred to as KCl. The fertilizer source is a 1:1 ratio of K and chlorine (Cl) and is a great source of Cl for plants as well. Muriate of potash has a fertilizer analysis of 0-0-60, and is produced from a mixed mineral called sylvinite, which is a combination of sylvite (KCl) and halite (NaCl). Sylvinite can be mined and processed by crushing to remove the salts from the KCl or dissolved from underground deposits in hot water where the brine is pumped to the surface and KCl is harvested. Dissolving this fertilizer will increase soluble salt concentrations in the soil, so care should be taken when applying near germinating seeds. Muriate of potash has one of the highest K contents of all K fertilizers and is relatively inexpensive, making it a popular K fertilizer source.

Potassium Magnesium Sulfate

Also referred to by its mineral name, langbeinite, potassium magnesium sulfate is a K fertilizer source that also supplies plants with magnesium (Mg) and sulfur (S). The fertilizer analysis for this source is 0-0-22. It is produced by mining langbeinite, a mineral salt found in few locations of the world formed by the evaporation of ancient ocean beds. All commercial langbeinite is sourced from Carlsbad, New Mexico. Potassium magnesium sulfate has a neutral pH, so it does not contribute to soil acidity or alkalinity unlike some other fertilizer sources.

While this source is completely soluble in water, it dissolves slower than other sources because it is denser and thus is not suitable for application through irrigation practices.

Potassium Nitrate

Also referred to as nitrate of potash (NOP) or potassium nitrate (KNO_3) is typically produced by reacting KCl with a nitrate source. Sources of nitrate for NOP production may be sodium nitrate, nitric acid, or ammonium nitrate. This K fertilizer source is also a good source of N for crops which benefit from nitrate additions, but not suitable for all plant types. Because of this, NOP is a less popular form of K, but still important. It is high in K content, with a N:K ratio of roughly 1:3. Fertilizer analysis of NOP is 13-0-45.

Potassium Sulfate

Potassium sulfate was traditionally made by reacting KCl with sulfuric acid until it was discovered that many naturally occurring minerals in the Earth's surface could be manipulated to produce potassium sulfate (K_2SO_4). Minerals such as kainite and schoenite are K-containing minerals that can be mined and rinsed with solutions of water and salt to produce K_2SO_4. The fertilizer analysis of K_2SO_4 is 0-0-50. An advantage of using this source over others is that it also supplies sulfate to crops in addition to K. It is also an advantageous K source on sites where application of chloride (Cl-) should be limited. A disadvantage of this source is that it is not nearly as soluble as KCl. Foliar applications of K_2SO_4 can be used for later season K and S applications, but caution should be taken to ensure the concentration is not so high that leaf damaged may be induced. When needed in high demand, K_2SO_4 application should be split into multiple doses to avoid surplus K accumulation.

Soil Testing

Soil testing is defined by the Soil Science Society of America as a chemical, physical, or biological procedure that estimates the suitability of the soil to support plant growth (SSSA, 2024). Soil testing is the best available technology for predicting crop nutrient needs prior to a growing season when remedial action, or appropriate fertilizer application, can be taken (Olson et al., 1982).

Soil testing has been widely used and accepted since the 1940s as the key tool in determining agricultural lime and fertilizer recommendations for producers (Zhang et al., 2021). Soil tests are performed by state universities as well as commercial soil testing laboratories (Olson et al., 1982). These laboratories use different soil testing methods and/or philosophies for recommending fertilizer rates, which often result in different fertilizer recommendations, even for the same soil (Southern Cooperative Series, 2014). It is important to note that soil testing does not directly measure the total amount of nutrient in the soil, but rather reports a nutrient index relative to field calibration (Mylavarapu et al., 2002).

Importance of soil testing in crop production

The importance of soil testing can be summarized as 3Ps: Productivity (identify nutrient variability within a field and implement proper management of plant nutrition), profitability (increasing or maintaining yields at the economic optimum rate of nutrients) and protection (prevents over application which promotes environmental protection and quality) (Olson et al., 1982; Southern Cooperative Series, 2014).

Productivity

Variations in soil nutrient availability are often observed across agricultural fields. The uneven distribution of nutrients in a field is caused by several factors including soil parent material, climate conditions, field topography, soil type, past land use, and historical farming practices (Gao et al., 2019). Variation in soil nutrients without proper nutrient management is a detriment to field productivity and thus crop yield (Singh et al., 2021).

Soil testing identifies the variability in soil nutrients across a field, allowing proper implementation of nutrient management. A study from Singh et al. (2021) demonstrated the benefits of determining nutrient variability through soil testing and application of a soil test crop response-based fertilizer application rate when compared to generally recommended application rate. In all trials, the soil test crop response-based fertilizer application rate out-yielded the generally recommended application rate by 20.2% to 32.3% (Singh et al., 2021).

Profitability

Mineral fertilizer application is a large cost associated with agricultural production. In the past several decades, fertilizer prices have increased and are predicted to continue to rise (Brunelle et al., 2015). Fertilizer costs are volatile and change rapidly with the supply of raw materials, such as oil, natural gas, and phosphate rock, for fertilizer production as well as changes in global trade of fertilizer resources (Kenkel, 2017). This coupled with the increased demand for agricultural products experienced with a growing world population has led to an increase in the consumption and price of fertilizers (Arovuori and Karikallio, 2009). This creates a need for appropriate, soil test-based fertilizer recommendations to maximize profitability.

Soil testing is crucial to the profitability of production systems, as it prevents over or underuse of valuable fertilizer resources. Both over and under fertilization result in a loss of profit for producers (Hergert et al., 2015). When over fertilization occurs, nutrients are lost to the environment through several pathways, such as runoff and leaching. When fertilizer nutrients are lost, so is the producer’s dollar spent on that fertilizer. When under fertilization occurs, yield potential is limited and grain quality can be reduced, impacting the crop's profitability. By determining the appropriate amount of fertilizer needed to ensure yield, grain quality, and prevent environmental losses, soil testing increases profitability for producers.

Based on interpretation of soil test results, an appropriate fertilizer rate is recommended for growers by a laboratory or land grant university. Rates are typically developed based on one of three points: (i) the point where the maximum returns per acre from a crop are expected, (ii) the point at which cost of the last increase in fertilizer increments is equal to the resulting yield increase, (iii) or at a lower point in which yield return may be several times higher than the cost of fertilizer inputs (Peck and Soltanpour, 1990). The most cost-effective option is iii, which in many cases is not the option that produces the highest yield but should lead to the highest profitability.

Protection

Earlier soil tests determined deficiencies of a nutrient in a soil while today's tests have been developed to inform end users where nutrients are deficient, adequate, or excessive. The determination of not only deficiency, but also excessive amounts and toxicity of nutrients has become important with an increase in emphasis placed on environmental protection and quality (Peck and Soltanpour, 1990). When nutrients are excessively available or applied, agricultural fields can become a non-point source of pollution due to fertilizer runoff (Sims, 1993). The most common issue associated with runoff is eutrophication resulting in the pollution of surface water from excessive use of P in agricultural systems (Sims, 1993). A survey performed in 1993 reports that the northeastern, north-central, mid-Atlantic, and Southeastern regional soil testing committees state that 84% of the states reported 40% or more of their commercial soils as high or excessive in P (Sims, 1993). This can be attributed to long-term fertilization and application of manures. These soils have potential to lose P and cause environmental harm in the form of P pollution and eutrophication in surrounding watersheds. In addition to being the key information upon which fertilizer recommendations are based as well as providing information to help producers to make environmentally conscious decisions when it comes to fertilizer application, soil testing can also be a tool in economic decision making (Peck and Soltanpour, 1990).

Developing Soil Test Based Fertilizer Recommendations

The process of developing fertilization recommendations from accurate soil testing procedures includes three steps: (1) determining the relationship between plant nutrient uptake and the amount of nutrient extracted by a particular soil test method (correlation), (2) determining the crop nutrient requirement at different soil test values (calibration), and (3) developing nutrient application recommendations from soil test concentration, and other soil crop, economic, and environmental and climatic information (interpretations) (Drescher et al., 2021; Southern Cooperative Series, 2014; SSSA, 2024).

Correlation

The first step in developing an accurate soil test is correlation. Soil test correlation is defined as the process of determining the relationship between plant nutrient uptake or yield and the amount of nutrient extracted by a particular soil test method (Southern Cooperative Series, 2014). Hence, the process of correlation begins with identifying the appropriate soil test extractant that is best suited to a particular plant and soil type in a given area (Corey, 1987).
A soil test/chemical extractant estimates the soil's nutrient-supplying capacity for a particular crop/plant during that growing season. A chemical extractant, as its name suggests, is a solution of various chemicals that removes some amount of plant available nutrient from the soil. The extractant does not measure the actual supply of plant available nutrients, but rather an index of

nutrient availability in a given soil. There are several chemical extractants used by soil testing laboratories in the US including Mehlich 1 and 3, Bray I, DTPA, Lancaster, etc. (Mylavarapu et al., 2002; Heckman et al., 2006; Southern Cooperative Series, 2014; Zhang et al., 2021). Some of these extractants were developed to provide an availability index for a specific nutrient or multiple nutrients. The two extractants widely used by university and private soil testing laboratories that operate within the Southeast region of the US are Mehlich 1 and 3 (Southern Cooperative Series, 2014; Slaton et al., 2024). Mehlich 1 is considered the first universal extractant developed, which was suitable for acidic and low soil organic matter soils (Mylavarapu et al., 2002). Mehlich 3 was developed in 1984 to overcome some of the limitations of Mehlich 1 (Holford, 1980). Mehlich 3 was developed for a wide range of soil pH, cation exchange capacity, and base cation saturation. Several university laboratories use Mehlich 3 soil test based on correlations with previous soil test methods. A list of the states of the Southeastern region and their corresponding soil test extraction methods used by public soil testing laboratories is shown in **table 1.3** and represented as a map in **figure 1.7**. The University of Tennessee began using Mehlich 1 extraction method in December of 1981 (Savoy, 2009).

To identify the appropriate extractant, laboratory or field experiments are carried out by testing the extractants of interest in several soils or locations to identify which extractant has a stronger relationship with nutrient uptake (Corey, 1987). A good extractant is one that is well related to nutrient uptake. In **figure 1.8**, extractant 2 was highly related to plant nutrient uptake. Extractant 1, however, is not as strongly correlated, because there is considerable variation in plant uptake with extractable nutrients. After a soil test extractant has been selected because of its high correlation with nutrient uptake, the next step in the correlation process is to identify the critical soil test value (CSTV), or the maximum soil test value below which crops are expected to show a

Table 1.3 States in the Southeastern US and their corresponding soil test extraction methods.

State	Extraction Method
Alabama (AL)	Mehlich 1 (and Lancaster for STK only)
Arkansas (AR)	Mehlich 3
Florida (FL)	Mehlich 1
Georgia (GA)	Mehlich 1
Kentucky (KY)	Mehlich 3
Louisiana (LA)	Mehlich 3
Mississippi (MS)	Lancaster
North Carolina (NC)	Mehlich 3
Oklahoma (OK)	Mehlich 3
South Carolina (SC)	Mehlich 1
Tennessee (TN)	Mehlich 1
Texas (TX)	Mehlich 3
Virginia (VA)	Mehlich 1

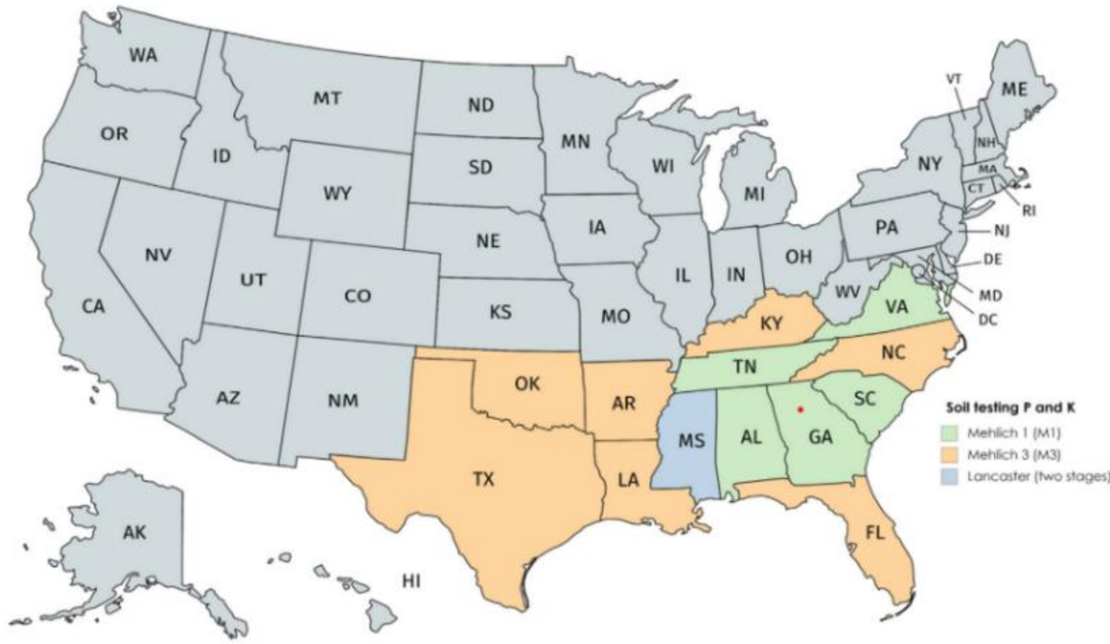

Figure 1.7 Map of soil test extraction reagents used by 13 Southeastern states adapted from Zhang et al., 2021.

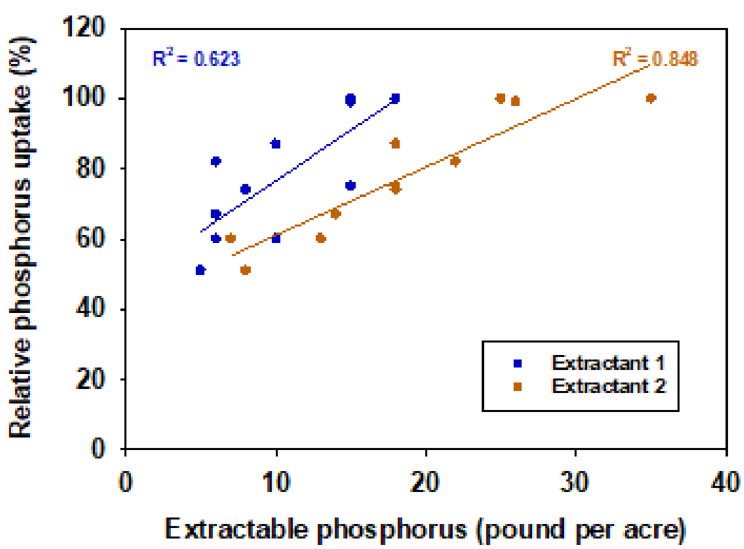

Figure 1.8 Relationship between relative phosphorus uptake and extractable phosphorus for two extractants (Unpublished data, UT).

yield response to fertilizer application (Slaton et al., 2024). This is achieved by evaluating the relationship between the amount of soil test nutrient extracted by the selected extractant and relative yield.

Relative yield is often used to standardize yield across several sites to minimize differences due to temporal and environmental factors. Correlation experiments require a minimum of two treatments, a control that has sufficient amount of all nutrients except the nutrient of interest and a treatment with sufficient amount of all nutrients including the nutrient of interest (Pearce et al., 2022). Critical soil test values can be influenced by a number of factors including crop, soil, extractant, and model used to evaluate the relationship between relative yield and soil test nutrient (Dodd and Mallarino, 2005). Soil test correlation uses models to evaluate the relationship between crop yield and soil test nutrient (Corey, 1987). Some of the commonly used models are Cate Nelson, arcsine-log calibration curve, exponential, linear plateau, and quadratic plateau (Slaton et al., 2024). Based on the CSTV, the response curve can be partitioned into several categories or groups, which are often referred to as levels, indexes, or rankings. Commonly used rankings include low (L), medium (M), high (H), and very high (VH) rankings or indices (**figure 1.9**). Some soil testing laboratories have fewer or more categories. The low, medium, high and very high rankings on the graph indicate that crop response is assured, possible, marginal, and unlikely, respectively, with fertilizer additions.

Calibration

The next step in developing a soil test is calibration. Soil test calibration is defined as the process of determining the crop nutrient requirement at different soil test values (Mylavarapu et al., 2002). So, while correlation determines the relationship between the soil test nutrient and

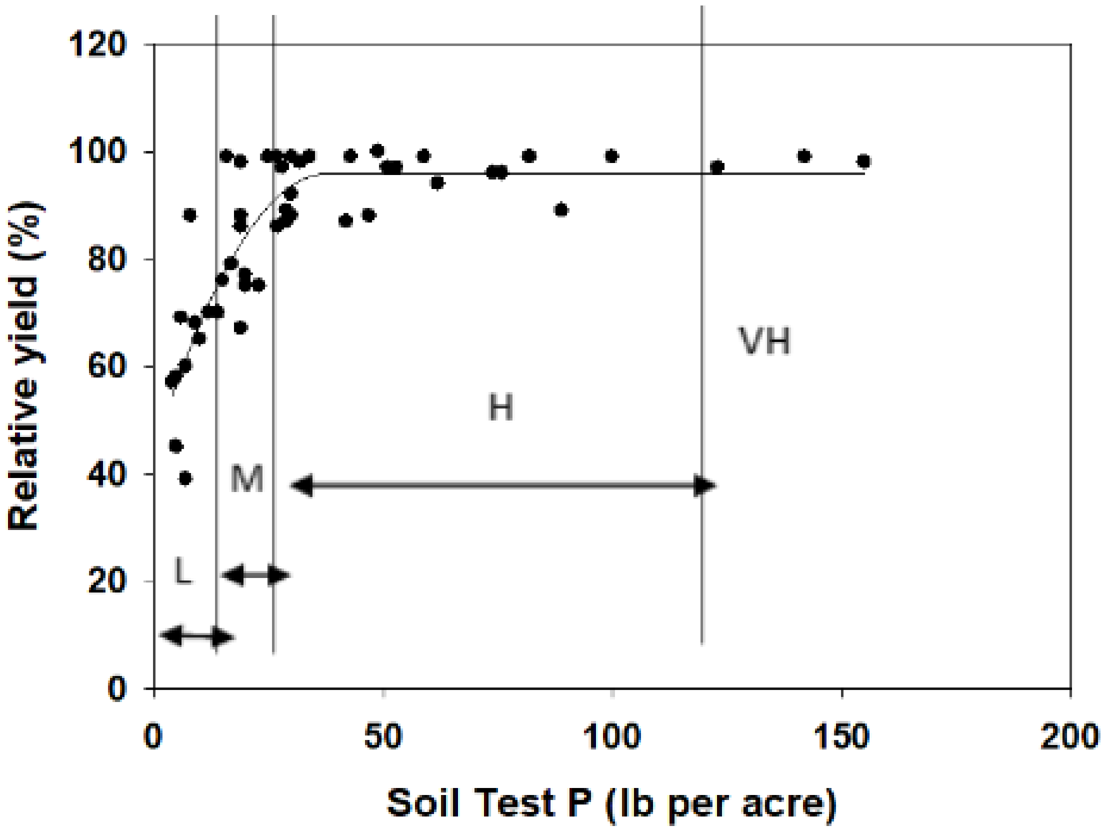

Figure 1.9 Crop response curve between relative yield and soil test P showing different soil test rankings.

nutrient uptake or relative yield, calibration focuses on the relationship between relative yield and fertilizer application rates. The primary goal of calibration is to generate a yield response to establish the appropriate nutrient fertilizer rate to obtain optimum yield. This step involves conducting field trials at sites with different soil test rankings to ascertain the nutrient requirement for the optimum crop yield at each ranking. The soils should range from low to very high testing soils to capture a representative distribution over the full range of yield response. Multiple fertilizer treatments consisting of increasing application rates of the nutrient of interest are evaluated in field experiments at several locations (Evans, 2015). Similar to correlation, models are used to estimate the appropriate nutrient application rate based on the relationship between relative yield and nutrient application rates. Two commonly used models are linear and quadratic plateau (Slaton et al., 2024). For example, In **figure 1.10**, three experiments were conducted on a low soil test P soil and the yield was maximized after 35 lb of P_2O_5/A.

Interpretation

Interpretation is the process of developing nutrient application recommendations from soil test concentration, and other soil, crop, economic, environmental, and climatic information (Southern Cooperative Series, 2014). There are several concepts of soil test interpretations or fertilizer recommendation philosophies, however three common fertilizer recommendation philosophies include (i) sufficiency, (ii) build and maintain, and (iii) basic cation saturation ratio (Olson et al., 1987; Hergert et al., 2015; Zhang et al., 2021). The sufficiency concept is often adopted and used by university or public soil testing laboratories. Among the three concepts, sufficiency is a more conservative approach with recommendations intended to meet crop needs and often referred to as 'feed the crop' (Zhang et al., 2021). This concept recommends the

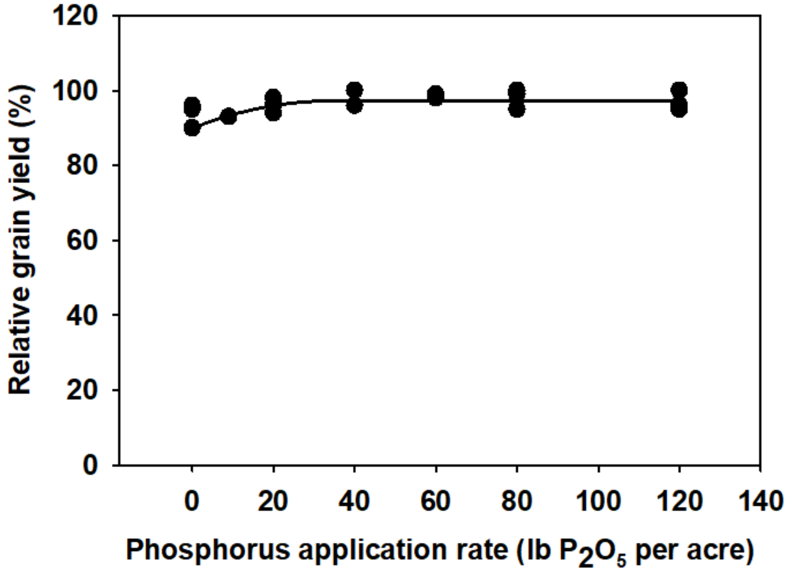

Figure 1.10 Response curve showing the relationship between relative grain yield and phosphorus application on three low-test P fields.

amount of nutrient that will contribute to the crop nutrient requirement during the growing season. The sufficiency philosophy tends to have defined rankings ranging from very low to very high, which often dictates if and how much of the fertilizer should be applied to complement the nutrients in the soil (Olson et al., 1987). The low test rankings receive the most amount and the high/very high requiring no fertilizer. In **figure 1.11**, the shaded rectangle represents the total crop nutrient requirement during the growing season, with the brown and green areas indicating the plant available nutrients in the soil and the amount of supplemental nutrients from fertilizer, respectively.

The build and maintain concept for prescribing fertility recommendations is a more liberal approach to recommending fertilizer applications. This concept is also referred to as the "feed the soil" approach. This approach recommends higher rates of fertilizer application than the sufficiency approach and is commonly used by commercial soil testing laboratories (Hergert et al., 2015). The fertilizer rates recommended based on this concept are not only intended to supply sufficient nutrient amounts to a crop in a given season, but also to rapidly build soil test levels and replace the nutrients removed from the soil by the crop at harvest (Olson et al., 1987). Fertilizer application is recommended for all soil test levels, including high and very high soil test levels. No yield improvements are seen with this method when compared to the sufficiency season, with the brown and green areas indicating the plant available nutrients in the soil and the amount of supplemental nutrients from fertilizer, respectively.

The build and maintain concept for prescribing fertility recommendations is a more liberal approach to recommending fertilizer applications. This concept is also referred to as the "feed the soil" approach. This approach recommends higher rates of fertilizer application than

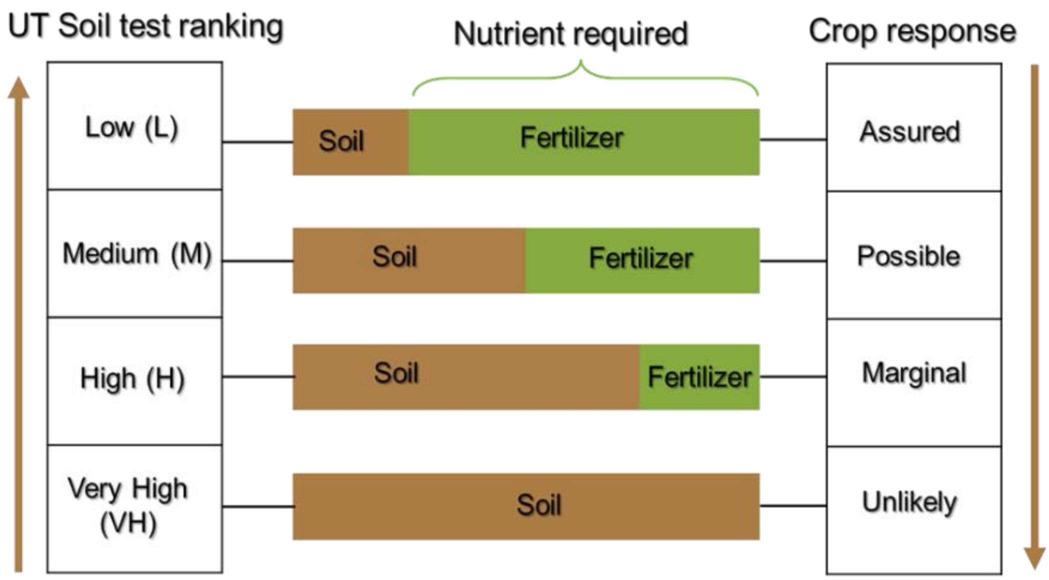

Figure 1.11 Diagram illustration of the sufficiency concept of fertilizer recommendations.

the sufficiency approach and is commonly used by commercial soil testing laboratories (Hergert et al., 2015). The fertilizer rates recommended based on this concept are not only intended to supply sufficient nutrient amounts to a crop in a given season, but also to rapidly build soil test levels and replace the nutrients removed from the soil by the crop at harvest (Olson et al., 1987). Fertilizer application is recommended for all soil test levels, including high and very high soil test levels. No yield improvements are seen with this method when compared to the sufficiency approach, while input costs for producers are increased. Additionally, arguments have been made that if this approach were to truly build and maintain soil nutrient levels, then this concept would recommend application of all 13 soil derived nutrients removed by plant uptake (Olson et al., 1987). The approach only recommends additions of 3 macro nutrients in plant production: N, P, and K.

The basic cation saturation ratio (BCSR) approach is based on the concept of an “ideal” soil distribution of exchangeable cations. The widespread use of the BCSR concept is credited to a soil scientist named William Albrecht from the University of Missouri. Albrecht promoted the belief that maintaining a basic cation saturation concentration of 65% Ca, 10% Mg, and 5% K was the best way to achieve maximum yield (Kopittke and Menzies, 2007). Recommended fertilizer applications using the BCSR concept aim to balance the CEC of a soil to maintain optimal basic cation concentrations. The BCSR concept is widely used, especially in organic farming practices. While this concept is still adopted by producers today, there is little evidence that there are any benefits seen from the BCSR approach to soil fertility as compared to the sufficiency approach (Culman et al., 2021; Kopittke and Menzies, 2007; McLean et al., 1983).

Justification/ Objectives

Today, there are several types of chemical soil test extractants available for use in the United States. The two most commonly used extractants in the Southeastern region of the United States are Mehlich 1 and Mehlich 3 (Southern Cooperative Series, 2014; Slaton et al., 2024). The University of Tennessee has used the Mehlich 1 soil test extractant since 1981, while most commercial laboratories have converted to the Mehlich 3 soil test extractant following its release (Savoy, 2009). These differences cause confusion for producers when attempting to use land grant university soil test based fertilizer P and K recommendations from the University of Tennessee, but have received soil test results from private laboratories using Mehlich 3. Several states facing the same issue have developed correlation equations to compare Mehlich 1 and Mehlich 3 extractable P and K values (Sikora, 2005). The University of Tennessee currently recommends the use of an equation developed in Kentucky for the conversion of Mehlich 3 to Mehlich 1 values to remedy the issue, but no equation has been developed specifically for the various soil regions of Tennessee. Since the overall focus of this study is soybean crops, which are primarily grown in West TN, the question arises: What is the relationship between Mehlich 1 and Mehlich 3 as P and K soil test extractants in West Tennessee soils? The objectives of the second chapter of this thesis will be to (i) evaluate the relationship between Mehlich 1 soil test P and K and Mehlich 3 soil test P and K and (ii) develop a conversion equation for Mehlich 1 and Mehlich 3 P and K values for West TN soils.

Though they have been evaluated since their establishment, current University of Tennessee soil test based fertilizer recommendations for soybean in TN have not been updated since 2009 (Savoy and Joines, 2009).). Recent P and K verification work has been done for small grain/soybean rotation (Singh et al. 2019). Rates for small grain/soybean rotations differ from rates recommended for soybean grown not in rotation (Savoy and Joines, 2009; Duncan et al., 2015) Improvements in soybean genetics and precision agriculture technology have led to improved nutrient uptake efficiency and yield increases in Tennessee soybeans (McClure, 2022a). Variances in P and K fertilizer recommendations for soybean occur due to differences in recommendation philosophies between the University of Tennessee and commercial laboratories. The University of Tennessee uses the sufficiency philosophy to recommend fertilizer application rates, while most commercial labs will use the build and maintain philosophy to recommend higher application rates (Hergert et al., 2015). The increased yields and nutrient uptake efficiency coupled with higher commercial laboratory recommendations has led to growing concern from producers that university P and K recommendations for soybeans are too conservative. Results from an unpublished survey have indicated producer interest in a validation trial for current University P and K recommendation rates for soybeans (Unpublished survey, UT). This leads us to the question: Are current fertility recommendations for P and K in soybeans accurate**?** The objective of the third chapter of this thesis will be to validate the accuracy of current P and K fertilizer recommendations for soybean in Tennessee.

References

Adotey N., A.M. McClure, T.B. Raper, & R. Florence. (2021). Visual Symptoms: A Handy Tool in Identifying Nutrient Deficiency in Corn, Cotton and Soybean. Extension Publication, W976.

Adotey, N. (2022). Soil Fertility and Nutrient Management in Soybean. UT Extension Publication PB 1912-E. https://utcrops.com/wp-content/uploads/2022/11/Chapter-5-final-PB_1912-E_Soybean_Handbook.pdf

Arovuori, A., & Karikallio, H. (2009). Consumption patterns and competition in the world fertilizer markets. In *19th Symposium of the International Food and Agribusiness Management Association, Budapest, Hungary* (pp. 20-21).

Brunelle, T., Dumas, P., Souty, F., Dorin, B., & Nadaud, F. (2015). Evaluating the impact of rising fertilizer prices on crop yields. *Agricultural Economics (United Kingdom)*, *46*(5), 653–666. https://doi.org/10.1111/agec.12161

Bullock, D. G. (1992). Crop rotation. *Critical Reviews in Plant Sciences*, 11(4), 309-326.

Corey, R.B. 1987. Soil Test Procedures: Correlation. (21): 15–22.

Culman, S. W., Brock, C., Doohan, D., Jackson-Smith, D., Herms, C., Chaganti, V. N., ... & Spargo, J. (2021). Base cation saturation ratios vs. sufficiency level of nutrients: A false dichotomy in practice. *Agronomy Journal*, *113*(6), 5623-5634.

Dodd, J.R., and A.P. Mallarino. 2005. Soil-Test Phosphorus and Crop Grain Yield Responses to Long-Term Phosphorus Fertilization for Corn-Soybean Rotations. Soil Sci. Soc. Am. J. 69(4): 1118–1128. doi: 10.2136/sssaj2004.0279.

Drescher, G.L., N.A. Slaton, T.L. Roberts, and A.D. Smartt. 2021. Corn yield response to phosphorus and potassium fertilization in Arkansas. Crop. Forage Turfgrass Manag. 7(2): 1–17. doi: 10.1002/cft2.20120.

Duncan, L., H. Savoy, and D. Joines. 2015. "UT Fertility Recommendations for Tennessee Row Crops." UT Extension, SP 763. https://extension.tennessee.edu/ publications/Documents/SP763.pdf

Egli, D.B., & P.L. Cornelius. (2009). A regional analysis of the response of soybean yield to planting date. Agron. J. 101(2): 330–335. doi: 10.2134/agronj2008.0148.

Evans, C.E. 2015. Soil Test Calibration. Soil Test. Sampling, Correl. Calibration, Interpret. (21): 23–29. doi: 10.2136/sssaspecpub21.c3.

Fredeen, A. L., Raab, T. K., Rao, I. M., & Terry, N. (1990). Effects of phosphorus nutrition on photosynthesis in Glycine max (L.) Merr. *Planta*, *181*, 399-405.

Gao, X. S., Yi, X. I. A. O., Deng, L. J., Li, Q. Q., Wang, C. Q., Bing, L. I., ... & Min, Z. E. N. G. (2019). Spatial variability of soil total nitrogen, phosphorus and potassium in Renshou County of Sichuan Basin, China. *Journal of integrative agriculture*, *18*(2), 279-289.

Havlin, J.L., Tisdale, S.L, Nelson, W.L., and Beaton, J.D. (2020) Soil Fertility and Fertilizers: An introduction to nutrient management (8th ed.). Pearson.

Hawkesford, M., W. Horst, T. Kichey, H. Lambers, & J. Schjoerring. (2011). Functions of Macronutrients. Elsevier Ltd.

Heckman, J.R., W. Jokela, T. Morris, D.B. Beegle, J.T. Sims, et al. (2006). Soil test calibration for predicting corn response to phosphorus in the northeast USA. Agron. J. 98(2): 280–288. doi: 10.2134/agronj2005-0122.

Hergert, G. W., Pan, W. L., Huggins, D. R., Grove, J. H., & Peck, T. R. (2015). Adequacy of current fertilizer recommendations for site-specific management. In *The State of Site-Specific Management for Agriculture* (pp. 283–300). wiley. https://doi.org/10.2134/1997.stateofsitespecific.c13

Holford, I. 1980. Effects of phosphate buffer capacity on critical levels and relationships between soil tests and labile phosphate in wheat growing soils. Soil Res. 18(4): 405. doi: 10.1071/sr9800405.

International Plant Nutrition Institute. (2019). Nutrient Source Specifics. International Fertilizer Institute. http://www.ipni.net/specifics-en. Accessed 9/2/2024

Interpretations: Sufficiency vs. Build-up and Maintenance! (21): 41–52.

Kenkel, P. (2017). *Causes of Fertilizer Price Volatility*. Accessed 08 July 2024 http://osufacts.okstate.edu

Kopittke, P. M., & Menzies, N. W. (2007). A review of the use of the basic cation saturation ratio and the “ideal” soil. *Soil Science Society of America Journal*, *71*(2), 259-265.

Liu, D. (2021). Root developmental responses to phosphorus nutrition. J. Integr. Plant Biol. 63(6): 1065–1090. doi: 10.1111/jipb.13090.

McClure, A., M. Salmerón, D. Verbree, & L.C. Purcell. (2016). Soybean Yield Response.

McClure, A. Introduction to Tennessee Soybean. 2022a. UT Extension Publication, PB 1912-A. https://utcrops.com/wp-content/uploads/2022/11/PB_1912-A_Soybean_Handbook_Ch1_WEB.pdf

McClure, A. Soybean production in Tennessee. 2022b. UT Extension Publication, PB 1912-D. https://utcrops.com/wp-content/uploads/2022/11/PB_1912-D_Soybean_Handbook_Ch4_PROOF_1.pdf

McLean, E. O., Hartwig, R. C., Eckert, D. J., & Triplett, G. B. (1983). Basic cation saturation ratios as a basis for fertilizing and liming agronomic crops. II. field studies 1. *Agronomy Journal*, *75*(4), 635-639.

Mylavarapu, R. S., Sanchez, J. F., Nguyen, J. H., & Bartos, J. M. (2002). Evaluation of Mehlich-1 and Mehlich-3 extraction procedures for plant nutrients in acid mineral soils of Florida*. *Communications in Soil Science and Plant Analysis*, *33*(5-6), 807-820. https://doi.org/10.1081/CSS-120003067

Olson, R. A., Frank, K. D., Grabouski, P. H., & Rehm, G. W. (1982). Economic and Agronomic Impacts of Varied Philosophies of Soil Testing 1 . *Agronomy Journal*, *74*(3), 492–499. https://doi.org/10.2134/agronj1982.00021962007400030022x

Olson, R. A., Anderson, F. N., Frank, K. D., Grabouski, P. H., Rehm, G. W., & Shapiro, C. A. (1987). Soil testing interpretations: Sufficiency vs. build-up and maintenance. *Soil testing: Sampling, correlation, calibration, and interpretation*, *21*, 41-52.

Pearce, A.W., N.A. Slaton, S.E. Lyons, C.H. Bolster, T.W. Bruulsema, et al. (2022). Defining relative yield for soil test correlation and calibration trials in the fertilizer recommendation support tool. Soil Sci. Soc. Am. J. (March): 1338–1353. doi: 10.1002/saj2.20450.

Raghothama, K. G. (2005). Phosphorus and plant nutrition: an overview. *Phosphorus: Agriculture and the environment*, *46*, 353-378.

Savoy, H. (2009). Interpreting Mehlich 1 and 3 soil test extractant results for P and K in Tennessee. *University of Tennessee, Institute of Agriculture*.

Savoy, H., & Joines, D. (2009). *Lime and fertilizer recommendations for the various crops of Tennessee. Chapter II. Agronomic crops*.

Sikora, F. J., Mylavarapu, R. S., Hardy, D. H., Tucker, M. R., & Franklin, R. E. (2005). *Conversion equations for soil test extractants: Mechlich-1 and Mechlich-3. Southern Regional Fact Sheet*. SERA-IEG-6* 5.

Sims, J. T. (1993). Environmental soil testing for phosphorus. *Journal of Production Agriculture*, *6*(4), 501-507.

Singh, V. K., Gautam, P., Nanda, G., Dhaliwal, S. S., Pramanick, B., Meena, S. S., ... & Hossain, A. (2021). Soil test based fertilizer application improves productivity, profitability and nutrient use efficiency of rice (Oryza sativa L.) under direct seeded condition. *Agronomy*, *11*(9), 1756.

Singh, S., Savoy, H. J., Yin, X., Schneider, L., & Jagadamma, S. (2019). Phosphorus and potassium fertilizer rate verification for a corn–wheat–soybean rotation system in Tennessee. *Agronomy Journal*, *111*(4), 2060-2068.

Slaton, N., A. Pearce, L. Gatiboni, D. Osmond, C. Bolster, et al. (2024). Models and sufficiency interpretation for estimating critical soil test values for the Fertilizer Recommendation Support Tool. Soil Sci. Soc. Am. J. (October 2023): 1–19. doi: 10.1002/saj2.20704.

Smith A., and B. G. Bowling. 2024. Field Crop Budget for 2024. UT Extension Publication, D33. https://utia.tennessee.edu/publications/wp-content/uploads/sites/269/2024/01/D33.pdf

Southern Cooperative Series. 2014. Soil Test Methods From the Southeastern United States. (Southern Cooperative Series Bulletin 419). Georgia Agricultural Experiment Station. https://aesl.ces.uga.edu/Sera6/PUB/Methodsmanualfinalsera6.Pdf

SSSA, 2024 *Glossary of Soil Science Terms* Retrieved 24 June, 2024 from https://www.soils.org/publications/soils-glossary/#

Steckel, L. Weed Management in Soybean. 2022 UT Extension Publication, PB 1912-I. https://utcrops.com/wp-content/uploads/2023/01/PB_1912-I_Soybean_Handbook_Ch9_Final.pdf

Nebraska institute of Agriculture and Natural Resources. (2020, August 31). *Symptom identification key for nutrient deficiencies in soybeans*. CropWatch. https://cropwatch.unl.edu/soils/soybean-nutrients

Taliman, N. A., Dong, Q., Echigo, K., Raboy, V., & Saneoka, H. (2019). Effect of phosphorus fertilization on the growth, photosynthesis, nitrogen fixation, mineral accumulation, seed yield, and seed quality of a soybean low-phytate line. *Plants*, *8*(5), 119.

The Nature Conservancy. (2022). Farming for the Future. Cover Crops: Trends & Next Steps for Tennessee https://www.nrcs.usda.gov/sites/default/files/2022-11/Cover%20Crop%20Trends%20and%20Next%20Steps%20in%20Tenessee.pdf. Accessed 13 June 2024.

USDA/NASS. (2023). *2023 State Agriculture Overview for Tennessee*, www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=TENNESSEE. Accessed 14 June 2024.

USDA/NASS. (2019) *Fertilizer Use and Prices,* https://www.ers.usda.gov/data-products/fertilizer-use-and-price/. Accessed 27 July 2024.

USDA/NASS. (2018). *2018 Tennessee Tillage Systems*, www.nass.usda.gov/Statistics_by_State/Tennessee/Publications/Special_Surveys/tillage2018.pdf. Accessed 14 June 2024.

Zhang, H., Antonangelo, J., Grove, J., Osmond, D., Slaton, N. A., Alford, S., Florence, R., Huluka, G., Hardy, D. H., Lessl, J., Maguire, R., Mylavarapu, R., Oldham, J. L., Pena-Yewtukhiw, E. M., Provin, T., Sonon, L., Sotomayor, D., & Wang, J. (2021). Variation in soil-test-based phosphorus and potassium rate recommendations across the southern USA. Soil Science Society of America Journal, 85(4), 975–988. https://doi.org/10.1002/saj2.20280

CHAPTER 2 : EVALUATION OF THE RELATIONSHIP BETWEEN MEHLICH 1 SOIL TEST PHOSPHORUS AND POTASSIUM AND MEHLICH 3 SOIL TEST PHOSPHORUS AND POTASSIUM

Abstract

Several different soil test extractants are used in the Southeastern United States. Differences in the extractant used to generate soil test results can cause differences in interpretation and fertilizer recommendations (Southern Cooperative Series, 2014). Two commonly used soil test methods are Mehlich 1 (M1) and Mehlich 3 (M3). The University of Tennessee, Tennessee's 1862 Land Grant University, adopted the M1 soil test extractant in 1981. The M3 soil test extractant was considered an improvement on the M1 formula developed in 1984, but due to low correlation with nutrient uptake in some soils and the difficulties associated with calibrating a new soil test extractant many Land Grant Universities such as UT did not adopt M3 (Savoy, 2009). Most commercial laboratories in Tennessee, however, have adopted the M3 soil test extractant. This can cause difficulties for Tennessee farmers when they have soil test results from a M3 soil test extractant, but prefer to or are required to use Land Grant University fertilizer recommendations based on M1 calibration. To aid farmers in interpreting M3 results for M1 calibrated fertilizer recommendations, a conversion equation can be developed by correlating the two extractants. The objectives of the study were to evaluate the relationship between M1 extractable phosphorus (M1P) and potassium (M1K) and Mehlich 3 extractable phosphorus (M3P) and potassium (M3K) and to develop a conversion equation between the extractants. To create a correlation between M1 and M3, a total of 520 samples were collected from 11 site years at 5 location across West Tennessee between 2022 and 2023. Soils were analyzed for pH, M1P, M3P, M1K, and M3K. Differences in the amount of extractable P were observed in soils with pH < 6 and pH ≥ 6, thus P samples were split into two groups. Strong correlations between the extractant were observed for P in soils pH < 6 (R=0.92), P in soils pH ≥ 6 (R=0.93), and K (0.87). Two equations with a simple conversion coefficient were developed for converting M1P

to M3P depending on soil pH. In soils with $pH < 6$ the equation $M3P = 2*M1P$ can be used to convert between M1P and M3P values. In soils with $pH \geq 6$ the equation $M3P = 1.7*M1P$ can be used. To convert M1K to M3K, the equation developed in this study is $M3K = 1.33*M1K + 33.62$.

Introduction

Soil testing is defined by the American Society of Agronomy as a chemical, physical, or biological procedure that estimates the suitability of a soil to support plant growth (SSSA, 2024). In more specific terms in the context of agronomy, it is the rapid chemical analysis of soils that assesses plant available nutrient status along with other soil properties such as salinity and elemental toxicity (Peck and Soltanpour, 1990). Soil testing provides the most accurate information available from which to base fertilizer and liming recommendations on the farm or field level. Creating accurate recommendations offers environmental, economic, and agronomic benefits (Hergert et al., 2015; Peck and Soltanpour, 1990; Singh et al., 2021) by limiting the amount of excess nutrients in soil that could be lost to the environment, limiting excessive spending on fertilizer from which a crop response would not be observed, and ensuring soils have adequate amounts of each nutrient to support optimal crop yields.

The generation of a soil test and subsequent fertilizer recommendations can be summed up into three main steps: correlation, calibration, and interpretation (Southern Cooperative Series, 2014; SSSA, 2024). Correlation is the process by which the relationship between plant nutrient uptake or yield and the amount of nutrient extracted by a particular soil test method or extractant is determined (Southern Cooperative Series, 2014). Correlation is followed by calibration, or the step in which crop nutrient requirement is determined at different soil test levels (Mylavarapu, 2002). Finally, the data from correlation and calibration steps are interpreted by soil testing labs using various soil testing philosophies to generate fertilizer recommendations (Drescher et al., 2021).

In the Southeastern US, several soil test extractants are used in the soil test correlation process, the most common of which are Mehlich 1 (M1) and Mehlich 3 (M3). Developed by Dr. Adolf Mehlich in 1953 for the extraction of bioavailable phosphorus (P), potassium (K), calcium, and magnesium from soils, Mehlich 1 is considered the first universal soil extraction for its ability to simultaneously extract several plant available nutrients and is best suited to acidic soils with cation exchange capacities less than 10 cmolc kg-1 (Southern Cooperative Series, 2014; Mylavarapu et al., 2002). Mehlich 1 is also referred to as the double dilute acid method, as it is composed of 0.05 M HCl and 0.0125 M H_2SO_4. Limitations observed in M1 for the extraction of P in diverse soils across North Carolina including calcareous soils, and soils containing phosphate rock led to the development of M3, an improvement on the formula for M1 (Southern Cooperative Series, 2014). Mehlich 3 is composed of 0.2 M acetic acid, 0.25 M ammonium nitrate, 0.015 M ammonium fluoride, 0.013 M nitric acid, and 0.001 M EDTA. It is suitable to acidic and neutral soil conditions as well as calcareous soils, overcoming limitations of M1 due to the pH buffering potential of the acetic acid. In addition to overcoming the limitations observed with M1, the M3 formula is able to extract greater soil P than M1. The addition of the fluoride component allows M3 to remove additional soil P that has been bound to Al or Fe (Southern Cooperative Series, 2014).

Several states within the Southeastern US region have switched to the M3 soil test extraction (Zhang et al., 2021). The process requires multiple time-consuming studies with a very large number of samples from numerous locations across the state. For this reason, it is not practical for all states to convert to the use of M3 for soil testing. Most commercial laboratories use the M3 soil test extractant, which can cause issues for producers when they prefer (or are required) to use Land Grant University fertilizer (LGU) recommendations that use M1 extractant. Hence, receiving soil test results in M3 values but trying to use M1 calibrated recommendations can cause frustration and confusion. For this purpose, the development of a conversion equation of M3 values to M1 values and vice versa is required. States may switch to M3 by evaluating the relationship between M1 and M3 and then generating a conversion equation (Sikora, 2005).

The need for evaluation of M1 and M3 and their ability to extract P and K in TN soils has arisen over the past several decades. The increase in the practice of no-till agriculture in TN has led to an increase in soil organic matter (Arshad et al., 1990), which can increase buffering capacity in soils. Mehlich 1 is not suitable for use in well buffered soils, so the use of M3 may be more representative. Additionally, soil pH has been of greater concern to TN producers over the last several decades as well. Liming practices have received more attention so that soil pH has increased to more neutral conditions, for which M3 is better suited to than M1.

There is an existing equation for similar soils in Kentucky that is currently used to convert M3 to M1 values in Tennessee (Sikora, 2005; Duncan et al., 2015), but there are some differences in soils between the states (**figure 2.1**), as well as management practices such as no-till between the states (The Nature Conservancy, 2022). The most recent conversion research between M1 and M3 in Tennessee was conducted between 1996 -1998 (Essington, 2000). Since then P and K fertilizer recommendations have been updated and there has been an increase in the adoption of practices such as cover crops in Tennessee. According to a 2022 report from The Nature Conservancy, the cover crop acreage in Tennessee increased by 85% between 2012 and 2017 (The Nature Conservancy, 2022).

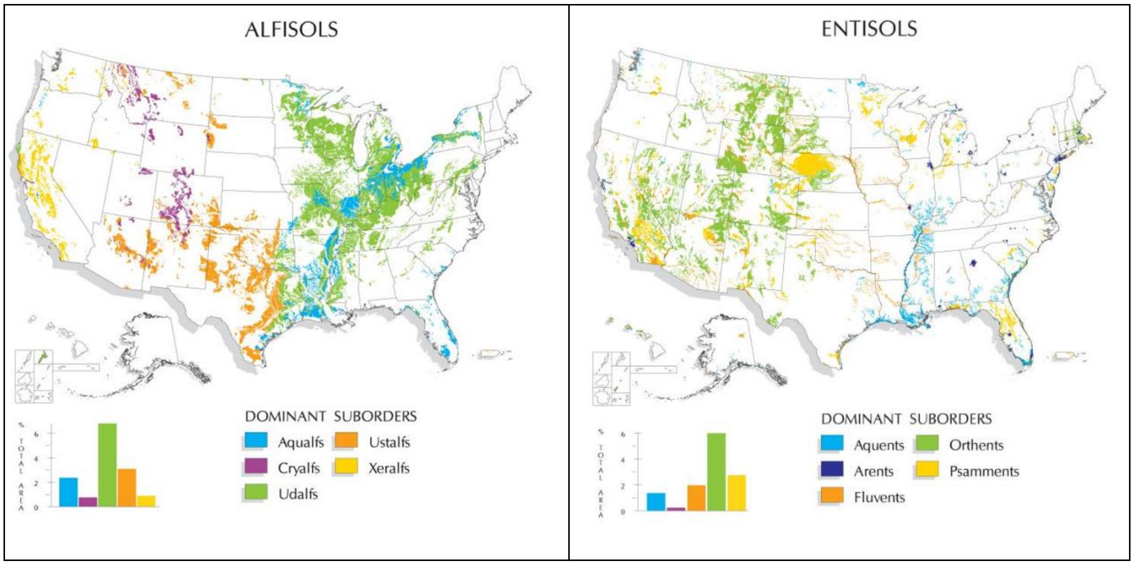

Figure 2.1 Soil maps showing differences between Kentucky and Tennessee soils (Retrieved from NRCS n.d.

Some studies have reported that cover crops can influence the availability of soil nutrients (Blanco-Canqui et al., 2015; Soltangheisi et al., 2020). The differences in soils and management practices between Tennessee and Kentucky creates the need for a Tennessee specific equation. The objectives of this study are to (i) evaluate the relationship between Mehlich 1 soil test P and K and Mehlich 3 soil test P and K and (ii) develop a conversion equation for Mehlich 1 and Mehlich 3 P and K values for West TN soils.

Materials and Methods

Experimental sites

This study was carried out at 5 locations across west Tennessee in 2022 and 2023. Data from a total of 11 site years was used to develop M1 and M3 relationships. **Figure 2.2** shows these locations include the University of Tennessee's West Tennessee AgResearch and Education Center (WTREC) in Jackson, Tennessee, The University of Tennessee's AgResearch and Education Center at Milan (RECM) in Milan, Tennessee, Ames AgResearch and Education Center (AAPREC) in Grand Junction, Tennessee, and A producer field (CC) in Jackson, Tennessee. Most of the sites were managed in a no-till corn-soybean rotation (**table 2.1**). The sites selected had soils with low (0-30 lb. P/A; 0-90 lb. K/A) or medium (31-60 lb. P/A; 91-160 lb. K/A) soil test P or K, where a response to fertilizer P or K was likely. These sites were chosen in order to be able to calibrate soil test extractable nutrients for Mehlich 1 and Mehlich 3 with crop response data in later studies. Site descriptions, including assigned site reference letter, year, trial number, location information, and soil information for each site can be found in **table 2.2**. All trials were arranged as a randomized complete block design with 6 rates of P and K with four replications except the trial at site E, which had 5 rates of P and K (n = [(10*12*4) + (1*10*4)]. Plots were 10 ft by 30 ft planted with 4 rows of crop. Soybean rows were planted with

Figure 2.2 Location of the trial sites in West Tennessee

Table 2.1 General site information and corresponding reference letters

Site ID	Year	Trial Number	Tillage	Cropping system	Previous crop
A	2022	WTREC- 03	No-till	Corn-Soybean	Soybean
B	2022	WTREC-04	No-till	Corn-Soybean	Corn
C	2022	RECM- 05	No-till	Corn-Soybean	Corn
D	2022	RECM- 06	No-till	Corn-Soybean	Corn
E	2023	WTREC-01	No-till	Corn-Soybean	Soybean
F	2023	WTREC- 03	No-till	Corn-Soybean	Soybean
G	2023	WTREC-04	No-till	Corn-Soybean	Soybean
H	2023	RECM- 05	No-till	Corn-Soybean	Soybean
I	2023	RECM- 06	No-till	Corn-Soybean	Soybean
J	2023	AAPREC- 01			
K	2023	CC- 01	No-till	Corn-Soybean	Soybean

Table 2.2 General site information and corresponding reference letters

Site ID	Year	Trial number	Location	GPS coordinates	Soil Series
A	2022	WTREC- 03	Jackson, TN	35.620452, -88.84278	Collins silt loam
B	2022	WTREC-04	Jackson, TN	35.624064, -88.84212	Collins silt loam
C	2022	RECM- 05	Milan, TN	35.925520, -88.716061	Grenada silt loam
D	2022	RECM- 06	Milan, TN	35.923884, -88.711535	Grenada silt loam
E	2023	WTREC-01	Jackson, TN	35.630687, -88.852044	Lexington silt loam
F	2023	WTREC- 03	Jackson, TN	35.620452, -88.84279	Collins silt loam
G	2023	WTREC-04	Jackson, TN	35.624064, -88.84213	Collins silt loam
H	2023	RECM- 05	Milan, TN	35.925520, -88.716062	Grenada silt loam
I	2023	RECM- 06	Milan, TN	35.923884, -88.711536	Grenada silt loam
J	2023	AAPREC- 01	Grand Junction, TN	35.085774, -89.235785	Grenada silt loam
K	2023	CC- 01	Jackson, TN	35.676254, -88.720031	Feliciana silt loam

Taxonomy classes: *Collins silt loam* is Coarse-silty, mixed, active, acid, thermic Aquic Udifluvents; *Grenada silt loam* is Fine-silty, mixed, active, thermic Oxyaquic Fraglossudalfs; *Lexington silt loam* - Fine-silty, mixed, active, thermic Ultic Hapludalfs; *Feliciana silt loam* - Fine-silty, mixed, active, thermic Ultic Hapludalfs (From USDA/NRCS official soil series descriptions)

30 inch spacings between each row and there were 10 ft alley ways between individual plots at each site.

Soil Sampling and Analysis

Soil samples were collected from field trials that were established at the sites to assess soybean response to P and K fertilization. A total of 520 soil samples were collected from the 11 site years across the 5 locations during the 2022 and 2023 growing season. Samples were collected after harvest of the previous year's crop but before application of fertilizers during fall and early spring between the months of October and April.

A composite soil sample from each of the 40 or 48 plots at every site was collected by combining and homogenizing 6-8 soil samples from the 0-6 -inch depth using a 7/8 inch diameter probe. Composite samples from each plot were air dried, ground and passed through a 2mm (US No. 10 mesh) sieve and then analyzed by the University of Tennessee's Soil, Plant, and Pest Center (UTSPPC) for soil pH, Mehlich 1 soil extractable P and K, and Mehlich 3 soil extractable P and K. Soils were analyzed for soil pH using a 1:1(w:v) solution of soil/water. A 10 g scoop of soil was added to 10 mL of deionized water. The solution was stirred and soil pH was measured using the LabFit Dual Probe 3010D pH analyzer after instrument calibration (Southern Cooperative Series, 2014). Extraction and analysis of Mehlich 1 P and K was performed using a 1:4 (w:v) soil to solution ratio. Five grams of soil were added to 20 mL of Mehlich 1 (0.05 M HCL + 0.025 M H_2SO_4) solution. The solution was shaken for 5 minutes and filtered through a size 2 Whatman paper filter before analysis for P and K by the inductively coupled plasma spectrometer method (ICP). Mehlich 3 extractable P and K were extracted and analyzed by a 1:10 (w:v) soil to solution ratio. Two grams of soil were added to 20 mL of Mehlich 3 (0.2M CH_3COOH, 0.015M NH_4F, 0.013M $HN0_3$, and 0.25M NH_4N0_3, 0.001M EDTA) solution. The solution was shaken for 5 minutes and filtered using a size 2 Whatman paper filter before analysis for P and K by ICP. The ICP analysis was performed using the Perkin-Elmer 7300 ICP-OES instrument (PerkinElmer, Shelton, Connecticut, U.S.). The method used in this publication is based on the soil test methods from the Southern United States (Southern Cooperative Series, 2014).

Statistical Analysis

Basic descriptive statistics (range, mean, median, and interquartile) for pH, Mehlich 1 extractable P and K, and Mehlich 3 extractable P and K data were analyzed using the GLIMMIX procedure in SAS version 9.4 for all sites. Descriptive statistics were used to explain variations in the soils among the sites and assist in data interpretation. Data were represented graphically using SigmaPlot 14.5 where a linear regression model was fit to the data to describe the relationship between Mehlich 1 and Mehlich 3 extraction for corresponding P and K.

Results and Discussions

Soil pH

Along with Mehlich 1 and Mehlich 3 extractable P and K, pH was also analyzed for soils across the sites due to the large impact pH has on available nutrient concentration in soil solution. **Figure 2.3** shows the mean, median, and interquartile dispersion for the pH at each site. Soil pH at the sites varied significantly ($p < 0.05$). Although variations in soil pH can be influenced by soil properties (i.e. soil organic matter), management practices (i.e. fertilization, liming), and environmental conditions (i.e. temperature and rainfall) (Brady and Weil, 2008), the variation of soil pH between sites in this study is primarily due to liming practices. Mean soil pH values at each site are presented in **table 2.3**. Soils in this study represented neutral to acidic conditions

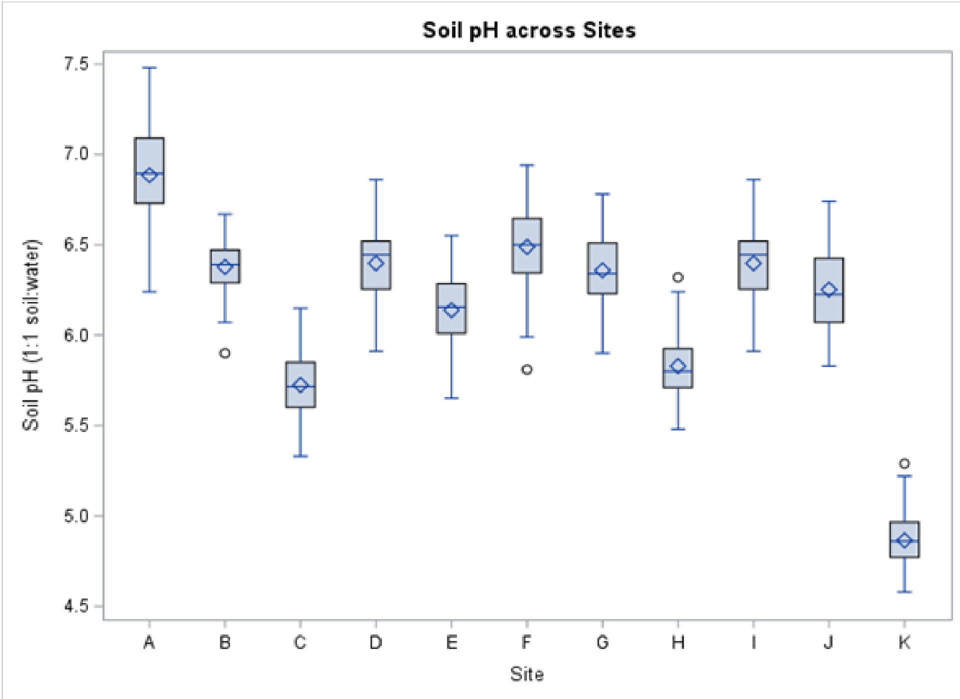

Figure 2.3 Range, mean, median, and interquartile dispersion of pH of sites

Table 2.3 Mean soil pH of sites

Site	Soil pH
A	6.88 a
B	6.38 bc
C	5.72 g
D	6.40 bc
E	6.14 e
F	6.46 b
G	6.36 c
H	5.83 f
I	6.40 bc
J	6.25 d
K	4.86 h
P value	<0.0001

with pH ranging from a low of 4.6 at site K to a high of 6.9 at site A. When soil pH is below 6 the availability of certain nutrients for plant uptake, especially P, is limited (Barrow, 2017). All sites had a pH of 6 or greater excluding sites C, H, and K which had a pH of 5.72, 5.83, and 4.86 respectively.

Extractable Phosphorus

Mehlich 1

The range, mean, median, and interquartile dispersion of M1P across sites is shown in **figure 2.4**. Across the trial sites, the range of M1P varied significantly from 4 lb. P/A at site K to 97 lb. P/A at site E ($p < 0.05$; **table 2.4**). With the exception of site E, the M1P concentrations observed in this study are consistent with concentrations previously observed in West TN soils (Essington, 2000). Site E was significantly higher than all other sites in M1P, which can be attributed to previous fertilizer trials at this site. The mean M1P of soils at sites B, C, F, G, H, J, and K were in the low soil test level (0-18 lb. P/A). Mean M1P for sites D and I were in the medium soil test level (19-30 lb. P/A). At sites A and E, mean M1P were in the high soil test level (31-119 lb. P/A) according to University of Tennessee recommendation guidelines (Duncan et al., 2015). Based on current recommendations from the University of Tennessee (Savoy, 2009; Duncan et al. 2015) soil test results suggest that approximately 80% of the sites require P_2O_5 fertilization to obtain optimal soybean yield.

Mehlich 3

The range, mean, median, and interquartile dispersion of M3P by site are presented in **figure 2.5**. Significant variability ($p < 0.05$) in M3P was observed between study sites (**table 2.4**). The M3P

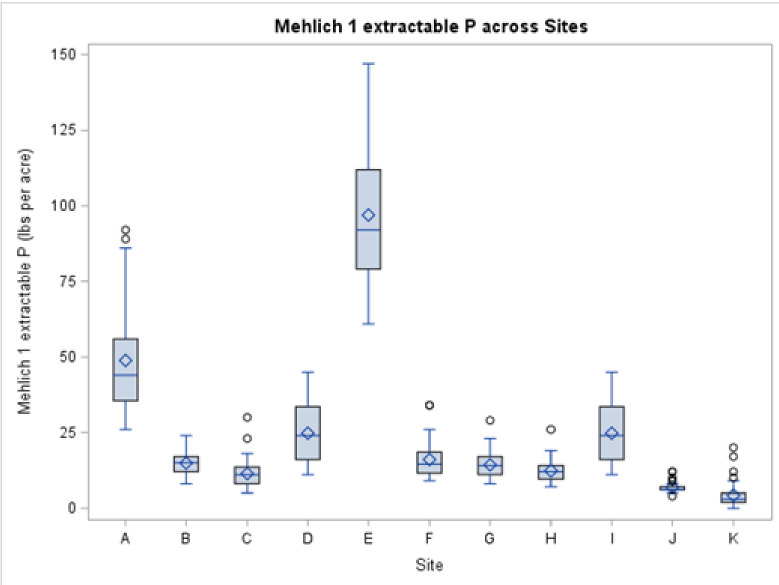

Figure 2.4 Range, mean, median, and interquartile dispersion of M1P of sites

Table 2.4 Mean M1P and M3P of sites

Site	Soil pH	Mehlich 1 P	Mehlich 3 P
		---------- lbA^{-1}	----------
A	6.9 a	49 b	67 b
B	6.4 bc	15 de	33 cd
C	5.7 g	11 e	35 c
D	6.4 bc	25 c	62 b
E	6.1 e	97 a	162 a
F	6.5 b	16 d	28 c-e
G	6.4 c	14 de	23 ef
H	5.8 f	12 de	27 de
I	6.4 bc	25 c	62 b
J	6.3 d	7 f	17 fg
K	4.9 h	4 f	12 g
P value	<0.0001	<0.0001	<0.0001

Means with the same letter within a column are not significantly different concentrations varied between a low of 17 lb. P/A and a high of 162 lb. P/A. Site K had the lowest M3P value at 17 lb. P/A, which was statistically similar to site J which had an M3P value of 23 lb. P/A. The highest M3P was reported at site E (162 lb. P/A) and was significantly higher than any of the other sites. This is once again attributed to previous fertilizer trials at Site E. Excluding site E, the range of M3P concentrations at the study sites is consistent with previously observed M3P ranges in West TN soils (Essington, 2000). Mean M3P concentrations at sites F, G, H, and K were in the low testing soil level (0-30 lb. P/A). Soils from sites B and C had M3P concentrations in the medium soil test level (31-60 lb. P/A). Sites A, D, E, and I had soils with M3P concentrations in the high soil test level (61-210 lb. P/A). Soil test level classifications are based on current UT recommended guidelines using the conversion equation developed at the University of Kentucky to define M3P soil test levels (Duncan et al., 2015; Southern Cooperative Series, 2014). Following the University of Tennessee's current fertilizer recommendations, approximately 55% of the study sites required P_2O_5 fertilization to attain optimum soybean yields (Duncan et al., 2015).

Relationship between M1P and M3 P

Outliers affecting the development of a robust conversion equation from regression analysis were removed. Outlier detection and removal was performed using the interquartile range method, represented visually using the box and whisker plots in **figures 2.4 and 2.5**. A possible explanation of outliers with abnormally high soil test values is the presence of P

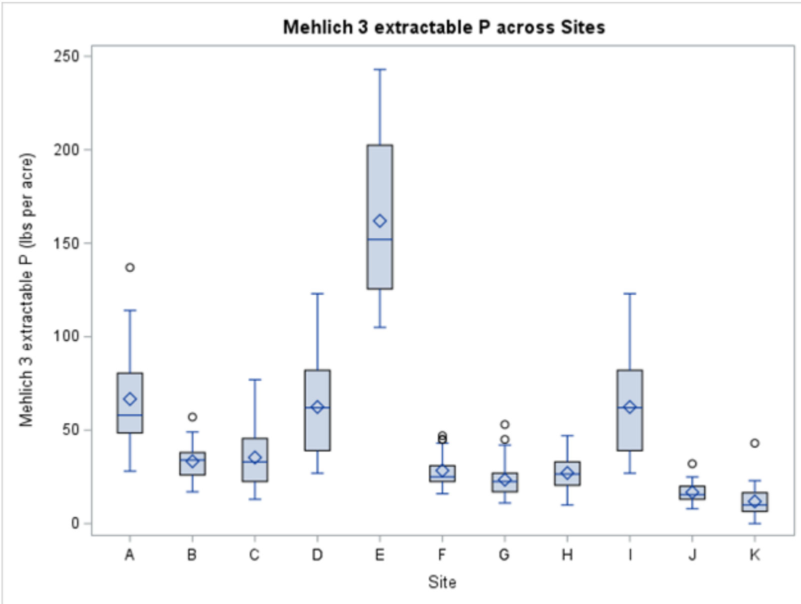

Figure 2.5 Range, mean, median, and interquartile dispersion of M3P of sites

amounts of plant available P, the highest availability between the pH range of 6 and 7.5. For this reason, samples were split into groups having pH < 6 or pH ≥ 6 to better represent the relationship between M1P and M3P and develop two separate equations. Similar grouping of data based on the same pH ranges was done in order to develop two separate conversion equations at the University of Kentucky (Southern Cooperative Series, 2014). After the removal of outliers and grouping the samples based on plot pH, 150 samples were used to develop a M1 to M3 P conversion equation for soils with a pH less than 6 and 347 samples were used to develop a M1 to M3 P conversion equation for soils with pH 6 or greater.

Regardless of pH, M3 consistently extracted higher amounts of extractable P than M1. This can be explained by the differences in the composition of M1 and M3. The acid composition of M1 is weaker compared to that of M3. M3 is also buffered to a pH of 2.5 in order to take advantage of the fluoride component of the extractant. The addition of fluoride (0.015M NH4F) to the M3 extractant enables the removal of additional P that has been bound to Al and Fe in the soil (Southern Cooperative Series, 2014). Similar findings were observed in previous studies. In soils from the Mid-Atlantic United States (Gartley et. al, 2002), Northeast Florida fertilizer in soil samples at testing. Combined, there was a total of 23 outliers from the M1P and M3P datasets that were removed for regression analysis. After the removal of outliers, 497 soils samples remained for use in the development of a conversion equation to M1P and M3P.

Samples for M1P and M3P were further split in the development of the conversion equation based on soil pH. Soil pH has a large influence of the amount of plant available P in soil solution (**figure 2.6**) In soils with a pH of below 6, P in soil solution tends to become plant unavailable by binding with aluminum and iron compounds. Soils with a pH of 6 or greater

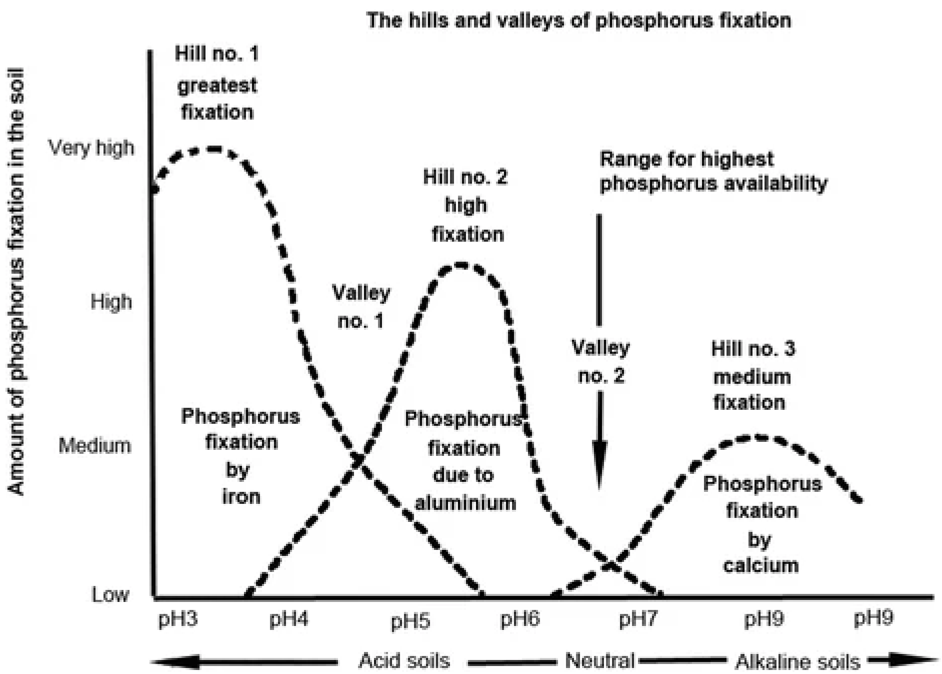

Figure 2.6 Representation of soil phosphorus availability at different soil pH. Picture adapted from (Barrow, 2017)

contain greater(Sandhu et. al., 2023), acid mineral soils of Florida (Mylavarapu et. al. 2002), and Atlantic coastal plains soils (Sims, 1989) M3 also extracted higher amounts of P than M1.

Regression analysis between M1P and M3P for soils of pH < 6 and pH ≥ 6 is presented in **table 2.5**. At both soil pH levels, there was a significant ($p < 0.05$) positive linear relationship between M1P and M3P. The relationships between M1P and M3P in soils of pH < 6 and pH ≥ 6 are presented in **figure 2.7** and **figure 2.8** respectively. In general, M3P increased steadily with increasing M1P.

A strong and significant correlation was observed between M1P and M3P in soils regardless of soil pH. In soils with pH < 6, the correlation coefficient was 0.93. In soils with pH ≥ 6, a correlation coefficient of 0.93 was found (**table 2.5**). A study by Gartley et al. (2002) determined through regression analysis that when appropriate, a simple conversion factor could be used to convert M1P to M3P. The use of a simple conversion factor, or the use of a no-intercept regression model makes the application of a conversion equation easier and less prone to error (Gartley et al., 2002). The regression for M1P to M3P conversions revealed strong positive linear correlations using a no intercept model (**table 2.5**), with a significant linear relationship ($p < 0.05$) observed in soils pH < 6 (R2 = 0.87) and soils pH ≥ 6 (R2 = 0.92). Equations developed from the regression analysis are listed below (equation 1, equation 2). According to the linear regression, M3P extracted approximately 2 times as much P than M1 in soils with a pH < 6 and 1.7 times as much P than M1 in soils with pH ≥ 6. The magnitude of M3P increases over M1P observed is similar to the magnitude observed in Kentucky soils (Southern Cooperative Series, 2014). In Kentucky, M3 extracted 2.13 times more P in soils of pH < 6 and 1.43 times more P in soils with pH ≥ 6. Findings from Gartley et. al (2002) in the

Table 2.5 The coefficient of determination (R2), equation, root mean square error (RMSE), and P value for the relationship between Mehlich 1 and 3 extractable P and K across sites

Nutrient	P value	R	R2	RMSE	Equation
P					
pH<6	<0.0001	0.96	0.92	11.6	Y= 2x
pH≥ 6	<0.0001	0.93	0.87	15.7	Y = 1.7x
K	<0.0001	0.87	0.76	31.7	Y = 1.33x +33.62

R2, Coefficient of determination; RMSE, Root mean square error

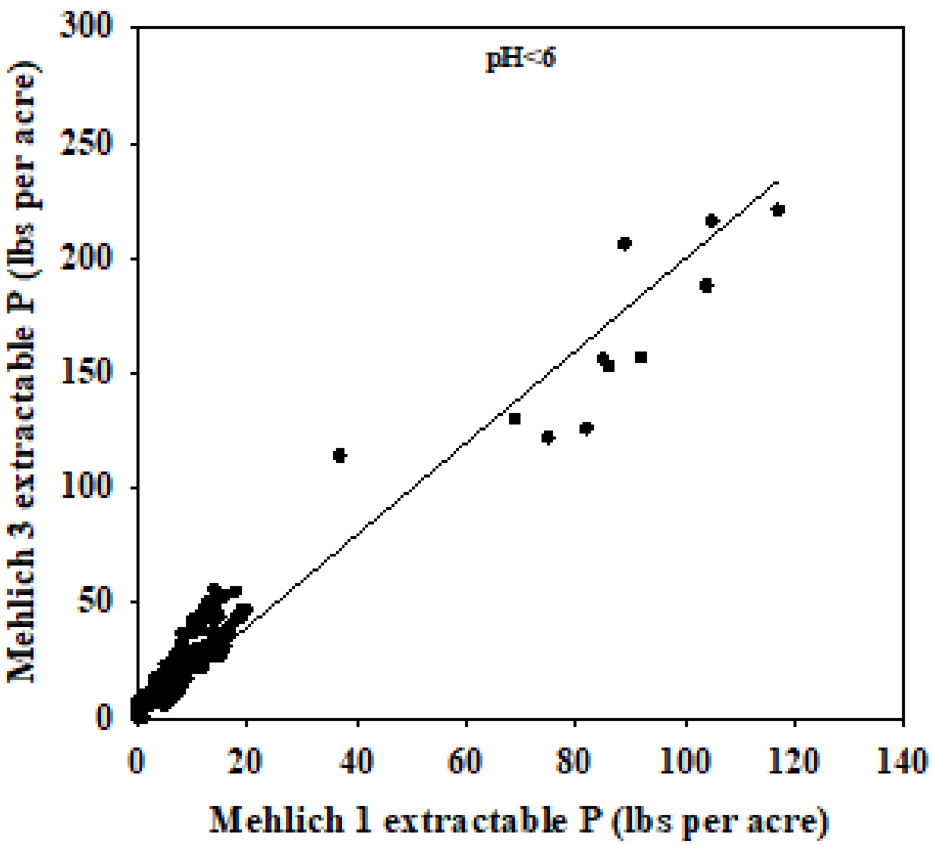

Figure 2.7 The relationship between Mehlich 1 and 3 extractable P for soils with pH<6

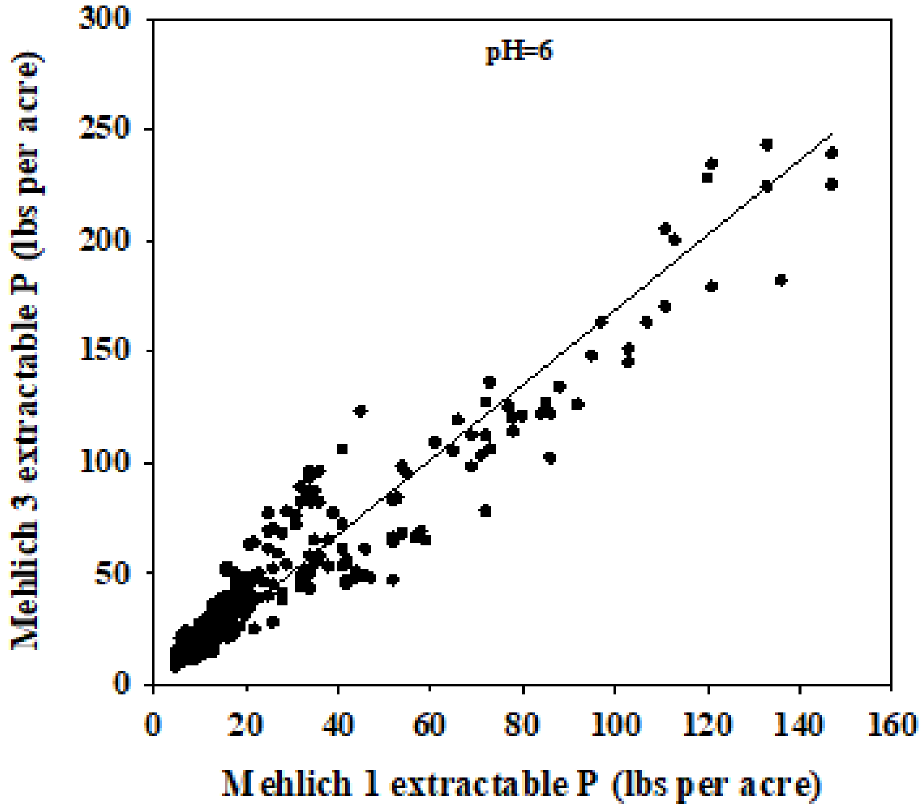

Figure 2.8 The relationship between Mehlich 1 and 3 extractable P for soils with pH≥6

Mid-Atlantic United States suggest similar magnitudes. Other studies reporting higher extractable P with M3 than M1 reported equations of lower magnitudes. In sandy Atlantic coastal plains soils, M3 extracted approximately 1.6 times more P than M1 (Sims, 1989). In the highly variable acid mineral soils of Florida, M3 extracted approximately 1.5 times more P than M1 (Mylavarapu et al., 2002).

$$\boldsymbol{M3}\text{P}=\mathbf{2}*\boldsymbol{M1}\text{P} \qquad \boldsymbol{where\ pH}<\mathbf{6}$$

…………………………………………. Equation 1

$$\boldsymbol{M3}\text{P}=\mathbf{1}.7*\boldsymbol{PM1}\text{P} \qquad \boldsymbol{where\ pH}\geq\mathbf{6}$$

………………………………………. Equation 2

M1P = Mehlich 1 extractable phosphorus

M3P = Mehlich 3 extractable phosphorus

Extractable Potassium

Mehlich 1

The range, mean, median, and interquartile dispersion of M1K across sites is shown in f**igure 2.9**. There was significant variability in the M1K concentrations ranging from 57 – 139 lb. K/A ($p < 0.05$) (**table 2.6**). The lowest mean M1K concentration was 57 lb. K/A and observed at both site D and I. Mean M1K at sites G (68 lb. K/A) and B (70 lb. K/A) are statistically similar to sites D and I. The highest M1K concentration of 139 lb. K/A was observed at site K. There were no M1K concentrations that were significantly higher than the rest of the values. The range of M1K concentrations is consistent with those found in unpublished data from previous studies in West TN (Essington, 2000). Based on University of Tennessee recommendation guidelines soils from sites B, D, E, G, and, I are in the low testing soil level for M1K (0-90 lb. K/A) (Duncan et al., 2015). Soils at sites A, C, F, H, and K were in the medium soil test level (91-160

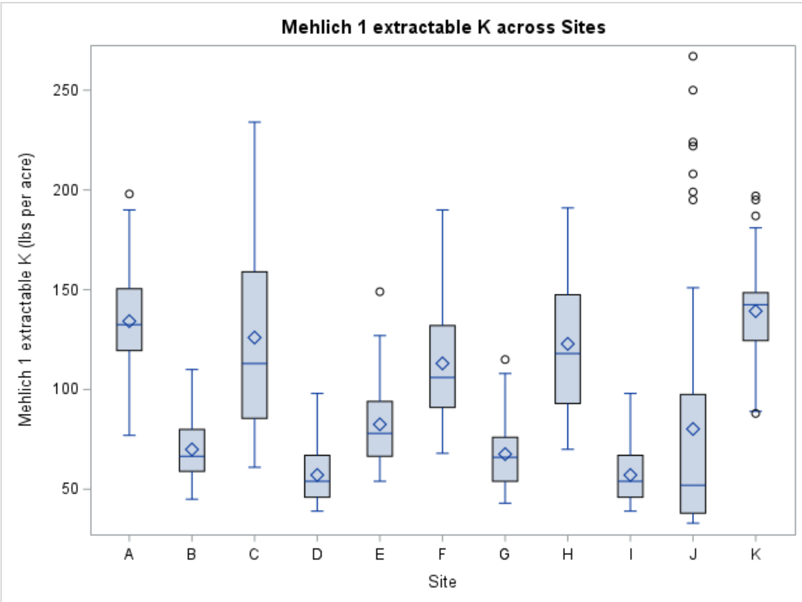

Figure 2.9 Range, mean, median, and interquartile dispersion of M1K of sites.

Table 2.6 Mean soil pH, M1P concentration, and M3P concentrations for the study sites

Site	Soil pH	Mehlich 1 K	Mehlich 3 K
		---------- lbA^{-1} ----------	
A	6.88 a	134.23 ab	205.00 bc
B	6.38 bc	69.96 d-f	222.71 ab
C	5.72 g	126.02 bc	244.79 a
D	6.40 bc	57.13 f	97.65 f
E	6.14 e	82.53 d	146.20 de
F	6.46 b	113.08 c	182.37 cd
G	6.36 c	67.60 ef	117.42 ef
H	5.83 f	122.85 bc	210.96 bc
I	6.40 bc	57.13 f	97.65 f
J	6.25 d	80.21 de	89.67 f
K	4.86 h	139.27 a	197.83 bc
P value	<0.0001	<0.0001	<0.0001

analysis. While soil pH impacted the measurement of M1P and M3P at pH < 6 and pH ≥ 6, the same effect is not observed in K. (Chen and Barber, 1990). Species of K do not vary with soil pH in the same way as P. For this reason, soil samples for M1K and M3K were not split by soil pH. The University of Kentucky also did not split their samples for K based on soil pH (Southern Cooperative Series, 2014).lb. K/A). No sites in this study had soils in the high M1K soil test level (161-319 lb. K/A). According to current University of Tennessee fertilizer recommendations soil test results suggest that all sites would require K_2O fertilizer application to attain optimal soybean yield (Savoy, 2009; Duncan et al., 2015).

Mehlich 3

The range, mean, median, and interquartile dispersion of M3K are shown in **figure 2.10**. Significant variability ($p < 0.05$) was observed in M3K concentration means across the sites ranging from a low of 90 lb. K/A at site J and a high of 245 lb. K/A at site C (**table 2.6**). The range of concentrations is consistent with those found in previous unpublished data in West TN (Essington, 2000). The mean M3K concentrations at sites D, I, and J were in the low soil test level according to the University of Tennessee recommendations guidelines (Duncan et al., 2015). Soils at sites E, F, G, and K were in the medium testing soil level (115-203 lb. K/A). Sites A, B, C, and H had soils with M3K in the high soil test level (204-405 lb. K/A). Based on current University of Tennessee fertilizer recommendations, approximately 64% of the sites in this study required application of K_2O fertilizer for optimal soybean yields (Savoy, 2009; Duncan et al., 2015).

Relationship between M1K and M3K

Outliers and missing data were removed from the M1K and M3K datasets to improve the accuracy of the conversion equation. Outliers were removed using the same outlier detection and

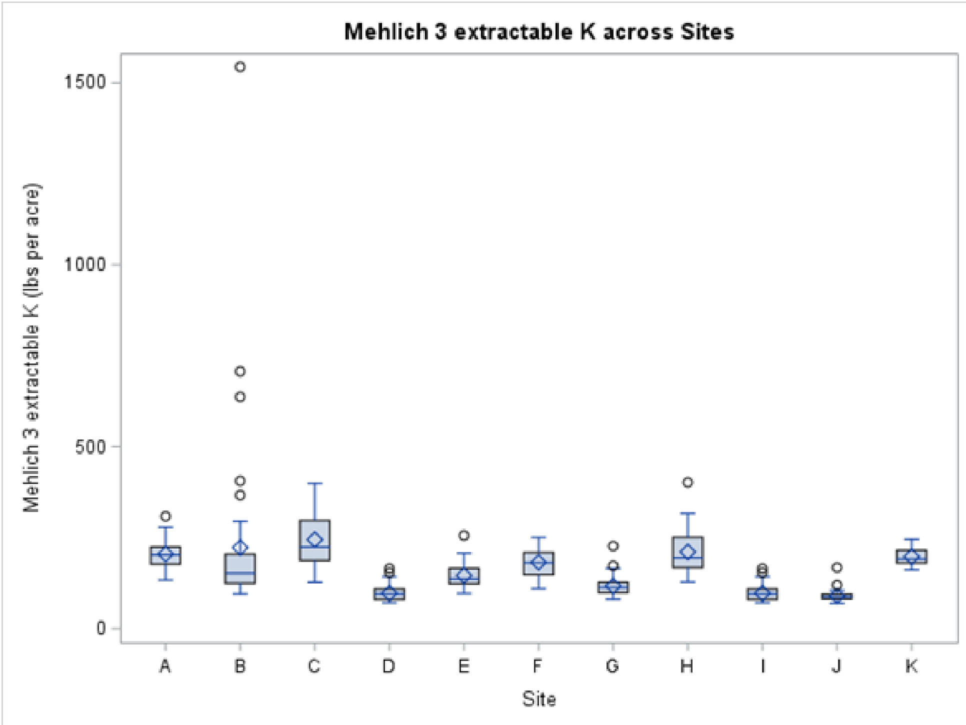

Figure 2.10 Range, mean, median, and interquartile dispersion of M3K of sites

removal process as in M1 P and M3P data, the interquartile-range method. This revealed the need for removal of 49 data points for the M1K and M3K data (**figure 2.8, figure 2.9**). Extremely high M1 and M3 soil test K values are likely due to residual fertilization from the fields. Upon removal of missing values and outliers, 471 samples remained for regression

As seen with P, extractable M3K was higher than extractable M1K for all sites. The ammonium nitrate in the composition of M3 is partly responsible for higher extraction of K. Stronger extraction efficiencies for M3K than M1K were observed in Atlantic coastal plains soils (Sims 1989) and soils in northeast Florida (Sandhu et al., 2023). Gartley et al. (2002) also report that M3 extracted more soil K than M1 in the Mid-Atlantic U.S. Meanwhile, studies from the acid mineral soils of Florida reported approximately the same amount of K was extracted with M1 and M3 (Mylavarapu et al., 2002). These studies all agreed, there was strong correlation between M1K and M3K. A significant correlation and a strong linear correlation were shown between M1K and M3K in this study (**table 2.5**). A correlation coefficient of 0.87 was observed between the extractants. The relationship between M1 and M3 extractable K is shown in **figure 2.11**. The intercept developed for the regression equation between M1K and M3 K was found to be 33.62, which was not considered negligible. The high intercept value has the ability to drastically affect soil test interpretation levels. For this reason, the intercept was included in the equation. The slope of the regression equation was 1.33. This is similar to the slope of the equation from Kentucky, which was 1.27. Although the slopes were similar, the Kentucky equation had a lower intercept of 12, which was included in the equation as well (Southern Cooperative Series, 2014). The conversion equation for M1K to M3K is presented below (Equation 3).

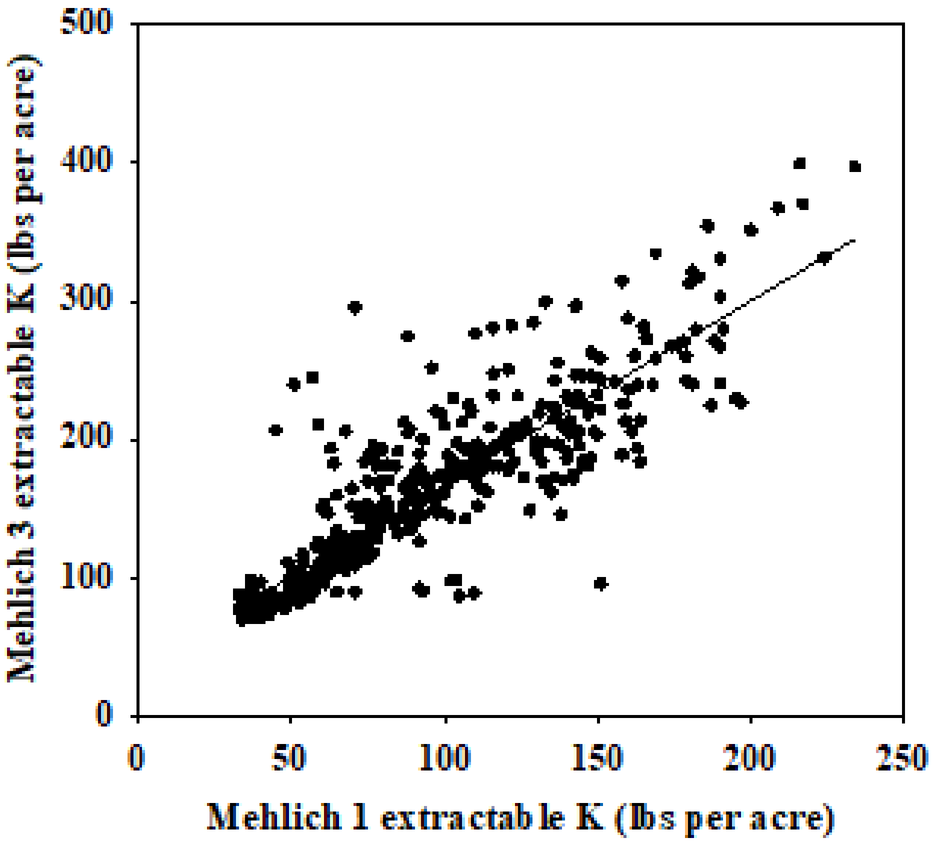

Figure 2.11 The relationship between Mehlich 1 and 3 extractable K for soils

$$M3K = 1.33 * M1K + 33.81 \text{………….………. Equation 3}$$

Where M1 K is Mehlich 1 extractable K

M3K is Mehlich 3 extractable K

The conversion equations developed in this study alter the threshold values of M3 P and K soil test levels from those reported using the current equation (Duncan et al., 2015). **Table 2.7** shows the soil test levels and their corresponding ranges for M1P, ranges developed using the current conversion equation for M3P, and soil test ranges for M3 P in soils pH < 6 and soils pH ≥ 6 using the conversion equation developed in this study. While the current conversion equation applies to all soil pH ranges, the new conversion equations require knowledge of soil pH for use. Differences are observed between the threshold values for soil test levels when converting M1 to M3 P using the current equation and the equations developed in this study. For example, a M3P value of 31 would be a medium testing soil based on the current conversion equation. However, when using the new conversion equations a soil with a M3P value of 31 would be a low testing soil in both soils of pH <6 and pH ≥ 6. This difference is critical due to the potential implications it has on fertilizer recommendations. If the soil was reported as a medium soil test level, fertilizer application of 20 lb. P_2O_5/A would be recommended, whereas an increased rate of 40 lb. P_2O_5/A would be suggested for a low testing soil. Similarly, soil pH impacted the threshold for soil test levels when using the new equations. If a soil has a pH of less than 6, then a calculated M3P value of 35 would indicate the soil is a low testing soil. However, in soils with a pH greater than or equal to 6, conversion to an M3P value of 35 would yield a soil in the medium testing category. The same potential implications on fertilizer recommendations occur, with an increase of 20 lb. P_2O_5/A between the recommended application rates for low and medium testing soils. For this reason, it is imperative that users test for and select the equation reflecting their soil pH.

Table 2.7 Mehlich 1 extractable P concentration for the various rankings by the University of Tennessee and the corresponding Mehlich 3 P conversions (M3 P*) using the conversion equation from this study.

Ranking		Current UT conversion equation	Conversion equation in this study	
	M1 P	M3 P*	M3 P (pH <6)	M3 P (pH =>6)
	--lb P A^{-1}----------------------------			
Low	0-18	0-30	0-36	0-31
Medium	19-30	31-60	37-60	32-51
High	31-119	61-210	61-238	52-201
Very High	≥ 120	≥ 211	≥ 239	≥202

The current ranges for M1K soil test levels, ranges developed using the current equation for M3K, and ranges developed using the equation developed in this study for M3K are presented in **table 2.8**. Differences in threshold values for K soil test levels were also observed between ranges developed from the current equation and those developed using the equation in this study. For example, based on the current equation a soil with an M3K value of 170 would be a medium testing soil. In contrast, when using the equations developed in this study an M3K value of 170 would put a soil in the low testing category. Application of 80 lb. K_2O/A would be recommended in the low testing soil, where as a medium soil would have a recommendation of 40 lb. K_2O/A.

Conclusion

The purpose of this study was to evaluate the relationship between the M1 and M3 soil test extractants for P and K and to develop subsequent conversion equations. Linear regression analysis revealed a strong linear correlation between the extractants for P and K at the 95% confidence level. In general, M3 extracted higher amounts of P and K than M1. For P only, correlation of M1 and M3 improved when data were split into soils with pH < 6 and pH ≥ 6. Two equations were developed for conversion between M1P and M3P for depending on soil pH. In soils with pH < 6, M3 extracted 2 times the amount of extractable P than M1. In soils with pH ≥ 6, M3 extracted 1.7 times the amount of extractable P than M1. A conversion equation between M1K and M3K was derived where M3K=1.33*M1K+33.81. By using the equations developed in this study, producers will be able to easily compare soil test results from labs using the M1 extractant and labs using the M3 extractant. The data in this study represent a small portion of West Tennessee soils. Further research should be done to validate these equations using a larger

Table 2.8 Mehlich 1 extractable K concentration for the various rankings by the University of Tennessee and the corresponding Mehlich 3 K conversions (M3 K*) using the conversion equation from this study.

Ranking		Current UT conversion equation	Conversion equation in this study
	M1 K	M3 K*	M3 K
	--	------lb P A^{-1}------	----------------------------
Low	0-90	0-114	0-185
Medium	91-160	115-203	186-304
High	161-319	204-405	305-572
Very High	≥ 320	≥ 406	≥ 573

sample size for Tennessee soils. When utilizing the conversion equations in this study, attention should be paid to pH when converting M1P to M3P.

References

Arshad, M. A., Schnitzer, M., Angers, D. A., & Ripmeester, J. A. (1990). Effects of till vs no-till on the quality of soil organic matter. *Soil Biology and Biochemistry*, *22*(5), 595-599.

Barrow, N.J. The effects of pH on phosphate uptake from the soil. *Plant Soil* **410**, 401–410 (2017). https://doi.org/10.1007/s11104-016-3008-9

Blanco-Canqui, H., T.M. Shaver, J.L. Lindquist, C.A. Shapiro, R.W. Elmore, et al. 2015. Cover crops and ecosystem services: Insights from studies in temperate soils. Agron. J. 107(6): 2449–2474. doi: 10.2134/agronj15.0086.

Chen, J.-H. and Barber, S.A. (1990), Soil pH and Phosphorus and Potassium Uptake by Maize Evaluated with an Uptake Model. Soil Science Society of America Journal, 54: 1032-1036. https://doi.org/10.2136/sssaj1990.03615995005400040017x

Drescher, G.L., N.A. Slaton, T.L. Roberts, and A.D. Smartt. 2021. Corn yield response to phosphorus and potassium fertilization in Arkansas. Crop. Forage Turfgrass Manag. 7(2): 1–17. doi: 10.1002/cft2.20120.

Essington, M. 2000. Comparison of Mehlich-1 and Mehlich3 P and K from a West Tennessee field. Personal communication to UT Soil Fertility Committee.

Gartley, K. L., Sims, J. T., Olsen, C. T., & Chu, P. (2002). Comparison of soil test extractants used in mid-Atlantic United States. *Communications in Soil Science and Plant Analysis*, *33*(5-6), 873-895.

Hergert, G. W., Pan, W. L., Huggins, D. R., Grove, J. H., & Peck, T. R. (2015). Adequacy of current fertilizer recommendations for site-specific management. In *The State of Site-*

Specific Management for Agriculture (pp. 283–300). wiley. https://doi.org/10.2134/1997.stateofsitespecific.c13

Mylavarapu, R. S., Sanchez, J. F., Nguyen, J. H., & Bartos, J. M. (2002). Evaluation of Mehlich-1 and Mehlich-3 extraction procedures for plant nutrients in acid mineral soils of Florida. Communications in Soil Science and Plant Analysis, 33(5-6), 807-820.

Mylavarapu, R. S., Sanchez, J. F., Nguyen, J. H., & Bartos, J. M. (2002). Evaluation of Mehlich-1 and Mehlich-3 extraction procedures for plant nutrients in acid mineral soils of Florida. *Communications win Soil Science and Plant Analysis*, *33*(5-6), 807-820.

Peck, T. R., & Soltanpour, P. N. (1990). The principles of soil testing. Soil testing and plant analysis, 3, 1-9.

Sandhu, A. K., Sharma, A., Kaur, N., Zotarelli, L., Morgan, K., & Sharma, L. K. (2023). Evaluate the use of Mehlich-III compared to Mehlich-I as a soil test in Northeast Florida. *Farming System, 1*(3), 100056.

Savoy, H. (2009). Interpreting Mehlich 1 and 3 soil test extractant results for P and K in Tennessee. *University of Tennessee, Institute of Agriculture*.

Sikora, F. J., Mylavarapu, R. S., Hardy, D. H., Tucker, M. R., & Franklin, R. E. (2005). *Conversion equations for soil test extractants: Mechlich-1 and Mechlich-3. Southern Regional Fact Sheet*. SERA-IEG-6* 5.

Sims, J. T. (1989). Comparison of Mehlich 1 and Mehlich 3 extractants for P, K, Ca, Mg, Mn, Cu and Zn in Atlantic coastal plain soils. *Communications in Soil Science and Plant Analysis*, *20*(17-18), 1707-1726.

Singh, V. K., Gautam, P., Nanda, G., Dhaliwal, S. S., Pramanick, B., Meena, S. S., ... & Hossain, A. (2021). Soil test based fertilizer application improves productivity, profitability and nutrient use efficiency of rice (Oryza sativa L.) under direct seeded condition. *Agronomy*, *11*(9), 1756.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Official Soil Series Descriptions. Available online. Accessed [08/02/2024].

Soltangheisi, A., A.P.B. Teles, L.R. Sartor, and P.S. Pavinato. 2020. Cover Cropping May Alter Legacy Phosphorus Dynamics Under Long-Term Fertilizer Addition. Front. Environ. Sci. 8(February): 1–12. doi: 10.3389/fenvs.2020.00013.

Southern Cooperative Series. 2014. Soil Test Methods From the Southeastern United States. (Southern Cooperative Series Bulletin 419). Georgia Agricultural Experiment Station. https://aesl.ces.uga.edu/Sera6/PUB/Methodsmanualfinalsera6.Pdf

SSSA, 2024 Glossary of Soil Science Terms Retrieved 24 June, 2024 from https://www.soils.org/publications/soils-glossary/#

The twelve orders of soil taxonomy. Natural Resources Conservation Service. (n.d.-b). https://www.nrcs.usda.gov/resources/education-and-teaching-materials/the-twelve-orders-of-soil-taxonomy

Zhang, H., Antonangelo, J., Grove, J., Osmond, D., Slaton, N. A., Alford, S., Florence, R., Huluka, G., Hardy, D. H., Lessl, J., Maguire, R., Mylavarapu, R., Oldham, J. L., Pena-Yewtukhiw, E. M., Provin, T., Sonon, L., Sotomayor, D., & Wang, J. (2021). Variation in soil-test-based phosphorus and potassium rate recommendations across the southern USA. Soil Science Society of America Journal, 85(4), 975–988. https://doi.org/10.1002/saj2.20280

CHAPTER 3 : VALIDATING CURRENT SOIL TEST BASED SOYBEAN FERTILITY RECOMMENDATIONS FOR WEST TN SOYBEANS

Abstract

Soybeans are a major row crop in Tennessee, grown predominantly in the Western part of the state. Soybeans require phosphorus (P) and potassium (K) in soils testing low in these nutrients. In Tennessee (TN), the University of Tennessee (UT) has developed soil test-based recommendations for soybean crops which have not been updated in over a decade since their publication in 2009. Producer interest in response trials, improved soybean varieties, and changes in soil management practices have led to a need for validation for current P and K fertilizer recommendations for soybean. Trials were established at four site-years between 2022 and 2023 at the West Tennessee AgResearch and Education Center in Jackson, Tennessee. Independent P and K response trials were established at each site using a randomized complete block design with four replicates. Three sites were treated with 6 P application rates (0, 20, 40, 60, 80, and 120 lb P_2O_5/A) in P response trials or 6 K application rates (0, 40, 80, 140, 160, and 200 lb K_2O/A) in K response trial. One location received only 5 rates of P (0, 20, 40, 60, and 80 lb P_2O_5) and K (0, 40, 80, 140, and 160 lb K_2O) due to spatial limitations within the field. Yield response to fertilization was analyzed using the GLIMMIX procedure in SAS version 9.4. The linear and linear-plateau model were used to predict the relationship between yields and fertilizer application rates. No significant crop response to P fertilization was observed. In contrast, crop response to K fertilization occurred at 2 of 4 site-years with low testing soil K and maximum yields were observed at 140 lb K_2O/A. Results from this study suggest that UT's published P recommendations for soybean are sufficient, while UT's published K rates may need to be increased pending further investigation.

Introduction

Soybean (Glycine max (L.) Merr.) is a crop of agronomic and economic importance in Tennessee. Roughly 1.65 million acres of soybean are harvested annually in Tennessee with an average yield of 46 bushels/acre based on a ten-year average (McClure, 2022b). Soybean was the highest valued crop in 2023 above corn, cotton, and wheat. The economic value derived from soybeans was $1 billion from approximately 1.6 million acres averaging 51 bu/A (USDA/NASS, 2023). Approximately 65% of Tennessee's soybean production takes place in West Tennessee (McClure, 2022b).

Phosphorus and potassium fertilization is essential for optimal soybean production in Tennessee. Approximately 76% of soybean acreage in Tennessee is fertilized with P fertilizers and 72% is fertilized with K fertilizers (USDA/NASS, 2019). Selecting an appropriate fertilizer application rate helps producers to ensure adequate plant nutrition and prevent excessive fertilizer use, minimizing the cost of fertilizers and associated environmental impacts (Singh et al., 2021; Hergert et al., 2015; Sims, 1993). Soil test-based fertilizer recommendations offered by land grant universities (LGUs) ensure that the appropriate rate is used to meet plant nutrient requirements (Zhang et al., 2021). Recommendations based on soil testing are created in a three-step process. First, the relationship between plant nutrient uptake or yield and the amount of nutrient extracted by a soil test method is determined through soil test correlation. The University of Tennessee's recommended rates are correlated with the Mehlich 1 (M1) extractant (Savoy, 2009). Second, calibration studies are performed to assess crop nutrient requirements across soil test levels. Finally, interpretations are made from calibration data to select a recommended rate. Interpretations can be made using several philosophies. Three philosophies commonly used to create these recommendations are build and maintenance, sufficiency, and basic cation saturation ratio (BCSR) (Olson et al., 1987; Hergert et al., 2015; Zhang et al., 2021). The build and maintenance philosophy recommends overapplication of fertilizers to build soil test levels for following seasons; the sufficiency philosophy recommends only the amount of nutrient required by the crop in a given year; and the BCSR philosophy recommends fertilization to meet an ideal distribution of exchangeable cations in the soil. Most LGUs, including the University of Tennessee, use the sufficiency philosophy to ensure crop needs are met while fertilizer costs and environmental impacts of fertilization are reduced (Duncan et al., 2019). Current University of Tennessee fertilizer recommendations for soybeans can be found in **tables 3.1 and 3.2** (Duncan et al., 2015). These rates were established in 2009 and while they have been periodically evaluated, they have not been updated (Savoy and Joines, 2009; Duncan et al. 2015). Validation work in West Tennessee has thus far been limited to rates for small grain/soybean rotations, which differ from the recommendations for soybean not grown in rotation (Singh et al., 2019). A recent survey from the University of Tennessee has indicated producer interest in validation of P and K rates for soybeans (Unpublished survey, UT). Improvements in soybean genetics in recent years have led to improved soybean nutrient uptake and higher yields (McClure, 2022a), which could result in a need to increase recommended rates. Additionally, changes in soil management practices over the past several decades such as increased liming and adoption of no-till may impact the amount of extractable nutrients in soils. Rate validation will help producers continue to minimize costs and environmental impacts while meeting crop nutrient requirements. The objective of this study is to validate the accuracy of current P and K fertilizer recommendations for soybean in West Tennessee.

Table 3.1 University of Tennessee's Soil Test Based P Fertility Recommendations for Soybeans (adapted from Duncan et al., 2015)

Ranking	M1 Soil Test P (lb P A^{-1})values	Application Rate(lb P_2O_5 A^{-1})
Low	0-18	40
Medium	19-30	20
High	31-119	0
Very High	≥ 120	0

Table 3.2 University of Tennessee's Soil Test Based K Fertility Recommendations for Soybeans (adapted from Duncan et al., 2015)

Ranking	M1 Soil Test K (lb K A^{-1}) Values	Application Rate (lb K_2O A^{-1})
Low	0-90	80
Medium	91- 160	40
High	161- 319	0
Very High	≥ 320	0

Materials and Methods

Study Sites

Four trials were established in 2022 and 2023 on 3 fields at the West Tennessee AgResearch and Education Center (WTREC) in Jackson, Tennessee. Sites were tested for extractable M1P and M1K. Sites with low- or medium- testing soils were selected where crop response to fertilization was likely. Descriptions for each site-year, including reference letter, GPS coordinates, and M1 soil test P and K rankings, can be found in **table 3.3**. Two independent trials were established at each site-year for P and K rates. In the year prior to trial establishment, sites B and F were under corn production and sites E and F were under soybean production. All sites were dryland and under no-till management. Soils at Site E field belong to the moderately well drained Colins silt loam soil series (fine-silty, mixed, active, thermic Ultic Hapludalfs). Soils at the Sites B, F and G belong to the well drained Lexington silt loams soil series (coarse-silty, mixed, active, acidic, thermic Aquic Udifluvents). Climate data including average monthly rainfall and average daily temperature for the 2022 and 2023 growing season are shown in **figure 3.1** (NOAA, 2024).

Fertilizer Treatment and Study Design

All trials were arranged in a randomized complete block design, with 6 treatments and 4 replications at Sites F, B, and G and 5 treatments and 4 replications at Site E. Phosphorus trials at sites B, F, and G received 6 rates of P fertilizer reflecting the current UT recommended rates as well as rates above and below UT's recommendation (0, 20, 40, 60, 80, and 120 lbs P2O5/A). All P trials were fertilized with the recommended K rate at each site to eliminate K as a yield limiting factor for the P response trial. Potassium trials at locations B, F, and G received 6 rates

Table 3.3 Site Descriptions for experimental sites

Site	Year	Trial number	GPS coordinates	M1 Soil Test P level	M1 Soil Test K level
B	2022	WTREC 04	35.624064, -88.842120	Low	Low
E	2023	WTREC 01	35.630687, -88.852044	High	Low
F	2023	WTREC 03	35.620452, -88.842780	Low	Medium
G	2023	WTREC 04	35.624064, -88.842120	Low	Low

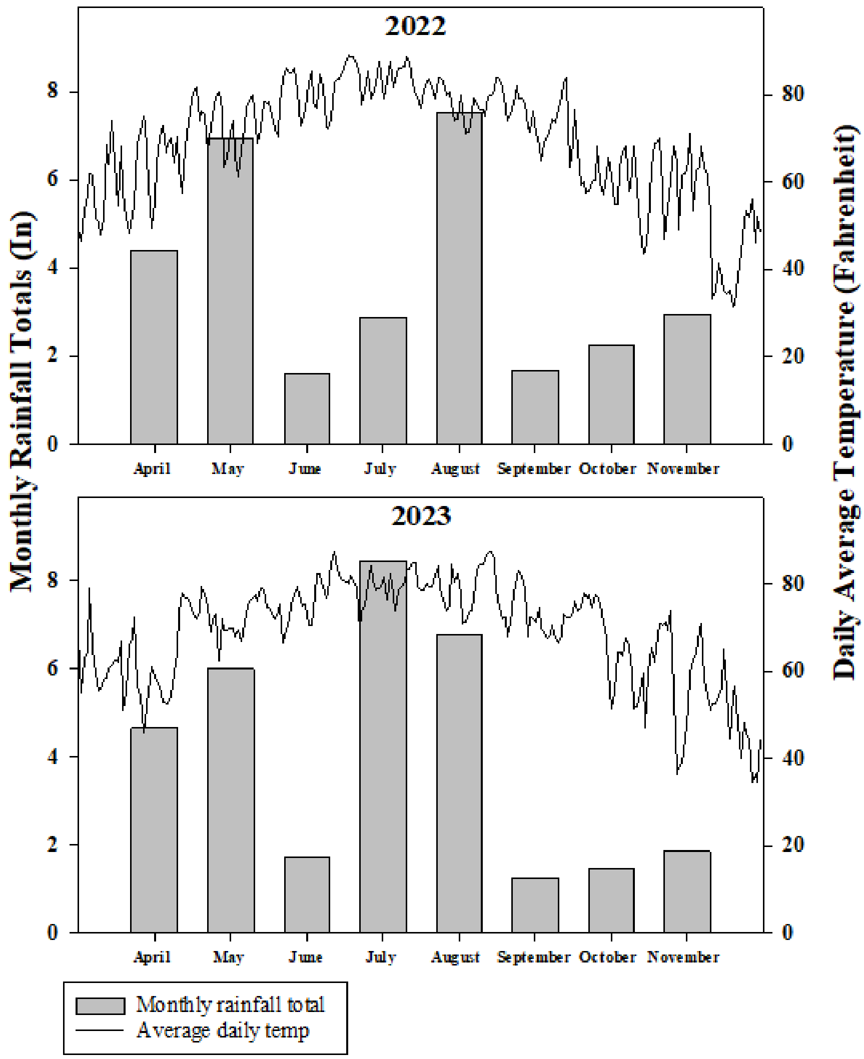

Figure 3.1 Average monthly rainfall (inches) and daily average temperatures (°Fahrenheit) for Jackson, Tennessee during the period of April – November for 2022 and 2023 (NOAA, 2024).

of K fertilizers reflecting the current UT recommended rates as well as rates above and below UT's recommendation (0, 40, 80, 140, 160, and 200 lb. K_2O/A). Phosphorus and potassium trials at site E were limited to 5 rates of P (0, 20, 40, 60, and 80 lb. P_2O_5/A) and K rates (0, 40, 80, 140, 160 lb. K_2O/A) due to spatial limitations created by flooding in the field's lower corner. Triple super phosphate (TSP) was used as the source of P and Potassium Chloride (KCl) was applied as the K source at all sites. Fertilizers were broadcast by hand directly after preplant soil sampling between the months of October and April. Fertilizers were not incorporated due to no-till management of the study sites. Plots were 10 ft by 30 ft with 4 crop rows with 30-inch row spacing. The variety of soybean used was an MGIV variety recommended for growth in TN.

Soil Sampling and Analysis

Soil sampling was conducted in 2022 and 2023 prior to soybean planting but after harvest the previous year. Soil samples for each plot were composited by collecting 6-8 samples per plot with a 7/8 inch diameter probe, combining the samples, and homogenizing them. Samples were air dried and passed through a 2mm sieve and sent to the University of Tennessee's Soil, Plant, and Pest Center in Nashville, TN. Soils were analyzed for pH by using a 1:1 (w:v) soil to water ratio solution. The solution was stirred, and pH was measured using a LabFit Dual Probe 3010D pH probe after instrument calibration. Soils were analyzed for Mehlich 1 extractable P and K using 1:4 (w:v) soil to solution ratio by adding 5g of soil to 20 mL of Mehlich 1 (0.05 M HCL + 0.025 M H_2SO_4) solution. The solution was shaken for 5 minutes and filtered through a size 2 Whatman paper filter before analysis for P and K by the inductively coupled plasma spectrometer method (ICP) using the Perkin-Elmer 7300 ICP-OES instrument (Southern Cooperative Series, 2014; PerkinElmer, Shelton, Connecticut, U.S.). The groupings for soil test extractable P and soil test extractable K levels for Tennessee soils based on the Mehlich 1 extractant are listed in **table 3.4** (Savoy and Joines, 2009; Duncan et al., 2015).

Yield Measurements

Soybean grain yield was measured by harvesting the middle two rows (5 ft by 30 ft) of each plot with a plot combine. Grain yield calculations were performed using a 13% moisture content.

Statistical analysis

Mixed-model ANOVA was performed using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC) to determine the fixed effects of fertilizer rate on grain yield for each site. Means were separated using Tukey at the 0.05 probability level. In addition, a linear, or linear plateau (LP), or quadratic plateau (QP) model was used to evaluate the relationship between fertilizer application rates and yield for each site and then predict the optimal rate where maximum yield occurred using SigmaPlot version 14.5 (Grafiti LLC., Palo Alto, CA). For data best fit to a linear model, no critical value is observed. When a LP or QP model best fits the data, critical rates were selected by determining the value where the model met the predicted yield plateau.

Results and Discussion

Soil properties

Mean soil pH, Mehlich 1 extractable P and K, and recommended P and K application rates of experimental sites are presented in **table 3.5**. According to the University of Tennessee established soil test levels (Duncan et al., 2015), Mehlich 1 P at sites B, F, G are ranked as low

Table 3.4 Groupings for P and K soil test level ratings based on the Mehlich 1 soil test extractant adapted from Savoy and Joines, 2009 and Duncan et al., 2015.

Ranking	M1 Soil Test P (lb P A^{-1})	M1 Soil Test K (lb K A^{-1})
Low	0-18	0-90
Medium	19-30	91- 160
High	31-119	161- 319
Very High	≥ 120	≥ 320

Table 3.5 Average soil pH, Mehlich 1 extractable P and K, and recommended P and K application rates of experimental sites

Site	pH	M-1P (lb P A^{-1})	Soil Test P Ranking	Recommended P (lb P_2O_5 A^{-1})	M-1K (lb K A^{-1})	Soil Test K Ranking	Recommended K (lb K_2O A^{-1})
B	6.4	14.7	Low	40	69.6	Low	80
E	6.1	97.0	High	0	82.5	Low	80
F	6.5	15.9	Low	40	112.6	Medium	40
G	6.4	14.3	Low	40	67.6	Low	80

soil test P, and E is ranked as high soil test P. Hence it expected that application of P fertilizer at sites B, F, and G would likely increase yield. In contrast, an increase in yield would not be expected at site E. Based on the soil test rankings, P fertilization is recommended for three out of the four sites (B, F, and G), with the recommended application rate of 40 lb. P_2O_5/A. Referring again to the University of Tennessee soil test levels from Duncan et al. (2015), Mehlich 1 K at sites B, E, and G is ranked as low soil test K, while site F is ranked as medium soil test K. Therefore, yield increases in response to fertilization are expected at sites B, E, and G, and response to fertilization at site F is possible, but not assured. Based on the soil test levels, K fertilization is recommended for all four sites, with recommended application rates of 80 lb K_2O/A for sites B, E, and G and 40 lbs K_2O/A for site F.

The average pH for each site falls within the optimal pH range for soybean production (Adotey, 2022); thus no liming application was recommended for any of the sites.

Soybean response to phosphorus fertilization

There was no significant difference in yield among the P application rates ($p<0.05$), regardless of experimental sites (**table 3.6**). Sites B, F, and G had low soil test ranking, so soybean yield increase was expected from the addition of P fertilizer. However, the yield of the fertilized P treatment was statistically similar to the unfertilized treatment. Site E had high soil test P ranking and no soybean yield increase was expected nor observed from the addition of P fertilizer. At sites B and G, the highest grain yield was observed at the 120 lb. P_2O_5/A rate, which was similar to the yield from the other P rates. In contrast the highest yield at site E was observed at the unfertilized P treatment and the 40 lb. P_2O_5/A rate. At site G, the highest yield was seen at

Table 3.6 Mean actual yield for each P rate and associated P value for the rate effect

	Actual Yield (bu A^{-1})						
Site	0	20	40	60	80	120	P-value
	-----------------------------lb. P_2O_5 per A^{-1}	----------------------------					
B	49.2a	50.4a	49.8a	50.3a	51.9a	58.5a	0.09
E	78.5a	77.4a	78.5a	74.3a	76.3a	-	0.68
F	64.7a	69.5a	72.1a	71.3a	68.6a	68.6a	0.29
G	70.4a	68.9a	70.7a	71.9a	73.0a	73.4a	0.78

Means of actual yield followed by the same letter within a row are not significantly different at $\alpha = 0.05$

40 lb P_2O_5/A rate. The numerical increases observed at sites B, F, G, was more than 15, 10, and 4%, respectively, than the unfertilized P treatments. Site E had no numerical increase in the highest yielding treatment and the unfertilized P treatment. Due to numerical differences observed, the data were fit to several models in SigmaPlot V.14.5. The best fit model (linear, LP, or QP), P value, and coefficient of determination (R2) for grain yield response to P fertilizer application at sites B, E, F, and G are shown in **table 3.7**. The P response was best fit to a linear model at sites B, E, and G while linear plateau (LP) was a better fit at site F based on the R^2 value. The LP model (**figure 3.2**) at site F was not significant (p = 0.236) but predicted that grain yield reached an inflection point of 70 bu/A at the 20 lb. P_2O_5/A.

While there were numerical increases in yields between the 0-rate treatment and the rate with the highest yield at sites B, F, and G, there was no statistically significant response to P fertilization at any of the sites. Site E experienced no numerical difference. Previous studies have reported the lack of response of soybean yield to P fertilization. Helget (2016) conducted a study evaluating soybean yield response to P fertilization in South Dakota. Of the 21 sites in the study, P fertilizer was recommended for 11 sites where crop response to fertilization was expected. However, only one of the 11 sites with P fertilizer recommendations experienced a positive yield response (Helget, 2016). While no crop response to fertilization at site E was expected, we did expect a response at sites B, F, and G. The lack of response at the low testing sites suggests that soybean plants were able to extract sufficient P from the soils at these locations and did not require additional fertilizer inputs. The crop response curves at sites B, E, and G suggest no agronomically optimal rate of fertilizer among treatment rates. The crop response curve at site F, while not showing a significant crop response or a significant model fit, does reach an inflection

Table 3.7 Model, P value and R2 for grain yield response to P fertilizer application at sites B, E, F, and G

Site	Model	P value	R^2
B	Linear	0.005	0.30
E	Linear	0.322	0.05
F	Linear Plateau	0.236	0.13
G	Linear	0.377	0.03

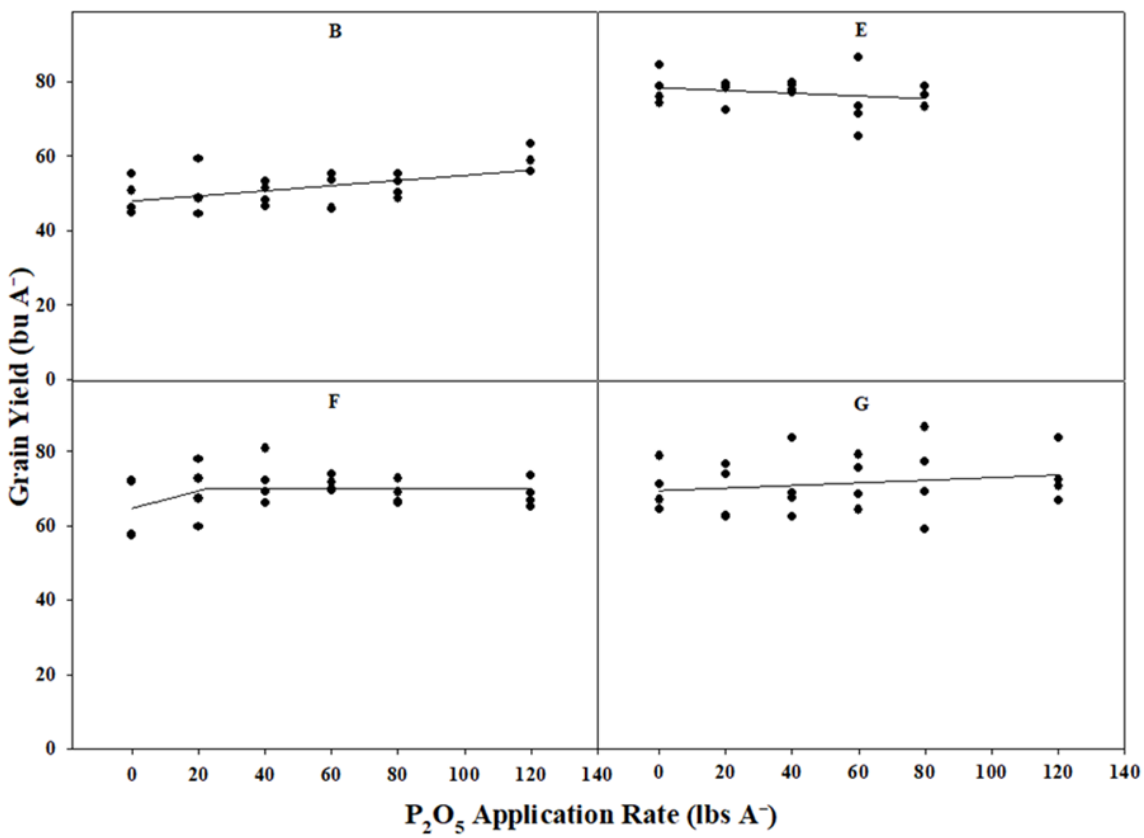

Figure 3.2 Grain yield response to P fertilizer application at sites B, E, F, and G

point at the 20 lb. P_2O_5/A. This is lower than the current rate suggested by the University of Tennessee for low testing soils, which is 40 lb. P_2O_5/A (Duncan et al., 2015). Due to the lack of a significant yield response coupled with the optimal fertilizer rate indicated by the model at site F, increases in soil test-based P fertilizer recommendations from UT are not recommended.

Soybean yield response to potassium fertilization

There was no statistically significant difference in yield among fertilizer treatments at sites E and F ($p<0.05$; **table 3.8**). However, a statistical difference in yield among K fertilizer treatments was observed at sites B and G ($p<0.05$). Site E tested low for soil test K and a yield increase to fertilizer application was expected, but not observed. Site F tested medium for soil test K and a yield response was possible, but not assured or observed. Sites B and G had a significant difference among treatment rates ($p<0.05$) which was expected due to low soil test K. For sites B and G, the highest observed yield occurred at 200 lb. K_2O/A.

Although not statistically significant, numerical differences were observed as sites E and F, where the highest observed yield was at a rate of 120 lb. K_2O/A. The highest yield at sites B, E, F, G, was had a numerical increase of more than 48, 12, 6, and 31%, respectively, compared to unfertilized K treatments. Due to the numerical differences observed, data were fit to a model in Simplot V.14.5 The K responses at site B, F, E, and G were best fit to a QP, linear, LP, and LP model respectively, based on R^2 values. Model, P value, and R2 for grain yield response to K fertilizer application at sites B, E, F, and G are shown in **table 3.9**. QP models at sites B ($p = 0.013$) and G ($p = 0.032$) were significant and predicted that grain yield reached an inflection point of 55 bu/A at the 160 lb. K_2O/A rate and 80 bu/A at the 140 lb. K_2O/A rate respectively (**figure 3.3**). The LP model at site E was not significant ($p = 0.097$), but an inflection point for

Table 3.8 Mean actual yield for each K rate and associated P value for the rate effect (SAS)

	Actual Yield (Bu A^{-1})						
Site	0	40	80	120	160	200	P-value
	----------------------------lb. K_2O per A^{-1}	----------------------------					
B	38.7d	47.7c	49.6bc	50.9abc	57.5ab	57.6a	0.0013
E	71.0a	73.3a	75.0a	80.0a	78.2a	-	0.09
F	66.6a	71.2a	69.3a	68.2a	71.0a	71.2a	0.32
G	61.5d	65.2dc	66.0bd	80.6a	78.5abc	79.8ab	0.03

Means of actual yield followed by the same letter within a row are not significantly different at $\alpha = 0.05$

Table 3.9 Model, P value and R^2 for grain yield response to K fertilizer application at sites B, E, F, and G

Site	Model	P value	R^2
B	Quadratic Plateau	0.013	0.63
E	Linear Plateau	0.097	0.39
F	Linear	0.163	0.09
G	Linear Plateau	0.032	0.33

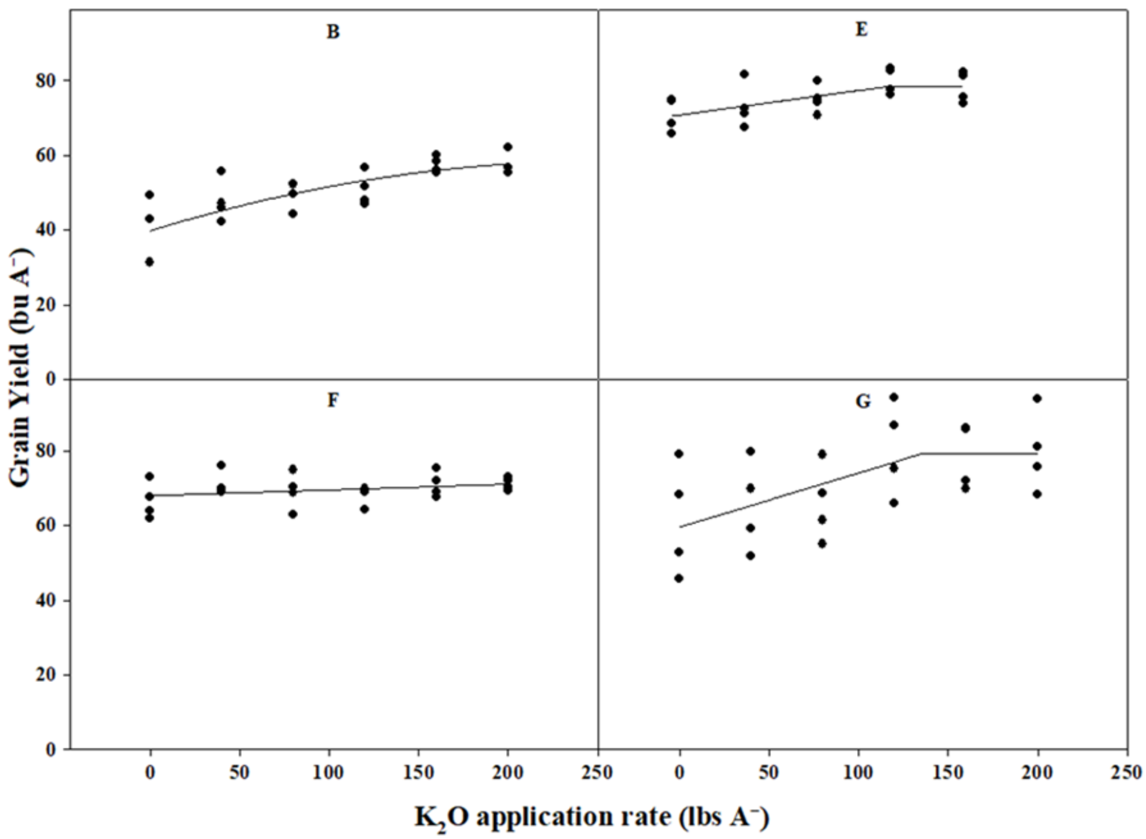

Figure 3.3 Soybean grain yield response to K fertilizer application at sites B, E, F, and G.

grain yield was predicted at 80 bu/A at the 140 lb. K_2O/A rate. Response to fertilization at low testing K soil sites B and G suggest that a significant increase is observed with fertilizer additions. Although no significant differences were observed among rates for site E and the model was not significant, the LP model does reach an inflection point similar to the models for sites B and G. The lack of a yield increase or leveling off point on the response curve of F was expected as it is a medium testing soil. The soils at this location were able to supply sufficient amounts of P without fertilizer additions. The results of the K response study suggest rates of 160 and 140 lbs K_2O/A are appropriate, which are higher than the University of Tennessee's current recommendations. Further investigation into K fertilizer response should be made, as existing rates may be too low, especially in low testing soils.

No crop response to nutrients in low testing soil

In soils testing low in P or K, crop response to nutrient application is likely. Soils at sites B, F, and G tested low for soil test P and site E tested low for soil test K, but exhibited no statistically significant crop response. This could be due to a shift in nutrient availability leading to higher available nutrients from the time of soil testing in the fall to the start of the growing season. Changes in microbial activity, climate, and other conditions will cause a shift in nutrient availability over a short period of time.

Conclusion

No yield response was observed for any site year for P response, while yield response to K was observed at 2 out of 4 site years. Lack of response at three low testing P sites and one medium-testing P site indicate no significant benefit from soybean P fertilization. Response observed at the 2 low-testing K sites suggest that significant yield benefits may be observed with K application. The models fit to P response data indicate no increase in current recommendations at this time. Models fit to the K response data suggest current recommendations are lower than the agronomically optimal rate. Additional investigation into UT's current recommended K rates is needed for further evaluation and updating for newer soybean varieties.

References

Adotey, N. (2022). Soil Fertility and Nutrient Management in Soybean. UT Extension Publication PB 1912-E. https://utcrops.com/wp-content/uploads/2022/11/Chapter-5-final-PB_1912-E_Soybean_Handbook.pdf

Duncan, L, Savoy, H., Walker, F., Essington, M., Buschermohle, M., Jagadama, S., Hawkins, S., Tyler, D., Florence, R., McClure, A., Raper, T., Allen, G., Qualls, D., Wilson, J. (2019). University of Tennessee Fertilizer Recommendation Development. Extension publication, W795. https://utia.tennessee.edu/publications/wp-content/uploads/sites/269/2023/10/W795.pdf

Duncan, L., H. Savoy, and D. Joines. 2015. “UT Fertility Recommendations for Tennessee Row Crops.” UT Extension, SP 763. https://extension.tennessee.edu/ publications/Documents/SP763.pdf

Helget, R. L. (2016). Soybean yield and plant response to phosphorus fertilization (Order No. 10164124). Available from Agricultural & Environmental Science Collection; ProQuest Dissertations & Theses Global. (1844998269). https://utk.idm.oclc.org/login?url=https://www.proquest.com/dissertations-theses/soybean-yield-plant-response-phosphorus/docview/1844998269/se-2

Hergert, G. W., Pan, W. L., Huggins, D. R., Grove, J. H., & Peck, T. R. (2015). Adequacy of current fertilizer recommendations for site-specific management. In *The State of Site-Specific Management for Agriculture* (pp. 283–300). wiley. https://doi.org/10.2134/1997.stateofsitespecific.c13

McClure, A. Introduction to Tennessee Soybean. 2022a. UT Extension Publication, PB 1912-A. https://utcrops.com/wp-content/uploads/2022/11/PB_1912-A_Soybean_Handbook_Ch1_WEB.pdf

McClure, A. Soybean production in Tennessee. 2022b. UT Extension Publication, PB 1912-D. https://utcrops.com/wp-content/uploads/2022/11/PB_1912-D_Soybean_Handbook_Ch4_PROOF_1.pdf

NOAA (National Oceanic and Atmospheric Administration). (2024). Daily Summaries. Retrieved September 16, 2024, from https://www.ncei.noaa.gov/cdo-web/search

Olson, R. A., Anderson, F. N., Frank, K. D., Grabouski, P. H., Rehm, G. W., & Shapiro, C. A. (1987). Soil testing interpretations: Sufficiency vs. build-up and maintenance. *Soil testing: Sampling, correlation, calibration, and interpretation*, *21*, 41-52.

SAS Institute Inc. 2024. SAS/STAT® 9.4 User's Guide. Cary, NC: SAS Institute Inc.

Savoy, H. (2009). Interpreting Mehlich 1 and 3 soil test extractant results for P and K in Tennessee. *University of Tennessee, Institute of Agriculture*.

Savoy, H. Soil Testing. 2013. UT Extension Publication, PB 1061. https://plantsciences.tennessee.edu/wp-content/uploads/sites/25/2021/11/Soil-testing-UT-Publication-PB1061.pdf

Savoy, H., & Joines, D. (2009). *Lime and fertilizer recommendations for the various crops of Tennessee. Chapter II. Agronomic crops*.

Singh, S., Savoy, H. J., Yin, X., Schneider, L., & Jagadamma, S. (2019). Phosphorus and potassium fertilizer rate verification for a corn–wheat–soybean rotation system in Tennessee. *Agronomy Journal*, *111*(4), 2060-2068.

Southern Cooperative Series. 2014. Soil Test Methods From the Southeastern United States. (Southern Cooperative Series Bulletin 419). Georgia Agricultural Experiment Station. https://aesl.ces.uga.edu/Sera6/PUB/Methodsmanualfinalsera6.Pdf.

USDA/NASS. (2019) *Fertilizer Use and Prices,* https://www.ers.usda.gov/data-products/fertilizer-use-and-price/. Accessed 27 July 2024.

USDA/NASS. (2023). *2023 State Agriculture Overview for Tennessee*, www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=TENNESSEE. Accessed 14 June 2024.

Zhang, H., Antonangelo, J., Grove, J., Osmond, D., Slaton, N. A., Alford, S., Florence, R., Huluka, G., Hardy, D. H., Lessl, J., Maguire, R., Mylavarapu, R., Oldham, J. L., Pena-Yewtukhiw, E. M., Provin, T., Sonon, L., Sotomayor, D., & Wang, J. (2021). Variation in soil-test-based phosphorus and potassium rate recommendations across the southern USA. Soil Science Society of America Journal, 85(4), 975–988. https://doi.org/10.1002/saj2.20280

VITA

Sydney Logwood was born in Portsmouth, Virginia. She moved around growing up, but ultimately finished high school in Nolensville, TN. After graduating high school Sydney attended the University of Tennessee in Knoxville, TN and graduated magna cum laude with a bachelor of science in environmental and soil sciences with a concentration in environmental conservation and agricultural sustainability. Sydney attended an internship in Jackson, TN where she worked as an intern under Dr. Nutifafa Adotey in the soils management lab at the West Tennessee AgResearch and Education Center. Sydney was interested in pursuing a graduate degree, and expressed this to Dr. Adotey. After seeing her work for a few weeks, he let her know he had an open graduate position and thought she would be a good fit. After meeting with the project's co-advisor Dr. Lori Duncan, based in Knoxville, TN, Sydney was offered the graduate assistantship. Sydney began her masters of science in environmental and soil sciences in at UT in Knoxville in January of 2023. Sydney finished her degree in December of 2024. Sydney's research interests include soil health and conservation, and she has a strong interest in conservation outreach and education. Post-graduation, Sydney will pursue a career in environmental or agricultural outreach and education. Sydney is grateful to have the support of the department as well as her friends, family, and rescue dog Diesel.