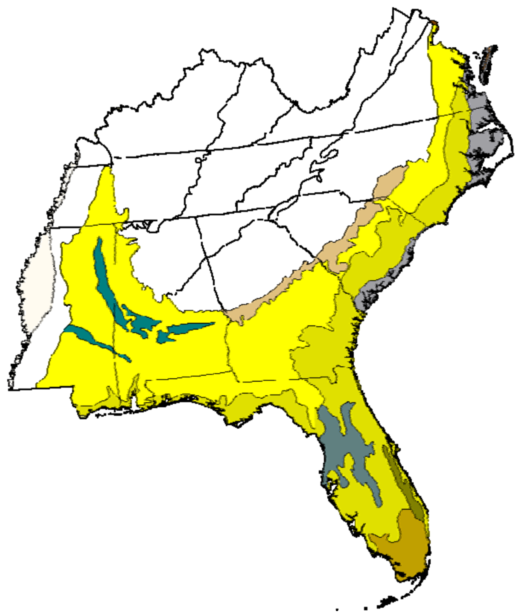
Research-based Soil Testing and Recommendations for Cotton on Coastal Plain Soils



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I. INTRODUCTION

C.C. Mitchell

The successful eradication of the cotton boll weevil in the southeastern U.S. during the 1990s and the advent of genetically modified crops that allowed better boll worm control ushered in renewed interest in cotton production on the predominantly sandy, Coastal Plain soils of this region. Cotton acreage expanded rapidly in southern Alabama, Georgia, and the Coastal Plain region of South Carolina, North Carolina, and Virginia during the 1990s into the early 2000s. Cotton growers wanted to know if existing interpretations and recommendations were suitable for the newer cultivars, higher yields, and modified production practices (e.g., conservation tillage and irrigation) used on this expanded acreage in the Coastal Plain region.

The objective of this publication is to review existing soil fertility research for cotton on Coastal Plain soils and to establish soil test calibration and nutrient recommendations for optimum production. A similar publication was produced for peanuts on Coastal Plain soils (Mitchell, 1994). Much of the traditional soil fertility research with cotton today may not be published in refereed journals. This bulletin will report relevant research and extension demonstration results. This bulletin may be used by both public and private soil test laboratories and crop advisors to establish a research-based, region-wide basis for soil test interpretations and recommendations.

The term "optimum production" is casually used by many researchers, extension specialists, and consultants to mean the highest possible yields and/or quality that any particular site is capable of producing under the normal limitations of weather, soil conditions, and production practices. When reporting soil test calibration research, optimum yield refers to the highest or near highest yield under the conditions of the experiment. Researchers may report a critical soil test value for optimum yield as being 95 percent of maximum yield. The optimum yield concept is much easier to justify in making research-based fertilizer recommendations than the "yield goal" approach of some laboratories. Yield goal is the yield that a producer expects to achieve based on overall management imposed and past production records (SSSA, 1997). Some modify this term with *realistic* yield goal. The yield goal approach to nutrient recommendations is used for N recommendations on grain crops and forages where large quantities of N are removed in the harvested portion of the crop. Nitrogen and sometimes K recommendations can be correlated with yield potential in grain and forage crops. However, correlation research with P, Ca, Mg, and micronutrients with yield potential is weak or non-existent.

This publication seeks to establish an unbiased basis for soil test interpretation and recommendations based on research that has been done with cotton on Coastal Plain and closely associated soils of the southeastern U.S.

A Note about Soil Test Units and Recommendations

Public soil testing laboratories have always tried to make soil test results and recommendations easy for producers to understand and use. This has led to differences among states and laboratories in the way soil test results are reported. These differences often lead to confusion when comparing results from one lab to another. For example, most laboratories run extractable plant nutrients using metrics such as milligrams per liter (mg/L or mg L^{-1}) for liquids or milligrams per kilogram (mg/kg or mg kg^{-1}) for solids. Some may use millimoles or centimoles per liter (mmol/L or cmol/L). Others may simply report parts per million (ppm) which is essentially the same as mg/L or mg/kg) or parts per billion (ppb) for extremely small concentrations. The North Carolina Department of Agriculture's laboratory has made strong arguments over the years that soil test results should be reported as milligrams per deciliter (mg/dL or mg dL^{-1}) because roots grow in a volume of soil and not a weight of soil (Mehlich, 1972, Tucker, 1984). If one knows the density of the soil being tested, one can easily convert from mg/L to mg/kg to mg/dL. Soil densities are not often reported on soil test results and will change in the field due to soil compaction and disturbance. To avoid confusion among farmers and other lab customers, the North Carolina laboratory reports results based on an index (Hatfield, 1972). An index of 50 is considered optimum. Different indexes among states can lead to further confusion in soil testing. In 1994, Alabama dropped a soil test sufficiency index where an index of 100 was considered sufficient because it was confusing to customers.

Many laboratories still report soil test results as "pounds per acre" of extractable nutrients. Technically, an acre is an area measurement. It has value when making fertilizer recommendations to be spread on a surface acre of land, but this value is really erroneous when reporting soil test results. Laboratories that use it assume that an acre of soil approximately 6 inches deep weighs about 2,000,000 pounds. Therefore, ppm or mg/kg x 2 = pounds per acre. Even though the term was intended to put soil test results into a form that farmers could understand, it also creates confusion. Some growers erroneously conclude that they can subtract the "soil test results" from the pounds per acre of nutrients contained in the crop at an expected yield.

To avoid confusion regarding units, this paper will report all soil test values of extractable nutrients as mg/kg. Recommendations for nutrients will be made in pounds per acre of N, P_2O_5, K_2O, etc. because all public soil testing laboratories use the same units for recommendations.

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II. SOILS OF THE SOUTHEASTERN COASTAL PLAIN REGION

C.C. Mitchell

The Coastal Plain physiographic region encompasses a large area from Maryland and New Jersey to Texas. All these soils were formed from marine sediments. However, for the purposes of this publication, emphasis will be on those well drained soils formed from sandy marine sediments along the Atlantic and Gulf of Mexico coastal regions from Mississippi through Virginia encompassing USDA-NRCS Major Land Resource Area 133A, Southern Coastal Plain (USDA-NRCS, 2006). The Coastal Plain region encompasses what may be known locally as Upper Coastal Plain, Lower Coastal Plain, and Coastal Flatwoods. Cotton is produced primarily on the Paleudults, Hapludults, Kandiudults, and some Fragiudults. Throughout the Coastal Plain region are broad river terraces formed from alluvial deposits. These are some of the most productive soils in the region. The state soils of Alabama (Bama series), Georgia (Tifton series), South Carolina (Lynchburg series) and Virginia (Pamunkey series) are all found in the Coastal Plain physiographic regions of these states.

Traffic pans can severely restrict root growth in some Coastal Plain soils.

Most Coastal Plain soils have surface soil textures ranging from loams to loamy sands with cation exchange capacities less than 9 cmol/kg. They tend to be naturally acidic throughout the soil profile although there are exceptions. The application of ground limestone (or other liming material) based upon a soil pH and lime requirement test is necessary to maintain a suitable pH for optimum cotton production (see Chapter XI)
.

Because of low soil organic matter (typically less than 2 percent) and the change in soil texture with depth, many Coastal Plain soils tend to develop traffic pans or plow pans following mechanical plowing or cultivation. A restricted root zone can limit moisture and nutrient uptake by cotton and create saturated zones during periods of heavy rainfall. A 1991 cotton survey in the central Alabama Upper Coastal Plain region that was repeated in 2001 indicated an average surface soil organic matter of 0.6% with 66 percent of the fields having traffic pans within the upper 10 inches of soil (Kuykendall et al., 2002). Although conventional tillage (moldboard plowing or chiseling followed by disking and mechanical cultivation) is still a common practice for cotton production on these soils, many producers have adopted conservation tillage practices that often includes in-row subsoiling or para-plowing and planting into old crop residue or a winter cover crop of rye, wheat, clover or vetch.

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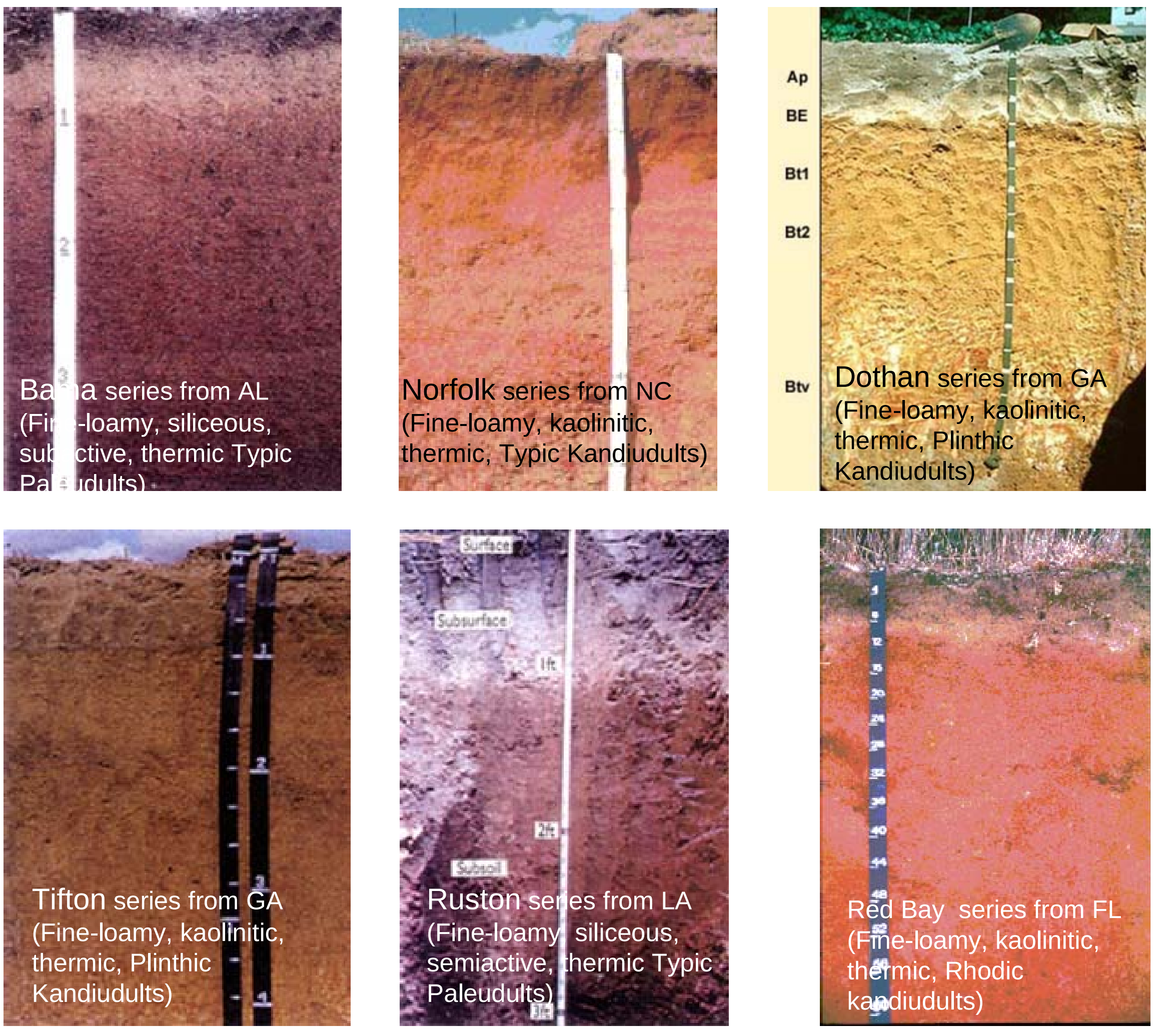

Examples of profiles of soil series from Coastal Plain sites where cotton could be produced.

III. SOIL SAMPLING FOR COTTON ON COASTAL PLAIN SOILS

Larry Oldham, Leticia S. Sonon, and David E. Kissel

Introduction

Determining the fertility status of soils through soil sampling and testing is one of the most important steps to attain success in crop production. Soil testing provides information on nutrient deficiency and availability for plant uptake and thus, guides the grower on determining the appropriate nutrient amendment that is compatible with crop needs. The overall goals of soil sampling and testing are (Peck and Soltanpour, 1990):

1. accurately determine the nutrient status of a soil;
2. convey to the manager the seriousness of any nutrient deficiency or excess;
3. form the basis for fertilizer decisions; and
4. allow an economic assessment of the fertility management options.

Moreover, increased awareness of environmental issues by growers has elevated the importance of soil testing for satisfying both plant nutrient needs and environmental stewardship.

Successful nutrient management based on soil testing depends on sound soil sampling procedures, i.e., to be able to collect samples that best represent a field or field area. The quality of the soil sample determines the relevance of the test results. Soil itself is heterogeneous; additionally, field variability in vegetation, terrain or slope, drainage, organic matter content, texture, and previous fertilizer application can all affect the uniformity of soil fertility. Errors in test results due to poor sampling are generally greater than those arising from the chemical analysis. Representative composite samples are crucial for reliable test results and interpretation, which will lead to optimum production, maximum investment return, and improved environmental quality.

Defining Fields or Samping Areas

Soil sampling should always begin with a field plan or map that defines different areas to be tested. Historically, farmers have used their personal knowledge of soils, soil characteristics, crop growth patterns, drainage, and other factors to delineate field areas that are sampled on a 'whole field' basis. With technological advances, farmers now have the option to use more intensive sampling patterns within fields on either geometrical grid patterns or user-defined soil management zones. Soil management zones are identified through criteria such as soil series, texture, drainage, yield maps, or use history. The methods used to choose either grid sampling or soil management zones is beyond the scope of this chapter. Growers may work with crop consultants, Extension personnel, or others to determine the best sampling pattern.

Soil Sampling

There are a few basic tenets to a better soil sampling program:

- use of proper equipment;
- random sampling in the field, grid, or zone;
- accounting for previous banded fertilizer applications;
- collecting samples from appropriate soil depths;
- compositing an adequate number of subsamples;
- consistent time of sampling from year to year; and
- proper handling of samples.

Equipment

Soil may be collected in several ways. Specialized soil test probes are available, but not absolutely necessary, for soil sampling. However, only stainless steel, or other non-reactive metal tools should be used to extract soil samples in the field. Stainless steel is preferred because some other materials react with the soil sample and produce skewed results for some metals. Galvanized metal equipment, for instance, will dramatically increase the zinc levels in a sample, as reconfirmed in the coastal plain region of Mississippi in 2007 (M. Howell, personal communication).

Random Sampling

Soil samples should be selected at random across the testing area in a random walk, zig-zag pattern when using a whole field basis. Soil sampling patterns within grids or management zones have been researched extensively in recent years (Anderson-Cook et al., 1999; Buscaglia and Varco, 2003; Flowers et al., 2005; Mallarino and Wittry, 2004). One option is “grid cell”, which considers each grid as a separate whole field, and sampled with a random walk. Another option is “grid point” where samples are obtained within a relatively small radius of a midpoint within the grid. Where in-field nutrient levels are thought to be relatively high, “grid cell” is the better option. “Grid point” should be better when in-field nutrient level variability is low. Fields with a history of banded phosphorus and/or potassium fertilizer applications should be noted. Approaches to sampling these fields are available in Clay et al. (2002).

Depth of Sampling

Fertilizer recommendations are generally based on the assumption that the samples were collected from the surface 6 inches of soil. However, broadcast application of immobile phosphorus and potassium fertilizers in minimum tillage production systems leads to stratification of these nutrients near the soil surface. When minimum or no till is used, a soil sample depth of four inches is typically recommended.

Number of Cores

A large number of soil cores should be composited to properly represent a field area, because variability of nutrients such as P and K are typically high due to lack of uniformity of previous years’ fertilizer applications. Soil variability of surface soil is also generally higher, and therefore more cores should be collected. In general, a composite sample of 20-30 individual borings should be taken to represent an area of 20 acres in size. Even smaller areas of 10 acres in size should have 15-20 cores composited.

Time of Sample Collection

Samples should be collected every year in multiple cropped fields in order to monitor fertility trends and use this information in managing the fertility program. For less intensive cropping, sampling every two to three years may be adequate. Soil test results for some nutrients, pH, and lime requirement vary by season due to climatic conditions, crop growth, and other factors (Kowalenko, 1991). For better consistency, fields should be sampled during the same month, whether on an annual or multi-year schedule.

Sample Handling and Record Keeping

Soil samples should be collected into clean plastic buckets and mixed well. Galvanized buckets should be avoided as they may contaminate samples if micronutrients are being tested. Cores should be broken up and well homogenized before taking a composite subsample for laboratory analysis. Most soil testing laboratories provide small moisture- resistant boxes, sacks or bags that hold about a pint of soil. These are preferred by the laboratories for operational ease, but if not available, samples may be submitted in plastic bags. Each sample box or bag should bear a unique identification that corresponds to the sample information given on the submission form

Complete field records should be kept and maintained, including field map and names, sampling points and timing, cropping and fertilization history, and other management activities undertaken. This information along with the soil test reports will allow monitoring the changes in the fertility status of fields and field areas over time.

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IV. SOIL TEST METHODOLOGY

C.C. Mitchell

Methods used by public soil testing laboratories in the Coastal Plain region are reported by Savoy (2009, http://www.clemson.edu/sera6/srbull190aug09version.pdf). Most of the state laboratories with cotton on Coastal Plain soils (AL, GA, FL, SC, TN, and VA) use the Mehlich-1 extraction procedure for P, K, Mg, and Ca. North Carolina uses the Mehlich-3 procedure. The Mehlich-3 procedure was designed to improve extraction of P and micronutrients (Zn, Fe, Cu, Mn) on soils with higher cation exchange capacities (CEC) and higher soil pH than the Mehlich-1 procedure. Modern analytical instrumentation (e.g., ICAP spectrophotometry) is allowing more and more laboratories to detect and report additional extractable nutrients using both the Mehlich-1 and Mehlich-3 extraction. Currently no public laboratory in the southern region routinely reports micronutrients on their soil test report although all laboratories may offer a micronutrient soil test as a special analysis. Most private laboratories report extractable micronutrients but interpreting these values are weak at best.

All public laboratories in the southeastern U.S. except the University of Georgia test soil pH using a 1:1 soil: water ratio but the method of determining lime requirement varies. The lime requirement test could result in some variability among different laboratories. In 2004, the Georgia laboratory switched to measuring soil pH in a 0.01 M $CaCl_2$ solution to reduce the season-to-season variability associated with fertilizer salts in sandy soils. The pH_{salt} values reported will generally be about 0.6 pH unit lower than traditional pH_{water} values. The laboratory reports both the measured pH_{salt} and an equivalent pH_{water} (http://www.clemson.edu/sera6/Soil%20pH%209-23-041.htm).

V. NITROGEN RECOMMENDATIONS

C.C. Mitchell and S. Phillips

Nitrogen (N) is the most difficult nutrient to manage in cotton production. Nitrogen is a primary constituent of plant protein, is required for photosynthesis and boll retention, and has more impact on yield, earliness, and lint quality than any other primary plant nutrient. Like all nutrients, apply too little N and yields drop; however, too much N can result in rank growth, slow fruiting, delayed maturity, and greater susceptibility to insect and disease pressure. It is also one of the highest input costs per acre for plant nutrients. In addition, excess soil N is a driving force behind water quality issues and nutrient management planning policies focused on reducing nitrate-N leaching into groundwater. Nitrogen is biologically active, is easily transformed into several chemical forms, and can be mobile in the environment. Thus, there are several factors that complicate making N fertilizer recommendations including inherent soil N supply, potential losses of both soil and fertilizer N, and predicting N availability of green manures, animal manures, composts, biosolids, and other N sources.

Soil Testing

Soil testing is the foundation for many nutrient recommendations. Measuring soil inorganic N prior to the season in dry climates is used to improve fertilizer N recommendations. However, N monitoring in the soils of the humid southeastern U.S. is not a widespread practice. Seasonal variations in inorganic N concentrations in these soils greatly affect the ability of a soil test to accurately predict soil N contributions to crop nutrient requirement in a given growing season. Jackson (1998) monitored nitrate and ammonium accumulation and movement under long-term N rate studies with cotton in two Alabama Coastal Plain soils, a Benndale sandy loam and a Lucedale fine sandy loam. Figure 1 illustrates how quickly N applied as ammonium nitrate in the spring can migrate through these soils by fall.

Current N Recommendations for Cotton

Rather than using an elusive soil test for monitoring N, states in the southeastern U.S. have developed N recommendations for cotton using N-rate experiments conducted throughout the region (Table 1).

Alabama is the only state that has on-going N rate experiments for cotton. Alablama's current, standard N recommendations were developed from these same N rate experiments in the 1950s and 60s, modified in the 1970s, and refined in the 1980s (Scarsbrook and Cope, 1957; Cope, 1970, 1984; Touchton et al., 1981). If cotton responds to N rates differently today, the difference would be expected to be a consequence of improved varieties, higher yields, and different management. Nitrogen-rate variables on long-term soil fertility experiments with cotton were summarized from 1992 through 2003 at five Alabama locations:

Benndale l.s. near Brewton, AL
Lucedale f.s.l. near Monroeville, AL
Lucedale s.c.l. near Prattville, AL
Dothan s.l. near Headland, AL
Decatur si.c.l. near Huntsville, AL

Figure 2 is a compilation of mean relative yields for N rates at each location over the period 1992-2003. Relative yield is the percentage yield of each treatment compared to the standard N rate of 90 pounds per acre. Cotton on Coastal Plain soils (all soils except the Decatur) appear to respond to N similarly and are combined into one curve with a near maximum yield at 90 pounds N per acre. Cotton on the finer textured, Decatur soil of the Tennessee Valley reaches a near maximum yield at 60 pounds N per acre, probably due to less leaching loss and some N retention. Other states have followed similar strategies by providing a range of recommended N rates and guidelines for adjusting N rates according to changes in soil properties (Table 1).

Recommendations among states in the Southeast are similar with suggested N rates in the 60 to 90 lb/acre range. This similarity is not surprising as cotton is largely grown on soils common throughout the region and average lint yield potentials are comparable among states.

Table 1. Standard total N recommendations (lb/acre/yr) for cotton in the southeastern U.S.

Alabama:	90±30 in split application for all soils
Florida:	60 in split applications
Georgia:	60 to 105 in split applications based on realistic yield goals of 750 to 1500 lb. lint/acre.
Mississippi:	50 to 60 per bale on "light-textured soils"; 60-70 per bale on "medium-textured soils"; split applications if over 100 lb N per acre applied.
North Carolina:	50 to 70 in split applications
South Carolina:	70±30 in split applications
Virginia:	60 to 90
Tennessee:	30 to 60 on bottom soils; 60 to 80 on upland soils

Yield Goals for Cotton

Two states in the region, Mississippi and Georgia, recommend N rates for cotton based on expected yield goal. Basing N fertilizer rate recommendations on expected yield is commonly used in grain crops such as corn and wheat as these crops remove large quantities of N in the harvested portion of the crop. However, because the cotton plant is by nature a perennial that is forced to grow as an annual, managing N solely based on yield goal is especially challenging and is not as widely used. Cotton plants take up 80 lb N/acre to produce one bale of harvested cotton. Of this 80 lb N/acre, approximately 32 lb N/acre is removed in the harvested crop. The yield-based system used in Georgia ranges from 60 lb N/acre for a 750 lb cotton lint yield (1.5 bale) to 105 lb N/acre for a 1500-lb crop (3 bale). This scale calculates into 40 lb N required/bale at the lower yield level and only 35 lb N/bale being needed at the highest yield level. This difference suggests that N use efficiency is much higher in the higher yielding environments, possibly due to more productive soil types due to increased water and nutrient retention, higher soil N contributions, or less risk of N loss. Mississippi also makes adjustments for apparent differences in N use efficiency recommending 50 to 60 lb N/expected bale on "light textured soils" and 60 to 70 lb N/bale on "medium textured soils". Yield-based N recommendation systems are subject to the uncertainty of annual yield estimates and the variable nature of crop response to N fertilizer applications from year to year. One of the problems with yield-based N rate recommendation systems is that they assume that crop responsiveness to fertilizer inputs is constant across locations and years. In other words, a high yielding crop always has a high N fertilizer requirement. Yield levels are known to vary widely in a given environment from year to year; however, crop responsiveness to N fertilizer also fluctuates as a result of the environment, independent of crop yield potential.

A summary of Alabama's long-term N-rate experiments on non-irrigated cotton from 1992 through 2003 demonstrates the extreme variability associated with cotton yield and responsiveness to N fertilizer application (Fig. 3). At the five sites illustrated in Fig. 3, non-irrigated cotton lint yields varied two- to three-fold over the years at a given location. What is especially interesting about these data is that these wide yield ranges occurred at a consistent N fertilizer application rate, showing a lack of relationship, for the most part, between response to N fertilizer and yield level. For example, at the Decatur site, the N rate needed to achieve the average lint yield over the 7-yr test period (1100 lb/A) was 60 lb N/A (Fig. 3e). However, in a low yielding year (800 lb lint/A) and the highest yielding year (1600 lb lint/A) the optimum N rate remained 60 lb/A, indicating the site's ability to adapt to changing yield potentials by supplying the N needed for the higher production levels. Similarly on a Lucedale soil (Fig. 3c and d), the recommended N rate of 90 lb/A was sufficient to sustain yield increases of approximately one bale/A in the highest yielding years. In the lowest yielding year, the 90-lb N/A rate resulted in decreased yield of 200 lb lint/A, probably due to rank growth and suggesting that a lower rate may have been needed (Fig. 3c and d). The Dothan site (Fig. 4b) is an example of where increased yield potential did warrant an increase in N fertilizer rate. However, the overall results of this study indicate that a yield-based N rate recommendation is not a reasonable approach for Alabama's non-irrigated cotton producing regions. Despite the reliance of some states on this method, it is expected that irregularity in the relationship between lint yield and optimum N rate, particularly under dryland conditions, will commonly occur throughout most of the Southeast.

Tissue Testing

Most N fertilizer rate recommendations, whether they be soil test- or yield-based, are made prior to establishing the crop or very early in the growing season. However, to be fully committed to matching nutrient supply with plant demand throughout the growing season, some in-season monitoring may be necessary. One of the more common in-season methods is plant tissue analysis.

Plant tissue analysis is the sampling of a diagnostic plant part and measurement of the nutrient concentration in the tissue or the sap from the tissue. Nutrient deficiencies identified by tissue testing can be corrected in some situations or direct corrective action for future crops. While a range of nutrient concentrations is often provided to help guide the plant nutrient analysis interpretation, adequate concentrations can vary with crop, variety, plant part sampled, growth stage when sampled, environment, geographic area, and other factors. Collecting tissue and soil samples from both 'poor' and 'good' areas of a field often helps to diagnosis nutrient deficiencies.

A comprehensive document providing interpretation of both petiole nitrate and leaf blade N for Southeast cotton has been reported in a web-based, Southern Coop. Series Bulletin (http://www.clemson.edu/sera6/scsb394notoc.pdf).

Optical Sensor Technology

A strategy for determining in-season N fertilizer application rates that is rapidly gaining popularity is the use of optical sensors. Most optical sensors currently being used for making N rate decisions are active sensors, meaning they have an internal light source, rather than using sunlight. The sensors emit light at specific wavelengths and measure the portion of the light reflected back to the sensor. The amount of reflected light is correlated with plant characteristics such as greenness (much like a chlorophyll meter) and biomass. One type of sensor that has been used to make on-the-go adjustments in N rate is the GreenSeeker®. This sensor measures reflected red and near-infrared light to calculate a vegetation index [Normalized Difference Vegetation Index (NDVI)], which has been correlated with leaf area index, leaf N content, and crop yield. The NDVI values measured by the sensors are entered into an algorithm using an on-board computer and an N rate requirement is calculated. Nutrient rate algorithm components vary by region, but most are fairly sophisticated taking into consideration several factors. Some of the factors used in various N rate algorithms include in-field reference measurements that are usually collected from "non-limiting" or "nutrient-rich" areas established earlier in the growing season to compare with the target measurements at the time of fertilization; consideration of spatial and temporal conditions that affect crop growth, soil nutrient availability, overall yield potential; and estimates of crop responsiveness to applied fertilizer that account for other nutrient sources such as manures or early-season mineral fertilizer applications.

Variable-rate N applications in cotton have not been developed as rapidly as in grain crops such as wheat and corn, probably for the same reasons that the yield-goal approach to N fertilization does not work as well for cotton as for grain crops. However beginning in 2008, Cotton Incorporated named sensor technology as its precision agriculture research focus. In addition to the internal work being conducted in their core program, Cotton Inc. is coordinating university research in 13 states across the US cotton producing regions. As part of this program, various methods to determine cotton N requirement using optical sensors are being evaluated. Researchers at Mississippi State University have established strong relationships between leaf N and sensor measurements across a range of cotton growth stages. The ability to use sensors to indirectly determine leaf N can result in accurate N rate recommendations without having to collect and analyze leaf tissue samples. Several southeastern states have not advanced past small-plot research work, but those that have taken the technology to grower fields are encouraged by the results.

Cotton Following Soybean or Peanut

A comment on soil test reports for cotton in Alabama recognizes that residue from a good soybean or peanut crop may contribute 20 to 30 pounds N per acre to the following cotton crop (Adams et al., 1994). The University of Georgia indicates that 30 to 40 lb N/A may be available following peanuts and Virginia Tech guidelines suggest that similar availability can be considered for a good soybean crop. The North Carolina cotton production guide indicates only 20 to 25 lb N/acre is needed to get the crop through sidedress time and if the crop is following peanut or soybean, no initial N may be required. Florida also recommends reducing the total N rate applied for cotton by 30 lb/A following a legume crop.

However, because as many as 6 months could elapse between soybean/peanut harvest in the fall and cotton planting the following April or May, much of the residual N may be lost from the cotton-producing soils in the Southeast. Data from N-rate treatments on a long-term cotton experiment in Alabama (circa 1929) verify the variable nature of residual N from legumes (Fig. 2).

Adjusting N Rates for Tillage, Irrigation, and Starter Fertilizers

In general, N rate recommendations for cotton under conventional, reduced, or no-tillage systems in the Southeast do not differ. An exception is when reduced or no-till cotton follows small grain. In this situation, an additional 30 lb N/acre may be recommended. Alabama guidelines indicate that this additional N may be applied as a starter, while Florida recommendations suggest a surface application to help decompose the straw residue so that N needed for plant growth is not limited.

Several studies throughout the Southeast have shown that starter fertilizers can enhance early-season growth, promote earlier fruiting, and increase cotton lint yields. Significant increases in lint yields were observed in 13 of 18 locations in Mississippi in 3-yr field trials. Significant lint yield increases were also observed in Louisiana studies evaluating both 3-inch surface-band and in-furrow applications. Other starter application methods include 2x2 band placements, where yield increases were reported for four locations over a 2-yr period in North Carolina. Responses to N-only starter applications have been observed, but most of the larger yield increases have been due to N and P being applied together, typically as 10-34-0 or a similar ammonium polyphosphate solution. Starter effects are also most commonly seen on soils where lint yield potential are greater than 700 lb/A and other good management practices are followed. Starter N applications will not be as effective when the complete N fertilization program is not managed responsibly.

Irrigation does not typically affect crop response to N fertilizer applications. Usually, irrigated cotton will yield more than dryland cotton, resulting in a higher N requirement, but the subsequent change in optimum N rate is tied to the increased yield potential, not directly to the presence of water. Thus, states in the Southeast do not have separate N recommendations for irrigated and dryland cotton production. However, some states warn growers that the need to split N applications will be greater under irrigated conditions as the risk for leaching losses is higher.

Summary and Recommendations

Producers in the Southeast should follow the standard N recommendations provided for their state and make adjustments as experience and cropping systems dictate. To best achieve their economic and environmental production goals, growers should strive to apply the appropriate N rate for their crop in the most efficient manner possible.

Some techniques growers can use to try and optimize N use efficiency in cotton include:

- Split or multiple N applications
- Starter fertilizers
- Appropriate N fertilizer placement
- Foliar urea (46-0-0) applications during bloom
- Petiole monitoring
- Plant leaf analyses
- Proper water management (irrigation timing)
- Plant growth regulators (e.g., Pix Plus®)
- Urease inhibitors for urea-based fertilizers
- Nitrification inhibitors
- Cover crops
- Computer programs and plant growth models (e.g., Gossym-Comax®, NLEAP®, EPIC®, COTMAN®)
- Real-time monitoring and precision N application.

Efficient N management in cotton, as well as all crops, involves selecting the right fertilizer source and applying it at the right rate, at the right time in the growing season, and using the right placement method for each specific cropping system.

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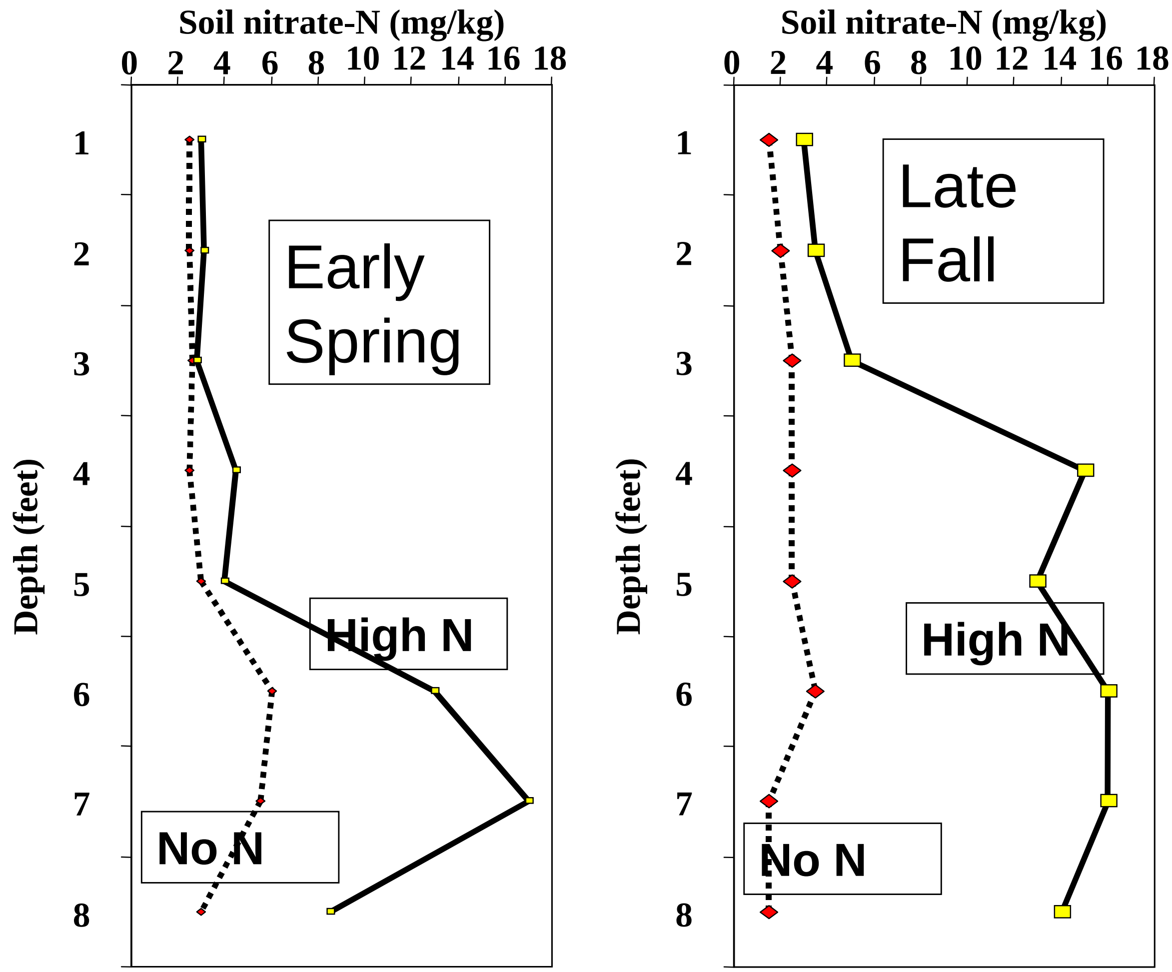

Fig. 1. Nitrate movement under cotton in a Benndale loamy sand fertilized with no N and 120 lb. N/acre/year (High N) (data from Jackson, 1998).

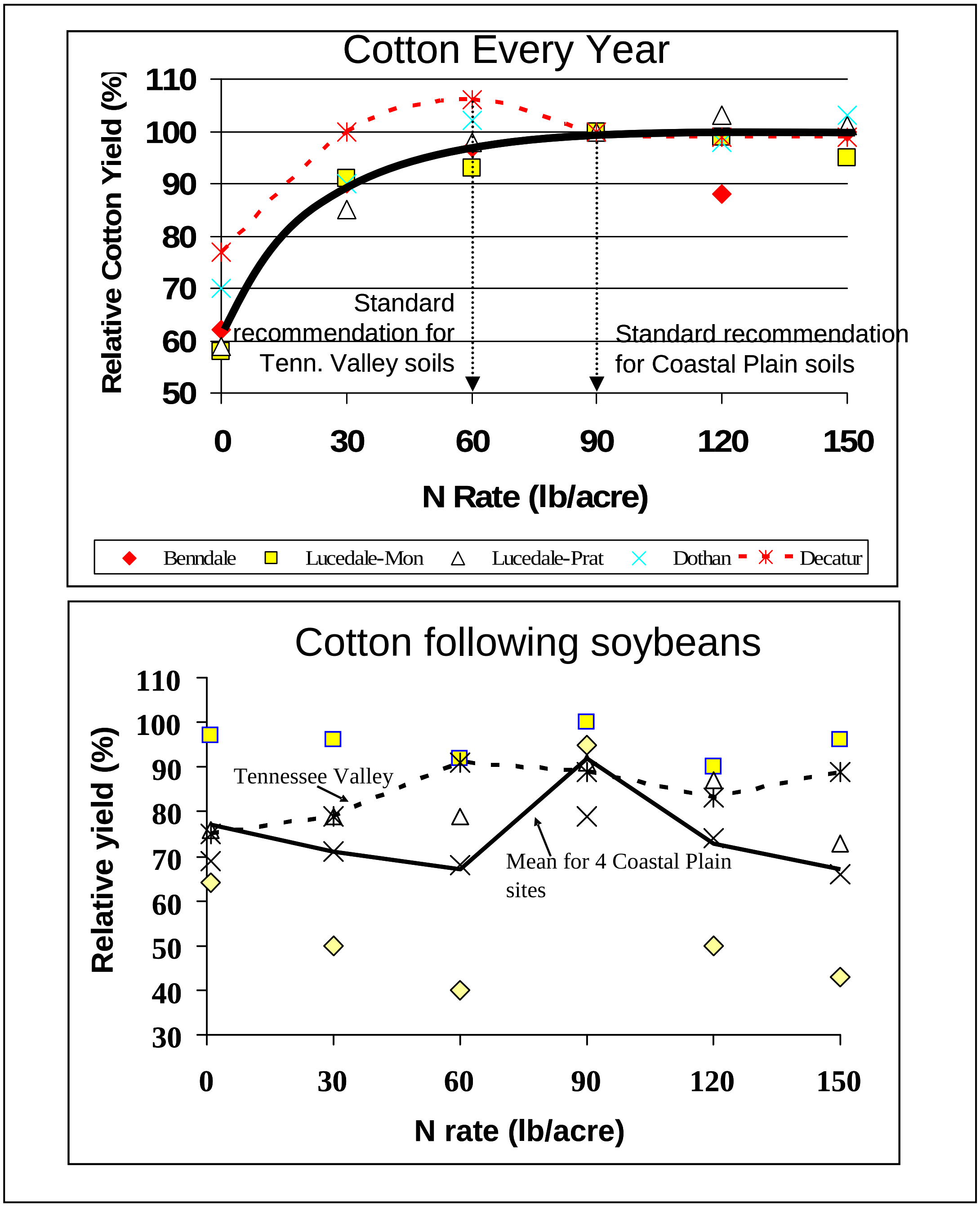

Fig. 2. Nitrogen rates where cotton is planted every year ("Rates of N-PK Test") and cotton following soybean ("Two-Year Rotation Experiment") at five Alabama locations, 1992-2003. Relative yield is the lint yield compared to the lint yield of a treatment receiving 90 pounds N per acre. All N is applied in split applications.

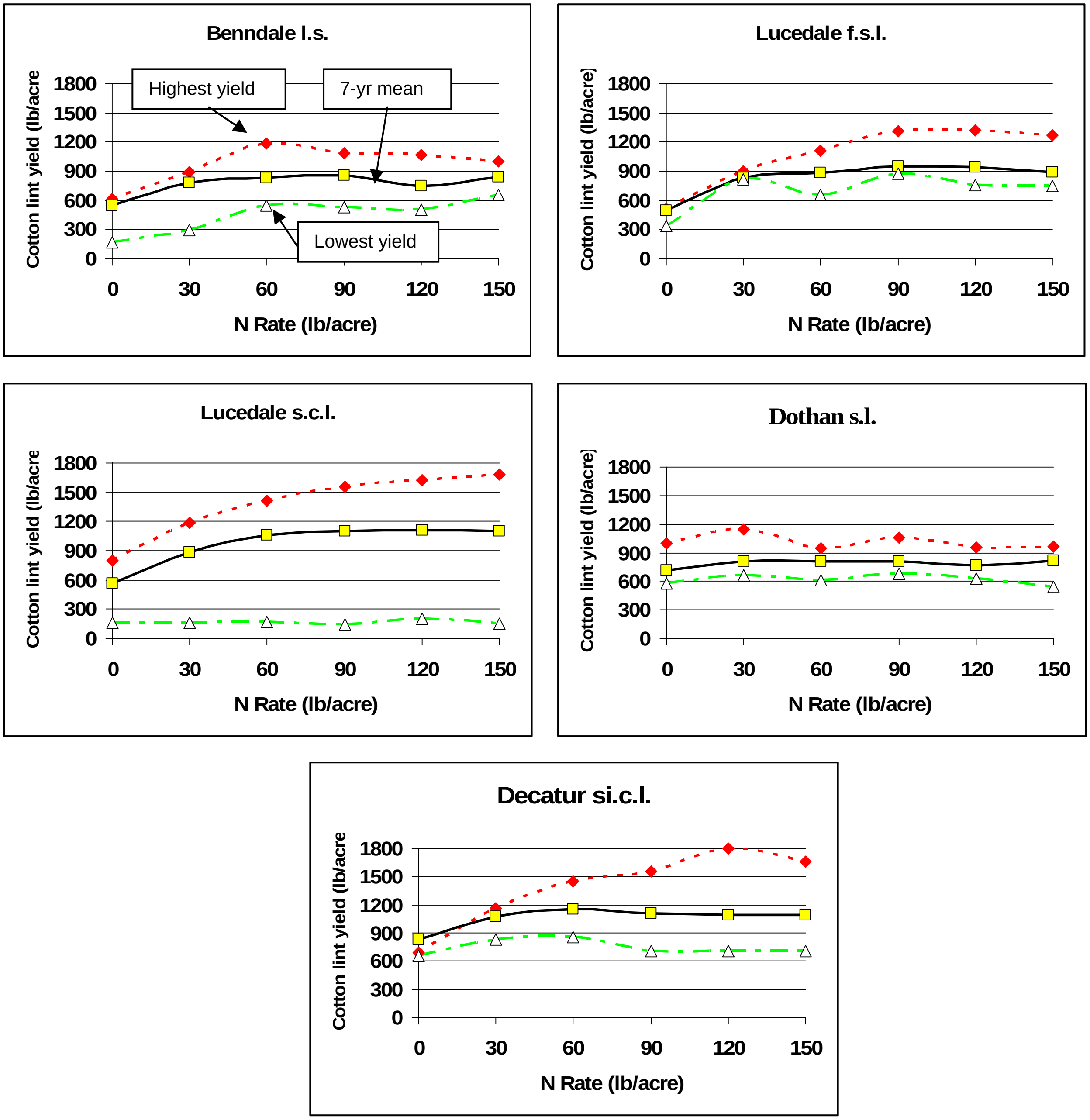

Figure 3. . Cotton yield response to N rates on the "Rates of N-P-K Test" (c. 1954) , 1992-2003, at five Alabama locations. Lines represent the highest yielding year, the lowest yielding year, and the mean of 7 years.

VI. MEHLICH-1 PHOSPHORUS

C. C. Mitchell

Mehlich-1 (dilute double acid) extraction is used by laboratories in Alabama, Florida, Georgia, South Carolina, Tennessee, and Virginia for testing Coastal Plain soils for P and other nutrients. Critical values for cotton range from 18 mg extractable P/kg to 30 mg/kg (Table 1).

Table 1. Calibration of Mehlich-1 extractable P for cotton by state soil testing laboratories in the southeastern U.S..

State	Soil test rating for P		
	Low	Medium	High (critical value)
	----Extractable P (mg/kg)-------		
Alabama			
CEC<9	<12.5	12.5-25	25+
CEC=9+	<7.5	7.6-15	15+
Florida			
All soils	<15	16-30	30+
Georgia			
Coastal Plain	<15	15-30	30+
Piedmont	<10	10-20	20+
South Carolina			
Coastal Plain	<15	15-30	30+
Piedmont	<10	10-20	20+
Tennessee			
All soils	<18	19-30	30+
Virginia			
All soils	<6	6-18	18+

Soil test calibration research on Alabama's long-term soil fertility experiments has tried to verify a critical Mehlich-1 extractable P value. Cotton lint yields relative to a high-P treatment were compared with residual extractable P on two long-term experiments at five locations from 1992 though 1997. All sites had treatments that had received no P fertilization and treatments with increasing residual soil P levels from up to 5 P rates prior to 1982. Treatments on all soils except the Lucedale s.c.l. at Prattville Experiment Field would be rated "low" by the southern public soil testing laboratories (Table 1). In some years and locations, the experiments failed to demonstrate any response to increasing levels of residual soil P. Failure to get dramatic responses all the time demonstrate the inherent difficulties of trying to make soil testing a definitive and infallible tool. However, when yield and soil data from both tests at all Coastal Plain locations over the entire 7-yr period are pooled (Fig. 1), a reasonable critical value for Mehlich-1 extractable P can be estimated. The current critical value used by the Auburn University Soil Testing Laboratory for these soils is 25 mg P/kg. The Soil Science Society of America (1997) defines *critical soil test concentration* as ". . . that concentration at which 95% of maximum *relative yield* is achieved. . . usually coincides with the inflection point of a curvilinear yield response curve." Above this value, no fertilizer P is recommended because the probability of a yield response is extremely low. Below this value, P is recommended in increasing increments. Alabama's critical value is within the range used by other public soil

testing laboratories in the region for Mehlich-1 P and cotton on Coastal Plain soil (18 to 30 mg P/kg). No attempt was made to fit a regression to these data because the purpose was to determine if the current critical values are still valid for modern yields, cultivars, and production practices. Evans (1987) summarized calibration results in on-farm tests for 7 Alabama crops on Coastal Plain soils and found a critical Mehlich-1 extractable P level of 18 mg/kg, somewhat lower than the 25 mg/kg value that has been used. He used the following regression for the responsive region of the curve in Fig. 1.
:

$$\textit{Relative yield} = 54.6 + 4.86\,(M\text{-}1\ P) - 0.132\,(M\text{-}1\ P)^2$$

The fine-textured soils of the Tennessee Valley have a high P fixation capacity and a lower critical P value as currently used by the Auburn University Soil Testing Laboratory (Adams et al., 1994). These data verify the current value of 15 mg P/kg for these soils (Fig. 1). Other state laboratories also recognize lower critical values for finer textured soils (Table 1).

The current soil test calibration for P on cotton as used by the Auburn University Soil Testing Laboratory was established by Rouse (1968) and verified and updated in numerous Alabama Agricultural Experiment Station reports since then (Cope, 1970, 1983, 1984; Burmester et al., 1981; Adams et al.; Cope et al., 1981). While the 25 mg P/kg value used for Coastal Plain soils (soils with CEC < 9.0 cmol/kg) is higher than that proposed by Evans (1987) and will result in more P fertilizer recommended for cotton than Evans suggested, it is still a reasonable critical value considering values used throughout the region. These data provide no evidence that P fertilization should be adjusted for yield goal (Cope and Rouse, 1973).

Because no additional P fertilization is recommended when M1 extractable P is rated "High" (25+ mg P/kg), growers often ask, "How many years can I grow crops before I have to resume P fertilization?" This question was addressed by the same experiments that established the calibration curve for cotton (Fig. 1). In these experiments, direct P applications were stopped from 1982 to 1998, a period of 16 years. Only one treatment continued to receive annual P applications and this treatment was used as the basis for calculating relative yield, e.g. the mean cotton yield of the fertilized control was 100% yield. All other treatments were compared to the fertilized control. Mean cotton lint yield, highest yield, and lowest yield for the control during the period 1992-1998 are presented in Table 2.

Table 2. Mean yield, highest yield, and lowest yield for cotton lint on the fertilized control treatment on long-term soil fertility experiments at 5 Alabama locations, 1992-1998.

	Cotton lint yields (pounds per acre)		
Soil series (location)	Mean	Highest	Lowest
Benndale l.s. (Brewton)	1020	1570	380
Dothan.s.l. (Headland)	760	890	610
Lucedale f.s.l. (Monroeville)	880	1140	700
Lucedale s.c.l. (Prattville)	1110	1500	390
Decatur si.c.l. (Belle Mina)	1150	1420	660

Composite, plow layer soil samples were collected every other year from each plot. Mean soil test P did not change very much during the entire 16 years at three of the five sites (Fig. 2). Grain crops (corn, wheat, soybean, and sorghum) and cotton were planted and harvested throughout the period. Soil test P did drop gradually on the highest rate of the Dothan soil because no P was applied to this treatment. Data from the Dothan soil was from a different experiment. Therefore, continuous cropping under the conditions of these experiments will have little effect on soil test P over a 16-yr period. Once soil test values reach a "high" rating, growers can expect them to stay near this value for many years even with no additional P fertilization. In fact, at all sites, "high" soil test P levels in 1982 remained "high" in 1998 although the actual values may have dropped where no P was applied.

Summary and Recommendations

Data from long-term fertility experiments in Alabama verify that the currently used critical values for Mehlich-1 extractable P for cotton on Coastal Plain soils in the Southeastern U.S. appear reasonable although critical values range from 18 to 30 mg P/kg depending upon state and soil textures within states. Above the critical value, no yield response to additional P is expected. These same experiments demonstrate that Mehlich-1 P values will drop very slowly due to cropping. In a 16-yr study, values that were high at the beginning of the experiment, remained high (above critical value) 16 years later although cropped to cotton and grain crops during this period.

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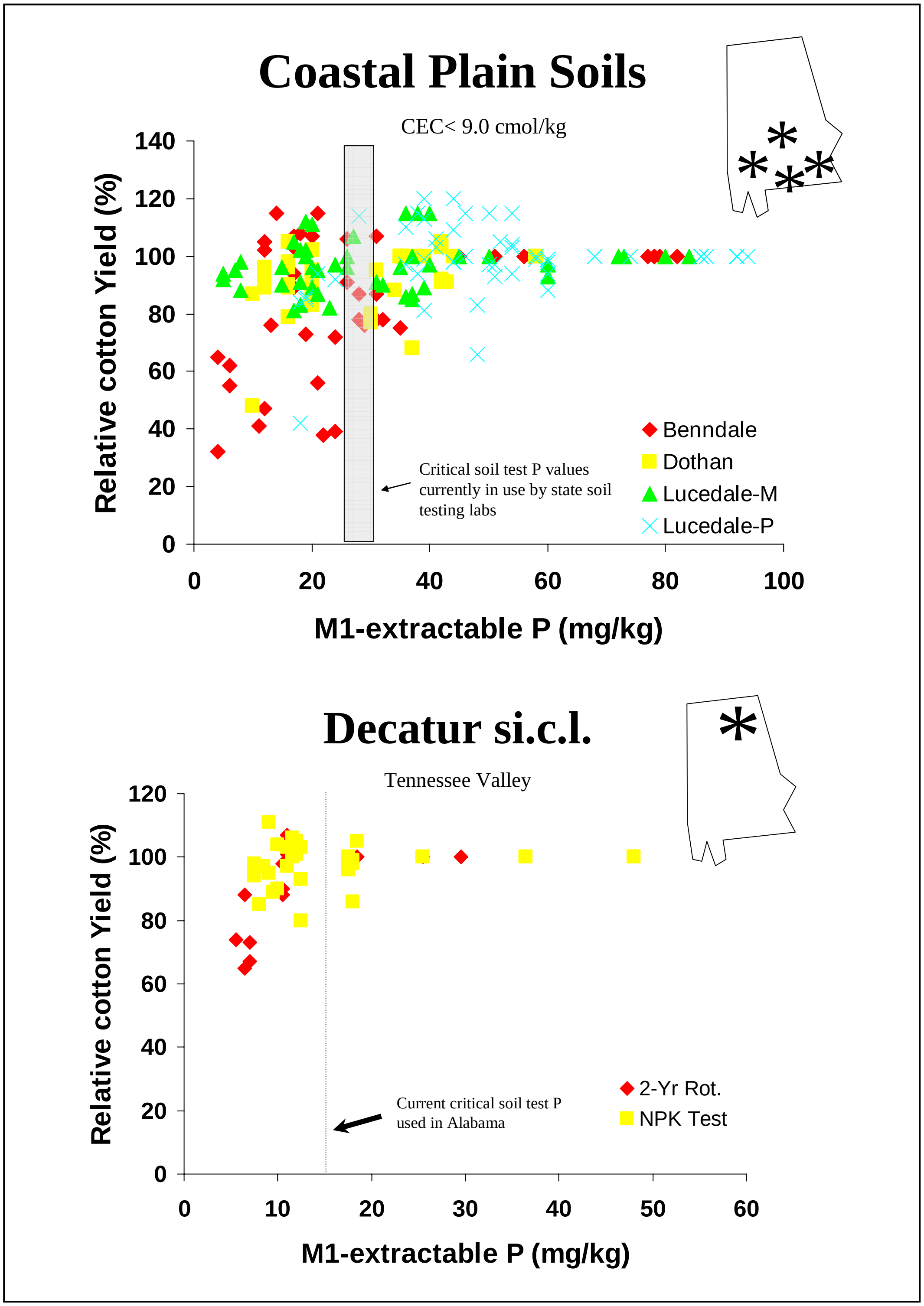

Fig. 1. Mehlich-1 soil test calibration for cotton based on data from Alabama's "Two-year Rotation" and "Rates of N-P-K" experiments at five Alabama locations. Shaded area includes the current critical Mehlich-1 extractable P values used by public soil testing laboratories in Alabama, Georgia, Florida, South Carolina, and Tennessee. All Coastal Plain soils in these experiments had CEC < 9.0 cmol/kg.

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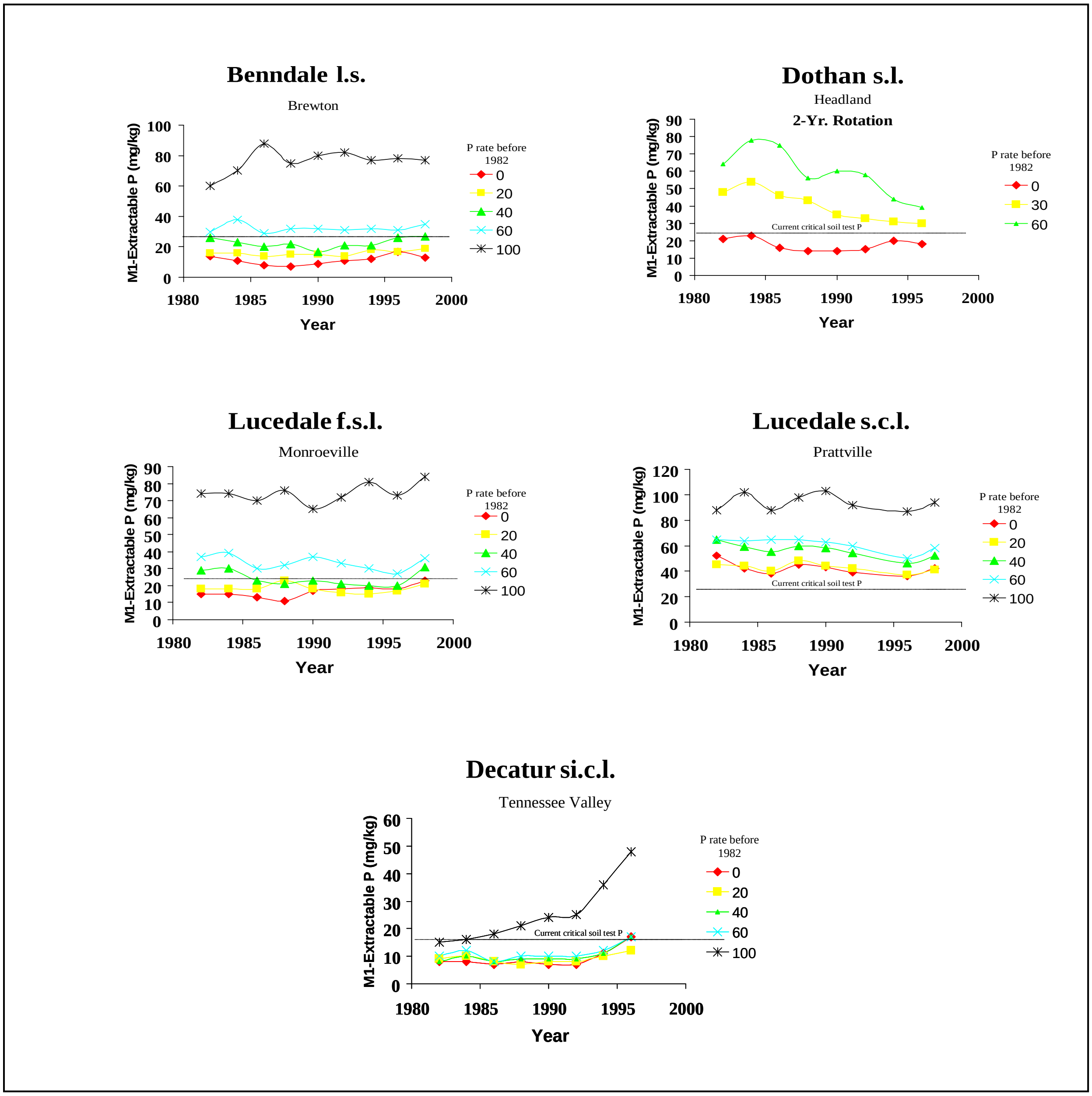

Fig. 2. Change in Mehlich-1 extractable P at five Alabama locations over 16 years. Only the highest P rate (100 lb. P_2O_5/acre/yr) was applied; the other rates were applied prior to 1982. The Dothan s.l. had no P applied to any of the treatments.

VII. MEHLICH-3 PHOSPHORUS

Carl R. Crozier and David H. Hardy

Mehlich-3 extraction is used by laboratories in Arkansas, Kentucky, Louisiana, North Carolina, Oklahoma, & Pennsylvania for testing soils for P and other nutrients (Hardy et al., 2007). The Mehlich-3 extractant was developed and adopted for routine use by the North Carolina Department of Agriculture & Consumer Services Agronomic Division Laboratory because it improved correlations between soil test P and crop yield over the Mehlich-1 extractant (0.05 N HCl + 0.05 N H_2SO_4), and was also effective in quantifying soil K, Ca, Mg, Na, Cu, Mn, and Zn (Mehlich, 1984).

Mehlich-3 critical P levels have been characterized for grain crops (Cox and Lins, 1984; Cox, 1996), and Irish potato (Solanum tuberosum L.) (McCollum, 1978) in North Carolina. Limited data are available for cotton, but reports include critical levels of 13 to 19 mg P kg^{-1} (Cox and Barnes, 2002) and 22 to 42 mg P kg^{-1} in North Carolina (Fig. 1, 2; Crozier et al., 2004), and 33 mg P kg^{-1} for cotton on the Texas High Plains (Bronson & Bowman, 2004; Booker et al., 2007).

Statistical analyses typically use linear-plateau regression to evaluate the effect of soil or plant tissue P concentration on seed cotton yield (Crozier et al., 2004) with the lower limit of the plateau portion of the function considered to be the critical level (Cate and Nelson, 1971). Crop responses to nutrient levels can also be characterized using analysis of variance, exponential, or quadratic-plateau functions. Nevertheless, the linear-plateau method provides a simple quantification of the critical level, independent of fertilizer and cotton price fluctuations (Cate and Nelson, 1971; Dahnke and Olson, 1990; Cox, 1996). Differences among studies could be due to soil, variety, or other climatic variables, but the North Carolina studies highlight the need to insure adequate fertility levels for other nutrients. Limitations due to K may have reduced yield response to P in the earlier years (Fig. 3; Cox and Barnes, 2002; Crozier et al., 2004).

General principles derived from studies with other crops that are probably applicable to cotton include soil texture effects, a need to account for variability in developing commercial fertilizer rate prescriptions, lack of correlation between critical level and yield level, and temporal fluctuations in soil test P associated with fertilizer addition and crop removal.

Studies with corn (Zea mays L.) document that the response to soil P gradients depends on soil clay content (Cox and Lins, 1984; Cox, 1994a). Their model suggests critical levels for corn ranging from < 20 to 125 mg kg^{-1} as clay content decreases from 40 to 5% (Fig. 4).

Since research estimates of critical P levels can vary substantially due to random experimental errors, soil test P variability, and textural variability, Cox (1992) presents justification for soil testing laboratories to recommend fertilization at P levels up to 50% greater than the average experimental critical level. According to this principle, and considering average critical levels for North Carolina as 40 mg P kg^{-1} in the tidewater region and 28 mg P kg^{-1} in the coastal plain, P fertilization would be recommended at soil test levels up to 64 mg kg^{-1} in the tidewater and 45 mg kg^{-1} in the coastal plain. This estimate yields results similar to projections of Cox and Lins (1984, Fig. 4) for soils with 10-20% clay, which are typical for these regions. For simplicity and due to the limited amount of calibration data, a single P recommendation function is used in North Carolina (Fig. 4).

Cox (1992) reported little correlation between critical P level and grain yield for corn and soybean. Perhaps this needs to be investigated for cotton, but no trends have been apparent and crop yield levels have been typical for the region in North Carolina studies to date.

The effectiveness of applied P to change extractable P has been shown to vary with clay content (Cox, 1994b). Mehlich-3 extractable P increases more (0.7 units per unit applied P) on soils with 10% clay than on soils with 40 to 50% clay (0.2 units per unit applied P). Thus, soils with higher clay contents are expected to have both lower critical levels and to show a lower extractable P response to fertilization than are soils with lower clay contents.

As with soil gradients, yield increases as the concentration of P in leaves increases (Fig. 1, 2). Mean critical tissue P levels appear to be relatively stable during the vegetative & early bloom period (2 to 3 g kg^{-1}), perhaps declining to 1.5 to 2 g kg^{-1} at later stages (Fig. 5).

Summary

Very limited data suggest critical Mehlich-3 soil P level to be 45-64 mg P kg^{-1} for coastal plain soils in North Carolina. These are similar to projections of a model derived for corn based on both soil-test P and clay content. Critical soil P levels in the most recent years with additional fertilizer K (Crozier et al., 2004) are much higher than those reported by Cox and Barnes (2002), apparently due to K limitation in the previous experiment. Critical leaf P levels are relatively stable across the vegetative and early bloom period.

The limited number of P-responsive sites in Cotton Belt states presents an opportunity for regional coordination for further understanding the relationship between soil fertility gradients, plant tissue concentrations, and crop yield. Preservation of these few existing sites is crucial since fertility levels on much commercial and research station farmland has already been fertilized to levels near or above critical levels. In some cases, several years might be required for sufficient crop nutrient removal to result in fertility levels low enough to detect responses to added fertilizer (Cox et al., 1981). A more credible fertility response database should enhance acceptance of research-based recommendations, and should enhance farm profits and reduce environmental impacts of farming.

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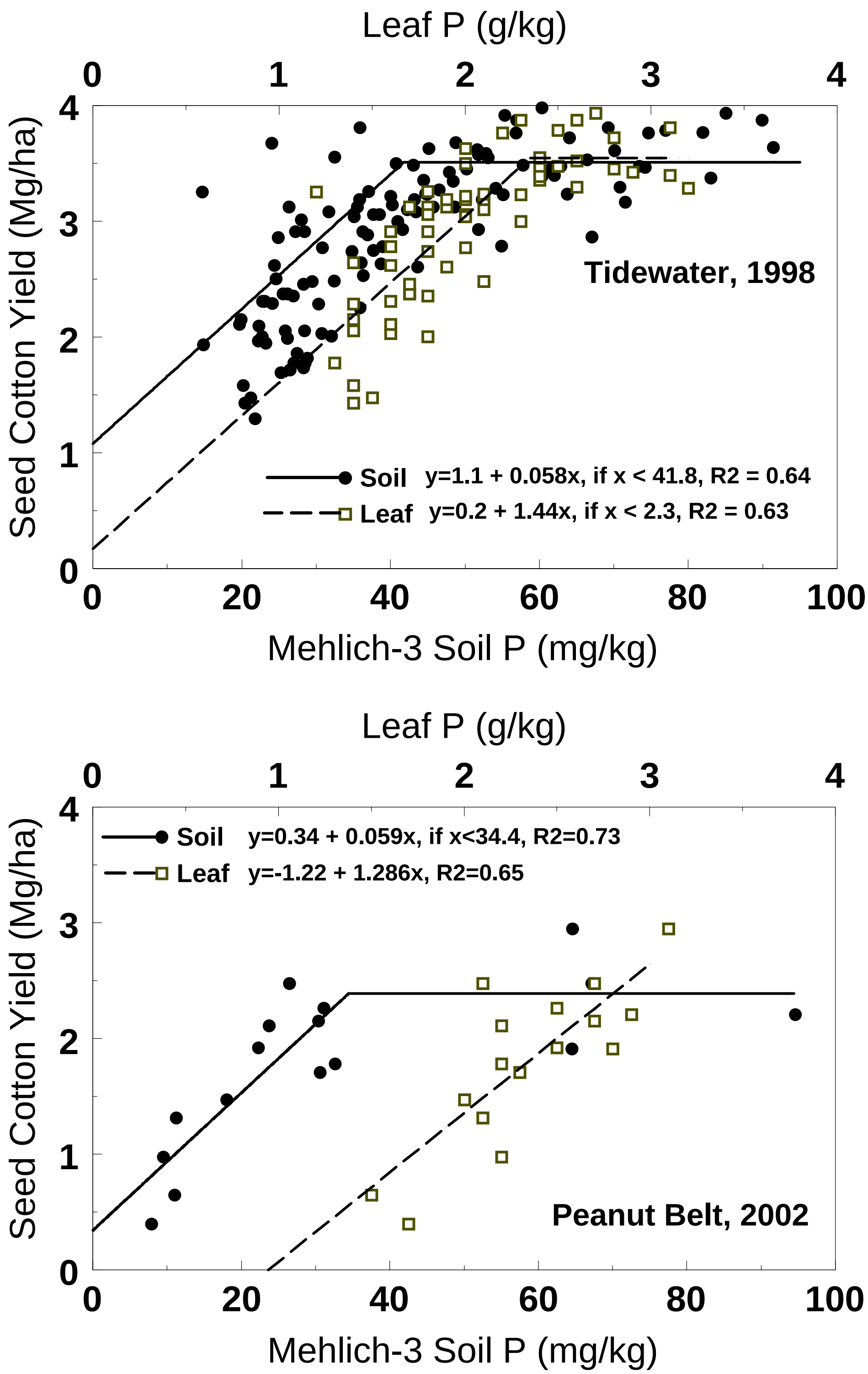

Figure 1. Yield response of cotton to soil and plant P levels at the Tidewater Research Station (a) 1998 and (b) 1999. Plant tissue results are for samples collected one week after first bloom. Each data point represents a single experimental plot.

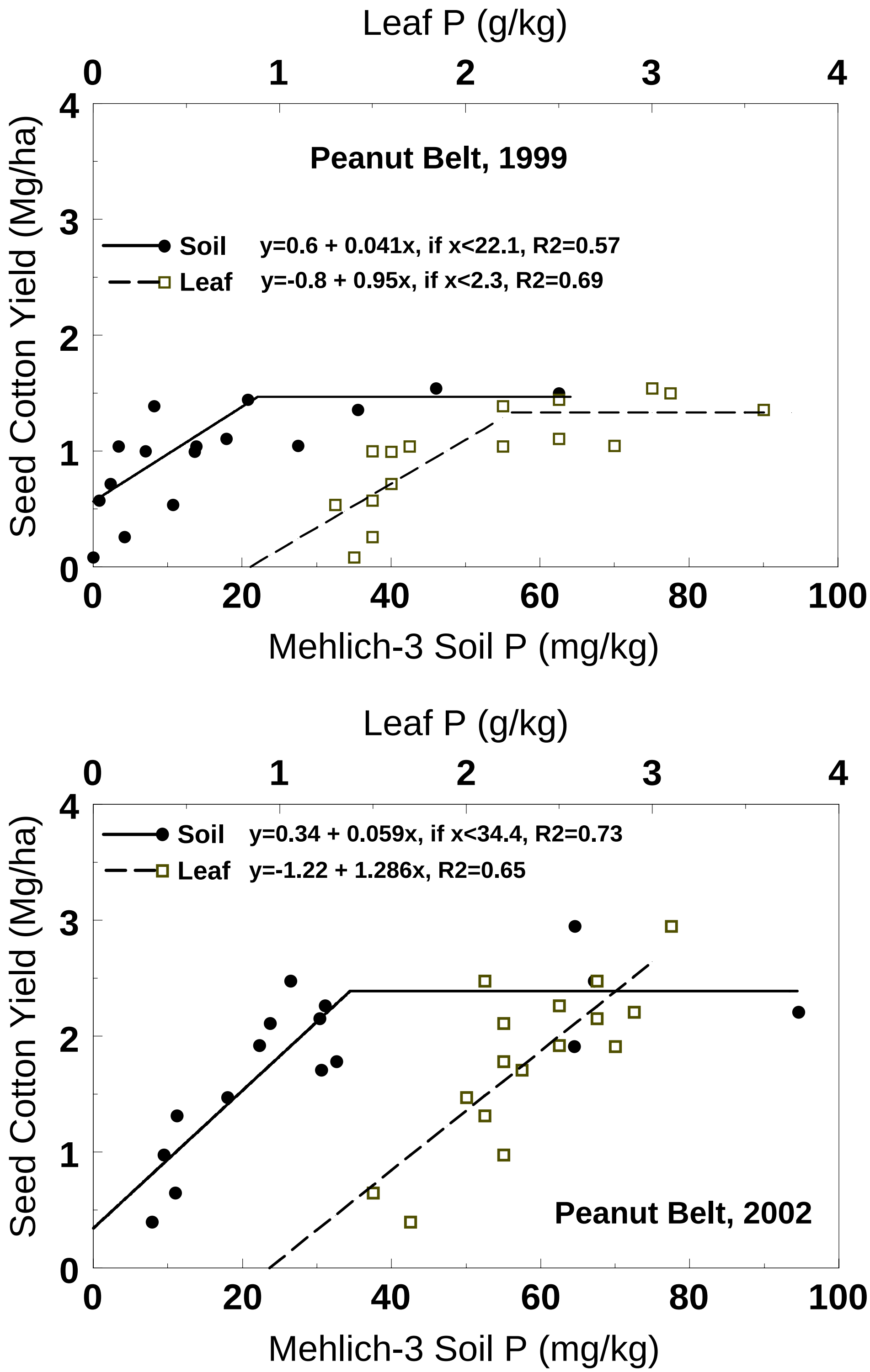

Figure 2. Yield response of cotton to soil and plant P levels at the Peanut Belt Research Station (a) 1999 and (b) 2002. Plant tissue results are for samples collected one week after first bloom. Each data point represents a single experimental plot

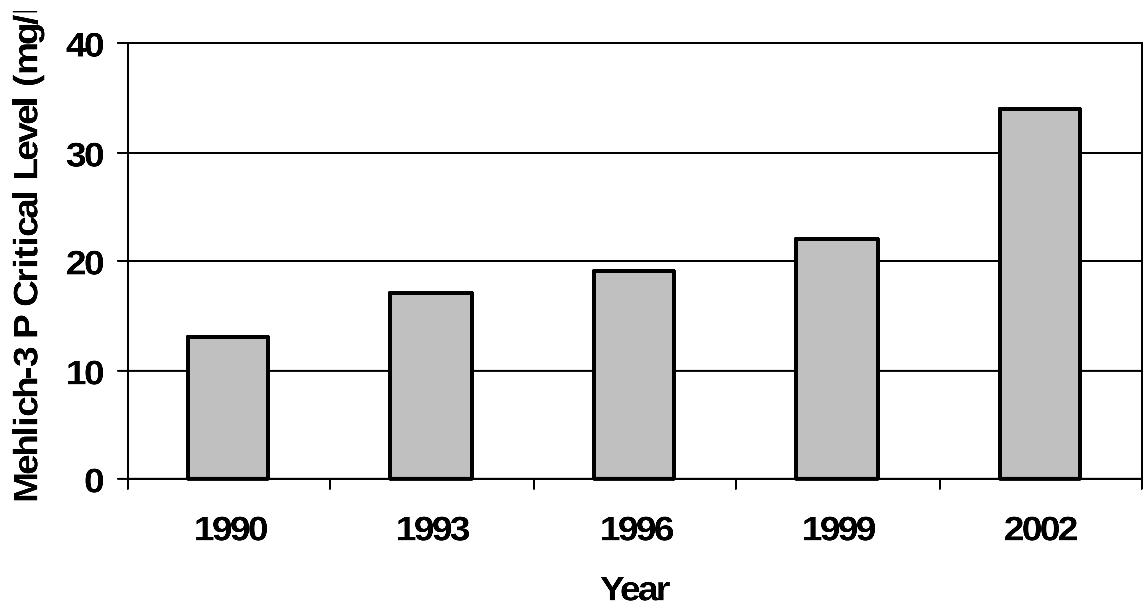

Figure 3. Critical Mehlich-3 soil P levels at the Peanut Belt Research Station from 1990-2002. Fertilizer K rates increased as indicated during this interval (Cox & Barnes, 2002; Crozier et al., 2004).

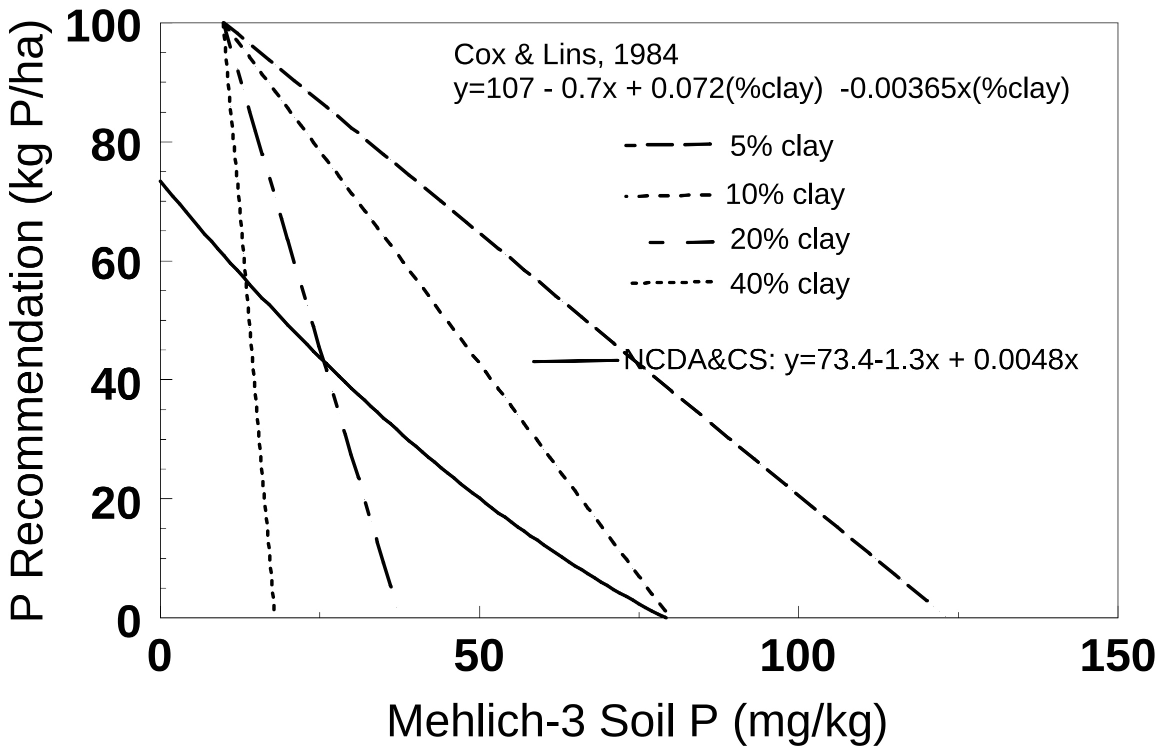

Figure 4. Recommended P fertilizer rates for corn based on soil Mehlich-3 P and clay content (Cox & Lins, 1984) and the North Carolina Department of Agriculture & Consumer Services (NCDA&CS) guideline based Mehlich-3 P alone (Hardy et al., 2007).

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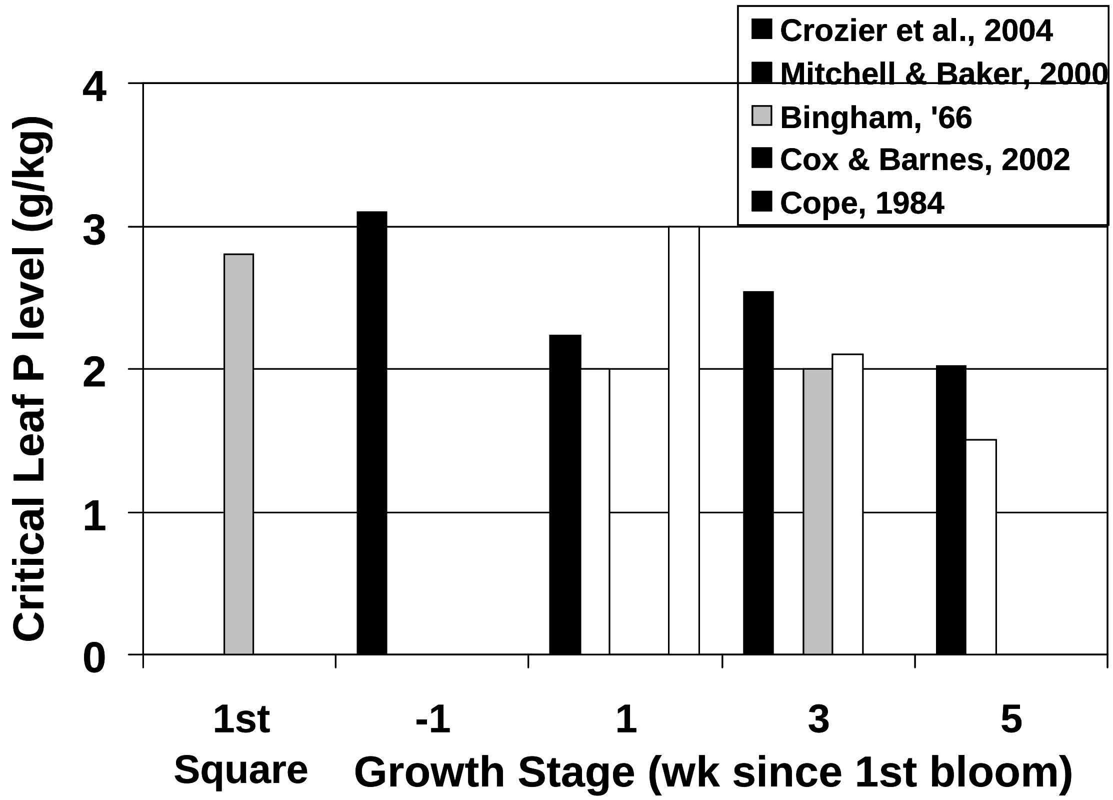

Figure 5. Critical leaf P levels at different growth stages from selected publications.

VIII. MEHLICH-1 POTASSIUM

C. C. Mitchell

Potassium nutrition of crops on acid, infertile Ultisols of the southeastern U.S. has always been a concern, especially for cotton which is susceptible to K deficiencies. With increasing acreage and yields of cotton on these soils, new varieties, eradication of the boll weevil, and new technologies for insect control, K nutrition is of renewed concern to growers. Alabama's "Two-year Rotation" experiments at 6 locations (c. 1929) have provided information for fertilizer recommendations and data for soil test calibration since their beginning (Cope, 1970, 1981, 1984). In 1982, these experiments were put into a residual P and K mode for 15 years. Cotton has been a principal crop in these experiments for 46 of the 69 years from 1929 to 1997. Since 1992, they have been in a cotton-soybean rotation. Therefore, these experiments offer an excellent opportunity to study soil K changes with time and re-evaluate K nutrition of cotton. Mehlich-1 extractable K has been analyzed from most of the plots in these experiment periodically since 1954.

In 1982 when annual K applications ceased on all treatments except the 56 kg K ha^{-1} treatment, the two highest K treatments were at or above what was considered to be a "high" soil test K level for cotton (Fig. 1-2). A "high" soil test is above an established critical value and is defined as an adequate supply of that nutrient; no additional application of that nutrient is recommended (Adams et al., 1994). On the finer textured soils (Decatur and Lucedale series), soil test K changed very little during the following 15 years when no additional K was applied (Fig. 2). Applications of 56 kg K ha^{-1} to cotton since 1982 resulted in only a slight trend toward increasing levels of extractable K in the plow layer. These data suggest that once these more highly buffered soils reach a "high" level of soil test K, they may be cropped to cotton and soybeans for several years before K becomes a limiting factor.

At the same time, applications of 56 kg K ha^{-1} will maintain or slightly increase soil test K. This is reasonable considering that 1120 kg lint ha^{-1} (about 2 bales per acre) would remove only around 25 kg K ha^{-1} (27 lb. $acre^{-1}$) (Mullins and Burmester, 1990). However, on the sandier, weakly buffered soils of the Coastal Plain, the Benndale and the Dothan series, there were gradual declines in soil test K during the 15-yr residual study (Fig. 1). Although 56 kg K ha^{-1} were applied each year to cotton in the standard treatment, after 15 years plow-layer K was at or below the critical value for cotton for all treatments.

Further differences in the K buffering capacity of these soils are evident when extractable profile K is examined at three of the five sites included in this study (Fig.3) (Netshivhumbe (1992). In the Lucedale and Decatur soils, K accumulated in the upper soil horizons. Highest K levels were in the Ap horizon. However, in the weakly buffered Benndale ls at Brewton Experiment Field, highest extractable K was found in the upper part of the argillic horizon between 20 and 40 cm. Because of the low CEC of this soil, much less total K accumulated in the soil profile compared to the finer textured soils. There is a trend toward lower yields on the weakly buffered soils (Table 2).

Mean cotton lint yield from each residual K treatment was compared with mean yield for the standard fertilization treatment that received 56 kg K ha^{-1} to calculate a relative yield. Relative yield is expressed as a percentage of the standard treatment yield. Relative yield by location and year was then compared to the mean soil test K value for each treatment at that location to develop a soil test calibration for cotton for the period 1992 through 1997 (Fig. 4). There has been much grower concern that with higher yielding, earlier maturing, modern varieties, soil test calibration for K on cotton needs adjusting. However, these data indicate that the sufficiency level approach to *critical K values as used by the Auburn University Soil Testing program in Alabama (Adams et al., 1994) is still very reliable and accurate*. The weakly buffered soils with a CEC ≤ 4.6 cmol kg^{-1} (the Dothan and Benndale series) are included in one graph and the two Lucedale soils (CEC = 4.6 to 9.0 cmol kg^{-1}) are included in another graph according to current Alabama soil test calibration. The Decatur soil which is representative of cotton producing soils of the Tennessee Valley region has the highest CEC (10.0 cmol kg^{-1}) and the highest critical soil test K level. In a separate but related study, we found that cotton yields on the two Lucedale soils and on the Benndale soil were highly significantly related ($P<.05$) to soil test K in the 0 to 20 cm depth, in the 20 to 40 cm depth, or in the 40 to 60 cm depth. However, using soil test K from different depths did not improve soil test calibration (Mitchell et al., 1995).

Potassium recommendations (in pounds per acre of K_2O) are made according to the following equations when soil test K is reported in “pounds per acre” (2 times mg kg^{-1}):

Soil CEC (cmol kg^{-1})	K_2O recommendation (lb $acre^{-1}$)
0 – 4.6	120 – 0.99 (soil test K)
4.6 – 9.0	120 – 0.67 (soil test K)
9.0+	120 – 0.50 (soil test K)

Summary and Recommendations

Cotton and soybean cropping of five Alabama soils that had received 54 years of variable K rates did not deplete soil-test (M1) K dramatically over 15 years of no K fertilization. Potassium applied prior to 1982 accumulated in the upper soil horizons. Loss of K by leaching should not be a concern except in those soils with a CEC < 5 cmol kg^{-1}. Current soil test calibration critical extractable K values for Alabama soils are still accurate for modern varieties and yields. Plow-layer, soil test K is still a very reliable tool for predicting the need for K fertilization on Alabama soils when other factors are not limiting.

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Table 1. Physical and chemical properties of the soils in this study.

Horizon	Depth	Texture	CEC	Organic C	Mineralogy
	-cm-		-cmol/kg-	----%-----	
			Benndale ls		
			(*coarse-loamy, siliceous, thermic Typic Paleudults*)		
Ap	0-30	ls	3.1	0.7	
Bt1	30-75	sl	2.9	0.1	kaolinite, HIV
Bt2	75-105	sl	3.2	0.1	--
			Dothan sl		
			(*fine-loamy, siliceous, thermic Plinthic Kandiudults*)		
Ap	0-15	sl	4.5	---	
Bt1	15-33	l	4.5	---	kaolinite, HIV
Bt2	33-70	scl	5.6	--	
Bt3	7 0-105	scl	3.7	---	
			Lucedale scl (Prattville)		
			(*fine-loamy, siliceous, thermic Rhodic Paleudults*)		
Ap	0-20	scl	7.9	0.6	
Bt1	20-33	scl	6.1	0.2	kaolinite, HIV
Bt2	33-105	scl	6.3	0.2	
			Lucedale fsl (Monroeville)		
			(*fine-loamy, siliceous, thermic Rhodic Paleudults*)		
Ap	0-30	fsl	5.5	0.6	
Bt1	30-45	scl	5.1	0.2	kaolinite, HIV
Bt2	45-75	scl	4.8	0.2	
B3	75-105	scl	4.5	0.1	
			Decatur sicl (Tenn. Valley)		
			(*clayey, kaolinitic, thermic Rhodic Paleudults*)		
Ap	0-30	sil.c.l.	10.0	0.7	
Bt1	30-60	sil.c.	11.0	0.4	kaolinite, smectite,
Bt2	60-105	clay	10.4	0.3	HIV, mica

Table 2. Mean Cotton Lint Yields from the Standard Fertilization Treatment in the "Two-Year Rotation" at 5 Locations, 1992-1997.

	Soil series and location				
Year	**Benndale ls** (Brewton)	**Dothan sl** (Headland)	**Lucedale fsl** (Monroeville)	**Lucedale scl** (Prattville)	**Decatur sicl** (Tenn.Valley)
	cotton lint yield (kg ha^{-1}				
1992	1210	860	800	1480	1420
1993	1220	610	900	730	1150
1994	600	----	890	1500	1420
1995	1570	820	820	390	660
1996	1160	890	1140	1040	1040
1997	380	610	700	1520	1190

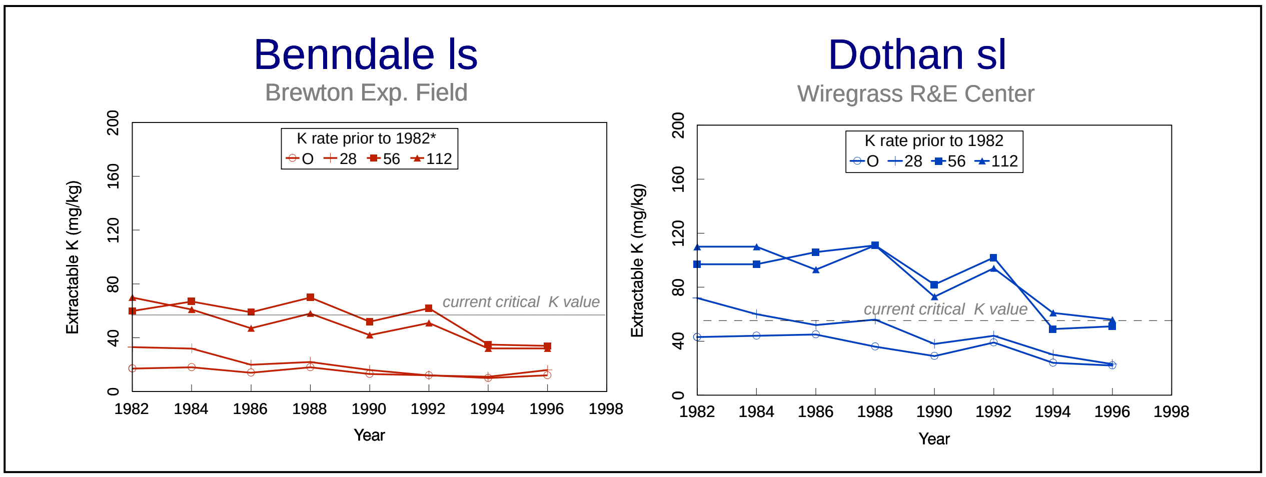

Fig. 1. Changes in Mehlich-1 extractable soil K in the plow layer during 15 years of a residual K study on two Coastal Plain soils with a CEC < 4.6 cmol/kg. The 56 kg K ha^{-1} was an annual application to cotton. Other rates received no K during the period.

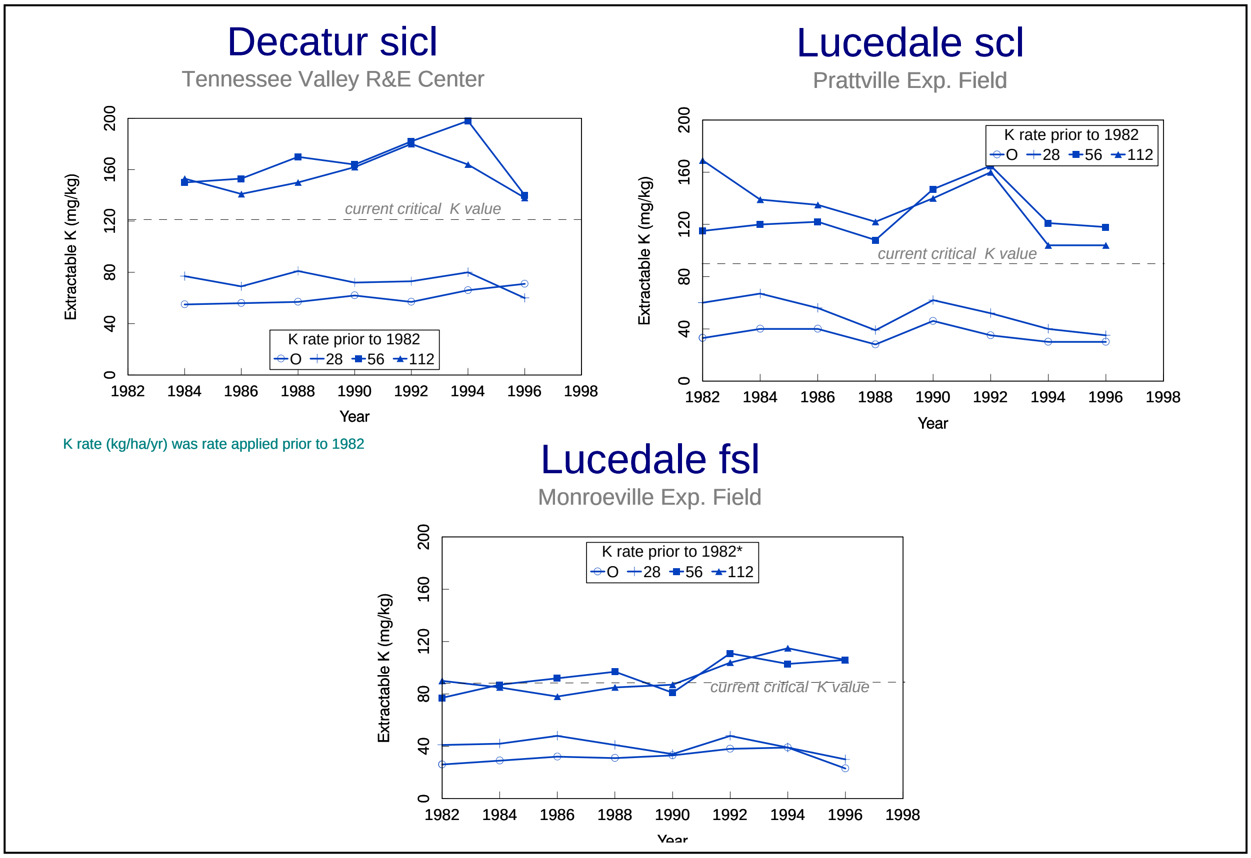

Fig. 2. Changes in Mehlich-1 extractable soil K in the plow layer during 15 years of a residual K study on sites with finer textured soils (CEC> 4.6 cmol/kg). The 56 kg K ha^{-1} was an annual application to cotton. Other rates received no K during the period.

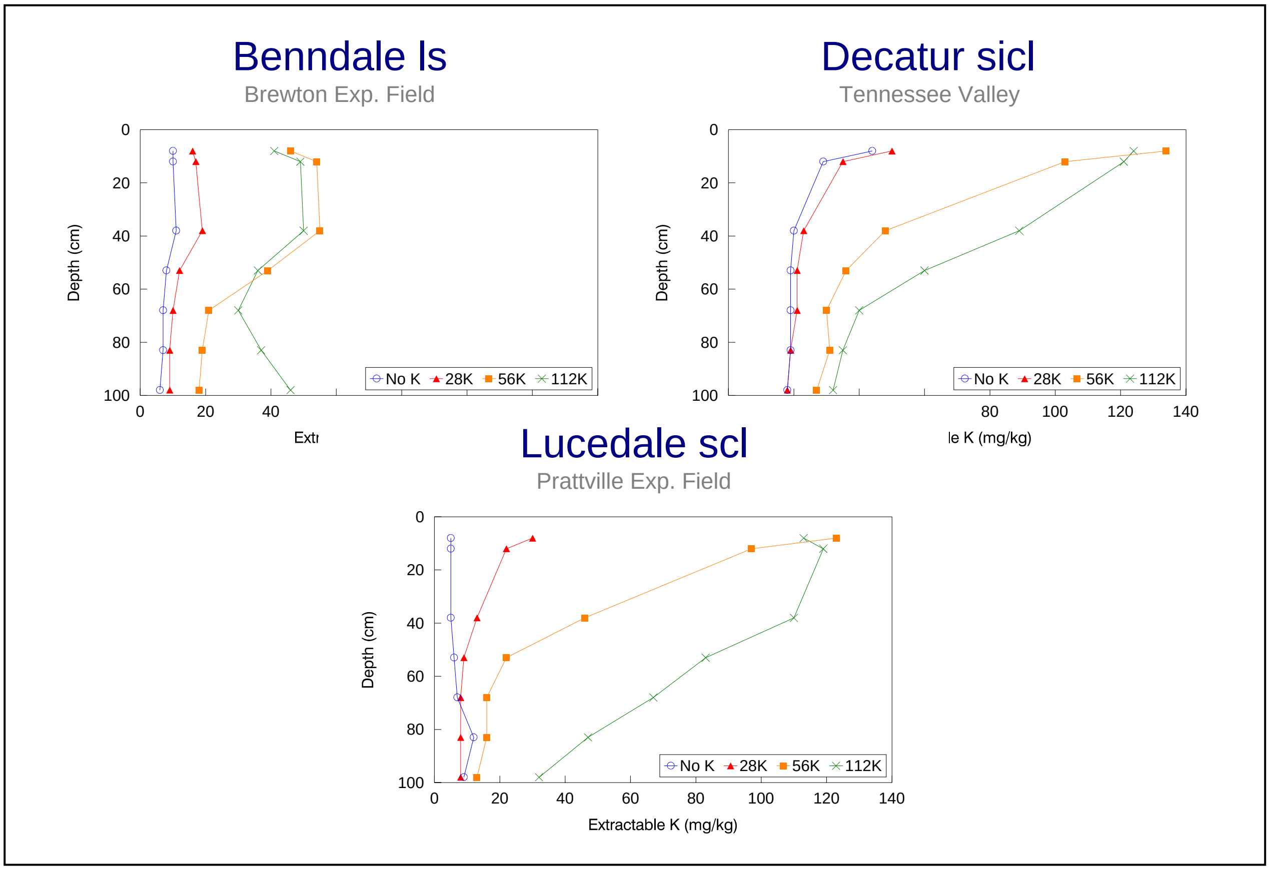

Fig. 3. Soil profile K (Mehlich-1 extractable) at 3 locations after 8 years in the residual K study (from Netshivhumbe, 1992).

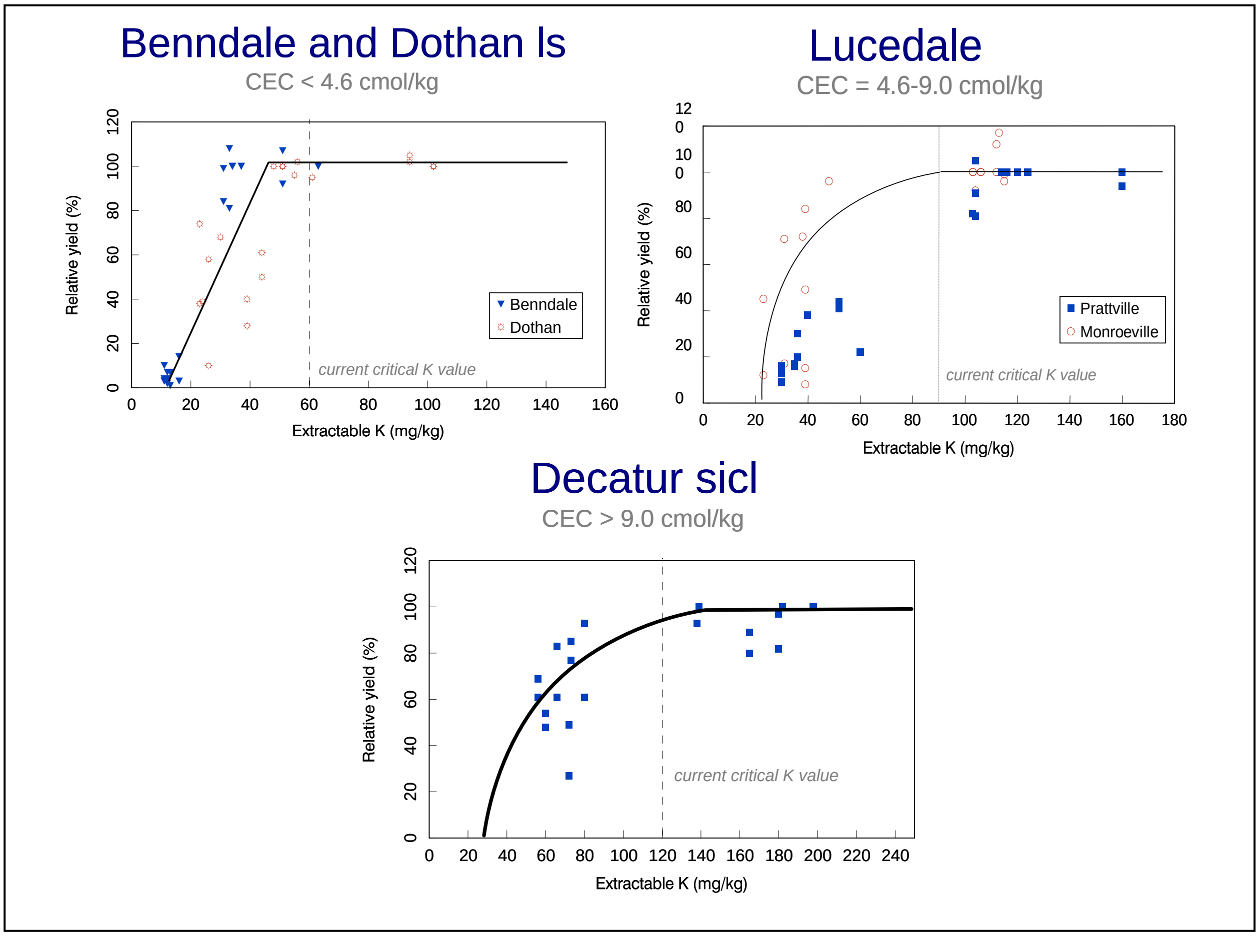

Fig. 4. Relative cotton lint yields as affected by residual soil test K levels,1992-1998, compared to existing critical soil test K values.

VIX. MEHLICH-3 POTASSIUM

Carl R. Crozier & David H. Hardy

Mehlich-3 (Mehlich, 1984; Hardy et al., 2007) extraction is used by laboratories in Arkansas, Kentucky, Louisiana, North Carolina, Oklahoma, & Pennsylvania for testing Coastal Plain soils for K and other nutrients. Potassium deficiency reduces lint yields (Figs. 1,2, Crozier et al., 2004; also Adeli and Varco, 2002; Cox and Barnes, 2002; Pettigrew, 2003) and may also influence nematode infestation levels (Pettigrew et al., 2005). Studies also document reductions in lint turnout and fiber quality due to K deficiency (Bennett et al., 1965; Cassman et al., 1989; Pettigrew et al., 1996; Gormus and Yucel, 2002; Bauer et al., 1998). Differences in fiber quality are possible, but not always substantial. A reduction in 50% span length from 1.37 cm to 1.35 cm and a reduction in micronaire from 4.1 to 3.7 (Pettigrew et al., 1996), while statistically significant, represent relatively minor differences considering the 0.08 cm difference between staple length categories and the optimal micronaire range of 3.5 to 4.9 (Perkins et al., 1984, p. 447). Commonly observed two- to three-fold differences in crop yields will have a larger effect on production economics than will subtle differences in quality parameters.

Past fertilizer applications and residual K accumulation make it difficult to identify suitable experimental sites with K deficient soils in many regions. Numerous field studies in North Carolina have failed to detect yield increase with soil- or foliar-applied K fertilizer at sites with initial soil test K concentrations greater than 130 mg kg^{-1} (Fig. 3, Crozier et al., 2002; Nixon et al., 2002). Research on North Carolina's long-term soil fertility experiments has verified critical Mehlich-3 extractable K levels. Cox and Barnes (2002) used a single coastal plain site and Crozier et al. (2004) used both a coastal plain and a piedmont site.

Critical levels are based on the cotton yield response and plateau relationship. In North Carolina, a quadratic-plateau regression model was used (Figs. 1,2). Crop responses to nutrient levels can also be characterized using analysis of variance, exponential, or linear-plateau functions. The linear-plateau method simplifies quantification of the critical level, but requires higher fertility levels in some plots to document the yield plateau and limits the ability to incorporate fertilizer and cotton price fluctuations (Cate and Nelson, 1971; Dahnke and Olson, 1990; Cox, 1996). In the North Carolina work, fertility levels for K were often not high enough to result in a clearly defined response plateau. In these cases, the quadratic-plateau approach may still predict the plateau level, and the fertility level at 95% of the maximum yield is considered the critical level (Fig. 1b, 2) (Tisdale et al., 1993). If there is no projected critical level within the data range, linear regression alone can define the response relationship, without specifying a critical level (Fig. 1a).

The critical soil K level of 64 mg kg^{-1} in 2002 at the coastal plain (Peanut Belt) site was higher than the 39 mg kg^{-1} value previously reported by Cox & Barnes (2002), but lower than the 130 mg kg^{-1} suggested in Mississippi (Pettigrew, 2003; Pettigrew et al., 2005) and 125 mg kg^{-1} critical level used for Texas High Plains cotton (Bronson & Bowman, 2004). The critical level of 137 mg kg^{-1} at the North Carolina piedmont site was more similar to the values reported from Mississippi and Texas.

Yield also increased as leaf K and petiole K concentrations increased, with critical leaf and petiole K levels usually identifiable (Figs. 1,2; Crozier et al., 2004). Because there were few data points in the plateau region of these relationships, the reliability of these critical K levels is less certain than for critical leaf P levels in associated plots (Crozier et al., 2004). Either leaf K or petiole K can be used to assess K fertility status, but critical concentrations of both decline during the several weeks of the flowering period. This is consistent with other reports. Critical leaf K declines from 10 to 15 g kg^{-1} at initiation of bloom to 5 to 10 g kg^{-1} by 3-5 weeks later (Fig. 4a). Similarly, critical petiole K level declines from 30-40 g/kg at initiation of bloom to 10-30 g/kg by 4-8 weeks later in North Carolina (Crozier et al., 2004), Tennessee (Howard et al., 2001) and California (Stromberg, 1960; Bassett and MacKenzie, 1976; Weir et al., 1996) (Fig. 4b).

Summary

When K is deficient, yield increases several-fold in response to fertility gradients. The critical level at a North Carolina coastal plain site was 64 mg/kg, lower than estimates of 125-137 mg/kg from Mississippi, Texas, and the North Carolina Piedmont. Critical leaf and petiole K levels depend upon sampling time relative to floral initiation, with a reduction occurring as the crop matures.

Both calibration data and suitable sites with sufficiently low soil Mehlich-3 K levels are limited. This presents an opportunity for regional coordination to further understanding the relationship between soil fertility gradients, plant tissue concentrations, and crop yield. Preservation of the few existing suitable sites is crucial since much commercial and research station farmland has already been fertilized to levels near or above critical levels. In some cases, several years might be required for sufficient crop nutrient removal to result in fertility levels low enough to detect responses to added fertilizer (Cox et al., 1981). A more credible fertility response database should enhance acceptance of research-based recommendations, and should enhance farm profits and reduce environmental impacts of farming.

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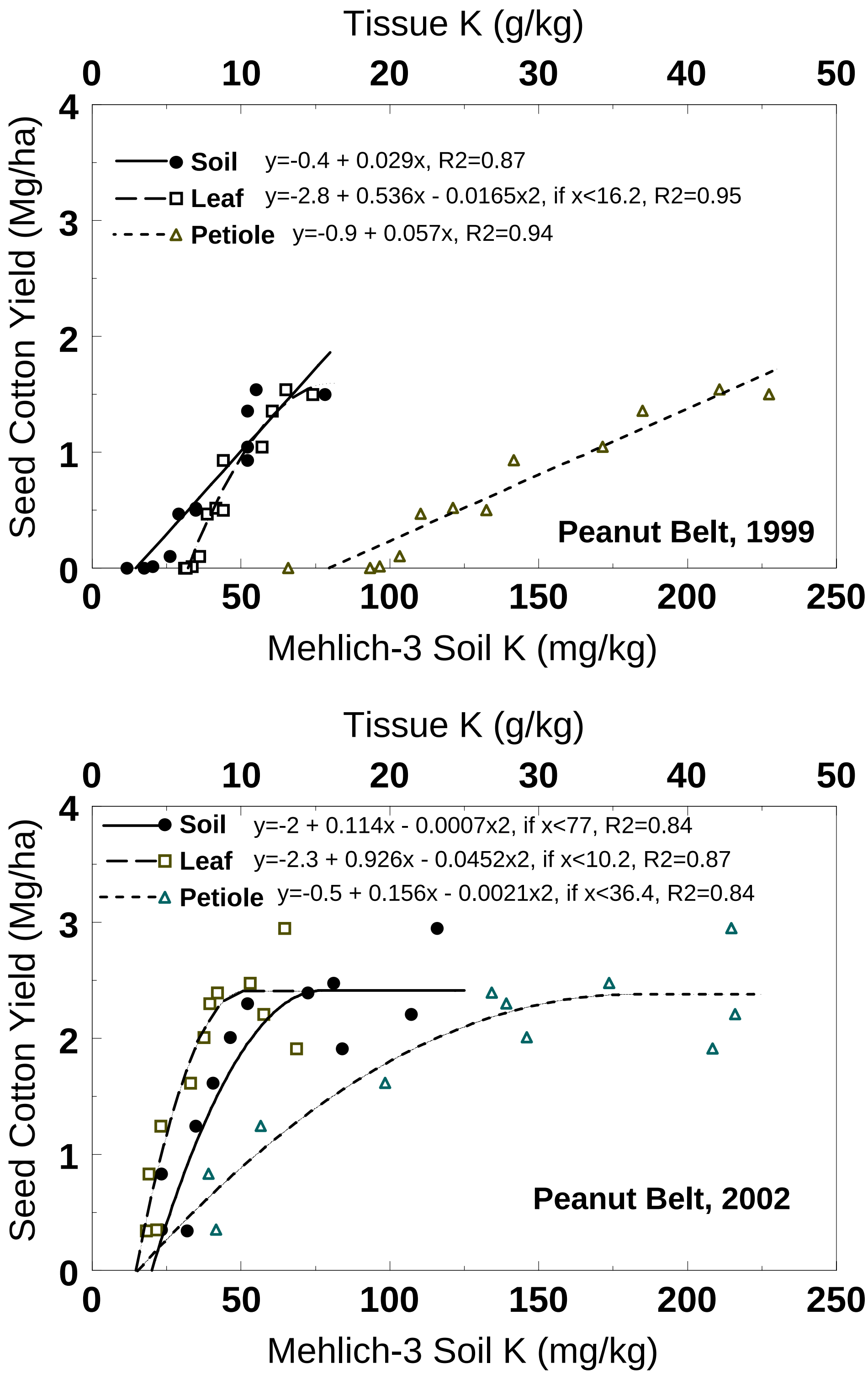

Figure 1. Yield response of cotton to soil and leaf K levels at the Peanut Belt Research Station (a) 1999, (b) 2002. Plant tissue results are for samples collected one week after first bloom. Each data point represents a single experimental plot. Based on the 95% of maximum yield criteria; in 1999, critical leaf P level in 1999 was 14.0 g/kg; and in 2002, critical levels were 64.3 mg/kg (soil), 8.6 g/kg (leaf), and 29.0 g/kg (petiole).

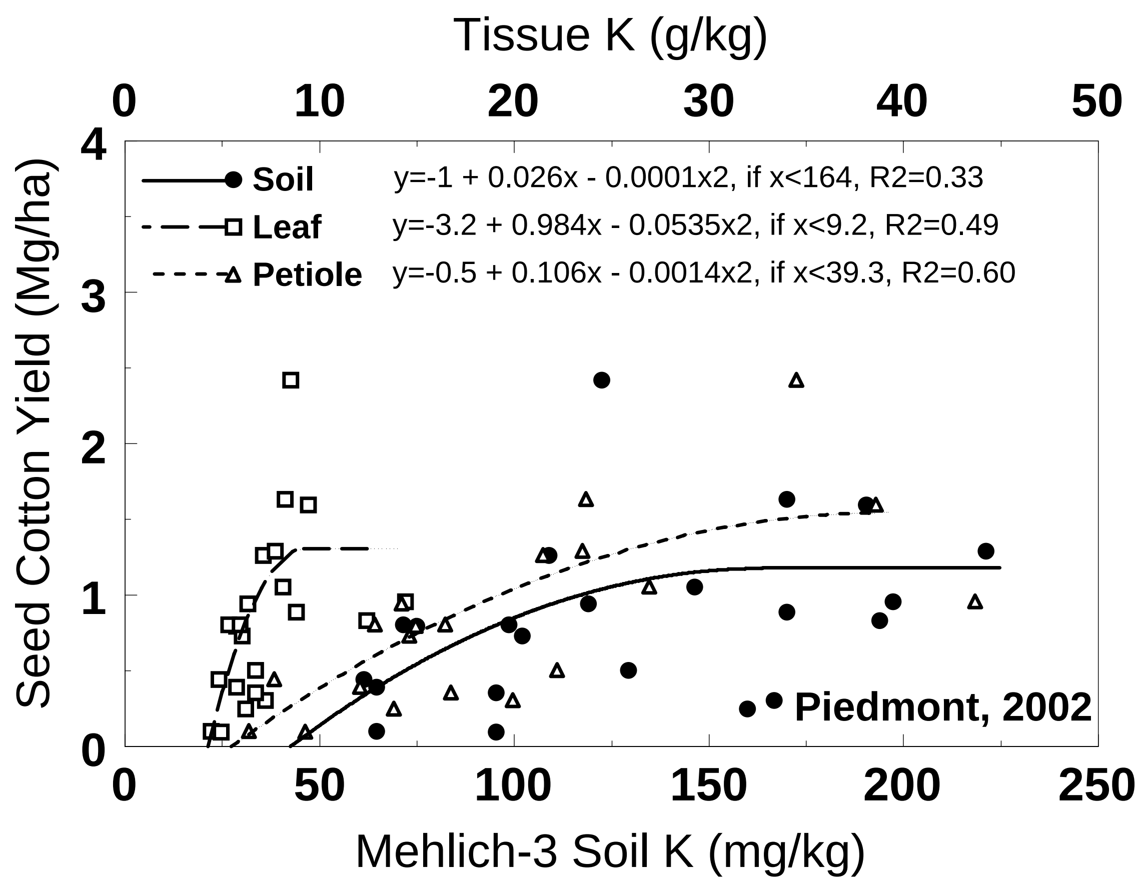

Figure 2. Yield response of cotton to soil and leaf K levels at the Piedmont Research Station 2002. Plant tissue results are for samples collected one week after first bloom. Each data point represents a single experimental plot. Based on the 95% of maximum yield criteria; critical levels were 137 mg/kg (soil), 8.1 g/kg (leaf), and 31.7 g/kg (petiole).

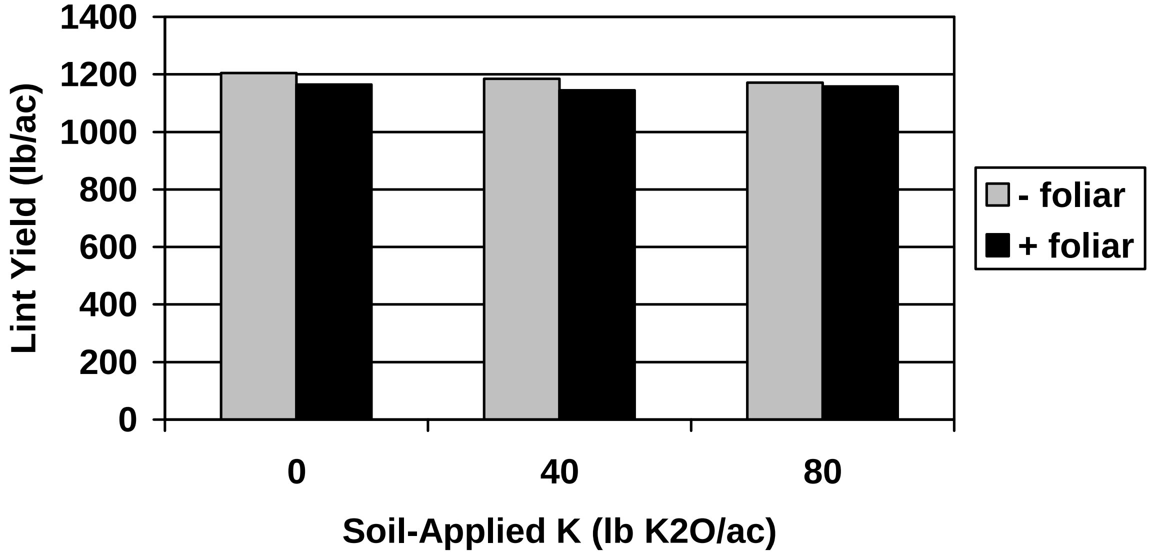

Figure 3. Lack of yield response of cotton to soil-applied K at a North Carolina coastal plain site with intial Mehlich-3 soil K level of 130 mg/kg. Foliar K application decreased lint yield by a small, but statistically significant amount.

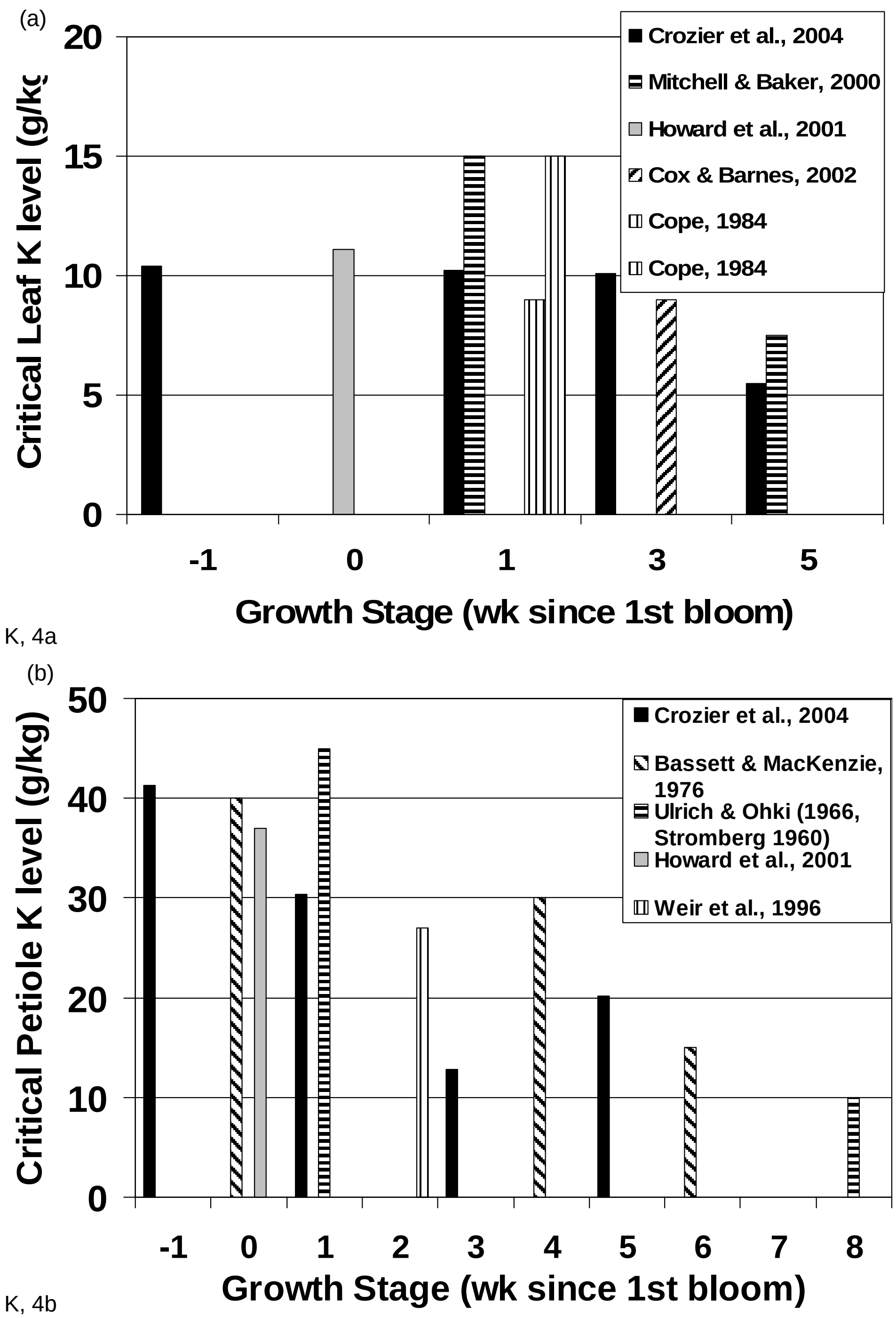

Figure 4. Critical leaf (a) and petiole (b) tissue K levels at different growth stages from selected publications.

X. MICRONUTRIENTS

C.C. Mitchell

Most of the micronutrient research on cotton for Coastal Plain soils was done in the 1960's, and early 70's. The results of over 2 decades of field plot work is summarized in Alabama's current micronutrient recommendations for cotton (Adams et al., 1994):

> *Apply 0.3 Ib. of. boron (B) per acre in the fertilizer or in the insecticide spray or dust. On-going research and soil test evaluation trials indicate that this recommendation is still reliable for production of maximum cotton yields under irrigated or non-irrigated conditions on Alabama soils.*

Micronutrients in cotton are just as important as nitrogen, phosphorus, or potassium. They are just needed in much, much smaller quantities, thus the name, "micronutrients".

Nutrient	Approximate concentration in cotton leaves at early bloom (%)
Nitrogen	2.1
Phosphorus	0.31
Potassium	1.51
Calcium	0.60
Magnesium	0.35
Sulfur	0.35
Micronutrients	
Boron	0.005
Zinc	0.011
Copper	0.0015
Manganese	0.015
Iron	0.015

The metallic micronutrients, zinc, copper, manganese, and iron, are essential components of plant enzymes necessary for many biochemical reactions in plant cells. Boron is thought to be essential in the transport of sugars within the plant. All are immobile and therefore deficiencies or toxicities of micronutrients are usually observed in new growth or in the buds (Price et al., 1972).

Boron

Boron toxicities from contaminated fertilizers were more evident on cotton than B deficiencies prior to World War II. Boron deficiencies in cotton were first reported in the early 1960's on the upland silt loam and sandy soils of Mississippi, Tennessee, and Arkansas where yield increases of 200 to 300 pounds of seed cotton per acre were reported (Hinkle and Brown, 1968). These reports were followed by a flurry of research throughout the southern U. S. Research by Dr. J. I. Wear in Alabama found a 3-year average yield increase of 150 pounds seed cotton per acre (about 55 pounds lint) from the addition of B on a Hartsells fine sandy loam on Sand Mountain.

Other tests in other areas of the state showed an average yield response to B of about 51 pounds of seed cotton (19 pounds of lint) per acre. At the time, the return was about $6 for a $.50 investment in B (Wear, 1976).

Long-term fertility experiments at 7 locations have been planted to cotton in Alabama (Table 1). Positive, average yield increases to micronutrient fertilization were observed at 6 of these locations. Although plots received a complete micronutrient mix, the yield response is attributed to B. Only the Tennessee Valley failed to give an average increase to B. At only one location was the response statistically significant (Brewton), but the trend is certainly in favor of B fertilization.

Table 1. Response of non-irrigated cotton lint yields to B application in Alabama's long-term soil fertility experiments.

Experiment & Location	Dates	No B	+B	Yield response to B
		------------------------lb. lint/acre------------------------------		
Cullars Rotation Experiment (circa 1911)				
Auburn*	1975-1986	810	870	+60
Two-Year Rotation Experiments (c. 1929)				
Brewton*	1959-1967	910	1000**	+80**
Monroeville*	1959-1967	810	930	+120
Prattville*	1959-1967	990	1010	+20
Sand Mountain	1959-1967	1060	1070	+10
Tennessee Valley	1959-1967	1000	980	-20
Wiregrass*	1959-1967	1040	1120	+80
State Average	1959-1967	970	1020	+50

*Coastal Plain sites

**Difference significant at 5% probability level.

These long-term fertility rotation plots and the research by Wear in the 1960's led to Alabama's current B recommendation. Many Alabama fields don't need B for high yields. Fine textured (clayey) soils of the Tennessee Valley and Black Belt may not need B fertilization for cotton. In fact, Odum (personal communication) citing research from the 1980s by Pinyard et al. (1984) claims that the lack of cotton yield responses to added B today is a result of several decades of B fertilization and B accumulation in the finer textured subsoils of many Coastal Plain soils.

Because B is mobile in the soil and is needed in such small quantities, annual applications are usually applied by growers as insurance - particularly on sandier soils. Because the greatest demand by the plant is during fruit set, one or more foliar applications in combination with insect control may be the most efficient and effective way of applying B.

Boron deficiencies in cotton are seldom evident under field conditions. The first symptom may be an excessive shedding of flower buds and young bolls, a symptom that could be attributed to insect damage, excessive nitrogen fertilizer, wet and cloudy weather, and dry weather. In severe cases of B deficiency, the internodes become shorter and the terminal bud often dies, producing a short bushy plant with excessive branching. The younger leaves are yellowish green in color and are often distorted if the deficiency is severe. However, one is not likely to observe such symptoms on most Coastal Plain soils.

Although B fertilization is an established practice in high-yield cotton production in the southern U. S., verification research continues on long- term, experiment station plots, and occasional on-farm tests. In a 3-year study in the Tennessee Valley Substation (unpublished data), yields were not increased with additions of B, Mg, S, or all three (Table 2).

Table 2. There were no significant effect of B, Mg, and S on cotton yields in a Decatur silt loam in the Tennessee Valley of North Alabama. Boron was added a Solubor®; Mg was added as dolomitic limestone; and S was added as gypsum (calcium sulfate).

Treatment	1987	1988	1989	3-yr average
	------------------------lb. lint/acre------------------------------			
Check (no B, Mg, or S)	840	530	570	640
No B	740	470	480	560
No Mg	790	470	520	590
No S	530	500	560	610
+B, +Mg, + S	810	450	510	560

Boron soil tests

Although some micronutrient sales literature advocates B soil tests, this is not a practical or reliable way to determine crop response to B application. Research by Pinyard et al. (1984) on a Norfolk loamy sand in Central Alabama has demonstrated that B will accumulate in deeper soil horizons but leaches rapidly from the sandy plow layer. We usually sample the plow layer and not the subsoil. Plant analysis may prove valuable as a diagnostic technique, but even this procedure has problems. Many labs use borosilicate glassware for routine sample preparation; this introduces some contamination when digesting and preparing plant samples for analysis. Sample preparation to avoid possible B contamination would increase the cost of routine analysis such that it would be prohibitive as a diagnostic tool for the average grower.

Although hot water extraction is the only method recognized and published for measuring soil B in the southern region of the U.S. (Isaac, 1992), some laboratories report B extraction using Mehlich-1 and Mehlich-3. Cox and Kamprath (1972) reviewed soil tests for B and noted that acidic extracts are generally poorer, or at least no better, than hot water extract for B. Critical levels of hot water extractable B vary with soil type, crop, climate and soil pH. In general, some early published critical values for hot water extractable B are listed below:

0.75 mg B/kg for beets (Berger and Truog, 1940)
0.5 mg B/kg for Illinois soils (Deturk and Olson, 1941)
0.35 mg B/kg for alfalfa (Dawson and Gustafson, 1945; Lehr and Henkens, 1959)

0.15 mg B/kg for legumes in Alabama (Rogers, 1947)

Zinc

Cotton yield response to zinc fertilization has not been reported in the southeastern U. S. in spite of numerous experiments. Zinc deficiency has been reported in California on calcareous or saline soils. In Coastal Plain soils of the southeastern U.S., most cotton is produced on well-drained, upland sites with an acid, clayey subsoil. These soils tend to have adequate labile zinc. If a zinc deficiency were observed, it would probably be on a deep, sandy soil that had been grossly overlimed. Cotton is not generally produced on deep, sandy soils.

A cotton survey of fields in northern and central Alabama showed no cotton leaf samples with zinc concentrations below what is considered an acceptable level (25 mg kg^{-1}). Leaf analysis should be a fairly reliable measure of the zinc status of cotton plants. Plow-layer soil samples revealed that 94 percent of the topsoils had M1 extractable Zn levels above 0.8 mg kg^{-1} which is considered adequate for our region. Subsoil, as expected, had much lower Zn levels because Zn does not leach (Mitchell et al., 1992). Another survey in 2001 of cotton in Coastal Plain soils in Central Alabama also found no evidence of low Zn concerns for cotton. (Kuykendall et al., 2002).

Therefore, no evidence exists that Zn fertilization of cotton will produce higher yields on Coastal Plain soils. Zinc is often recommended for corn and for certain other crops. Crop rotations will dictate the need for zinc fertilization. Zinc toxicities in some crops have been reported on land that has had excessive applications of zinc in the past - either as a fertilizer or in organic amendments such as sewage sludge. Growers should be cautioned against over-applying any micronutrient, especially zinc and copper.

Managanese

Manganese should be a micronutrient of concern if cotton is produced on poorly drained, overlimed, low organic matter soils along the Gulf and Atlantic Coast. Cotton is generally not produced on these typical, "flatwoods" type soils. These soils are more common in Georgia, South Carolina, and North Carolina than along the Gulf Coast. Symptoms of deficiency in cotton are leaf cupping and interveinal chlorosis; the veins remain green. The chlorosis starts in the young leaves. These are also the symptoms of zinc deficiency where it occurs. Symptoms will appear spotted in a field and generally appear in the lower areas. Where a history of manganese deficiency has been observed on soybeans and other crops, suggested treatments include foliar sprays containing manganese sulfate or a manganese chelate and liming to a soil pH no higher than 6.0. Soil applications are often expensive because so much is needed to correct a problem.

Manganese toxicity or "crinkle leaf" on very acid soils is much more common in Upper Coastal Plain soils. Leaves will crinkle or pucker at the edges which cup downward. The edges may become quite ragged. These leaves are thicker and more brittle than normal. Affected leaves are often partially chlorotic or yellowish green. Like most deficiencies and toxicities, symptoms will be in isolated areas within a field rather than throughout the entire field. Soils in the Piedmont, the Tennessee Valley, and much of the Coastal Plain are very high in manganese. Manganese availability is determined more by soil pH than an absolute quantity in the soil. In many soils, crinkle leaf may be the first sign of a critically low soil pH. Fortunately, most cotton growers do a good job of liming to avoid this problem.

Copper

Some "flatwood" soils high in organic matter along the Georgia to Virginia coast have produced crops, particularly small grains and vegetables, that respond to copper fertilization; cotton is not one of them. Cotton is not generally produced on these high organic matter soils where crops need copper fertilization. No confirmed case of copper deficiency has been reported on any field crop in Alabama. Copper toxicities where excess copper has been applied inadvertently to the soil will become more of an issue than copper fertilization of cotton.

Iron

Iron deficiencies in cotton are common on calcaeous and saline soils of the arid Southwest, but are rare on Coastal Plain soils. Iron availability is very pH dependent. Most cotton-producing soils are high in iron and slightly to very acid. Iron deficiency should not be a micronutrient consideration in cotton production for Coastal Plain soils.

Summary

Micronutrient research and on-farm experience throughout the southeastern United States over the past 40 years have clearly revealed that boron (B) is the micronutrient of primary concern to cotton producers. Seed cotton yield increases up to 150 pounds per acre could be expected on sandy soils. Annual yield responses to B fertilization on the finer-textured soils of the Tennessee Valley are unlikely. Boron fertilization would become more critical under irrigated conditions where leaching is more likely. Cotton yield responses to fertilization with zinc, manganese, copper, and iron are highly unlikely on most cotton soils of the Southeastern Coastal Plain region. Micronutrient soil tests are generally unnecessary to predict cotton response to micronutrients. Hot water or acid extractable B can be used but calibration with modern varieties and yields are not available. Micronutrient soil test may be more valuable in identifying fields or areas where metal accumulation , e.g., Zn or Cu, could lead to potential toxicities.

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XI. LIMING AND pH ADJUSTMENT FOR COTTON

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Liming to increase soil pH and supply Ca and Mg is a long-standing practice on most soils of the southeastern coastal plain where cotton is produced. This is largely due to widely-distributed Ultisols occupying much of this region (Adams, 1984). These soils are naturally acidic due to their formation from highly weathered parent material under climatic conditions where rainfall exceeds evapotranspiration.

Although inherently acid, routine N management may generate significant acidity through nitrification if ammoniacal N fertilizers are applied. Mineralization of organic residues also is a source of acidity as well as plants in maintaining charge balance across root membranes with nutrient uptake (Havlin et al., 1999; Marschner, 1986).

Soil pH is not only adjusted to manage adverse effects of soil acidity but the many processes that it also influences and regulates. In these coastal plain soils, cation exchange capacity (CEC) is comprised of both permanent and pH dependent charge. This variable charge may originate along broken edges of clay minerals, on surfaces of Al and Fe oxides, and from organic matter's carboxylic and phenolic groups (Thomas and Hargrove, 1984). The solubility and availability of many essential nutrients, activity of soil biota, and N transformations are all influenced by soil pH; liming may also promote soil tilth, and reduce disease and pests (Sumner and Yamada, 2002).

In this chapter, we focus on reviewing information on lime and pH primarily related to cotton growth. Our discussion specifically covers:

1. cotton response to liming and pH as conducted in Alabama and other states
2. critical soil pH and relationships to toxicities and deficiencies as related to cotton growth
3. liming requirements for cotton in the southeastern U.S. and
4. lab methods used for the determination of lime requirements

Lime and pH Studies with Cotton in Alabama

Much of the benefit of lime and pH adjustment to cotton production is based on the work of Dr. Fred Adams at Auburn University during the period of the late 1950s to mid-1980s. His field work is found in numerous experiment station publications (Adams, 1956; Adams, 1958; Adams, 1968) with his own detailed summary within the book chapter "Crop Response to Lime in the Southern United States" (Adams, 1984). Many of the studies conducted were also done in conjunction with N, P, and K variables. Lime in these studies was typically applied at one time, not in multiple years as lime is used today.

Important findings of early work on coastal plain soils from Adams (1958) were:

- Cotton was tolerant of moderate soil acidity; large increases in yield usually did not occur until soil pH was below 5.5;

- Soils where cotton was produced were well fertilized overall and although liming benefitted cotton yield on most coastal plain soils, yield increases were relatively small. This was possibly due to supplying small amounts of Ca and Mg through use of dolomitic lime or superphosphate in non-acid mixed fertilizers applied yearly;

- Substantial cotton yield increases from liming were noted in cases with significant drops in soil pH caused by increased use of acid-forming N fertilizers- ammonium nitrate and ammonium sulfate.

Adams (1968) summarized responses of cotton to lime in field experiments over various geographic areas of AL. Figure 1 provides data taken from five different studies on a Norfolk sandy loam soil (fine-loamy, kaolinitic, thermic, Typic Kandiudults). Note the yield plateau beginning at about pH 5.8. Similar results were found for Magnolia (fine-loamy, mixed, semiactive, mesic Typic Paleudalfs), Dothan (fine-loamy, kaolinitic, thermic, Plinthic Kandiudults), and Alaga (thermic, coated Typic Quartzipsamments) series. Although these data are typical for many coastal plain soils, it did not hold true for the Lucedale (fine-loamy, siliceous, subactive, thermic, Rhodic Paleudults), Decatur (fine, kaolinitic, thermic, Rhodic, Paleudults) and Savannah (fine-loamy, siliceous, semiactive, thermic, Typic Fragiudults) coastal soils where pH requirements were much less (around pH 5.0). Major conclusions from these studies were:

- Cotton was tolerant of a wide range of soil pH without significant yield loss;

- Soils varied in response to lime at different maximum pH levels;

- Source of limestone, calcitic or dolomitic, was important on some soils to prevent Mg deficiency;

- Considerable fluctuation in soil pH from year to year and season to season was seen. Some fluctuation was understood given kinds and amounts of fertilizers applied but some year to year variation was not explained.

Additional lime / pH data were made available from long-term fertility experiments (1929-1982) on cotton, corn and soybeans, sorghum and peanuts on a wide range of soils (Cope, 1984). No-lime treatments were a part of two experiments- a two-year rotation fertilizer (TYR) and a N, P, and K study (NPK). Lime was not applied since 1929; otherwise, soil pH was maintained at pH 5.8 to 6.5. On a Dothan fine sandy loam, the no-lime treatment yielded 90% and 63% of the standard treatment with lime for the TYR and NPK studies, respectively. On a Lucedale fine sandy loam at a pH of 5.3, no-lime had very little effect at one site in the NPK study; at another site lime increased yield by 10%. On a Savannah sandy clay loam at a pH of 5.1, an increase of 200 pounds per acre of seed-cotton was noted for the NPK study. Other studies with cotton in Alabama generally indicate that a response to liming is limited unless soil pH is less than 5.3 (Mitchell et al., 1977; Burmester et al., 1981).

Cotton Liming and pH Studies in Other States

In a greenhouse study, McCart and Kamprath (1965) in North Carolina reported that liming sandy, low CEC soils [Norfolk, Plummer (loamy, siliceous, subactive, thermic Grossarenic Paleaquults] to a pH of 6.2 to 6.5 was desirable for cotton. On the Norfolk soil, 100% relative growth of dry matter was attained at pH 6.1 as compared to 36 and 84% at pH of 4.6 and 5.5, respectively.

In Arkansas on a Dundee sandy loam (fine-silty, mixed, active, thermic, Typic Endoqualfs), no significant difference was found in yield when lime was applied at pH 5.7 (Mascagni et al., 1991). Soil pH attained by liming in the 2-year study was 6.1 the first year and 6.5 the second year.

Some of the more recent data come from Gascho and Parker (2001) in Georgia as they studied the long-term effects of liming coastal plain soils [Pelham (loamy, siliceous, subactive, thermic, Arenic Paleaquults) and Tifton (fine-loamy, kaolinitic, thermic, Plinthic Kandiudults)] on crop production as related to soil profile pH, Ca, and Mg levels. In this study, dolomitic lime expressed as $CaCO_3$ equivalency was applied at zero, low (1.1 – 2.1 Mg ha^{-1}), medium (2.1 – 4.2 Mg ha^{-1}), and high rates (4.2 – 8.4 Mg ha^{-1}) at 4 different times over 31 years for the Tifton soil and zero, low (2.1 – 2.6 Mg ha^{-1}) and high rates (4.2 – 7.0 Mg ha^{-1}) at 6 different times over 21 years for the Pelham soil.

Figure 2 represents relative yield as a function of soil pH at the 0-15 cm depth as measured in plots of all lime rates in the spring before fertilizer application. At soil pH above 6.1, 100% relative yield was attained for both soils; at pH range of 5.5 to 6.1, 63% of sites in this category had relative yields of 90% or greater. Overall, yield was not severely affected until soil pH was < 5.5 which is similar to what Adams (1958) reported; this was more notable in the Pelham soil that had the lower pH in the zero lime plots. Also note the plateau beginning at about pH 5.8 which is very similar to data from Adams (1968) presented in Figure 1. On the Dothan soil, crop response to lime generally occurred when substantial amounts of acid-forming N was applied.

Critical Soil pH and Relationship to Toxicities and Deficiencies Potentially Affecting Cotton

Adams (1984) defined the critical soil pH as being “the maximum pH at which liming increases crop yield.” He clarified an important point by stating, “crop response to liming is not discussed with the presumption that yields are increased because soil pH is raised to above some magical value. It is fully recognized that some yield-limiting factor, e.g. Al, Mn, or Ca is corrected by liming, and that is the reason for increased yield.”

Manganese Toxicity and Deficiency

Availability of Mn and potential toxicity are controlled by a number of factors including total Mn, pH, organic matter, aeration, and microbial activity (Foy, 1984).

Cotton is documented as sensitive to Mn toxicity resulting in a condition referred to as “crinkle leaf” as it affects younger developing leaves (Adams and Wear, 1957; Martens and Westermann, 1991); yield effects are reported as slight reduction to complete crop failure (Adams and Wear, 1957). Although induced by excessive Mn, the crinkling of the younger leaves may be caused by inhibition of Ca movement to the meristematic tissue although other mechanisms are reported (Marschner, 1986; Foy, 2004). Manganese toxicity does not affect roots except indirectly through limitation of top growth (Adams, 1984).

Research has shown that sensitivity to Mn toxicity varies across cotton genoptyes (Foy et al., 1981 and Foy, 1984); however, correction through liming to pH above 5.5, which is cited by Adams (1984) as being the maximum pH at which Mn is expected be toxic, should be sufficient to decrease solubility of Mn and improve plant growth (Kamprath and Smyth, 2004; Martens and Westermann, 1991).

Soils vary in inherent Mn levels but are generally low in Atlantic coastal plains soils and lower there than gulf coastal plains soils (Adams, 1984; Foy, 1984; Welch et al., 1991). Many of these soils can be low in native Mn levels. If over-limed, Mn deficiency is documented as being a potential concern although based on our experience, cotton does not appear to be as sensitive to Mn deficiency as soybeans and small grain.

Hydrogen and Aluminum Toxicity

Many plants, including cotton, can be affected by H^+ ion toxicity if pH is sufficiently low (pH < 4). In such cases, plant root damage appears as brown or dull grey color with a short and stubby appearance. Effects on the root membrane permeability have been found to interfere with uptake of major nutrients such as P, K, and Ca (Foy, 1984).

Unless lime management is extremely poor, soil pH in mineral soils should rarely reach a pH where H^+ is toxic. In most acid soils, plant growth is probably most severely limited by Al^{+3} toxicity. Unlike Mn where effects are on above-ground plant parts, roots are affected by soil solution Al^{+3} concentrations in the micromolar range (Kamprath and Smyth, 2004).

In mineral soils, solution Al^{+3} is controlled by the extent that the CEC is occupied by Al^{+3} (Al^{+3} saturation) which is regulated by soil pH; in soils with significant OM, Al complexes may lower soil solution Al^{+3} at a given pH and significant solution Al^{+3} may not be found until pH is less than 5 (Dolman and Buol, 1967; Evans and Kamprath, 1970). Since solution Al^{+3} measurements are tedious and not easily done, Al^{+3} saturation of the CEC is typically measured using a neutral salt such as KCl and is near zero at pH of 5.5 in mineral soils (Sumner and Yamada, 2002; Kamprath and Smyth, 2004). Nutritionally, Al^{+3} is often associated with P and Ca interactions in acid soils (Foy, 1984).

During the early 1960's through the early 1980's, studies on soil pH and Al using subsoil or nutrient solution culture in short-term split-root systems were conducted with cotton since it was determined to be a sensitive plant. Important findings of these studies were:

- Soil pH *per se* in solution culture did not affect cotton root growth detrimentally until pH was less than 4.3 (Howard and Lund, 1965).

- Al^{+3} toxicity resulted in morphological changes in the root; thick, poorly branched, discolored, root systems were observed; toxicity appeared to have a pronounced effect on cell division regardless of Ca levels or other fertility (Rios and Pearson, 1963; Adams and Lund, 1966).

- For a given soil, relationships in root growth and critical soil pH levels or exchangeable Al^{+3} (extracted by 1 M KCl) existed. Although these relationships were found, levels where root growth was affected differed across soils. However, relationships for the molar activity of Al^{+3} were common among soils; activities in soil solution and nutrient solutions were similar with a critical level being around 0.15×10^{-5} M (Adams and Lund, 1966).

In a long-term liming study, Gascho and Parker (2001) found cotton yields in no-lime plots (2000 data) to be low when exchangeable Al^{+3} in the surface 45-cm of Tifton and Pelham soils exceeded 0.3 cmol kg^{-1}; Al^{+3} saturation was > 15% and 20%, respectively. They concluded a practical approach to pH management is to apply dolomitic lime to maintain surface pH near 6.0

through routine soil testing. Today, lime is recommended by southeastern states to maintain soil pH well above 5.5 to prevent Al^{+3} toxicity (Table 1). A discussion about current state lime recommendations is found later in this chapter.

Calcium Deficiency

Ca deficiency is not common in agronomic field crops like cotton. An exception is for peanuts, which have a special Ca requirement in pegging and pod formation (Adams, 1984). While lime is typically applied to reduce effects of soil acidity, it also supplies Ca and Mg depending on the lime source and certainly this helps prevent Ca deficiency, especially in low CEC soils with low levels of exchangeable Ca. When soil pH is not adequately managed, soils high in exchangeable Al^{+3} typically have low levels of exchangeable Ca (Adams, 1984; Kamprath and Smyth, 2002). Research has shown that supplementing Ca in soils without adequate pH adjustment provides no benefit to cotton growth (McCart and Kamprath, 1965; Gascho and Parker (2001).

Cotton has been used extensively to better understand Ca requirements for root development in subsoils as well as Al^{+3} toxicity as previously mentioned. The fact that an external source of Ca in close proximity to cotton roots is needed for their growth and development is well documented (Rios and Pearson, 1964, Adams and Lund, 1965). When Ca is not adequate, lack of development, deterioration, or death may result (Rios and Pearson, 1964; Adams and Lund, 1965). Howard and Adams (1965) also found the Ca requirement for rooting to be related to ratios of other cations (K and Mg) present in soil solutions. They generally concluded that Ca deficiency as related to cotton growth in subsoil was not common; however, later work by Adams and Moore (1983) found it in 8 of 18 subsurface horizons from 6 major Coastal Plains soils.

Magnesium Deficiency

The potential for Mg deficiency in cotton was documented early by Adams (1968) on some soils when only calcitic lime was used instead of dolomitic. In a study of supplying Ca and Mg to cotton on low CEC soils, McCart and Kamprath (1965) concluded that cotton growth was enhanced by supplying dolomitic lime over calcitic lime in a Norfolk soil when limed to a pH of 6.0; supplying Mg enhanced its uptake. Exchangeable Mg levels after liming were 0.5 cmol kg^{-1} soil as compared to 0.1 cmol kg^{-1} soil prior to lime addition (pH 4.6). Both McCart and Kamprath (1965), and Gascho and Parker (2001) found no gain in cotton yield without liming when Mg salts were added.

In reference to Alabama field studies from 1957-1973 on Mg availability for cotton, Adams (1984) reported the addition of Mg through use of magnesium sulfate or dolomitic lime to increase seed-cotton yield 200 to 400 kg ha^{-1} on most sandy soils when Mg levels were < 15 mg kg^{-1} (dilute, double-acid extractable); deficiency only occurred when exchangeable Mg was about 0.1 cmol kg^{-1} or less in the Ap horizon, possibly due to uptake from subsoil Mg.

Today, Mg deficiency in cotton, as with many field crops, is a concern primarily on low CEC sandy soils where excessive leaching may occur and when the proportion of CEC sites occupied by Mg is very low (Adams, 1984; Kamprath and Smyth, 2002); on such soils, pH management through use of dolomitic lime may be beneficial.

Lime Requirements in Cotton Producing States of the Southeastern U.S.

Liming soils where cotton is produced in the southeastern U.S is common in crop management today. Table 1 provides information on target pH, critical pH, and minimum lime recommendations provided by public laboratories across the Southeastern U.S. where cotton is produced. Critical pH is defined as the pH below which a lime recommendation is made; often this is dependent also on exchangeable acidity measurements as typically estimated by buffer pH methods. Note that few state labs have documentation as to where there target or critical pH comes.

North Carolina has a rather unique system in that target pH is based on soil class- organic, mineral-organic, and mineral. The rationale for this approach is based on the understanding that less Al^{+3} will exist at a given soil pH with increasing OM levels as already discussed.

Assuming all mineral soils, the target pH used by each state is above pH 5.6 which Kamprath and Smyth (2004) cite as being the pH where soil solution Al concentration is near zero. Using this information and historical data from cotton lime studies as presented here, cotton production is believed to be protected from low pH if lime recommendations are followed. Higher target pH may provide additional safeguard where there is potential for Ca deficiency or Mg deficiency on low CEC soils, the latter, if dolomitic lime is used. A slightly higher target pH may also be justified in fields with a high degree of spatial variability in pH. Liming to a slightly higher target pH ensures that those areas of a field with lower pH than the average will also be above the critical pH level of 5.6.

Historically, a typical procedure followed by farmers in the liming of acid soils has been to test entire fields based on a single composite soil sample, which is followed by application of a single uniform rate of aglime based on the soil test lab's recommendation. Based on a number of field studies and concerted education programs, it is becoming more common now to delineate subsections of a field and sample them separately based on soil characteristics, topography, drainage, etc as recommended in Chapter III. Early research by Peck and Melstead (1973) described how variable soil pH and lime requirement can be in a seemingly uniform field. They found a range of two units in pH values within two 16 hectare Illinois crop production fields sampled in 25 meter grids. More recent research has shown similar variability in soil pH and lime requirement. For example, when Heiniger (1996) sampled two fields of 101 and 162 hectares in 0.4 hectare grids, he found a range of more than two pH units. Leonard et al. (1992) reported a similar pH range of 1.9 pH units when a 7.5 hectare field was sampled on approximately 15 meter grids. We have observed similar variation in soil pH in South Georgia where we typically find a range in pH of 1.5 units in composite samples taken from 10 square meter sampling areas at 20 to 25 locations within a 16 hectare field.

Such variability cannot generally be predicted based on soil type, as was observed by Peck and Melstead (1973), and Leonard et al. (1992) and based on our own experience. Nor can a field be economically sampled at the scale needed to eliminate pH variability. Grid sampling or zone sampling based on soil or landscape properties or sampling of zones based on crop performance has been used in some areas for creating variable rate lime application maps. This level of soil analysis is costly, but it can help to reduce field spatial variability in soil pH and improve crop yields. Another way to reduce variability is to insist on proper lime spreader calibration and driving the lime spreader in different patterns each time lime is applied to the field.

Determining Lime Needs Today

A lime recommendation is made by soil testing laboratories based on the soil pH measured, the critical pH shown in Table 1, and some method to determine the pH buffering capacity of the sample if the sample is below the critical pH. The pH buffering capacity is an estimate of exchangeable acidity, Al^{+3} and H^+, that must be neutralized by lime to raise the measured soil pH by one pH unit. The total acidity to be neutralized is the Al^{+3} and H^+ from the soil's pH to the desired target pH.

These recommendations are typically based on a calibration curve that relates the lime requirement as pure calcium carbonate to the buffer pH measured, or in the case of the Adams-Evans or Mehlich buffer, the calibration requires both the measured water pH and the buffer pH values for determining the lime requirement. The lime recommendation of pure calcium carbonate may then be modified based on the lime quality as done by the University of Kentucky or with a single multiplier (the value of 1.5 is used by the University of Georgia) to convert the recommendation to the amount of lower quality agricultural limestone.

The soil pH buffers used in the southern region include the Adams-Evans buffer, the Mehlich buffer, the SMP buffer, or recent modifications of these buffers to eliminate the toxic chemicals in them. Recent buffer modifications include those by Sikora (2006), Sikora and Moore (2008), Huluka (2005), and Wolf et al. (2008). Another method recently developed by Georgia involves the use of a single addition titration with $Ca(OH)_2$ for the lime requirement as described by Kissel et al. (2007). A listing of lime requirement methods, along with soil pH methods is provided in Table 2.

Most public laboratories in the Southern Region measure pH in a 1:1 or 1:2 (v:v) soil:water ratio with deionized (DI) water. An exception is the University of Georgia, which now measures pH in 0.01 M $CaCl_2$ referred to as a pH_{salt} measurement. Georgia made this change to avoid the seasonal variation in pH due to fluctuations in the background ionic strength of the soil solution (electrical conductivity), fertilizer and manure application, and organic matter mineralization (processes that increase ionic strength). High levels of precipitation leach ions from soil and therefore decrease ionic strength (Kissel et al., 2009). When ionic strength is high, soil pH is lowered and this often is referred to as a salt depression of pH. In Georgia, the average pH is approximately 0.6 pH units lower in 0.01 M $CaCl_2$ as compared to DI water.

Extreme seasonal weather patterns for a given location can influence ionic strength and consequently affect lime recommendations because of its effects on the pH measured. For example, an unusually dry fall can result in a soil with high ionic strength and therefore a lower than normal pH, causing a lime recommendation on some samples that may not be needed. On the other hand, a wetter than normal winter season may raise soil pH abnormally high due to very low ionic strength, resulting in no lime recommendations for some samples that should receive a lime recommendation (Kissel et al., 2009). The pH_{salt} measurement provides consistency by controlling the ionic strength in the pH measurement solution, thereby removing these variations in soil pH measured with deionized water. This may provide better overall lime recommendations.

Table 1. Lime recommendation information from public soil testing labs for cotton in Southeastern U.S.

State Soil Lab	Target pH	Critical pH[a]	Min. Lime Recommended	Reference Publications[b]
			---ton $acre^{-1}$---	
Auburn University	6.5	5.6, 5.8[c]	1.0	Adams, 1958; Adams, 1965; Mitchell et al., 1977
Univ. of Arkansas	5.8-6.2[d]	5.8	1.0	unknown
	6.3-6.9	6.0		
Univ. of Georgia	6.0, 6.5	5.8	0.5	unknown
Louisiana State	6.5	5.8	1.0	unknown
Mississippi State	> 6.0	6.0	1.0	unknown
NCDA&CS	5.0, 5.5, 6.2[e]	5.0, 5.5, 6.2	0.3	McCart & Kamprath, 1965
Oklahoma State	6.5	6.5	0.5	unknown
Clemson Univ.	6.0, 6.5	6.0	0.5	unknown
Univ. of Tennessee	6.6	6.6	1.5	unknown
Texas A & M	> 6.0	5.95	1.0	unknown
Virginia Tech	6.2	6.2	0.5	unknown

[a]Critical pH is pH below which lime recommendation is made; lime recommendation in most states is also dependent on exchangeable acidity measurement.

[b]Publications establishing critical pH or of lime studies.

[c]A pH of 5.8 is for soil with ECEC < 9.0 cmol kg^{-1}, pH of 5.6 is for soil with ECEC > 9.0 cmol kg^{-1}.

[d]Optimum pH range considered to be 6.3-6.9; lower range is a medium range.

[e]Target pH dependent on soil class determined by humic matter content; lime recommendation is also based on measured pH and exchangeable acidity as measured by Mehlich buffer.

Table 2. Methods used by state soil testing laboratories in the Southern Region for determining soil pH and the lime requirement.

State	Soil: Solution Ratio	pH Solution	Equilibration Time	Exchangeable Acidity Method	Lime[a]
	--v:v--		---min---		
AL	1:1	DI H_2O	60	Modified Adams Evans buffer	Ag lime
AR	1:2	DI H_2O	30	pH and Mehlich -3 Ca[b]	Ag lime
FL	1:2	DI H_2O	30	Adams Evans buffer	90% CCE
GA	1:1	0.01 M $CaCl_2$	30	$Ca(OH)_2$ titration	Ag lime
KY	1:1	DI H_2O	15	Sikora buffer	ECC
LA	1:1	DI H_2O	120	$Ca(OH)_2$ titration	Ag lime
MS	1:2	DI H_2O	15	Modified Woodruff buffer	100%CCE
NC	1:1	DI H_2O	30	Mehlich buffer	90% CCE
OK	1:1	DI H_2O	30	Sikora buffer	ECC
PR	1:2	DI H_2O	30	$Ca(OH)_2$ titration	
SC	1:1	DI H_2O	60	Moore-Sikora buffer	Ag lime
TN	1:1	DI H_2O	30	Moore-Sikora buffer	Ag lime
VA	1:1	DI H_2O	120	Modified Mehlich	ECC

[a]Refers to type of lime recommended or some criteria for lime requirement; ECC = effective calcium carbonate equivalency.

[b] Mehlich-3 extractable Ca is used as a surrogate for soil texture.

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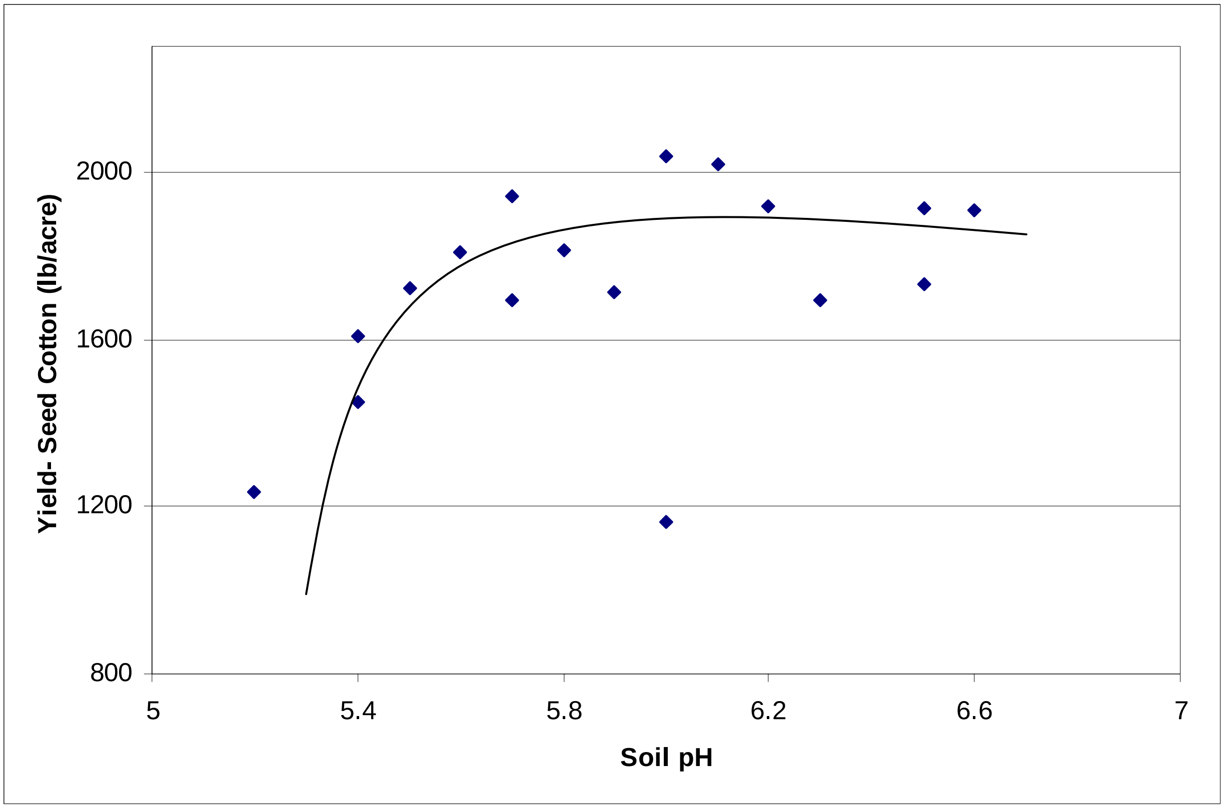

Figure 1. Average cotton seed yield (1958-1961) on a Norfolk soil as influenced by soil pH. Data taken from Table 1 in Adams (1968).

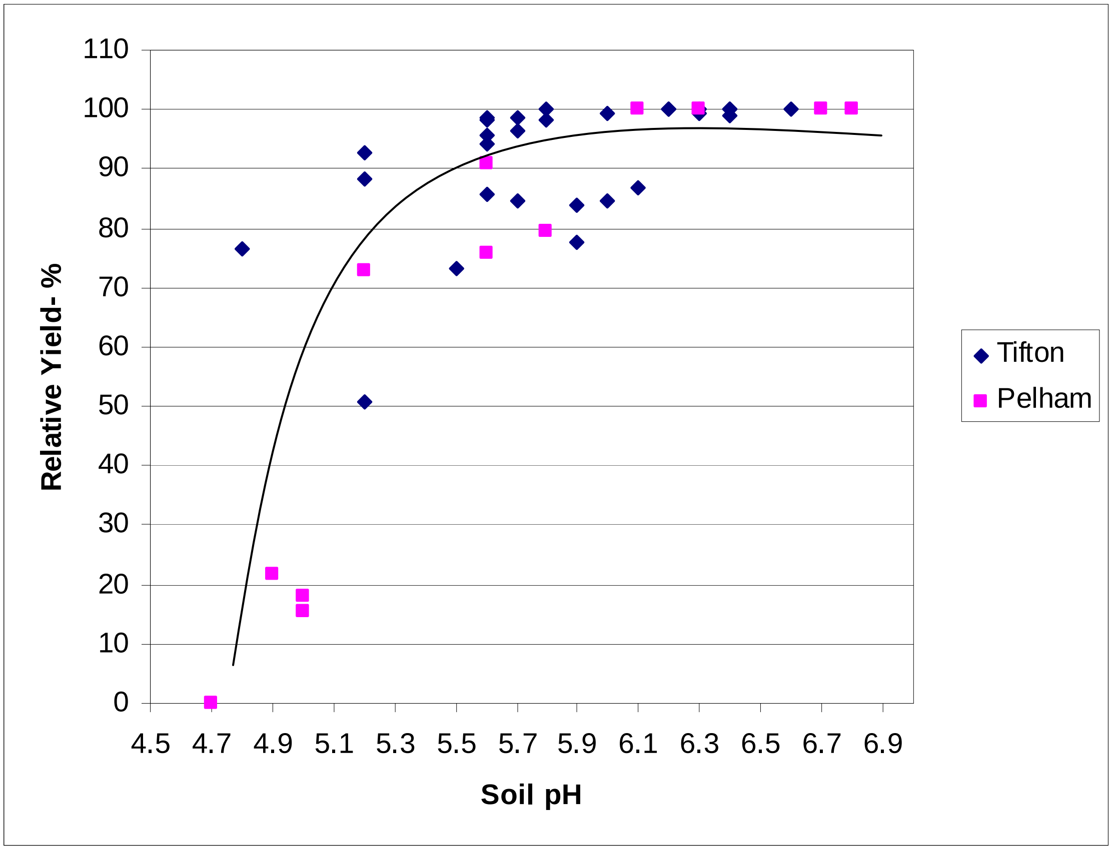

Figure 2. Relative yield of cotton as affected by soil pH in the top 0-15 cm soil. Data are taken from Figures 1 and 2 in Gascho and Parker (2001).