Diagnosis of Loblolly Pine (*Pinus taeda* L.) Nutrient Deficiencies by Foliar Methods

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ABSTRACT

Quick identification of loblolly pine nutrient deficiencies has troubled foresters who wish to increase productivity through fertilization. In the past, extensive field trials were established that did not allow for quick identification of a large number of possibly limiting nutrients in individual stands. This study used single-tree fertilization with macro-nutrients (N, P, K, Ca, Mg, S) and micro-nutrients (Mn, Zn, B, Cu, Fe, Mo) to identify deficiencies using foliar techniques in one growing season. Four study sites in TX, AL, GA, and SC were established in loblolly pine plantations at or near canopy closure. Nutrient concentrations relative to the critical level, optimal nutrient ratios, DRIS methodology, vector analysis, and changes in individual fascicle and total current year foliage weight/area were used to identify deficiencies. Phosphorus was repeatedly indicated as most limiting growth at TX while K was implicated at SC. The GA site revealed multiple deficiencies including N, K, and S. The AL site revealed only a very suspect B deficiency. Critical level methodology was effective in identifying deficiencies of N, P, and K, while B, S, and Cu appeared to be available at sufficient quantities when concentrations were below the published critical levels. Concentrations of S were especially below the critical levels and not increased by fertilization indicating that the critical levels were too high. Nutrient ratio interpretability was reduced by luxury uptake of N in comparison to other deficient nutrients. DRIS methodology was hampered by the inability to create effective comparative norms. Deficiency detection with vector analysis created problems when B and Mn displayed greater uptake relative to controls than the macro-nutrients that provided relative foliage mass increases. Resulting diagnosis indicated deficiencies when B and Mn were really taken up as luxury consumption. Vector analysis may not be as effective as its individual parts. Foliage weight/area responses detected fewer deficiencies than the other techniques. No significant foliar responses were seen at the TX or AL sites. However, K at the SC site was identified as deficient by all foliage mass variables, and multiple deficiencies were detectable at the GA site.

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This research was conducted on industrially owned timberland and my contacts were Emily Goodwin, Temple-Inland; Valerie Sawyer, Weyerhaeuser Co., Mike Cerchiaro, Forest Investment Associates; Ray Young, Forest Resource Consultants Inc.; and Andy Laviner; Mead Westvaco. David Mitchem and Ruth Lanni were also invaluable in laboratory analysis.

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INTRODUCTION

Diagnosis of nutrient deficiencies in loblolly pine (*Pinus taeda* L.) historically troubled foresters who sought to increase production through fertilization. Through 35 years, the Forest Nutrition Cooperative (FNC) has found few hard and fast rules regarding pine plantation's requirements for fertilization. A lack of 100% truisms regarding specific sites, times, and rates of required nutrient additions has not slowed the use of large-scale, operational fertilization. Since the early 1990's the number of acres fertilized by the members of the FNC has increased from 80,800 hectares to just less than 484,800 hectares in 2004. This total is down from a high in 1999 of nearly 646,400 hectares due mainly to rising cost of fertilizer materials (FNC, 2005a)

Increased use of fertilizer comes with the understanding that certain deficiencies are predictable. P fertilization at the time of planting increased the growth of pine on poorly drained flats of the Lower Coastal Plain. An application of 28 – 56 kg/ha of P increases the growth of a stand in a rotation and increases the site quality (Pritchett and Comerford, 1982). Large areas in the Upper Gulf Coastal Plain have also been identified as P deficient (Allen, 1990). These sites were never farmed and have not been fertilized. In contrast, the response to mid-rotation N+P fertilization tends to be widespread, with positive responses seen throughout the South. Long-term fertilizer trials by the FNC show 85 percent of stands are responsive to one-time applications of 224 kg/ha N and 28 kg/ha P. In these cases, volume increases of 30 percent ($3.5/m^3$/ha/year) over a six-year period were typical (Fox et. al, 2006). However, variation of response to mid-rotation N+P treatments is still high (Fig. 1), and the ability to determine the probability of response for an individual stand is uncertain.

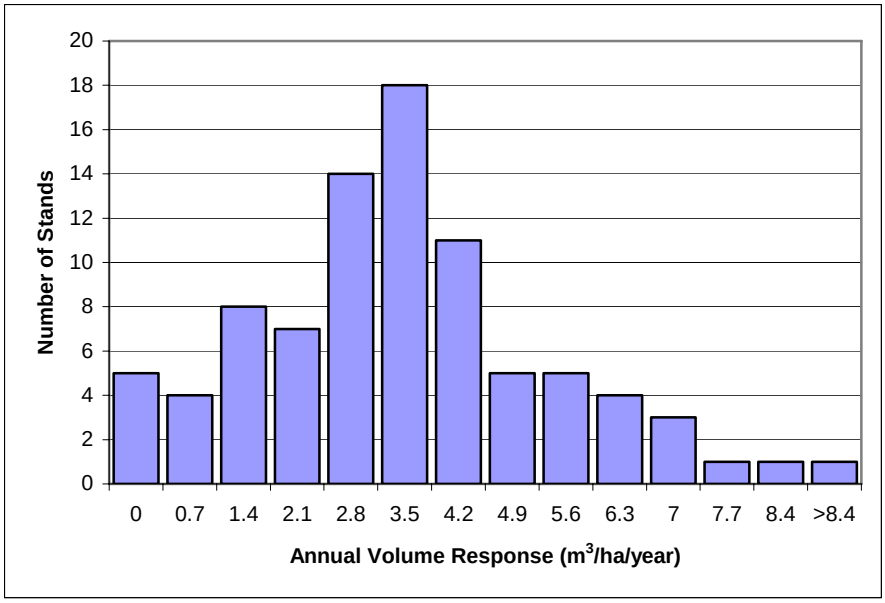

Figure 1: Frequency Distribution of four-year response to a one time application of 224N + 28P in 72 intermediate-aged loblolly pine plantations (Data taken from FNC RW 13, 15, and 17) (FNC, 2005b). Figure adapted with kind permission from the Forest Nutrition Cooperative.

An important question then remains: with the widespread addition of N and P to Southeastern pine plantations, what factors prevent certain stands from achieving an average or above average response to fertilization? Water availability, either too much or too little, was considered the resource that most limits pine productivity. This may be true for young stands that have not fully exploited the available soil volume, and throughout the entire rotation for stands on sites with poorly and excessively drained soils (Allen et. al. 2005). However, in most cases, root growth into deeper, finer-textured soil horizons with more water holding ability, and intensive cultural treatments such as bedding, ditching, and sub-soiling generally ameliorate these water availability issues. Recent findings indicate that low levels of available nutrients besides N and P, mainly K and B, may be restricting the growth of mid-rotation pine to a greater extent than limited water availability (Albaugh et. al., 2004). Identifying and correcting deficiencies of elements that limit growth is the key to increasing the productivity of pine plantations (Fox, et. al., 2004).

Recent evidence that K and micronutrients may increase growth in some stands (FNC, 2004) has stimulated interest in evaluating a large number of stands for such deficiencies.

At the same time, evidence that first year foliar mass response to fertilization may be an excellent predictor of four year volume response (FNC, 2005b) has similarly stimulated interest in using foliar methods to diagnose deficiencies. In the past, foliar critical range methods have primarily been utilized to identify nutrient deficiencies in pine stands. Due to questions regarding the utility of published critical values other than N and P (Jokela, 2004), methods that integrate some measure of growth as well as nutrition are useful in deficiency diagnosis.

To explore the possibility of using various diagnosis techniques based on foliar analysis to evaluate the nutrient needs of individual stands, a series of trials were established with the following objectives:

1. Establish single-tree fertilization plots at four sites across the southern U.S. to evaluate the effects of multiple nutrient combinations from the control, to basic (N+P), to complete (all essential nutrients).
2. Use differences in foliar mass, critical range, vector analysis, and the diagnosis and recommendation integrated system (DRIS) to diagnose nutrient deficiencies following one complete growing season after fertilization.
3. Measure and maintain plots for future workers who will compare first year diagnosis to long-term growth response.

LITERATURE REVIEW

Diagnostic Tools

Early nutritional diagnosis efforts primarily dealt with correlations of various measures of soil nutrient availability or mineralization potential to fertilizer application response. However, foresters began to realize that variability of soil chemistry, even within stand boundaries, is so high that reliable fertilizer decisions were not possible (Wells et. al., 1973). Most soil diagnostics now rely on broad groupings based on physical and not chemical characteristics because they seem to be as reliable and much cheaper to obtain for large industrial ownerships (Jokela and Long, 2000). Newer diagnostic techniques rely on the theory that correlates leaf area projection and light interception to volume production (Fox et. al, 2006). This theory implies that nutrient deficiencies are the

principle restrictions for leaf area production and in turn volume growth. It is also implied that addition of limiting nutrients will increase foliage production (Vose and Allen, 1988). These new diagnostics are able to integrate soil availability, tree uptake, and resulting biomass accumulation into an easily measurable attribute that can guide elemental applications in reaching the maximum attainable production. The following diagnostic techniques discussed in this review have all been tested throughout more than 35 years of forest fertilization research.

Soil Groups

Established soil groupings are the easiest and most applicable method to use when classifying potential sites for fertilization (Jokela and Long, 2000). Based on recognizable features such as texture or depth, soil classifications are used to identify stands where nutrient availability is low, or where moisture availability may limit growth. In the early 1980's the Cooperative Research in Forest Fertilization (CRIFF) program at the University of Florida developed 8 soil groups to aid in making forest fertilization decisions. These groupings proved to be useful in making responsible decisions regarding widespread fertilizer applications (Fisher and Garbett, 1980). In some instances fertilization decisions can be made based solely on the soil group (Jokela and Long, 2000). In other circumstances, response to fertilization was shown to vary greatly within a soil group (Jokela, 2004), indicating an oversimplification of response prediction variables and the need for more information to make informed decisions. Soil mapping and classification now aids in the integration of management decisions in all aspects of forestry operations (Fisher, et. al., 2005). These maps assist in decisions regarding regime intensity, species deployment, herbicide and fertilizer application, insect and disease hazard ratings, and harvest scheduling.

Foliar and Soil Testing

In contrast to soil groupings, foliar and soil tests provide more specific nutrient deficiency diagnosis because sampling is done in the candidate stand. Soil testing quantifies the nutrient supply of a site, while foliar testing integrates soil supply and nutrient uptake. However, the vast numbers of site and soil characteristics that influence tree growth reduce the reliability of chemical diagnostics when applied to many candidate

stands (Jokela, 2004). For example, correlation of height growth with soil and foliar P differs across physiographic regions and drainage classes (Wells et. al. 1973, Wells et. al. 1986). In other cases, foliar concentrations of N or P were not as closely correlated with volume production as exchangeable acidity, Al, or pH (Hart et. al., 1986). Keeney (1980) determined that because of the rapid circulation of N through foliage, litter, and soil, laboratory extraction methods that formulate fertilization recommendations are too variable to be of much use. However, by standardizing sampling techniques and evaluating years of foliage concentration data, critical levels, or the nutrient concentration needed to attain 90% of maximum growth, have been published for the macro-elements and micro-elements in southern pine species (Allen, 1987; Jokela, 2004; Pritchett and Comerford, 1983; Stone, 1968; Wells et. al., 1973). Unfortunately, there are uncertainties about the accuracy of critical levels except for N and P (Jokela, 2004), and their levels should be used with caution.

Visual Diagnostics and Fertilizer Field Trials

Quick and inexpensive diagnosis of individual stands has made the use of visual cues the most widely described and intuitive diagnostic technique. Foliar discoloration, needle twisting, needle cast, resin exudation, tip dieback, loss of apical dominance, and branch malformation are symptoms associated with nutrient deficiencies of conifer species (Stone, 1968). However, this system is not as simplistic as it first appears. The same symptom may be attributed to one or more separate nutrient deficiencies or to factors not associated with nutritional complications at all. For example, a widespread epidemic in Australian forests in the 1890's know as "tip dieback" was related to zinc deficiencies due to the conversion of natural forests to radiata pine (*P. radiata* D. Don) plantations (Boardman & McGuire, 1990b). Later, the same symptom was suggested to indicate boron and copper deficiencies because of these elements' involvement in lignification and cell wall formation. In contrast, "tip dieback" in loblolly pine is attributed to freezing injury, increased growth due to elevated CO_2 levels, and the presence of certain fungi and insect parasites (South et. al., 2002). Obviously, diagnosis by visual cues can only be conducted by individuals with years of regional experience, and even then should be verified by a foliar test. Also, the onset of visual symptoms indicates extreme

deficiencies, and any nutrient management strategy relying on visual diagnosis would miss opportunities to increase productivity through fertilization by correction of sub-acute deficiencies.

Fertilizer field trials are the most accurate approach in determining responses to fertilization (Jokela, 2004). Operational fertilization regimes have benefited from knowledge gained from field trials established by University/Industry/USFS cooperatives. Productivity gains are realized by integrating research involving fertilization materials, rates, and timings with other productivity determinants including classification, site preparation, thinning, and weed control (FNC, 2005a). Cost restraints and inability to garner results without waiting years for growth responses are why this technique has not been used to identify individual stand nutrient deficiencies. Regardless, large-scale field trials will continue to be used well into the future due to their potential to show what is possible under intensive management.

Response Models

Decision making software using long-term fertilization data has been developed to aid forest managers to predict responses to cultural treatments. Software packages are built upon base-line growth and yield models developed using extensive, long term measurement plots across large geographical areas and site conditions (Amateis et. al., 2000). Functions reflecting additional data from fertilizer trials are added to allow for extrapolation of growth from fertilizer inputs (Martin et. al, 1999). Many fertilizer trials have also tested the effects of other cultural treatments including site prep, weed control, and thinning, so models can also estimate stand development as a result of these treatments (Amateis et.al., 2005a). Incorporating financial analysis into fertilizer response models allow foresters to design rotation length management scenarios that efficiently utilize monetary inputs at the stand level. Finally, independent field-testing and calibration by users provides valuable feedback to developers who work to constantly improve the reliability of response models.

When applying response models, it is important to realize that they are only as good as the data they are based on and cannot reflect changes in future cultural treatments. For example, the FNC's FASTLOB2 was based on growth and yield data from stands grown using techniques common during the 1950's through 1970's that did not incorporate genetically improved planting stock or chemical weed control (Amateis et.al., 2005a). Subsequently, additions to the software that utilize expert systems allow users to model the effects of site conditions, site preparation, and first year silvicultural treatments that affect survival and growth with greater flexibility (Amateis, et. al., 2005b). This allows the system to accommodate a variety of users with a corresponding variety of silvicultural inputs, but data included from trials with nutrients other than N and P will be needed to predict responses to further additions.

Diagnosis by Leaf Area

Suboptimal growth in pine plantations can be attributed to low leaf area, with poor nutrition being the principle cause (Colbert et. al., 1990; Albaugh et. al., 1998). Correlation between growth, leaf area, and nutrition are so strong that leaf area is now considered a good indicator of the nutritional status in individual stands (Allen et. al., 2005). Current stand leaf area can be compared to its potential leaf area to estimate the responsiveness to nutrient additions and appropriate timings, rates, and elements of application. Current management guidelines developed by the FNC now recommend that fully stocked stands (BA >22.7 m^2/hectare) should have a leaf area index (LAI) of 3.5. Stands that do not reach this benchmark are likely to respond to mid-rotation fertilization, with a probability of response proportional to the degree of leaf area underperformance (Fox et. al., 2006). LAI of pine plantations can be quickly estimated using remote sensing data due to the species and spacing homogeneity of plantations (Allen et. al., 2005). Remote sensing of LAI can identify stands that will be responsive to fertilizer due to low LAI, and also monitor the changes in LAI following fertilization to determine the efficacy of the fertilizer additions (Flores et. al. 2006). Finally, coupling remotely sensed LAI data with stand, soils, geology, and silvicultural management data in a GIS allows for the prediction of nutrient deficiencies in individual stands across a landscape.

Principle Diagnostic Tools

Fascicle Mass/Total Branch Foliage Mass and Area

Leaf area index depends on tree age, stand density, and nutrient supply (Martin and Jokela, 2004). Deviation in a stand's current LAI from its maximum supportable LAI is used to predict response to fertilization because nutrient availability is the primary driver of LAI production (Vose and Allen, 1988; Albaugh et. al., 1998). Directly measuring LAI in small plots, although incredibly useful, can be troublesome. Methods require lengthy periods of litter collection, interpretation of hemispherical photos, or implementation of remote sensing systems. However, measuring fascicle mass is a less complicated and expensive surrogate for LAI. FNC data has shown that fascicle weight was correlated with LAI across many different site, stand, and fertilizer application conditions (NCSUFNC, 1991). Valentine and Allen (1990) found that changes in fascicle mass provided correct diagnosis of N and P deficiencies while foliar nutrient concentration provided no additional prediction power. Even more recently, first year fascicle mass response to fertilization was shown to correlate (R=0.75) with four-year volume response (FNC, 2005b). By relying on correlations such as this, the use of singletree plots and one-year foliage response will greatly reduce the time and expense of diagnosing nutrients needed in multiple stands.

Monitoring changes in fascicle mass to predict responses to N and P has worked well on species with determinate growth patterns like Douglas-fir (*Pseudotsuga menziesii* Franco.) (Brockley, 2000) and Balsam fir (*Abies balsamea* L. Mill) (Timmer and Stone, 1978). However, the technique may be problematic in loblolly pine because it produces multiple growth flushes in a year (Kozlowski and Pollardy, 1997). Loblolly pine may respond to fertilization by producing more but not necessarily heavier foliage. The problem can be overcome by quantifying the entire amount of current year foliage on a branch. The mass of the entire year's foliage could show differences between control and treated trees if the fertilizer response produces more but not larger foliage. The leaf area of individual foliated flushes could also be affected by fertilization. Equations are

available that have proven reliable in estimating the leaf area of individual flushes on lateral shoots (Murthy and Dougherty, 1997b)

Critical Level Methods

Critical level methodology is an extension of plant and soil analysis that incorporates the site's ability to supply a nutrient and the stand's demand for a nutrient (Allen, 1987). Throughout years of plant analysis, the critical levels for southern pines have been established (Table 1). Critical level in diagnosis is based on a function that correlates optimal nutrient concentrations to optimal plant productivity and yield (Fig. 2). The critical level of nutrient concentration for an element is reached when plant productivity is equal to approximately 90% of maximum growth (Fig. 2). Below the critical level, production is not at its maximum, but beyond this level growth is not affected. Nutrient sufficiency is seen as elemental uptake increases beyond that needed to achieve 90% of maximum growth. Further uptake with no additional increase in growth indicates luxury consumption. Toxicity of a nutrient occurs if nutrient concentrations increase further. However, for most nutrients and plant species, the range of nutrient concentration or availability between that needed to achieve 90% of maximum growth and the onset of toxicity is large (Stone, 1968).

Table 1: Critical level of nutrient concentration for commercial southern pine species in foliage of the current year. Table compiled from data kindly permitted by the Society of American Foresters.

Nutrient	Loblolly Pine (*P. taeda*)	Slash Pine (*P. elliottii*)
	---------- g/kg ----------	
Nitrogen (N)	12.0	10.0
Phosphorus (P)	1.2	0.9
Potassium (K)	4.0	3.0
Calcium (Ca)	1.5	1.0
Magnesium (Mg)	0.8	0.6
Sulfur (S)	1.2	0.8
	---------- mg/kg ----------	
Manganese (Mn)	40	40
Zinc (Zn)	20	20
Boron (B)	10	8
Copper (Cu)	3	3
Iron (Fe)	20	20
Molybdenum (Mo)	0.10	---

Allen (1987); Jokela (2004); Wells et. al. (1973)

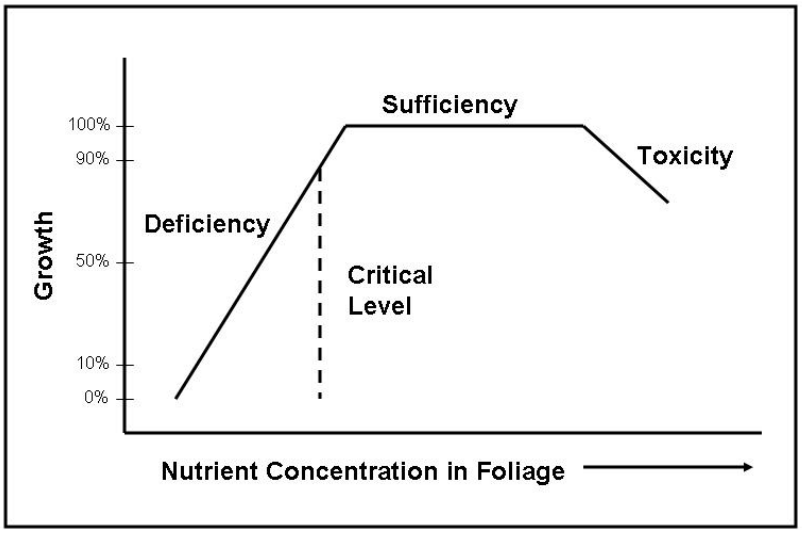

Figure 2: Model of growth as a percent of maximum potential relative to the nutrient concentration in foliage and specifically the critical concentration.

Critical level diagnosis of nutrient deficiencies is most powerful when one nutrient is deficient, and inference is lost when the uptake of one nutrient is affected by the status of others (Bates, 1971; Mead, 1984). Adding deficient nutrients increases growth to a point where adequately supplied nutrients are diluted. Gregorie and Fisher (2004) found that multiple, interacting deficiencies and dilution effects negatively affected the ability of the critical level method to diagnose loblolly pine responses to fertilization. When the number of elements at an optimal level increases; the range of sufficiency narrowed, making a sustained maximum level of production harder to maintain (Bates, 1971). Published critical levels are established for specific plant parts at specific physiological ages and inadequate sampling can flaw diagnosis. Variation is seen in nutrient concentration of older and younger needles and from tree to tree within stands. Concentrations of mobile elements (N, P, K, Mg, S, and Zn) decrease with foliage age while concentrations of immobile elements (Ca, Fe, B, Mn, Cu, and Mo) increase (Landis et. al., 2005). Critical levels are also affected by site and climate factors, nutrient interactions, and genotype (Hockman & Allen, 1990). Due to the many variables associated with tissue sampling, analysis based on critical ranges alone has many limitations (Jones, 1991).

Vector Analysis

Vector analysis is a graphical method of diagnosing plant nutrient deficiencies based on changes in nutrient concentration, fascicle mass, and nutrient content in response to fertilization (Timmer and Stone, 1978). Fascicle mass integrates interpretation of nutrient availability, nutrient demand, and plant growth. Vector analysis can interpret the effects of dry matter production on nutrient concentrations including dilution effects, nutrient imbalances, and element interactions (Timmer, 1991). Comparisons of several nutrients can be incorporated into an assessment of nutrient balance using a single graph. Diagnosis can be interpreted independently because vector analysis uses measurements compared to a control on site. This makes vector analysis independent of standard critical levels or nutrient ratios (Hasse & Rose, 1995).

Vector analysis involves plotting nutrient content as a function of nutrient concentration and foliar mass, allowing for graphical examination of nutrient status (Fig. 3). Data is plotted as vectors radiating from a common point represented by the control. Direction and length of vectors represent shifts in foliar nutrient levels and foliar mass. Longer vectors represent a greater response from the control than shorter vectors. Perfectly diagonal shifts indicate no change in foliar mass, whereas horizontal or vertical shifts indicate decreases or increases in foliage production. Horizontal vectors indicate no change in foliar nutrient concentration, but vertical vectors indicate increases or decreases in nutrient concentration. Shifts in foliar content are contrary to this relationship. Increases of all three variables produce vectors that increase vertically, and shift to the right. In this case, the nutrient displays a deficiency indicating the nutrient is limiting to growth. Interpretations for other vector shifts are summarized in table 2.

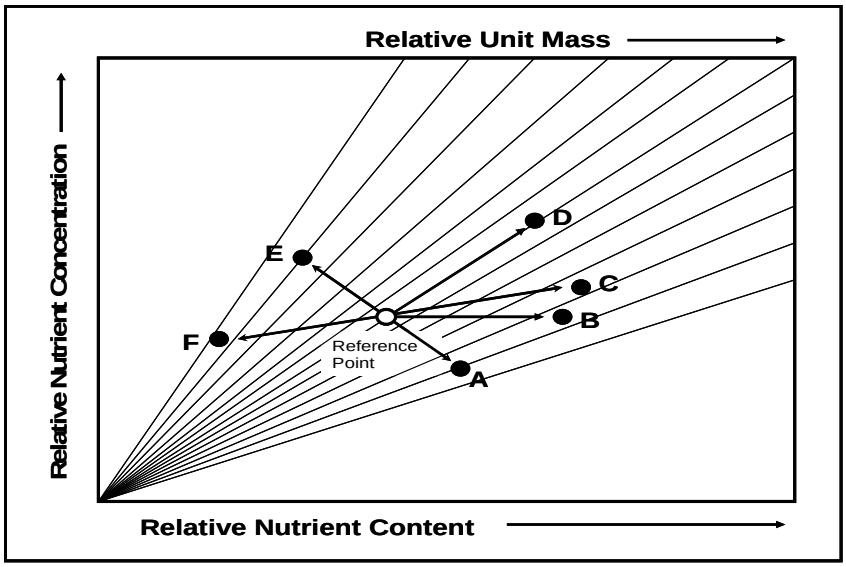

Figure 3: Graphical display of 7 possible shifts in loblolly pine foliar nutrition that can be diagnosed with vector analysis. Adapted from Timmer and Stone (1978) with kind permission from ISA-CSSA-SSSA.

Table 2: Interpretation of 7 possible shifts in nutrient concentration, nutrient content, and foliar dry weight created by vector analysis. Adapted from Timmer and Stone (1978) with kind permission from ISA-CSSA-SSSA.

Vector Example	Response in			Interpretation	Possible Diagnosis
	Dry Weight	Nutrient			
		Conc.	Content		
Reference	0	0	0	Control Point	Pre-Fert Nutrition
A	+	-	+	Dilution	Non-limiting
B	+	0	+	Sufficiency	Non-limiting
C	+	+	+	Deficiency	Limiting
D	0	+	+	Luxury Consumption	Non-toxic
E	-	++	±	Excess	Toxicity
F	-	-	-	Excess	Antagonistic

Vector analysis is used extensively in screening stands for potential response to fertilization. Many past studies utilizing vector analysis (Weetman and Fournier, 1982; Timmer and Stone, 1978; Chappell and Bennett, 1993) have used species with determinate growth habits. In these species the number of needles produced in a season is set in the lateral buds of the previous year, and fertilization can increase the size but not the number of needles in the following season (Binkley, 1986). Southern pines produce foliage indeterminately, which creates problems when vector analysis is employed.

Murthy and Dougherty (1997a) found that loblolly pine responds to fertilization with greater needle radius, length, and a greater number of current year fascicles. This confounds efforts to use vector analysis in some cases. Efforts with vector analysis in the South (Ngono and Fisher, 2001; Valentine and Allen, 1990; Bekele et. al., 1999) have succeeded in identifying nutrient deficiencies of N and P. In several cases, these deficiencies were verified by long-term growth responses. Vector analysis with micro-nutrients displayed that they are not capable of producing growth responses without macro-nutrient fertilization (Thelin et. al., 1999). Ngono and Fisher (2001) described precision of vector analysis deficiency detection between DRIS and critical levels, which were more and less sensitive, respectively.

Diagnosis and Recommendation Integrated System (DRIS)

The Diagnosis and Recommendation Integrated System (DRIS) has an advantage over single nutrient deficiency diagnosis techniques because it considers all nutrients simultaneously. DRIS can identify the nutrient most limiting to growth while ranking other deficiencies to create an index of total nutrient imbalance (Beaufils, 1971). DRIS is based on the assumption that as production reaches an optimum, the number of limiting factors decreases, the variance in the ratios of nutrients decreases and the nutrient balance of highly productive individuals becomes more similar (Walworth and Sumner, 1987) (Fig. 4). The ratios, or norms of the high-yielding population, are calculated for pairs of nutrients in every combination that significantly affects growth. The norms are compared to the sample in question by simple functions that average all of the ratios with a single element to produce nutrient indices. These indices evaluate the adequacy of each nutrient in relation to all of the others, resulting in the diagnosis of a proper nutritional balance for optimum production (Beverly, 1991).

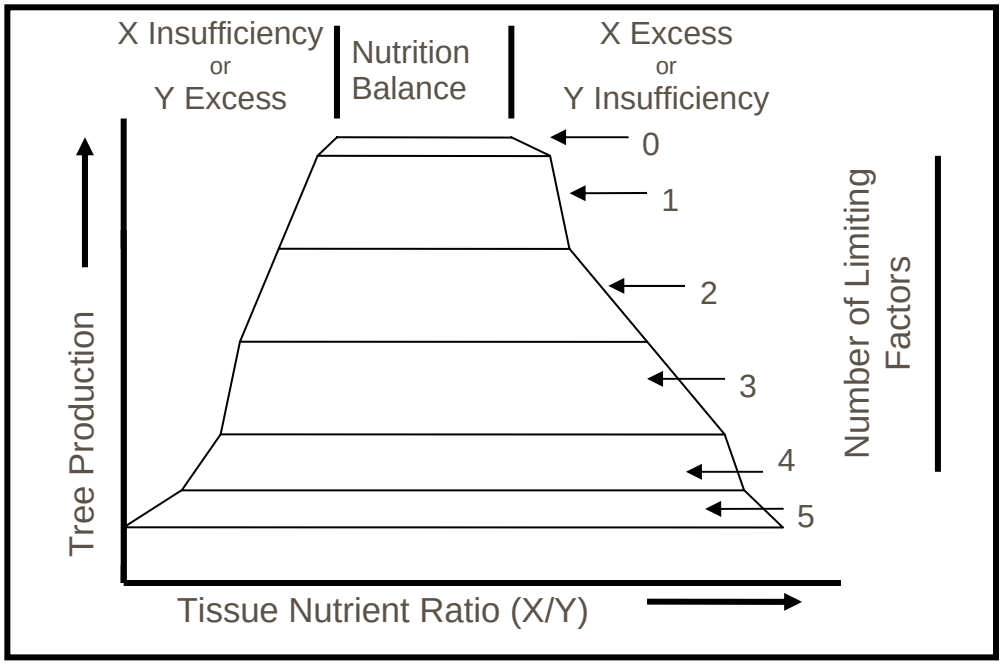

Figure 4: The underlying assumptions of DRIS methodology are that as plants gain limiting resources, the nutrient status of the most highly productive individuals becomes less variable. Taken from Walworth and Sumner (1987) with kind permission of Springer Science and Business Media.

Developing DRIS norms requires that a data set be divided into high and low yielding subsets. Higher yielding individuals have fewer limiting factors, leading to balanced nutrition that maximizes growth. The actual criteria used in separating high and low yielding populations varies from user to user, but norms selected for optimal fruit production may not be the same as norms selected for optimal dry matter production (Walworth and Sumner, 1987). After the separation of high and low-yielding populations, pairs of elements are expressed as the ratio A/B or its inverse B/A where A and B represent foliage concentrations of two different nutrients. DRIS can evaluate the nutrient status of many elements at a time and all relevant two-element combinations should be considered. The decision to select the expression A/B or B/A involves determining which best discriminates between high and low yielding populations. Selecting the expression that has the highest variance ratio ($Var_{Low\,/}\,Var_{Hi}$) conforms to the assumptions of DRIS.

Nutrient deficiency diagnosis using DRIS involves the creation of an index quantifying the relative need or excess of one nutrient relative to all of the others in the comparison.

One of two functions standardizes nutrient ratios from suspect stands based on whether their nutrient ratios are greater or less than the high yielding norm. Functions are also weighted by the inverse of the CV of the high yielding norm. Lastly, all intermediate functions that contain a specific element are averaged to produce an index of need or excess relative to all of the other elements. Equations for the creation of intermediate weighted functions and average elemental index values for hypothetical elements A through N include:

$$\text{A index} = \frac{[\, f\,(A/B) + f\,(A/C) + f\,(A/D) \ldots + f\,(A/N)]}{\#\ \textit{of ratios utilizing A}}$$

$$\text{B index} = \frac{[-f\,(A/B) + f\,(B/C) + f\,(B/D) \ldots + f\,(B/N)]}{\#\ \textit{of ratios utilizing B}}$$

$$\text{N index} = \frac{[-f\,(A/N) - f\,(B/N) - f\,(C/N) \ldots - f\,(M/N)]}{\#\ \textit{of ratios utilizing N}}$$

where, when $A/B \geq a/b$,

$$f(A/B) = ((A/B \,/\, a/b) - 1) \times 1000/CV$$

or, when $A/B \leq a/b$,

$$f(A/B) = ((a/b \,/\, A/B) - 1) \times 1000/CV$$

In this case, A/B represents the ratio of the plant to be diagnosed, *a*/*b* represents the ratio of the norm from the high-yielding population, and CV represents the coefficient of variation of the high-yielding population.

To provide meaningful diagnosis and recommendation, nutrient indices must be properly interpreted. Negative values are only indications of deficiency relative to the other nutrients, with a high-yielding population as the basis for comparison (Beverly, 1991). Factors related to site and genetics alter the nutrient demand of a plant, making its nutrient demand different from the high-yielding comparison plant. It is also important to

remember that a single value for a nutrient is meaningless alone, and all index values must be interpreted together. In some situations of very poor nutrient status, all of the individual index values could be negative. In these cases the magnitude of the negative values must be considered. DRIS indices display the order of nutrient limitation, and more negative index values limit production to a further extent than less negative values. Obviously, the inverse is true in situations where all index values are positive.

The few trials of DRIS in southern pines displayed the effectiveness of the method. Hockman and Allen (1990) reported that first year diagnosis of N and P deficiencies were correct 82 and 91 percent of the time, respectively after investigation of four year BA growth. A more recent East Texas study using DRIS found to it less accurate. First year diagnosis of N and P deficiencies predicted two-year volume response correctly in 42 and 58 percent of cases, respectively (Gregorie and Fisher, 2004). Interestingly, Hockman and Allen produced their diagnostic norms using data from a southwide dataset but indicated that norms produced from a more regional dataset or from specific soil groups would provide better diagnosis. Gregorie and Fisher (2004) produced their norms from trees in only a few East Texas counties; however, the precision and accuracy of their prediction was much lower than that of Hockman and Allen (1990). The assumption that DRIS norms are universal across spatial distances (Sumner, 1979) is clearly refuted by these and other studies that have found differences in DRIS to prediction of nutrient deficiencies, and different published norm values.

Likely Nutrient Deficiencies

As the world population and the demand for wood products increases, the need for intensely managed plantations requiring fertilizer additions will also increase. As new thresholds in pine plantation production are achieved, the demands on the supply of soil nutrients will increase causing a need for fertilizer additions. This situation is complicated by common silvicultural practices involved in site preparation and harvesting that remove topsoil and organic matter from a site. Also, much of the land in loblolly pine plantation production overlays infertile soils (Fox et. al., 2004). Finally,

induced deficiencies are possible due to a depleted soil source from years of management and heavy additions of primarily N and P fertilizers. A study of patterns associated with various nutrient deficiencies could shed light on possible problems associated with each.

Macronutrients

Nitrogen

Nitrogen deficiency symptoms are manifest as chlorosis, yellowing, abscission of older needles, and lack of vigorous growth (Will, 1985). Older needles are affected because N is mobile within plants. N is essential to the formation of amino acids, proteins, and growth hormones. N is also an important constituent of the chlorophyll molecule, making it the most important nutrient to plant growth and biomass accumulation (Marschner, 1986). N is one of the most abundant elements on Earth, but most N is unavailable to plants, existing in the atmosphere as N_2 and in the soil as unmineralized organic N (Marschner, 1986). The nitrogen cycle has been studied by foresters to reduce the dependence on chemical fertilizers. Modifying harvesting and site preparation methods to leave as much N containing organic matter on site has reduced the need for N additions and enhanced the sustainability of pine plantations (Fox et. al, 2004).

Soil nitrogen availability is highest following harvest and site preparation (Allen, 1990). These treatments create a conducive environment for rapid decomposition and mineralization of organic matter. Couple this with the site supporting only young trees with low leaf area and small root systems, and few deficiencies are seen. As stands develop, their requirements for N increase due to accumulation of biomass and forest floors. When forest canopies close, the optimal conditions for decomposition are reduced, and N mineralization is reduced (Allen, 1994). Consequently, N deficiencies occur following canopy closure, and thereafter leaf area and growth are regulated by soil N availability (Allen et. al., 1990) (Fig. 5). The widespread occurrence of this deficiency pattern is evidenced by FNC trials that have shown positive responses to additions of 224 kg/ha N and 28 kg/ha of P in over 85% of mid-rotation aged stands (Fox et. al., 2006).

Recommendations regarding N application are now made based on the amount of projected leaf area with adjustments for stands with high stocking, abundant woody competition, and impending thinning. Current guidelines by the FNC are to add 112-224 kg/ha of N when peak LAI is below 3.5. The critical level of N in loblolly pine foliage is 12.0 g/kg (Allen, 1987). Urea is the favored source of N for mid-rotation applications because of its high N concentration (46-0-0). However, the potential for losses due to volatilization of NH_3 following its use necessitate practices to increase the effectiveness of applied urea.

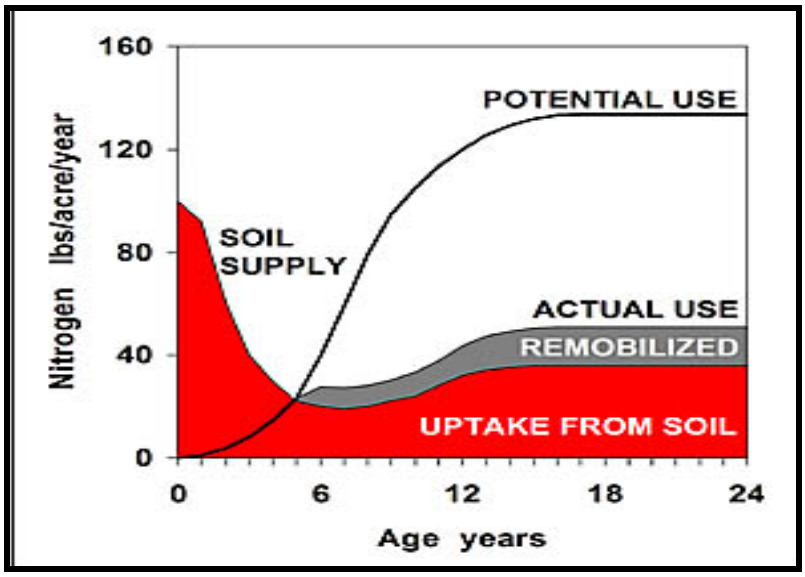

Figure 5: Conceptual model of the soils ability to supply nitrogen and the actual use of nitrogen throughout a plantations development. Taken from Allen et. al., (1990) with kind permission from Elsevier Publishing.

Applying urea ($CO(NH_2)_2$) during periods that result in very rapid hydrolysis to NH_4^+ favor the volatilization of NH_3. Hydrolysis of urea increases soil solution pH leading to the conversion of NH_4^+ to NH_3 and loss by volatilization. Conditions resulting in the greatest volatilization of urea after application include periods of short rain and humidity followed by drying periods with wind (NCSUFNC, 1997). Best management practices include applying urea in the winter when microbe activity is reduced and hydrolysis is slower, and also timing applications with substantial rainfall so that urea is transported from the surface into the soil where it is not vulnerable to gaseous losses (NCSUFNC, 1997). In the worst cases, more than half of the urea applied to forests can be lost

through volatilization (Kissel et. al. 2004). Consequently, uptake efficiency of urea is low with frequently only 20-30 % of the applied N recovered by the crop trees (Allen et. al., 1990). Ammonium nitrate (NH_4NO_3) and ammonium sulfate are other sources of elemental N at 34 % and 21 % N, respectively. However, higher handling and application costs per unit of elemental N limit these materials use in forestry (FNC, 2005a).

Phosphorus

The function of P in plants is to facilitate internal energy transfer as the main constituent of ATP. Unlike other essential elements, P is not chemically reduced as it enters cells. P remains in its highest oxidized form, allowing for a tremendous release of energy as the bonds are broken (Marschner, 1986). P also forms phospholipids that maintain semi-permeable plant membranes (Marschner, 1986). P deficient pines have narrow, thin crowns with poor needle retention. Severe deficiencies cause older needles to turn grayish-green (Will, 1985). The critical level of P in loblolly pine foliage is 1.2 g/kg (Allen, 1987)

Phosphorus is the most common nutrient limiting growth of newly established stands of loblolly pine in the Southeast (Jokela et. al., 1991a). P fertilization is needed at the time of forest establishment on poorly drained clay soils in the flatwoods of Georgia and Florida (Pritchett et. al. 1961). The addition of 56 kg/ha at these sites produces responses of 9.2 m^3/ha/yr over a 15 to 20 year period, turning non-commercial stands into commercially viable ones (Fox et. al., 2004). Newer findings have indicated large areas of the Upper Coastal Plain may also benefit from P at the time of planting (Allen and Lein, 1998). Possibly millions of hectares from Georgia to east Texas are moderately deficient and may respond to P additions throughout the entire rotation (Allen, 1994). Diammonium phosphate (DAP) (18-46-0) is the most utilized source of P at the time of planting, with elemental application rates ranging from 28 to 56 kg/ha. Responses to P are not seen often in established stands except in situations where foliar nutrient levels are extremely low (Fox et. al., 2006).

Phosphorus is tightly bound to Al, Fe, Ca and organic matter surfaces in acid soils of the Southeast and only a small portion is found in the soil solution (Wells et. al, 1973). The insoluble, non-labile fraction of soil P represents more than 90% to total soil P (Mengel and Kirkby, 2001). Plant demand for P is greater than the relatively small amount that is in the soil solution, so replenishment of solution P is initiated by root uptake. Buffer capacity of the soil is the driver of solution P replenishment (Marschner, 1986). This replenishment is inversely related to the sorption strength of the non-labile fraction of P (Holford, 1997). High sorption strength and low buffering capacity are reasons that severe P deficiencies are seen on heavy clay soils of the Lower Coastal Plain.

Nutrition of P is inhibited by the other nutrients that compete with phosphate for adsorption sites in soil as well as uptake by plant roots (Marschner, 1986). Problems associated with Zn or As are most often implicated. Nutritional complications involving phosphate and arsenate result from the similar molecular structure they share. Arsenate and phosphate compete for the same adsorption sites on kaolinite surfaces with arsenate having a greater capacity to replenish the soil solution following phosphate or arsenate uptake (Quaghebeur and Rengel, 2004). The same study reported that additions of P increased the concentration of arsenate in solution. The majority of cases involving zinc and phosphorus indicate that zinc nutrition is harmed more than phosphorus. However, one theory describing the Zn-P interaction in soil involves the formation of very insoluble Zn-phosphates, making both elements unavailable. This mechanism for Zn-P antagonism has been found in sandy soils supporting radiata pine plantations in southwestern Australia (Boardman and McGuire, 1990a), and Stone (1968) stated this reaction was more likely to occur in sandy soils because they have little ability to fix phosphorus.

Potassium

K is the most abundant cation within the cytoplasm of plant cells, and contributes greatly to the maintenance of turgor within all plants (Marschner, 1986). K concentrations control gas exchange and water loss by activating stomatal guard cells. K also activates over 50 enzymes, stimulates ATP proton pumps, binds proteins during tRNA synthesis, and counters the uptake of NO_3^- (Mengel and Kirkby, 2001). Will (1985) described

deficiencies of K in pine as uniform chlorosis of older leaves in the lower sections of the crown. Symptoms may intensify in the late winter as K accumulating pollen cones expand. The critical level of foliar K concentration is 4.0 g/kg (Allen, 1987).

Potassium deficiencies are more likely in stands on deep, sandy, undeveloped soil profiles. The univalent, high ionic radius nature of the K^+ ion leads to increased leaching on these sites (Marschner, 1986). K^+ retention in soils can be influenced by cation competition, and deficiencies are seen on "ultra basic" marine sediments that contain excess Mg^{+2} or Ca^{+2} (Will, 1985). Simultaneous applications of KCl and NH_4^+ in sandy soils also lead to excessive leaching of K^+ from more intense cation competition for plant and soil exchange (Philips, 2004). K deficiencies are not widespread in the South despite an abundance of sandy soils. Isolated responses to K were seen in FNC trials located on Pliestocene Sands soil groups on the Atlantic Coastal Plain in Georgia and South Carolina and in the Sandhills province of South Carolina (FNC, 2005b). The small number of K deficiencies in pine stands in the southeast may be due to the mobile nature of K within plants. Even K deficient plants are able to redistribute K to actively growing meristems to maintain growth despite poor nutrition (Marschner, 1986).

Calcium

The function of Ca within plants is the formation of the cell wall. Other requirements for Ca are the stabilization of phospholipids in cell membranes and the formation of callose in response to wounding (Marschner, 1986). Will (1985) describes resin exudation from buds and shoot death of the terminal leader as visual symptoms of Ca deficiency. Death of terminal shoots represents the immobility of Ca within plants and its utilization in the formation of cell walls. The foliar critical level of Ca in loblolly pine is 1.5 g/kg (Allen, 1987). If Ca deficiencies are expected, lime is not a preferable source for use in pine plantations. Loblolly pine has adapted to acid soils of the southeast, and adjusting the soil pH could reduce the ability of native pines to sequester nutrients. Gypsum is a source of Ca and S at 22% and 18%, respectively that does not alter soil pH.

Seldom has loblolly pine ever responded to added Ca in the form of lime or any other source. Isolated responses with no apparent pattern have been observed on pocossins, in the Piedmont, and in the Lower Atlantic Coastal Plain indicating no relationship between deficiencies of Ca and soils (Kyle et. al., 2005). Ca^{2+} can be leached from sandy soils, especially in the southeast where acid conditions and additions of NH_4^+ fertilizers create intense cation competition (Mengel and Kirby, 2001). Acid rain also decreases soil pH and thus increases Ca^{2+} leaching. In the worst of circumstances, for every 100kg of N or S added as NH_4^+ or SO_4^+, up to 45 kg of Ca^{2+} can be removed in drainage water (Mengel and Kirby, 2001).

Magnesium

The Mg^{2+} molecule is the central atom in the chlorophyll molecule. However, only 10% to 30% of the total amount of Mg taken up by the plant is connected to a chlorophyll molecule (Marschner, 1986). Other functions requiring Mg include acting as ribosome glue in protein synthesis and as an enzyme facilitator or activator. Deficiency symptoms in pine species are characterized by golden-colored chlorosis of needle tips on current year foliage in the upper-midcrown indicating immobility within the plant (Mitchell et. al., 2003). Severe deficiencies result in needle tips dying and turning brown. Will (1985) states that sub-acute deficiency symptoms resemble those of K deficiency, but that chlorosis due to K deficiencies tend to be paler and occur in the lower parts of the crown. The foliar critical level of Mg in loblolly pine is 0.8 g/kg (Allen, 1987). Fertilizer additions of Mg should not utilize dolomitic limestone. The corresponding increase in pH that follows would decrease the availability of some nutrients to southern pines. Magnesium sulfate (Epsom salt) is a highly soluble source of Mg and S at 10% and 13%, respectively.

Soil concentrations of Ca and Mg in the soil were reduced over a long period of observation in an old-field conversion to a loblolly pine plantation (Richter et. al., 1994). While in cotton production, applications of lime increased the pool of available base cations. Natural acidification of the soil due to pine litter decomposition increased the rate of Ca^{2+} and Mg^{2+} leaching. This pattern has likely been repeated many times across

the South, as most current pine plantations were formally in agricultural production (Fox et. al. 2004). Mg uptake and losses from leaching are influenced by cation competition, especially where large amounts of NH_4^+ or K^+ containing fertilizers are used (Sword et. al., 1998). Though Mg and Ca have similar properties relating their availability and solubility within soils, Mg^{2+} is even more easily leached from sandy soils because of its greater hydrated radii. As a result, Mg levels are generally low in highly leached Spodosols and sandy Entisols, but relatively high in water accumulating areas that may contain mucky or gleyed soils (Mengel and Kirby, 2001).

Sulfur

S, like N, is a constituent of proteins and the chlorophyll molecule (Mengel and Kirkby, 2001). S deficiency results in a lack of S containing amino acids needed to link and form protein strands (Marschner, 1986). Due to reduced protein and chlorophyll synthesis with S deficiency, visual symptoms are very similar to that of N deficiency. Plant vigor and health is reduced while older leaves undergo uniform chlorosis (Leaf, 1968). The critical level of S in loblolly pine foliage is 1.2 g/kg (Allen, 1987). Application of elemental S can be accomplished with many materials because sulfate (SO_4^{2-}) is available as the accompanying anion in many fertilizer salts including macro-nutrients and micro-nutrients.

Environmental regulations during the 1980's and 1990's reduced S emissions to the atmosphere and many N and P fertilizer sources now do not contain S. Therefore, atmospheric and fertilizer additions of S have been greatly reduced (Schnug and Haneklaus, 1998). However, not all sites with negative S balances show deficiencies thanks to the abundance of S contained in the lithosphere. The majority of S in soils, up to 95%, is held in organic complexes with the remainder contained in complexes of Ca and Fe. The mineralization of organic S fractions occurs at rates that not exceed 7-10 kg/ha/yr, and because organic matter immobilizes the same amount in a year, there is little freely available S for plant uptake (Schnug and Haneklaus, 1998). The amounts of free sulfate in solution and adsorbed onto clay and sesquioxide surfaces is low and is

affected by the soil pH and the clay content. Free sulfate in the form SO_4^{2-}, is leached from soils with low clay content or pH > 5 (Mengel and Kirby, 2001).

Micronutrients

Manganese

Mn deficiency reduces chlorophyll synthesis and enzyme activity in the O_2 production phase of photosynthesis (Römheld & Marschner, 1991). In most plants, Mn has a wide range of concentration sufficiency (Stone, 1968). Concentrations in conifers range from as little as 10 mg/kg to several thousands (Kavvadias & Miller, 1999). Foliar Mn concentrations in loblolly pine were more variable than Cu, B, Zn, or S in a southeastern regionwide trial (NCSUFNC, 1992). Grey (1988) reported the C.V.s of foliar Mn concentrations in radiata pine vary from 35% to 60% even with standardized sampling. Visual symptoms of deficiency in conifers are related to symptoms of Fe deficiency, in that chlorosis develops in young leaves leaving older foliage unaffected (Stone, 1968). Will (1985) reports that slight chlorosis can be seen on older foliage, especially on the needle tips. Bronze colored needles and a lack of lateral branching have also been described as deficiency symptoms (Grey, 1988).

A CRIFF fertilization trial showed limited success to Mn fertilization except on a somewhat poorly drained Spodosol in northern Florida. Mn fertilization lead to volume growth responses of 2.2 m^3/ha/yr over a 12 year period (Jokela et.al., 1991b). Mn is an immobile element in coniferous trees, but rapid nutrient cycling has been reported (Saur et. al., 1991). Therefore, a 12 year sustained response from a single application at the time of planting is within reason. Mn is not rendered immobile in low pH, high organic matter Spodosols, but the organic matter must act as an e^- donor to convert Mn^{4+} to Mn^{2+} for uptake (Mengel and Kirby, 2001). Mn immobilization occurs in sandy-textured soils in the Atlantic Coastal Plain that are very poorly drained or that fluctuate between waterlogged and well drained conditions (Moraghan and Mascagni, 1991). Fluctuating water tables coincide with high redox potential and the formation of insoluble oxide forms of Mn.

Zinc

Zn is a critical component in the process of cell replication and DNA synthesis (Marschner, 1986). Zn is also involved in tryptophane production (Havlin et. al., 2005). Deficiencies cause shortening of twig internodes and shoot dieback leading to multileadered apical growth (Boardman and McGuire, 1990a). Will (1985) states that rosetting of buds around the apical tip is a symptom specific to zinc deficiencies. Needle shortening, needle tip burn, or needle death might also be seen on the apical leader. When Zn deficiencies were diagnosed in Australia in the 1890's, the symptoms were broadly characterized as "dieback" (Boardman & McGuire, 1990b). Although dieback is a common symptom of Zn deficiency, rosetting of apical buds is the true diagnostic that separates symptoms of Zn deficiency from those of B (Will, 1985).

Total Zn varies greatly in parent materials, but levels may be lower in soils developed from sands and sandstones. Plant available Zn is higher in areas with low soil pH, such as southeastern Coastal Plain (Moraghan & Mascagni, 1991). Zn nutrition problems include intense cation competition among Zn^{2+}, Fe^{2+}, and Mg^{2+}. These species share similar ionic radii and compete for replacement on mineral surfaces and for plant uptake (Mengel and Kirby, 2001). After Zn is brought up to adequate levels by fertilization, concentrations remain adequate indicating mobility and retranslocation within plants. Boardman and McGuire (1990b) have reported radiata pine foliar levels of Zn to be maintained at adequate levels 15 years after moderate Zn fertilization on a Zn deficient site.

Interactions between P and Zn are well documented, but often contradictory. Zn concentrations in plants have been increased with increasing P concentration (NCSUFNC, 1992; Krause, 1991). The opposite of this relationship has also been seen (Boardman & McGuire, 1990a). P and Zn interactions are most likely in cases where both P and Zn are at low concentrations, and added P increases growth sufficiently to result in dilution of Zn (Loneragan & Webb, 1993). In this case, mechanisms for P depression of Zn include reduced mycorrhizae growth from increased soil P concentration, formation of insoluble Zn-phosphates, and decreased adsorption of Zn

following P additions. This could be especially important in sandy soils with relatively high levels of P in solution as apposed to fixed mineral surfaces. (Stone, 1968)

Boron

Boron is immobile in plant tissues, and the concentration of shoots and tissues is determined by the current uptake by the roots (Moraghan and Mascagni, 1991). Boron is needed for cell wall formation and the formation and elongation of new tissues (Marschner, 1986). Deficiency symptoms are described as dieback of the apical and lateral leaders (Will, 1985). Symptoms include necrosis of the terminal bud, death of the terminal bud, and even death of the terminal shoot (Stone et. al., 1982). Death of the terminal bud causes stem malformation because new leaders assume apical dominance. Crooks and forks occur, reducing wood quality and value. Extremely B deficient trees are bushy in appearance from repeated seasonal dieback of the apical leader (Will, 1985). Trials of radiata pine have shown that B supply also has a positive effect on wood strength or "brittleness" (Skinner et. al., 2003). Trees sufficient in B may have significantly thicker tracheid walls than B deficient trees (Skinner et. al., 2003). Boron deficiencies are closely associated with moisture stress, and shoot growth may seem normal until midsummer droughts cause symptoms to come on quickly (Brockly, 1990).

Response to B was found on Sandhills sites (Albaugh et. al., 1998), and in Lower Coastal Plain sites in the Carolinas (NCSUFNC, 1996) In these cases, foliar levels of B were increased following fertilization, but methods to determine volume response to B alone were not used. Soils of the southeastern Coastal Plain are susceptible to B deficiencies because B is leached from coarse-textured soils that dominate the region (Moraghan & Mascagni, 1991). B is also easily leached due to its presence in the nonionic form, H_3BO_3, at pH>7. Sorption of B onto organic matter is four times greater than to clay particles, so B leaching is reduced in high OM soils (Mengel and Kirby, 2001). Boron deficiency is also one of the most common micronutrient deficiencies in radiata pine on sandy soils in New Zealand and eastern Australia (Hopmans & Flinn, 1983).

As with any other nutrient, B deficiencies can be induced by additions of non-B fertilizers and caused naturally by soil with low B concentrations. Drought stress can also cause B deficiencies due to the need for water and H^+ for passive plant uptake (Moraghan & Mascagni, 1991). Ample water is needed to create pathways for passive exchange of ions and to maintain rhizosphere pH (Marschner, 1986). Passive uptake causes B deficiencies to come on quickly during drought conditions and be returned to normal levels as soon as soil moisture is increased by summer rain storms. Brockley (1990) recommended B fertilization in lodgepole pine (*Pinus contorta* Dougl.) stands to reduce B deficiencies seen when added N increases growth to a point where the soil moisture becomes limiting during the growing season. B deficiencies also occur in European forests after macro-nutrient fertilization. In Finland, B deficiencies of scots pine (*Pinus sylvestris* L.) on peat land only follow N, P, and K fertilization (Stone, 1990). This may be a case where the dilution effect is seen, or uptake of K^+ is influencing rhizosphere pH in such a way that uptake of H_3BO_3 with H^+ carriers may be affected.

Even a sub-acute B deficiency can reduce the value and form of plantation trees, so the goal of B nutritional management should be to prevent and not correct deficiencies (Stone, 1990; Will, 1985). However, B additions should be made with caution and consideration to site conditions. The range of B sufficiency in plants is narrow, and an adequate prescription for a stand over a clay soil may be toxic to a stand over a deep, sandy soil (Stone, 1990).

Copper

Cu is an electron donor in the photosynthesis and respiration processes, and it is involved in the formation of lignin (Marschner, 1986). Reduced lignin formation explains Cu deficiency including loss of upright growth habit, twisted growth habit, and limp needles (South et. al., 2004). Other symptoms include stem and branch twisting and fused and burned needle tips on new foliage (Turvey, 1984). Cu deficiency symptoms resemble "speed wobble," but true symptoms are almost always more severe (Will, 1985). Twisting is so extreme that it causes apical leaders to grow horizontally or even back toward the ground.

In loblolly pine plantations, soil pH is significantly correlated with foliar Cu concentrations—the lower the pH, the lower the foliar Cu concentration (NCSUFNC, 1992). At low pH, Cu is bound to humic acids, not mineral surfaces. This explains why soils high in organic matter have produced Cu deficient radiata pine stands (Turvey, 1984; Knight, 1975). Organic soils are high in total Cu, and Cu concentration in organic-rich illuvial horizons of Spodosols increase with depth. However, organically complexed Cu in illuvial layers is not easily extracted for plant uptake (Turvey & Grant, 1990). Once Cu deficiencies are determined, ground application of fertilizers correct symptoms and elevate foliar levels (South et. al., 2004). Cu fertilization corrected visual symptoms and increased height growth in slash pine (*Pinus elliottii* Engelm.) on a peat soil in Queensland, Australia (Turvey & Grant, 1990). Other deficiencies have been seen in radiata pine on deep, uncoated sands in New Zealand with near neutral pH (Will, 1972). Cu was likely bonded in insoluble Ca compounds. Among other soil types, Cu deficiencies are more likely on soils developed from sands or sandstones rather than soils developed from shales, clays, and basic rocks (Moraghan & Mascagni, 1991).

Cu, Zn, and Mn have similar valences and ionic radii, so these elements often compete for plant uptake and excesses of one can lead to reduced uptake of the others (Turvey & Grant, 1990). Cu, Zn, and Mn all tend to form insoluble compounds with Fe and Al by the same mechanism at pH < 4.5. This process is dependant on the amount of Fe and Al in soil solution (Krause, 1991). Balancing and managing Cu additions with those of Zn and Mn should be considered. Soil testing for available nutrients and pH prior to fertilization should shed light on these issues.

Iron

The function of Fe within the plant is as an electron transporter in the synthesis of ATP (Moraghan & Mascagni, 1991). Fe, along with Mg, is a component of the chlorophyll molecule. Fe is also an activator and component of many enzymes (Marschner, 1986). Deficiency symptoms manifest themselves in the youngest of foliage because Fe is an immobile element. Symptoms are uniform chlorosis of entire needles (Will, 1985).

Symptoms are described as resembling those of Mn deficiency. The critical level of Fe foliar concentration in loblolly pine is 20-40 mg/kg (Jokela, 2004).

The percentage of Fe in almost all soils is high and deficiencies are rarely seen unless they are induced or result from poor availability (Mengel and Kirby, 2001). The vast areas of Ultisols in the South contain large amounts of stable Fe oxides in the clay fraction with little soluble Fe in the soil solution. Exchange for plant available Fe^{3+} is pH dependant, with a decrease in Fe^{3+} activity of 1000 fold for each pH unit increase (Mengel and Kirby, 2001). In waterlogged soils, metabolism of anaerobic microbes produce Fe^{2+} that is also plant available under similar pH conditions as Fe^{3+}. Plant availability of Fe is further aided by the formation of Fe chelates in many soils. These microbe produced organic molecules have high affinity for Fe on mineral surfaces, and increase the solubility of Fe and other micro-nutrients across a much wider pH range (Mengel and Kirby, 2001).

Molybdenum

The most important function of Mo within plants is as an electron acceptor in the conversion and creation of ATP. Mo is also a principle component with Fe in nitrogen reductase, which catalyzes the reduction of nitrate to nitrite within plant leaves (Marschner, 1986). Deficiency symptoms in pine species are relatively unknown, but the general mobility of the element and its function in nitrogen reductase, indicate that symptoms similar to N are expected (Kaiser et. al., 2005). Applications of Mo should not require more than 300 - 500 grams of elemental Mo per hectare because critical levels in loblolly pine foliage are only 0.10-0.14 mg/kg (Stone, 1968).

Mo concentrations in soils are lower than most other micro-nutrients, but can vary depending on the nature of the parent material. Highly weathered, acid soils of the southeastern Coastal Plain are lower in Mo than other soils derived from granites or shcists (Mengel and Kirby, 2001). Mo exists as the anion molybdate (MoO_4^{2-}) in the soil solution, and is most readily available for plant uptake at high pH. Mo behaves similarly to P in soils in that the adsorption strength of Mo is very high and also pH dependant with

maximum retention seen around pH 4 (Kaiser et. al., 2005). As a result, leaching of the anion MoO_4^{2-} is of little concern in the acid soils of the Southeast. Limitations of Mo occur due to the lack of Mo in the soil solution due to low pH (Kaiser et. al., 2005).

MATERIALS and METHODS

Stand Descriptions

The loblolly pine stands in this study were located in Jasper County, Texas (TX) (31.03°N; 94.22°W), Lamar County, Alabama (AL) (33.55°N; 88.26°W), Ware County, Georgia (GA) (31.18°N; 82.64°W), and Colleton County, South Carolina (SC) (32.98°N; 80.75°W). Study installation occurred near the point of canopy closure in all stands. Individual stand ages and heights ranged from 6 to 10 years and from 6.10 to 9.15 meters, respectively. Stands were selected based on past observation that in each region, nutritional deficiencies and possibly multiple, interacting deficiencies existed. Soil groups and geologic formations identified as having suspect nutrient status and tree growth were targeted.

The Texas site was flat planted with 1-0 loblolly pine by hand in January of 1995 following chemical site preparation during the previous summer. Soils were poorly and somewhat poorly drained sandy loams over clays (Table 3) with relatively low natural fertility. Height and DBH of dominants and codominants at the time of study establishment averaged 6.12 meters and 10.83 centimeters, respectively (Table 4). There were 1,193 trees per hectare. The site was located on the Catahoula formation, which stretches across much of south Texas and Louisiana. The Catahoula formation is suspected to have several nutrition problems, including low levels of available P and high As levels (FNC, 2006). Levels of Mehlich I extractable P in the surface horizon were low, averaging 2 mg/kg (Table 5).

Table 3: Some initial surface soil physical and chemical characteristics of the 4 sites in the current study. Nutrients other than C and N were found in Mehlich I extracts.

Site	Soil Order	Drainage^	Surface Texture*	pH	C/N Ratio	Total C	Total N	P	K	Ca	Mg	Mn	Zn	B	Cu
						----- g/kg -----		---------- mg/kg ----------							
TX	Ultisol	SWP	SL	4.92	18.0	9.3	0.52	2.0	14.1	248	76.3	2.3	0.44	0.11	0.40
AL	Ultisol	MW	SL - SCL	5.30	15.4	19.4	1.26	2.5	50.6	448	89.6	18.6	1.31	0.22	0.49
GA	Spodosol	SWP - P	S	3.99	41.1	13.8	0.34	5.0	10.0	66	19.6	2.5	0.42	0.10	0.17
SC	Ultisol	P	LS - SL	4.02	29.1	40.2	1.38	2.4	14.8	75	16.3	4.3	0.65	0.11	0.34

^ SWP, Somewhat poorly; MW, Moderately Well; P, Poor
*SL, Sandy Loam; SCL, Sandy Clay Loam; LS, Loamy Sand; S, Sand

Table 4: Average initial tree attributes at each of the 4 sites in the current study.

	TX	AL	GA	SC
Ht (m.)	6.12	6.76	9.08	6.49
C.V.	10%	10%	7%	7%
DBH (cm.)	10.83	11.09	13.42	10.58
C.V.	20%	17%	12%	16%

Table 5: Average initial foliar nutrient concentrations at each of the 4 sites in the current study. N concentration was found with an Elementar varioMAX CNS analyzer, while other nutrients were determined by extraction with a 0.5 M HCl solution and inductively coupled spectrophotomery (ICP).

Site	N	P	K	Ca	Mg	S	Mn	Zn	B	Cu
	---------- g/kg ----------						---------- mg/kg ----------			
TX	13.8	0.70	3.70	2.00	1.10	0.50	203	42	15.0	2.11
AL	15.7	1.50	5.60	2.20	1.10	0.60	408	51	11.8	3.75
GA	13.3	1.50	4.20	2.00	1.60	0.60	179	43	18.3	2.88
SC	13.6	1.30	2.40	2.30	1.30	0.60	100	33	16.9	2.73

The Alabama site was prepared mechanically by sub-soil ripping in the fall of 1996 and hand planted with 1-0 loblolly pine in early 1997. Height and DBH of dominants and codominants at the time of study establishment averaged 6.76 meters and 11.09 centimeters, respectively (Table 5). There were 1,089 trees per hectare. Volunteers of oak species (*Quercus spp*.), sweetgum (*Liquidambar styraciflua L.),* and Chinese privet (*Ligustrum sinense Lour*.) comprise roughly 15% of the BA. Soils were well and moderately well drained sandy loams and sandy clay loams (Table 3). The Alabama site was located on the Eutaw formation that stretches from central Alabama to northeastern Mississippi. Moderate P deficiencies have been noticed on this older landscape relative to the other study sites.

The Georgia site was prepared in 1998 by burning, raking, chopping, disking, and bedding. Machine planting with 1-0 loblolly pine occurred in early 1999 followed by herbaceous weed control and application of 140 kg/ha of DAP in 2000. Soils were Spodosols with relatively poor drainage and low amounts of total N (Table 3). Growth at the Georgia site was greater than other sites in the study as indicated by the average height (9.08 m) and DBH (13.42 cm) of dominants and codominants at the time of study establishment (Table 5). There were 1,465 trees per hectare. The Georgia site was located on the Wicomico formation of South Carolina, Georgia, and Florida.

The South Carolina site was machine planted with 1-0 loblolly pine in early 1999 following shearing, windrowing, and bedding the previous year. Height and DBH of dominants and codominants at the time of study establishment averaged 6.49 meters and 10.58 centimeters, respectively. There were 1,393 trees per hectare. Soils were wet, sandy, and black indicating accumulation and storage of organic carbon (Table 3). Like the GA site, the South Carolina site was located on the Wicomico formation. Soils on this geologic formation are commonly deficient in P and possibly K and B (FNC, 2006).

Study Design

The study was installed using single-tree plots in a balanced, completely random design with 10 fertilizer treatments replicated 10 times at each site. Individual trees served as

the experimental unit, with 100 trees identified at each site. An eleventh treatment with 10 replications examining the effects of higher P application rates was added at the Texas site during May, 2005. Due to unforeseen mishaps during the study (e.g. death by beetles, blow down, and excavation by bull dozer), several experimental units were lost from the original 100 at each site. These events forced the original study design to change to an unbalanced completely randomized design. Regardless, no treatment at any site was replicated fewer than 8 times.

Screening of candidate stands and tree selection was done in January, 2005. Plantations had to be planted with loblolly pine, be 5-10 years old, be close to or just past canopy closure, and be from between 4.57 m and 9.14 m in height. In all stands, selected trees were in dominant or co-dominant canopy positions and were homogeneous with respect to height and DBH. The treatment trees were scattered throughout each stand, the smallest of which encompassed more than 32.3 ha. A buffer of at least 15.25 m separated individual treatment trees.

Treatments (Table 6) were applied to 0.004 ha circular plots centered on single trees. Granular and powdered fertilizers were applied by hand to designated plots during the 2nd and 3rd weeks of May, 2005. Fertilizer treatments utilized a ramped method (Table 6) of adding elements from one treatment to the next so that effects of individual nutrients could be isolated. A ramped approach was used because it was assumed that response to Ca, Mg, S and the micro-nutrients would not be significant until deficiencies of N, P, and K were corrected. Boron was applied as a treatment early in the sequence because deficiencies of B were suspected on several of the sites based on previous experience. Applied fertilizers were all mineral salts of essential elements. No fritted or chelated elements were used. Mixing of materials that supplied N and S allowed for balanced, uniform application of constant elemental rates per hectare of N, P, K, Ca, Mg, S, Mn, Zn, B, Cu, Fe, and Mo depending on elemental requirements in each treatment (Table 7).

Table 6: Ramped application scheme applied to the current study in May, 2005.

Treatment	Application	Rate kg/ha
1	Control	0
2	NP	112N+28P
3	NPB	112N+28P+1.7B
4	NPK	112N+28P+56K
5	NPKB	112N+28P+56K+1.7B
6	NPKB Ca Mg S	112N+28P+56K+1.7B+134Ca+23Mg+179S
7	NPKB Ca Mg S + Zn	112N+28P+56K+1.7B+134Ca+23Mg+179S+8.4Zn
8	NPKB Ca Mg S + Cu	112N+28P+56K+1.7B+134Ca+23Mg+179S+8.4Cu
9	NPKB Ca Mg S + Mn	112N+28P+56K+1.7B+134Ca+23Mg+179S+23Mn
10	NPKB Ca Mg S+Zn+Cu+Mn+Fe+Mo	112N+28P+56K+1.7B+134Ca+23Mg+179S+8.4Zn+8.4Cu+23Mn+23Fe+0.6Mo
11*	NPK	112N+112P+280K

* Only applied at the Texas site

Table 7: Mix of fertilizer materials applied to the current study in order to achieve consistent rates of elemental application from one treatment to the next. Materials providing elemental N and S were often altered to achieve even applications rates.

		Treatment – Application rate kg/ha										
Element	Material	1	2	3	4	5	6	7	8	9	10	11
N	Ammonium Nitrate		263	263	263	263	157	168	168	185	263	
P	Diammonium Phosphate		134	134	134	134	134	134	134	134	134	560
K	Potassium Chloride				112	112	112	112	112	112	112	560
Ca	Calcium Sulfate (Gypsum)						611	611	611	611	611	
Mg	Magnesium Sulfate (Epsom Salt)						224	224	224	224	224	
S	Ammonium Sulfate						168	150	150	112		
Mn	Manganese Sulfate									83	83	
Zn	Zinc Sulfate							24			24	
B	Sodium Borate (Granubor 15)			8.4		8.4	8.4	8.4	8.4	8.4	8.4	
Cu	Copper Sulfate pentahydrate								34		34	
Fe	Iron Sulfate										112	
Mo	Sodium Molydbate										1.85	

Data Sampling

Tree Attribute Sampling

Trees selected for the study were permanently marked with aluminum nails at DBH and flagged at the time of study establishment in January, 2005. DBH, height, and length of live crown were measured as baseline data prior to fertilization. Maintenance was preformed on tree markings during fertilization in May, 2005. In January, 2006, DBH, height, and length of live crown were once again measured to quantify one full growing season's response to fertilization.

Soil Sampling and Laboratory Analysis

Prior to fertilizer application in May of 2005, a composite sample of surface soil was collected from four random locations within the 0.004 ha circular plot around each tree. Soil was collected with a 2.58 cm by 51.6 cm cylindrical push probe. Roughly 0.5 kg of soil was collected from each plot. All samples were returned to the lab and dried at 50°C and sieved to pass a 2 mm screen to separate any coarse fragments. Soil pH was measured with an AGRI-Meter (Myron L Company, Carlsbad, CA) in a 1:2 soil to water mixture. Total C and N were determined using an Elementar varioMAX CNS analyzer (Elementar Americas Inc., Mt. Laurel, NJ). Other laboratory analysis was performed by extracting cations and anions in a Mehlich 1 solution (Mehlich, 1984). Solutions were then analyzed by a SpectroFlame Modula Tabletop inductively coupled plasma spectrophotometer (Spectro A.I. Inc. Fitchburg, MA) to determine concentrations of P, K, Ca, Mg, S, Mn, Zn, B, and Cu (Table 3).

Foliage Sampling and Laboratory Analysis

50 fascicles from the first flush of the previous year on lateral branches in the upper 1/3rd of the canopy were collected from each treatment tree prior to fertilization in January, 2005. Foliage from the same canopy position was collected in the same manner again in January, 2006, approximately seven months after fertilization. In addition, foliage from treatments 1, 2, 5, 6, and 10 was collected so an estimate of weight and area of the entire year's growth of foliage. A single branch was clipped from the upper 1/3rd of each treatment tree and the foliage area was calculated for each flush of the previous year's

growth using Murthy and Dougherty's flush area equation (1997b). This required that flush length, needle length, and density of needles within each flush be measured in the field. The entire year's foliage was then removed and placed in separated paper bags marked with tree and individual flush numbers. Each night following field collection, 50 fascicles from the first flush of each tree were separated and marked as such. This allowed for a consistent data set for obtaining individual fascicle mass and for nutrient analysis.

Foliage was stored in paper bags and dried at 50°C for at least 5 days. Samples were taken out, 10 at a time, and weighed. Weights of entire flushes were measured on samples collected in January, 2006 from treatments 1, 2, 5, 6, and 10. The entire weight of the first flush was the sum of the weight of 50 individual fascicles and the weight of the remainder of the entire amount of foliage. Following drying, the 50 fascicle samples were ground in a Wiley mill to pass a 1 mm screen. Total C and N were determined using an Elementar varioMAX CNS analyzer (Elementar Americas Inc., Mt. Laurel, NJ). Samples were dry ashed at 500°C for 24 h, the resulting ash was digested in 6 N HCl. Concentrations of P, K, Ca, Mg, S, Mn, Zn, B, and Cu were then determined by a SpectroFlame Modula Tabletop inductively coupled plasma spectrophotometer (Spectro A.I. Inc. Fitchburg, MA).

Data Analysis in the Application of the Diagnostic Techniques

Data Analysis

Analysis of variance with PROC GLM (SAS Institute, Cary, NC) was used to test for any pre-fertilization treatment effects on foliage mass or nutrient concentrations. Where initial treatment effects were insignificant, post-fertilization foliar variables were analyzed with ANOVA and LSD means separation of significant treatment effects. Where ANOVA indicated initial foliar variables had significant treatment effects, ANCOVA was utilized with LSD mean separation on significant treatments. Total branch foliage area and total branch foliage mass was not measured prior to fertilization and was only analyzed by ANOVA. Tree attributes such as tree height, DBH, and length

of live crown had insignificant site x treatment interaction terms, so all sites were grouped together for analysis. Foliar nutrient concentration data were analyzed as percents of dry matter, individual fascicle nutrient content was analyzed as mg per 100 fascicles and individual fascicle mass was analyzed as g per 100 fascicles. Nutrient content, mass, and area of total branch current year growth was expressed in absolute terms of the biomass production, regardless of individual fascicle sizes or numbers. All data passed tests of normality and met the assumptions required for analysis of variance. The benchmark for statistical differences was set at $P < 0.05$. SAS version 9.1 (SAS Institute Inc., Cary, NC) was used for all statistical analyses.

Table 8: Summary of p-values of initial foliar variables from ANOVA. Highlighted values indicate non-homogeneity among pre-fertilization treatment groups and the need for ANCOVA.

	TX		AL		GA		SC	
Foliage Wt.	<.0001		0.5930		0.3532		0.9095	
	Conc.	Content	Conc.	Content	Conc.	Content	Conc.	Content
N	0.7628	0.0087	0.9599	0.6789	0.2170	0.2864	0.7225	0.9124
P	0.7792	0.0037	0.6164	0.5091	0.8981	0.5961	0.1831	0.9485
K	0.7508	0.2496	0.3893	0.3387	0.9964	0.8131	0.1259	0.5516
Ca	0.0930	0.0211	0.4569	0.8304	0.2870	0.2500	0.6337	0.7378
Mg	0.5511	0.0128	0.5921	0.8987	0.7808	0.2022	0.1990	0.8068
S	0.2924	0.0014	0.9748	0.9763	0.9588	0.3293	0.4649	0.8121
Mn	0.5101	0.0884	0.2596	0.3640	0.7875	0.4701	0.5797	0.4531
Zn	0.3969	0.0380	0.6444	0.6167	0.5898	0.7333	0.5809	0.8723
B	0.7029	0.4011	0.2002	0.1568	0.6806	0.3080	0.1165	0.2952
Cu	0.7030	0.2527	0.1268	0.2314	0.9783	0.9703	0.6777	0.6403

Critical Level/Nutrient Ratio Approach

The critical level and nutrient ratio approaches require that comparisons be made between sample data and widely accepted optimal values. When used together, critical levels and optimal ratios integrate soil availability, plant uptake, and nutritional balance. However, published data are not necessarily definitive, and should only be a basis for comparison. Pre-treatment diagnosis was conducted using the average of nutrient concentrations from all trees sampled in January, 2005. Post–fertilization analysis of foliage collected in January, 2006 tested the average of all replications of individual treatments against published critical levels. Statistical analysis was performed by testing published critical

levels (Tab. 9) and optimal nutrient ratios (Table 10) against study data using one sample T-tests for means within SAS Analyst in SAS version 9.1 (SAS Institute Inc., Cary, NC).

Table 9: Current year foliage critical levels utilized for analysis in the current study.

Macronutrients	Deficiency	Micronutrients	Deficiency
	g/kg		mg/kg
Nitrogen	<12.0	Manganese	<40
Phosphorus	<1.2	Zinc	<20
Potassium	<4.0	Boron	<10
Calcium	<1.2	Copper	<3
Magnesium	<0.8		
Sulfur	<1.2		

(Values are % and ppm of dry weight)

Table 10: Optimum nutrient concentration ratios in current year loblolly pine foliage.

N/P	N/K	N/Ca	N/Mg	N/S	N/Mn	N/Zn	N/B	N/Cu
10.0	3.5	10.0	8.0	10.0	0.03	0.003	0.002	0.0003

FNC, 2005c

DRIS Approach

This dataset did not meet all of the assumptions required to create useful DRIS norms. A dataset developed from a nutrient deficient, low-yielding population does not allow for separation of high and low yielding populations. This dilemma was remedied by selecting stands from the Forest Nutrition Cooperative's Region Wide Trial #18 (FNC, 2005b) to be the high yielding population. Advantages of this were that data including macro-nutrient concentrations, micro-nutrient concentrations, and growth were available. Four RW18 sites, closely matched to a study site in geographic location and drainage class, were selected as pools for the high-yielding population. Foliage nutrition data from the fertilizer treatment in RW18 that created the largest growth response relative to the control in a specific year were used to develop DRIS norms. These data represent when all nutritional variables are at optimums, regardless of age or fertilizer treatments. Combined data from all of theses highly productive sites allowed for the testing of regionalism of DRIS norms.

DRIS norms were selected by the modified methodology presented by Wolworth and Sumner (1987) and are presented in Table 11. All possible ratios were retained as norms

to provide more balanced diagnosis. This is a point of contention in the application of the DRIS technique, as some users prefer to use only ratios that have significantly different variance ratios of high and low yielding populations. However, balanced elemental comparison was favored over strict separation of high and low yielding populations because it was noticed that nutrient ratios with low variance ratios also had high CV's and received little weight in the index equations. Five sets of DRIS norms were developed; four sets from the regional pairings and the set from the average of these regional parings.

Table 11: DRIS norms created from high-yielding RW18 sites. Each of the four matched, regional stands are represented, as well as a southwide norm created from the resulting averaged data set from these four stands.

	South		Texas		Alabama		Georgia		South Carolina	
	Average	CV	Average	CV	Average	CV	Average	CV	Average	CV
N:P	10.36	14%	11.08	9%	10.65	8%			8.98	23%
N:K	2.81	35%	1.86	22%	2.42	9%	2.71	9%	4.16	19%
N:Ca			7.54	23%						
N:S	13.59	10%	13.27	9%	14.31	9%	14.08	5%	12.77	15%
N:Mn			0.01	45%						
N:Zn									0.05	18%
N:B	0.08	34%	0.08	26%	0.09	14%	0.05	25%		
N:Cu	0.56	29%	0.48	30%					0.52	29%
P:N							0.09	7%		
P:K	0.28	44%	0.17	27%	0.23	12%	0.25	11%	0.47	18%
P:S	1.33	12%	1.20	11%	1.35	8%	1.32	5%	1.45	14%
P:B	0.01	41%			0.01	12%	0.00	22%		
K:S	5.42	37%	7.57	30%	5.92	8%	5.23	10%	3.11	12%
K:B					0.04	14%	0.02	23%		
Ca:N	0.11	48%			0.12	17%	0.06	81%	0.13	35%
Ca:P	1.09	46%	1.53	23%	1.22	14%	0.63	81%	1.13	29%
Ca:K	0.30	60%	0.27	48%	0.28	23%	0.16	80%	0.52	25%
Ca:Mg	1.91	42%					1.07	56%	1.92	14%
Ca:S	1.43	44%	1.83	21%	1.65	19%	0.84	82%	1.60	25%
Ca:Mn			0.00	34%						
Ca:Zn	0.01	38%					0.00	64%	0.01	21%
Ca:B	0.01	65%	0.01	51%	0.01	23%	0.00	70%		
Ca:Cu	0.05	39%	0.06	21%			0.03	69%	0.06	16%
Mg:N	0.06	32%	0.05	16%	0.05	22%	0.05	40%	0.07	32%
Mg:P	0.56	26%	0.56	19%	0.57	19%	0.53	39%	0.58	21%
Mg:K	0.16	50%	0.10	34%	0.13	28%	0.13	41%	0.27	16%
Mg:Ca			0.37	20%	0.47	9%				
Mg:S	0.74	26%	0.66	12%	0.78	25%	0.69	39%	0.83	16%
Mg:Mn			0.00	48%						
Mg:Zn			0.00	13%			0.00	27%	0.00	10%
Mg:B	0.00	49%	0.00	34%	0.00	25%	0.00	20%		
Mg:Cu	0.03	20%	0.02	27%	0.03	11%	0.03	21%	0.03	12%
S:B							0.00	22%		
Mn:N	82.04	119%			138.35	24%	6.23	151%	31.15	49%
Mn:P	859.87	116%	1978.05	57%	1460.40	19%	65.86	151%	283.81	60%
Mn:K	192.34	114%	369.97	85%	336.46	27%	16.83	156%	126.00	48%
Mn:Ca	617.35	101%			1193.99	12%	57.85	128%	237.15	33%
Mn:Mg	1562.21	125%			2561.41	15%	90.72	133%	460.71	40%
Mn:S	1100.35	116%	2426.57	63%	1973.09	24%	86.46	152%	386.94	45%
Mn:Zn	3.99	117%			7.05	24%	0.39	149%	1.55	46%
Mn:B	7.08	137%			12.44	26%	0.24	142%	3.25	52%
Mn:Cu	39.70	104%	81.61	46%	77.95	23%	3.21	146%	14.71	42%
Zn:N	18.44	28%	21.93	12%	19.73	9%	13.38	30%		
Zn:P	188.60	28%	243.87	18%	210.29	13%	141.95	27%	175.39	15%

Table 11: Continued

	South		Texas		Alabama		Georgia		South Carolina	
	Average	CV	Average	CV	Average	CV	Average	CV	Average	CV
Zn:K	50.65	40%	40.78	25%	47.56	6%	35.80	25%	81.41	13%
Zn:Ca			165.55	28%	176.49	24%				
Zn:Mg	349.10	27%			379.69	26%				
Zn:S	246.70	23%	290.41	14%	282.21	12%	187.26	28%	250.68	9%
Zn:Mn			0.16	48%						
Zn:B	1.47	45%	1.69	25%	1.77	14%	0.64	29%		
Zn:Cu	9.79	25%	10.41	24%	11.37	25%	8.23	20%	9.91	19%
B:N									9.93	19%
B:P			152.23	30%					86.64	15%
B:K	39.42	42%	24.71	23%					40.60	20%
B:Ca									83.73	36%
B:Mg									155.12	24%
B:S	200.20	42%	182.31	30%	161.90	16%			124.21	13%
B:Mn			0.10	49%						
B:Zn									0.50	19%
B:Cu			6.61	35%					5.03	30%
Cu:N					1.80	18%	1.64	24%		
Cu:P	19.80	28%	24.60	28%	19.05	15%	17.46	22%	18.50	29%
Cu:K	5.43	45%	4.31	48%	4.40	25%	4.43	24%	8.54	25%
Cu:Ca					15.73	15%				
Cu:S	25.95	25%	29.26	26%	25.88	21%	23.01	23%	26.36	26%
Cu:B	0.15	53%			0.16	21%	0.08	13%		

Vector Analysis Approach

Vector analysis is a graphical tool that integrates nutrient concentration, nutrient content, and foliage mass in a format that can diagnose nutrient dilution, toxicity, excess, and deficiency (Haas and Rose, 1995). Diagnosis is based on the vector created when nutrient concentration, nutrient content, or foliage mass of a treated tree are plotted relative to those of a control tree (Fig. 3) (Table 2). The relative size of vectors indicates the degree of response to nutrient additions. Because mass of entire branches was determined in January, 2006, vector analysis integrating nutrient concentration, nutrient content, and 1 year's foliage mass production was also possible. Actual vector diagrams were created by plotting the average of an individual element's nutritional status when that element was (+) and was not (-) applied in a treatment. Resulting vectors indicate the effect that application had versus the consequences of non-application. To facilitate the interpretation of vector diagrams created by specific elements in specific treatments, an overlaying decision matrix was created to identify nutritional shifts. The intention was to simplify the diagnosis of vector shifts without loosing site of meaningful changes in pine nutrition. To be interpreted as changed from control levels, a treatment must have had foliage mass, nutrient concentration, or

nutrient content changed by at least 10% from control levels (Fig. 6). Interpretation with the matrix allowed treatment by element effects to be categorized into 1 of 7 possible interpretations of nutritional shifts based on generalizations by Timmer and Stone (1978). Mean separation of nutrient concentration, nutrient content, and foliage mass used along with the interpretation matrix provided further insight into truly significant shifts in nutrition from the control plot.

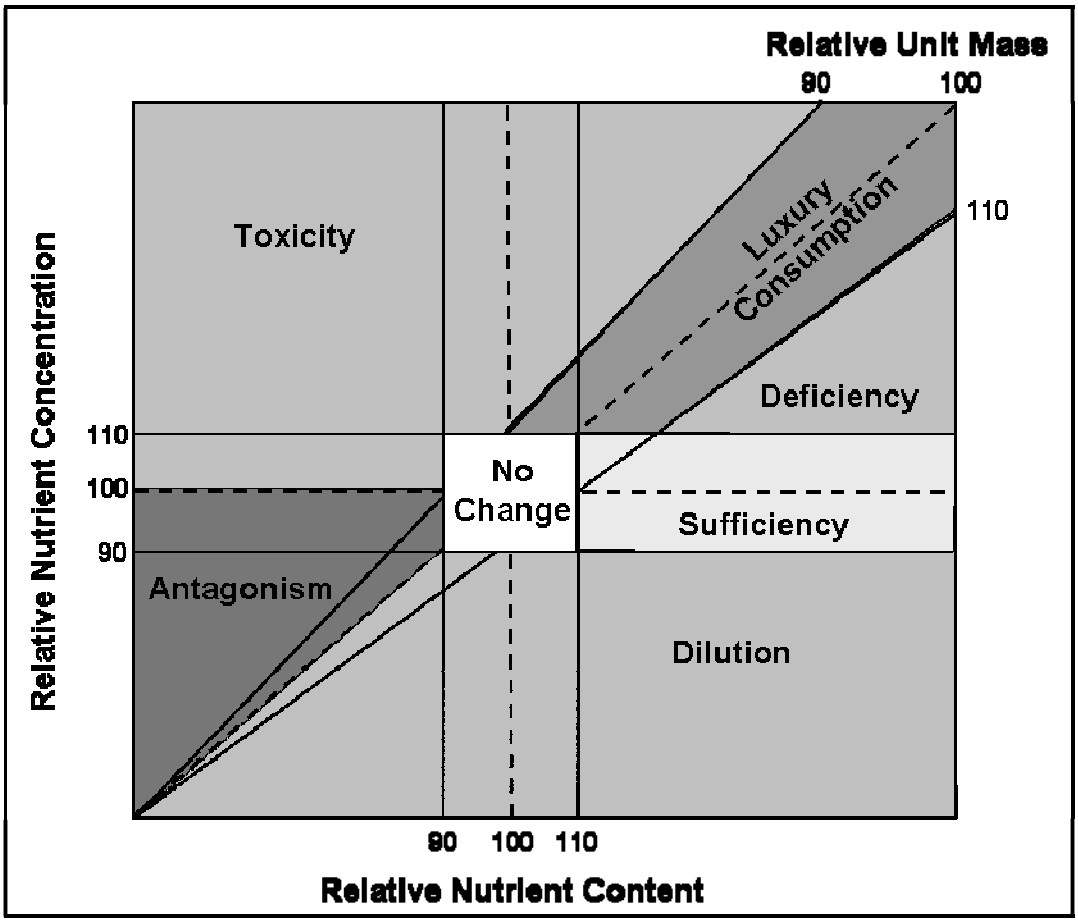

Figure 6: Interpretation matrix to be overlaid on vector diagrams to facilitate interpretation. A 10% increase or decrease in foliar nutrient concentration or content is required to not be interpreted as unchanged from the control.

RESULTS

Analysis of pretreatment data assured that pre-fertilization foliar and tree attributes data were statistically similar across treatments or had their variability accounted for with ANCOVA. Unless otherwise stated, reported data are post-fertilization results. Individual tree height, DBH, and crown length were not significantly affected by the treatments during the 7 month study period (Table 12). There were significant site effects on these growth parameters due to differences in stand age and productivity levels.

Table 12: Post-fertilization ANOVA results of tree variables from sites in the current study. Fertilization did not affect tree growth 1 year following application.

Source	Height		DBH		Crown Length	
	df	Pr>F	df	Pr>F	df	Pr>F
Site	3	<.0001	3	<.0001	3	<.0001
Treatment	10	.3076	10	.5427	10	.3425
Treatment x Site	27	.8508	27	.5108	27	.9055
Model	40	<.0001	40	<.0001	40	<.0001
Error	367		369		367	
Total	407		409		407	

Foliar Nutrient Concentration and Ratios

Examination of foliar nutrient concentrations and nutrient concentration ratios served as predictors of nutritional deficiencies. Foliar nutrient concentrations were evaluated relative to the control stand and published critical levels, while nutrient balance was evaluated with nutrient ratios. Published optimum ratios were combinations of nitrogen with other nutrients. These ratios assessed the balance of those nutrients, but not which one was deficient or excessive. Due to the large sample sizes used and the low variability of nutrient concentration data, the analysis had the power to find candidate stand nutrient ratios always different from optimum ratios. Therefore, only those changed enough to be biologically important will be discussed.

Texas

N concentrations in the control stand (13.7 g/kg) were above the critical level at the TX site (Table 13). However, fertilization with N significantly increased N concentrations in most treatments, reaching 15.0 to 17.0 g/kg. In contrast, P concentrations in the control

stand were below the critical level, averaging only 0.7 g/kg (Table 13). Fertilization with P significantly increased foliar P concentrations in all treatments. Following fertilization, foliar P concentrations approached or equaled the published critical level of 1.2 g/kg. Potassium concentrations were above the critical value in the control treatment and tended to increase when K was added in treatments 4-10 (Table 13). K balance was not far from adequate in the control stand as indicated by a N/K ratio of 3.3, and were largely affected by fertilization (Table 14). Levels of S below the critical level of 0.12% prior to fertilization were not corrected by S applications (Table 13), and ratios of N/S were further out of balance following N applications (Table 14). Foliar Cu concentrations below the critical concentration in the control trees were statistically elevated to or above the critical level by Cu fertilization in treatments 8 and 10 (Table 13). Treatments 8 and 10 also improved the Cu balance (Table 14). Foliar B concentrations of only 11 mg/kg were close to the critical level at the TX site (Table 13) and were significantly increased in treatments that contained B, reaching levels of between 25 and 40 mg/kg.

Table 13: Post-fertilization nutrient concentration. P values indicate the results of ANOVA conducted for each nutrient. LSD at α=0.05 was conducted for those nutrients with P<0.05. Highlighted values are significantly different from controls. Values with asterisk (*) are significantly below critical levels.

		N	P	K	Ca	Mg	S	Mn	Zn	B	Cu
		g/kg						mg/kg			
	Critical Level	12.0	1.2	4.0	1.5	0.8	1.2	40	20	10	3
TEXAS	P>F	0.0017	<.0001	0.0022	0.3485	0.5131	0.0013	0.0724	0.3748	<.0001	0.008
	LSD	1.7	0.2	0.7	None	None	0.1	99	None	9.8	0.69
	1 - Control	13.4	0.7*	4.2	1.3	1.1	0.4*	161	34.1	11.3	2.58*
	2 - NP	16.1	1.1*	4.1	1.5	1.0	0.4*	192	28.4	12.7	1.75*
	3 - NPB	16.8	1.2	4.0	1.6	1.0	0.5*	222	30.2	38.3	1.89*
	4 - NPK	15.1	1.1*	5.1	1.2	0.9	0.5*	154	31.6	13.3	2.31*
	5 - NPKB	15.6	1.1*	4.9	1.3	0.9	0.5*	227	33.1	28.6	1.86*
	6 - NPKBCaMgS	16.7	1.0*	5.2	1.0	0.9	0.5*	182	37.3	26.4	2.42*
	7 - " + Zn	14.7	1.0*	5.1	1.3	0.9	0.5*	183	31.3	25.9	2.48*
	8 - " + Cu	15.0	1.0*	4.8	1.2	0.9	0.5*	215	31.4	28.3	2.81
	9 - " + Mn	14.5	1.0*	5.2	1.4	0.9	0.5*	232	33.7	27.2	2.53*
	10 - Complete	15.3	1.0*	5.0	1.5	1.0	0.5*	290	37.3	33.8	3.10
	11 - NPK	16.1	1.2	5.1	1.9	0.9	0.4*	209	32.3	10.5	2.01*
ALABAMA	P>F	0.6418	0.5194	0.5349	0.9040	0.3382	0.1513	0.8107	0.4752	0.0001	0.5887
	LSD	None	None	None	None	None	None	None	None	8.4	None
	1 - Control	15.9	1.3	5.9	2.0	0.9	0.5*	376	41.7	9.1*	3.63
	2 - NP	16.6	1.2	5.7	2.0	0.9	0.4*	277	34.5	9.4	3.02
	3 - NPB	16.6	1.3	6.2	2.0	0.8	0.5*	386	40.1	18.4	2.85
	4 - NPK	16.4	1.2	5.6	2.1	0.9	0.4*	340	33.8	10.0	2.67
	5 - NPKB	16.9	1.2	6.9	1.7	0.7	0.4*	362	36.9	19.9	3.05
	6 - NPKBCaMgS	15.9	1.2	6.3	1.9	0.9	0.5*	334	36.4	19.5	2.91
	7 - " + Zn	17.2	1.2	6.5	2.2	1.0	0.5*	356	37.7	21.3	2.73
	8 - " + Cu	16.3	1.2	7.0	1.8	0.8	0.5*	409	38.6	18.8	3.13
	9 - " + Mn	16.4	1.1	5.2	2.1	0.8	0.5*	349	31.4	20.2	2.83
	10 - Complete	16.2	1.1	6.5	1.8	0.7	0.5*	389	37.9	18.7	2.72

Table 13: Continued

		N	P	K	Ca	Mg	S	Mn	Zn	B	Cu
		g/kg						mg/kg			
	Critical Level	12.0	1.2	4.0	1.5	0.8	1.2	40	20	10	3
GEORGIA	P>F	<.0001	0.0424	<.0001	0.0038	0.0898	<.0001	0.0044	0.0143	<.0001	0.6907
	LSD	1.8	0.1	0.5	0.5	0.2	0.4	57	5.5	10.1	None
	1 - Control	10.4*	1.1*	2.5*	1.7	1.3	0.4*	161	29.0	13.8	2.29*
	2 - NP	13.2	1.2	2.9*	2.1	1.4	0.4*	185	32.3	11.0	2.42*
	3 - NPB	13.1	1.2	2.7*	2.4	1.5	0.4*	165	27.9	40.8	1.89*
	4 - NPK	13.3	1.2	3.4*	2.4	1.5	0.4*	201	33.2	13.5	2.38*
	5 - NPKB	12.9	1.1*	3.6*	1.9	1.3	0.4*	170	30.4	44.9	2.14*
	6 - NPKBCaMgS	13.0	1.2	3.3*	2.4	1.6	0.8*	187	32.7	34.9	2.12*
	7 - " + Zn	12.5	1.1*	3.9	2.4	1.6	0.9*	201	36.0	37.9	2.02*
	8 - " + Cu	13.0	1.0*	3.2*	2.2	1.5	0.9*	185	31.4	27.7	2.08*
	9 - " + Mn	13.4	1.2	4.1	2.5	1.5	1.0*	246	34.5	36.9	2.35*
	10 - Complete	12.3	1.1*	3.7*	2.6	1.6	0.8*	258	39.0	30.2	2.32*
SOUTH CAROLINA	P>F	0.0959	0.7433	<.0001	0.0193	0.0058	0.0031	<.0001	0.039	<.0001	0.0068
	LSD	1.2	None	1.4	0.5	0.2	0.1	103	5.5	5.3	0.72
	1 - Control	13.0	1.2	2.9*	1.5	0.9	0.5*	71	24.1	13.1	2.44*
	2 - NP	14.8	1.3	2.7*	1.5	0.8	0.4*	51	21.6	15.9	1.55*
	3 - NPB	14.4	1.3	2.3*	1.5	0.8	0.4*	55	20.7	28.3	1.72*
	4 - NPK	14.1	1.3	5.6	1.1*	0.7	0.4*	83	25.7	12.4	2.04*
	5 - NPKB	14.2	1.2	4.9	0.8*	0.5*	0.4*	61	21.5	29.2	1.36*
	6 - NPKBCaMgS	14.7	1.3	4.5	1.1	0.7*	0.4*	54	23.1	20.8	1.39*
	7 - " + Zn	14.3	1.2	4.9	1.0*	0.7*	0.4*	57	28.5	23.0	2.29*
	8 - " + Cu	13.7	1.2	4.7	1.2*	0.7	0.5*	57	27.1	20.9	2.54
	9 - " + Mn	14.2	1.2	5.3	0.9*	0.6*	0.5*	210	24.0	20.6	1.67*
	10 - Complete	14.0	1.1*	4.3	1.2*	0.7*	0.4*	185	27.5	17.8	2.19*

Table 14: Post-fertilization ratios of nutrient concentration in current year foliage. Ratios were generally all statistically different from optimum, so interpretations of substantial biological changes were made in interpretation.

		N/P	N/K	N/Ca	N/Mg	N/S	N/Mn	N/Zn	N/B	N/Cu
	Optimum	10.0	3.5	10.0	8.0	10.0	0.03	0.003	0.002	0.0003
TEXAS	1 - Control	18.7	3.3	12.9	13.0	31.7	0.01	0.003	0.001	0.0002
	2 - NP	15.7	4.1	12.6	18.0	40.5	0.01	0.002	0.001	0.0001
	3 - NPB	14.7	4.2	14.4	17.2	37.0	0.01	0.002	0.002	0.0001
	4 - NPK	13.6	3.1	16.6	19.1	32.7	0.01	0.002	0.001	0.0002
	5 - NPKB	14.8	3.3	17.0	18.4	34.4	0.01	0.002	0.002	0.0001
	6 – NPKBCaMgS	17.6	3.3	18.6	19.3	31.7	0.01	0.002	0.002	0.0001
	7 - " + Zn	15.6	3.0	16.2	18.2	29.3	0.01	0.002	0.002	0.0002
	8 - " + Cu	14.9	3.2	15.3	17.3	32.6	0.01	0.002	0.002	0.0002
	9 - " + Mn	15.2	2.9	23.4	17.1	27.9	0.02	0.002	0.002	0.0002
	10 - Complete	16.0	3.1	10.8	17.0	30.3	0.02	0.003	0.002	0.0002
	11 - NPK	13.0	3.2	8.6	18.7	36.2	0.01	0.002	0.001	0.0001
ALABAMA	1 - Control	12.4	2.8	8.6	18.2	33.5	0.02	0.003	0.001	0.0002
	2 - NP	14.5	3.1	9.1	19.5	40.6	0.02	0.002	0.001	0.0002
	3 - NPB	13.1	2.8	8.9	21.2	36.1	0.02	0.002	0.001	0.0002
	4 - NPK	13.5	3.1	10.0	21.8	40.0	0.02	0.002	0.001	0.0002
	5 - NPKB	14.7	2.7	12.1	31.9	39.8	0.02	0.002	0.001	0.0002
	6 – NPKBCaMgS	13.7	2.7	9.4	18.3	34.3	0.02	0.002	0.001	0.0002
	7 - " + Zn	14.2	2.9	8.7	18.2	32.6	0.02	0.002	0.001	0.0002
	8 - " + Cu	13.8	2.5	9.4	19.8	33.4	0.03	0.002	0.001	0.0002
	9 - " + Mn	14.6	3.3	8.9	26.5	37.1	0.02	0.002	0.001	0.0002
	10 - Complete	14.5	2.6	10.6	24.0	33.3	0.02	0.002	0.001	0.0002
GEORGIA	1 - Control	9.9	4.1	6.4	7.9	32.3	0.02	0.003	0.001	0.0002
	2 - NP	11.2	4.6	6.6	9.6	36.5	0.01	0.003	0.001	0.0002
	3 - NPB	11.5	5.0	5.6	9.1	41.1	0.01	0.002	0.003	0.0001
	4 - NPK	11.6	3.9	5.6	8.9	38.3	0.02	0.003	0.001	0.0002
	5 - NPKB	11.5	3.6	7.0	9.8	37.7	0.01	0.002	0.003	0.0002
	6 – NPKBCaMgS	11.4	4.1	5.7	8.3	17.0	0.01	0.003	0.003	0.0002
	7 - " + Zn	11.2	3.2	5.9	8.1	14.7	0.02	0.003	0.003	0.0002
	8 - " + Cu	13.0	4.3	5.9	9.3	20.1	0.01	0.002	0.002	0.0002
	9 - " + Mn	11.6	3.3	5.6	8.9	15.2	0.02	0.003	0.003	0.0002
	10 - Complete	11.6	3.3	4.9	7.6	15.6	0.02	0.003	0.002	0.0002
SOUTH CAROLINA	1 - Control	10.9	4.6	10.8	15.1	26.9	0.01	0.002	0.001	0.0002
	2 - NP	12.0	6.2	11.1	21.3	41.7	0.00	0.002	0.001	0.0001
	3 - NPB	11.7	6.5	11.3	21.9	40.0	0.00	0.002	0.002	0.0001
	4 - NPK	11.2	2.9	16.3	23.8	36.1	0.01	0.002	0.001	0.0002
	5 - NPKB	12.1	3.0	21.7	27.3	37.2	0.00	0.002	0.002	0.0001
	6 – NPKBCaMgS	11.4	3.5	21.9	23.7	33.8	0.00	0.002	0.002	0.0001
	7 - " + Zn	12.2	3.1	34.8	22.7	34.0	0.00	0.002	0.002	0.0002
	8 - " + Cu	11.3	3.1	12.4	19.4	30.1	0.00	0.002	0.002	0.0002
	9 - " + Mn	11.7	2.9	21.3	26.9	30.4	0.01	0.002	0.002	0.0001
	10 - Complete	12.4	3.5	19.2	21.7	36.0	0.01	0.002	0.002	0.0002

Alabama

Foliar nutrient concentrations at the AL site were high, with levels of N, P, K, Ca, Mg, Mn, Zn, and Cu above critical levels (Table 13). Only levels of S (0.5 g/kg) and B (9.1 mg/kg) were below published critical levels (Table 13). Fertilization did not significantly affect the foliar concentration of any nutrient other than B. Concentrations of S were not significantly affected by any treatment and remained below critical (1.2 g/kg) levels in all treatments (Table 13). Because fertilization had little effect on foliar nutrient concentrations, nutrient ratios were not strongly affected either. N/P, N/K, and N/Ca ratios were maintained close to optimum while N/Mg and N/S were much greater than the established optimum (Table 14).

Georgia

At the GA site, N, P, K, S, and Cu concentrations were below critical concentrations in the control plot (Table 13). N applications in treatments 2-10 significantly increased concentrations from control levels of just 10.4 g/kg to at least the 12.0 g/kg critical level (Table 13). Foliar P concentrations were slightly increased from below critical levels in control trees to just equal to the critical level in most treatments where P was added (Table 13). Potassium concentrations were 2.5 g/kg in the control trees, but K fertilization in treatments 4-10 resulted in significant increases in K concentration (Table 13). However, K fertilization rarely increased K concentrations to above published critical levels. K applications did result in near published optimal N/K ratios in treatments 5, 7, 9, and 10 when levels had been substantially above the optimum without K additions (Table 14). S concentrations at the GA site were significantly increased over control levels by S fertilization and N/S ratios were reduced to levels more near the optimal in treatments 6-10 (Table 13). B fertilization dramatically increased B concentrations in all plots where B was applied (Table 13) and N/B ratios were increased to above the 0.002 optimum (Tab. 14). Cu concentrations were below the critical level in the control plots, and there was no effect of fertilization on Cu concentrations even in treatments 8 and 10 when Cu was applied (Table 13).

South Carolina

All nutrients except K (2.9 g/kg) and S (0.5 g/kg) were above critical levels in the control plots at the SC site (Table 13). K fertilization in treatments 4-10 significantly increased K concentrations (Table 13). The N/K ratio was reduced from levels above 6 when N was added without K to more optimal levels with K fertilization in treatments 4-10 (Table 14). N concentrations were also increased by fertilization in treatments 2-10. Increased concentrations of N and K accompanied dilution of Ca, Mg, S, and Cu concentrations in treatments that did not contain these elements (Table 13). Subsequently, N/Ca, N/Mg, and N/S ratios were all increased from levels closer to the optimal in the control treatment. Mn applications in treatments 9 and 10 increased concentrations by almost 300% over control levels of only 70 ppm (Table 13). P fertilization had no effect on foliar P concentrations in SC.

Diagnosis and Recommendation Integrated System (DRIS)

The underling assumption of DRIS is that once a sufficiently large population of plants has been sampled, nutrient ratio norms of the high-yielding population should provide sufficient nutritional diagnosis of any candidate population. However, workers who have tested DRIS in loblolly pine by creating norms from a large dataset across the southern pine belt reached the conclusion that norms drawn from more specific regions would be better at predicting nutrient deficiencies (Hockman and Allen, 1990). Further confounding the use of previously published norms was the lack of inclusion of micro-nutrient data which was of specific interest in this study. To respond to these issues, two stets of norms were created from four highly productive loblolly pine stands in close proximity to each of the stands in this study. One set was created from the individual high-yielding stands (regional norms), while the other was created from the average nutrient concentrations of these high-yielding stands (southwide norms). These two sets of norms contained micro-nutrient data and could be used to test the regionalism of DRIS norms. In this study, southwide and regional norms were found to provide similar diagnosis. However, southwide indices will be presented exclusively because they were much easier to interpret. Further explanation of the reliance on southwide norms and discussion of the regional norms can be found in Appendix 1.

Texas

Negative DRIS indices of the TX control plots were found for S, P, and B in that order. Positive indices were in the order Mg>Zn>N>Mn>Cu>Ca (Table 15). P indices were improved by P applications, especially in treatments 2, 3, 4, and 11. Other treatments where P was added (5-10) were also improved, but were influenced by increasing concentrations of non-limiting nutrients (Table 15). Severely negative S indices were not increased by S applications in treatments 6-10; furthermore, the indices indicated that S was still the most limiting nutrient following fertilization (Table 15). B fertilization in treatments 3-10 increased slightly negative indices in the control plots by creating slightly positive indices when B was added (Table 15). Cu indices were positive in the control plots and where Cu was added, but treatments not containing Cu had negative indices especially when Mn and Zn were not applied (Table 15). Fertilization with K had little effect on K indices as theyremained very near neutral levels in treatments 4-10, while excesses of N and Mn remained positive. No clear trends were found regarding the nutrient balance index. Both treatments 4 and 11 supplied N, P, and K; however, they result in very different but consistently unbalanced nutrition on P and Cu (Table 15).

Table 15: DRIS indices indicating deficient or excessive nutrient status based on southwide norms. Lower nutrient balanced indices (NBI) indicate more balanced nutrient concentrations.

	DRIS Indices										
	N	P	K	Ca	Mg	S	Mn	Zn	B	Cu	NBI*
TEXAS											
1 - Control	20	-26	0	1	29	-52	9	25	-10	5	177
2 - NP	33	-1	-1	5	25	-62	12	16	-7	-19	181
3 - NPB	24	-2	-8	3	19	-62	12	11	22	-17	180
4 - NPK	21	1	4	-2	13	-50	6	16	-6	-4	123
5 - NPKB	21	-5	0	-1	16	-57	14	18	11	-17	160
6 - NPKBCaMgS	22	-14	1	-8	11	-44	9	21	7	-4	141
7 - " + Zn	16	-12	1	-2	11	-43	9	14	8	-3	119
8 - " + Cu	17	-8	-1	-4	12	-56	12	14	10	3	136
9 - " + Mn	7	-12	0	-1	13	-43	14	17	8	-2	116
10 - Complete	13	-16	-3	-2	10	-55	16	17	14	6	153
11 - NPK	28	6	4	14	19	-60	14	23	-17	-31	214
ALABAMA											
1 - Control	18	2	1	1	7	-32	20	29	-43	-4	157
2 - NP	26	-1	1	4	13	-36	19	23	-42	-6	172
3 - NPB	19	0	0	3	5	-31	20	24	-38	-1	141
4 - NPK	24	2	2	5	9	-36	23	23	-45	-7	176
5 - NPKB	24	0	2	2	1	-35	18	21	-36	4	144
6 - NPKBCaMgS	18	-2	0	2	8	-27	17	18	-32	-1	124
7 - " + Zn	16	-6	-2	3	9	-25	19	18	-29	-3	130
8 - " + Cu	17	-2	0	0	4	-27	21	20	-32	0	124
9 - " + Mn	20	-2	-2	6	5	-30	19	14	-33	2	134
10 - Complete	18	-3	0	1	1	-27	19	20	-29	0	120
GEORGIA											
1 - Control	7	7	-17	13	50	-84	10	20	-5	0	213
2 - NP	16	7	-16	17	46	-83	10	21	-14	-5	234
3 - NPB	16	6	-25	23	52	-106	8	12	34	-20	302
4 - NPK	15	3	-11	21	50	-95	11	20	-8	-6	240
5 - NPKB	11	4	-12	12	39	-101	8	15	36	-12	249
6 - NPKBCaMgS	-5	-11	-21	16	41	-23	7	9	17	-31	182
7 - " + Zn	-11	-15	-15	11	35	-16	7	11	17	-25	162
8 - " + Cu	1	-15	-19	13	35	-24	8	8	10	-16	147
9 - " + Mn	-9	-15	-14	11	29	-15	9	5	16	-17	141
10 - Complete	-11	-18	-16	14	36	-22	11	15	10	-17	171
SOUTH CAROLINA											
1 - Control	13	8	-11	5	17	-38	-2	7	-3	3	109
2 - NP	35	20	-14	12	18	-65	-5	10	5	-15	198
3 - NPB	31	19	-19	10	15	-65	-6	5	23	-12	206
4 - NPK	23	15	7	0	7	-58	0	13	-5	-2	131
5 - NPKB	28	16	8	-7	4	-56	-4	8	22	-19	171
6 - NPKBCaMgS	30	17	3	4	14	-47	-5	12	9	-38	180
7 - " + Zn	20	9	3	-5	5	-54	-6	15	11	2	129
8 - " + Cu	15	8	2	1	6	-47	-6	11	7	3	106
9 - " + Mn	20	9	4	-12	4	-42	25	11	8	-27	163
10 - Complete	21	7	-1	-2	6	-62	12	15	7	-3	136

* NBI (Nutrient Balance Index) is the sum of absolute values of nutrient indices for a specific treatment.

Alabama

Negative DRIS indices in the control stand of the AL site were indicated for B, S, and Cu. The severity of those negative indices were in the order B>S>>Cu. Positive indices were found in the order Zn>Mn>N>Mg>P>K=Ca (Table 15). Negative B indices were uncorrected following treatments that contained B (Table 15) despite greatly increased foliar B concentrations (Table 13). Negative S indices were also uncorrected by any fertilizer treatments. Negative indices of Cu in the control trees following fertilization were corrected by Cu fertilization in treatments 8 and 10 (Table 15). K and P indices remained at or near neutral following all treatments regardless of the nutrients applied (Table 15). Positive indices of N were increased following fertilization in treatments 2-10. The nutrient balance index was not greatly affected by fertilization except when S was added in treatments 6-10 (Table 15), but the NBI was consistently lower than at other sites even though most nutrient concentrations were higher (Table 13).

Georgia

DRIS analysis indicated negative indices at the GA site of S, K, and B. The negative indices were in the order S>>K>B. Positive indices were found in the order Mg>Zn>Ca>Mn>N=P (Table 15). DRIS indices of S were more negative following fertilization in treatments that did not contain S, but S application in treatments 6-10 increased S indices, although they remained negative (Table 15). Application of S in treatments 6-10 also had an affect on N and P indices. In all treatments without S, N and P indices were positive, but the indices were negative when S was added (Table 15). Negative indices of K in control trees were not increased and remained negative following every treatment including treatments 4-10 where K was added (Table 15). Slightly negative indices of B were seen in the control, but were made positive in all treatments containing B due to vastly increased B concentrations. Neutral indices of Cu in the control were made negative in all treatments, even those where Cu was added (Table 15). The NBI indicated that S application did improve nutrient balance over control levels in treatments 6-10, while nutrient balance was worse without S applications (Table 15).

South Carolina

Negative DRIS indices in the control stand at the SC site were for S, K, B and Mn. Positive indices were found for Mg, N, P, Zn, Ca, and Cu (Table 15). Negative indices of K were more negative with N, P, and B applications in treatments 2 and 3, but were positive and more neutral following K additions in treatments 4-10 (Table 15). B indices were positive in all fertilizer treatments other than treatment 4 (N, P, and K) (Table 15). Large increases in Mn concentration when Mn was added greatly increased the Mn indices from slightly negative to positive levels. All fertilizer treatments resulted in more negative indices of S regardless of the nutrients applied (Table 15). Balanced indices of Cu in the control trees became negative in most treatments that did not contain Cu or Zn (Table 15). Positive indices for N in the control plots were increased by N application in all treatments. The NBI values of treatments 4-10 were lower than treatments 2 and 3 that only contained N, P, and B indicating that K application lead to more balanced nutrient concentrations. However, no fertilizer additions were able to reduce the NBI to levels substantially lower than the control (Table 15).

Fascicle Mass and Nutrient Content

The first year response to fertilization in foliage mass may serve as a short-term predictor of future volume response because strong correlations between the two have been found (FNC, 2005b). Changes in fascicle nutrient content may also be used as predictive measures of nutrient deficiencies. Content measures are not subject to possibly confusing dilution effects of nutrient concentration that are often seen when dry matter production is affected by fertilization. Graphical representations of changes and response in individual fascicle mass can be found in appendix 2.

Texas

There were no significant increases in individual fascicle mass following fertilization at the TX site. However, there were significant increases in foliar content of N, P, K, Mn and B that were caused by the combination of increased foliar concentrations and non-significant increases in foliage mass (Table 16). Fertilization with N and P increased

fascicle N and P content in all treatments except treatment 9 (Table 16). Although the differences were not significant, high application rates of P and K in treatment 11 led to a foliage mass increase of more than 3 g per 100 fascicles over the control levels (Table 16). In the same treatment there was a statistically significant increase of N and K content of more than 75 and 25 mg per 100 fascicles, respectively, while the content of P more than doubled from a control value of only 7.9 mg to more than 17 mg per 100 fascicles (Table 16). Potassium fertilization increased foliar K content in all treatments where K was added except treatment 9. B content also increased in all treatments when B was added (Table 16). Fertilization with S, Ca, Mg, Zn, and Cu did not affect fascicle nutrient content (Table 16).

Table 16: Impact of fertilization on individual fascicle weight and nutrient content of loblolly pine at the TX, AL, GA, and SC sites. P values indicate the results of ANOVA or ANCOVA conducted for each nutrient. LSD at α=0.05 was conducted for those nutrients with P<0.05. All weights are reported as (g) per 100 fascicles. Highlighted values are significantly different from controls.

		Foliage Wt.	N	P	K	Ca	Mg	S	Mn	Zn	B	Cu
		----- g -----	---------- mg ----------									
TEXAS	P>F	0.1226	0.0027	<.0001	0.0185	0.0028	0.7181	0.2139	0.0581	0.6482	<.0001	0.2183
	LSD	None	37.5	3.1	14.1	8.7	None	None	1.07	None	0.13	None
	1 - Control	10.77	144.1	7.9	45.5	14.7	11.6	4.6	1.67	0.36	0.12	0.03
	2 - NP	12.93	207.7	13.8	53.5	18.9	13.1	5.4	2.46	0.37	0.16	0.02
	3 - NPB	11.67	195.4	13.4	47.3	19.2	12.7	5.5	2.81	0.37	0.44	0.02
	4 - NPK	12.37	187.6	13.9	62.8	15.0	11.0	5.8	1.93	0.40	0.17	0.03
	5 - NPKB	12.69	196.3	13.5	62.6	16.1	11.5	5.9	2.75	0.42	0.37	0.02
	6 - NPKBCaMgS	11.86	201.9	11.7	62.2	12.5	10.6	6.4	2.15	0.44	0.31	0.03
	7 - " + Zn	12.33	181.7	11.8	63.4	16.3	10.8	6.5	2.29	0.39	0.32	0.03
	8 - " + Cu	13.05	193.2	13.2	63.0	16.9	11.7	6.1	2.74	0.41	0.36	0.03
	9 - " + Mn	11.29	163.9	11.0	58.1	15.6	10.4	5.9	2.55	0.38	0.31	0.03
	10 - Complete	12.04	184.7	11.6	59.6	17.8	11.4	6.2	3.51	0.45	0.41	0.04
	11 - NPK	13.94	223.0	17.2	71.4	26.6	12.8	6.2	2.92	0.46	0.15	0.03
ALABAMA	P>F	0.9061	0.8155	0.7937	0.6870	0.9245	0.5571	0.4276	0.8697	0.6780	0.0003	0.8588
	LSD	None	None	None	None	None	None	None	None	None	0.13	None
	1 - Control	16.40	261.1	21.0	96.3	33.9	15.3	8.0	6.04	0.69	0.15	0.06
	2 - NP	16.72	277.9	19.9	95.4	32.6	15.7	7.0	4.64	0.58	0.16	0.05
	3 - NPB	16.76	279.6	21.5	107.5	33.2	14.4	7.9	6.54	0.67	0.31	0.05
	4 - NPK	17.00	279.1	21.0	100.2	33.2	14.2	7.3	5.84	0.57	0.17	0.05
	5 - NPKB	16.65	281.8	19.7	113.3	28.4	12.7	7.3	6.17	0.62	0.33	0.05
	6 - NPKBCaMgS	16.76	268.0	19.7	106.7	32.0	15.5	8.2	5.63	0.62	0.33	0.05
	7 - " + Zn	17.18	300.2	21.3	113.8	37.4	18.1	9.4	6.18	0.66	0.36	0.05
	8 - " + Cu	15.93	262.1	19.3	115.6	28.3	13.5	8.3	6.34	0.63	0.30	0.05
	9 - " + Mn	14.75	240.6	16.7	75.9	30.9	11.6	6.6	5.06	0.46	0.30	0.04
	10 - Complete	17.56	285.5	19.7	117.6	30.0	12.6	8.9	6.65	0.65	0.31	0.05

Table 16: Continued

		Foliage Wt.	N	P	K	Ca	Mg	S	Mn	Zn	B	Cu
		---- g ----	---------- mg ----------									
GEORGIA	P>F	0.8064	0.0409	0.4193	<.0001	0.0919	0.6689	<.0001	0.0476	0.2308	<.0001	0.6801
	LSD	None	22.6	None	7.6	7.4	None	4.1	0.80	None	0.13	None
	1 - Control	11.10	115.7	11.8	28.1	19.2	14.9	4.2	1.78	0.32	0.15	0.03
	2 - NP	11.72	155.0	14.0	34.8	24.9	16.5	4.8	2.18	0.37	0.13	0.03
	3 - NPB	10.55	136.7	12.4	28.9	25.0	15.9	3.9	1.78	0.30	0.43	0.02
	4 - NPK	10.42	138.3	11.9	35.7	25.1	15.8	4.3	2.04	0.34	0.14	0.03
	5 - NPKB	11.86	152.2	13.3	42.6	22.8	15.8	4.6	2.06	0.36	0.52	0.03
	6 - NPKBCaMgS	11.38	148.1	13.2	38.1	27.7	18.0	9.0	2.13	0.37	0.39	0.02
	7 - " + Zn	11.13	138.3	12.4	43.0	26.6	18.1	10.4	2.25	0.41	0.43	0.02
	8 - " + Cu	10.79	140.2	11.1	35.1	24.1	16.2	9.6	2.01	0.35	0.30	0.02
	9 - " + Mn	11.12	149.2	12.9	45.4	28.2	17.2	10.8	2.73	0.38	0.41	0.03
	10 - Complete	11.10	136.0	11.9	41.7	28.9	18.0	8.9	2.93	0.44	0.34	0.03
SOUTH CAROLINA	P>F	0.0094	0.0122	0.1583	<.0001	0.1022	0.5650	0.0405	<.0001	0.0063	<.0001	0.0120
	LSD	2.82	47.8	None	31.7	None	None	1.9	1.60	0.10	0.11	0.01
	1 - Control	12.16	158.5	14.8	35.4	17.1	10.8	6.0	0.82	0.29	0.16	0.03
	2 - NP	14.06	208.9	17.8	38.1	20.6	10.5	5.1	0.69	0.30	0.23	0.02
	3 - NPB	14.27	206.3	18.7	33.5	21.0	10.8	5.4	0.80	0.30	0.40	0.02
	4 - NPK	15.65	222.4	20.8	92.1	17.1	10.4	6.5	1.29	0.41	0.20	0.03
	5 - NPKB	15.29	221.4	18.6	76.2	11.6	8.4	6.3	1.06	0.33	0.43	0.02
	6 - NPKBCaMgS	17.09	251.5	22.0	79.1	18.5	11.2	7.7	0.90	0.40	0.35	0.02
	7 - " + Zn	15.48	224.0	18.3	77.8	13.9	10.2	6.8	0.85	0.43	0.35	0.04
	8 - " + Cu	16.07	219.8	20.3	78.6	19.9	11.8	7.9	0.89	0.44	0.34	0.04
	9 - " + Mn	16.63	235.6	20.1	89.8	14.5	9.5	8.2	3.39	0.40	0.35	0.03
	10 - Complete	15.88	222.6	18.1	69.8	17.2	10.4	6.5	2.88	0.44	0.28	0.03

Alabama

There were no significant responses in foliage mass or nutrient content for any nutrient except B at the AL site. Boron content at least doubled from control levels of 0.15 mg per 100 fascicles in every treatment containing B, finally reaching a maximum of 0.36 mg per 100 fascicles in treatment 7 (Table 16). Fascicle mass and nutrient content at the AL site were greater than at the other three sites.

Georgia

There were no significant treatment effects on individual fascicle mass at the GA site (Table 16). Despite a lack of responses in foliage mass, nutrient content of N, K, Ca, S, Mn, and B was significantly increased by fertilizer treatments. Content of S in S fertilized treatments 6-10 were more than doubled over control levels of only 4.2 mg per 100 fascicles to greater than 10 mg per 100 fascicles in treatments 7 and 9 (Table 16). Magnitude of the response in S content at the GA site was far greater than at any other site even though pre-fertilization S concentrations were below critical levels at all four sites. N content increased in most N containing treatments. Response of N was largest in treatment 2 where N content was almost 40 mg per 100 fascicles greater than the control value of 115.7 mg per 100 fascicles (Tab. 16). Content of B doubled in all treatments where B was applied and was more than tripled to 0.52 mg per 100 fascicles by treatment 5 (Table 16). Content of Ca was also significantly increased over control levels of just 19.2 mg per 100 fascicles in treatments 6-10, reaching a maximum of 28.9 mg per 100 fascicles in treatment 10 (Table 16).

South Carolina

In contrast to the other sites, there was a significant increase in fascicle mass at the SC site following fertilization with treatments that included K (Table 16). K fertilization in treatments 4-10 increased foliage mass from between 3 and 5 g per 100 fascicles over control levels of 12.16 g per 100 fascicles (Table 16). Foliage content of K increased from 35.4 mg per100 fascicles in the controls to over 90 mg per100 fascicles in treatment 4. N content was also greatly increased over control levels by as much as 93 mg per 100 fascicles in treatment 6 (Table 16). As in other sites, B content was significantly

increased over control levels when B was included in the treatment, but no foliage mass increase could be attributed to B alone (treatment 3). Content of Mn was increased over levels in the control stand by more than 300% in both treatment 9 and 10 (Table 16), but Mn fertilization did not produce any increase in foliage mass. Concentrations of Ca, Mg, and Cu often decreased significantly with K fertilization due to apparent dilution effects (Table 13). Content of these nutrients remained relatively constant, indicating that fertilization with these nutrients did not affect nutrition and total uptake and demand was not affected.

Vector Analysis – Individual Fascicle Mass

Vector analysis was utilized to bridge the gap between diagnosis and interpretation of nutrient status by integrating measures of concentration, content, and fascicle mass. In order to provide useful diagnosis, an average vector of all treatments where an element was applied (+) was plotted along with an average vector of all treatments when the element was not applied (-). This was to avoid problems seen by other users when non-applied nutrients experienced unaccountable shifts in nutrition (Valentine and Allen, 1990). The intention was to simplify the diagnosis of vector shifts without loosing site of meaningful changes in pine nutrition. Magnitude and direction of the 2 vectors allowed for the interpretation and categorization of nutritional shifts into 1 of 7 possible diagnoses based on the generalizations of Timmer and Stone (1978). In cases where nutrition was not substantially shifted, the scale of vector diagrams allows for the determination of real versus only incidental shifts and a 10% increase or decrease is suggested as indicative of actual fertilizer influences. Interpretation of specific elemental effects in specific treatments is in appendix 3.

Texas

The N, P, and K vectors at the TX site generally indicated deficiencies of these elements (Fig. 7). The P vector had the greatest magnitude and was considered the most limiting. The vector of Cu also indicated deficiency. Vectors for Ca and Zn indicated sufficiency of these nutrients (Fig. 7). Vectors for S, Mn, and B indicated luxury consumption,

although the magnitudes of these vectors were greater than the vectors for other elements. Predictably, the vectors of all nutrients in plots where the nutrient was not added indicated dilution or sufficiency (Fig. 7).

Alabama

None of the vectors indicated nutrient deficiencies at the AL site (Fig. 8). The magnitude of the vectors was generally small and indicated sufficiency (N and K) or dilution (P, Ca, Mg, S, Mn, Zn, and Cu). The largest vectors were for B, which indicated luxury consumption. Vectors for all plots where the specific element was not applied indicated dilution (Fig. 8).

Georgia

Vector analysis at the GA site indicated luxury consumption for all elements except Cu regardless of whether the specific element was added or not (Fig. 9). Vectors of Cu indicated dilution in plots with and without Cu additions.

South Carolina

Vector analysis at the SC sites indicated that N, K, B, and Mn were all deficient (Fig. 10). The magnitude of the Mn vector was greater than for either N or K. The vector for P at this site indicated sufficiency. Vectors for Ca, Mg, S, and Cu all indicated dilution (Fig. 10). As with the other sites, the vectors for all nutrients in plots where the nutrient was not added indicated dilution.

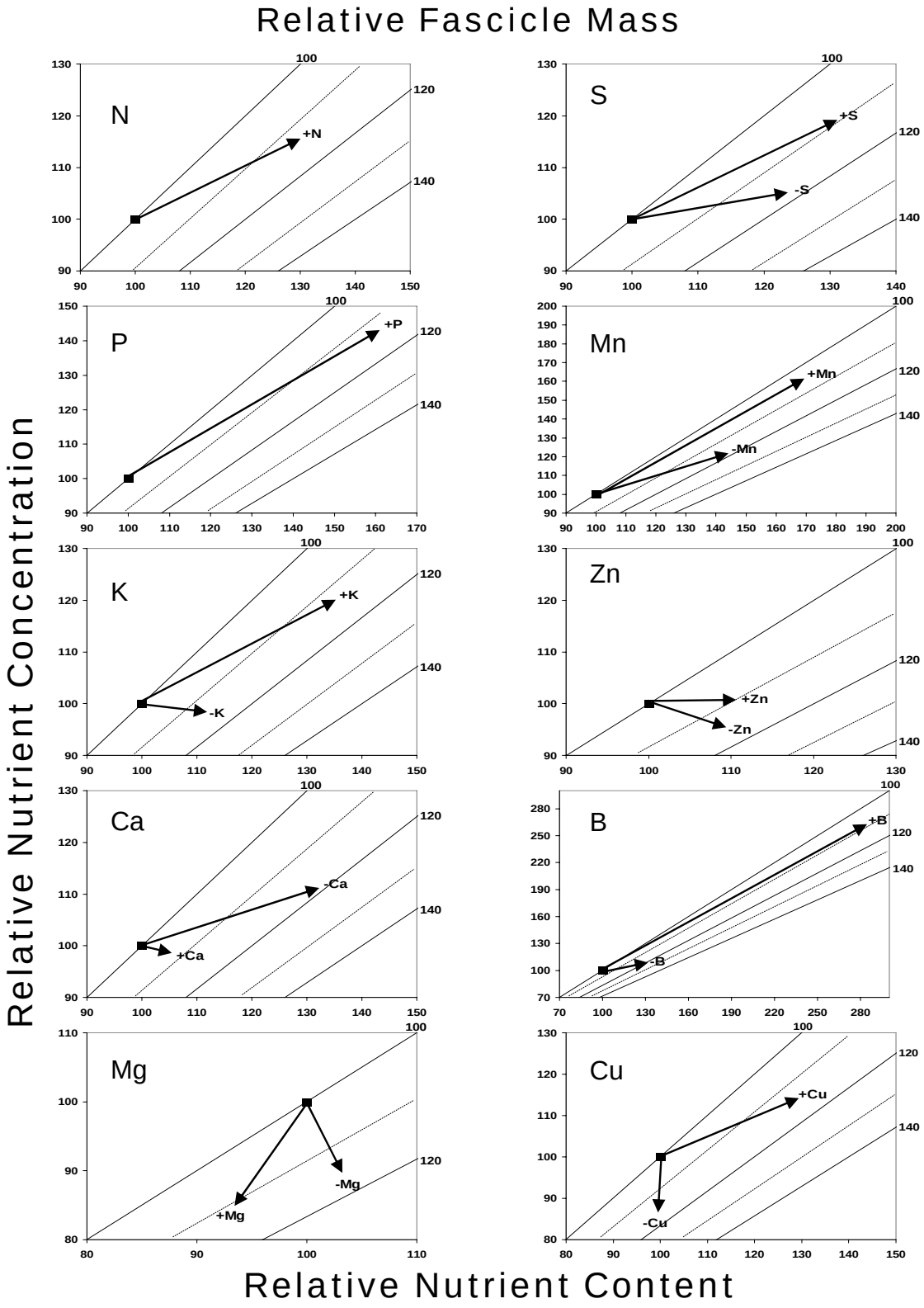

Figure 7: Vector Diagrams of the TX Site. All values are normalized to control values set at 100, represented by the closed square. Treatments where specified nutrients were applied were averaged and are represented by a (+) while treatments that lack the nutrient were averaged and are represented by a (-). Note differences in axis scales.

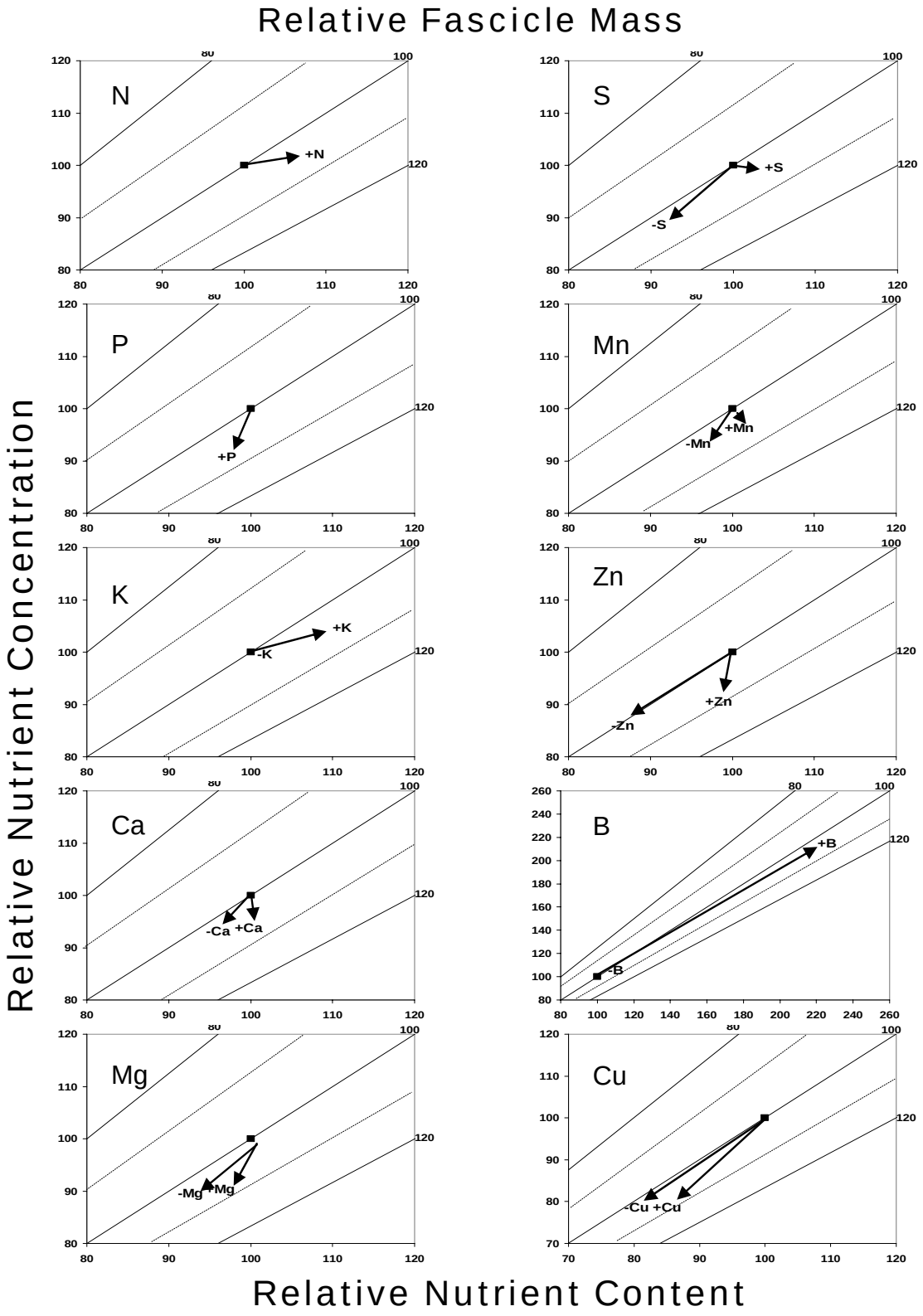

Figure 8: Vector Diagrams of the AL Site. All values are normalized to control values set at 100, represented by the closed square. Treatments where specified nutrients were applied were averaged and are represented by a (+) while treatments that lack the nutrient were averaged and are represented by a (-). Note differences in axis scales.

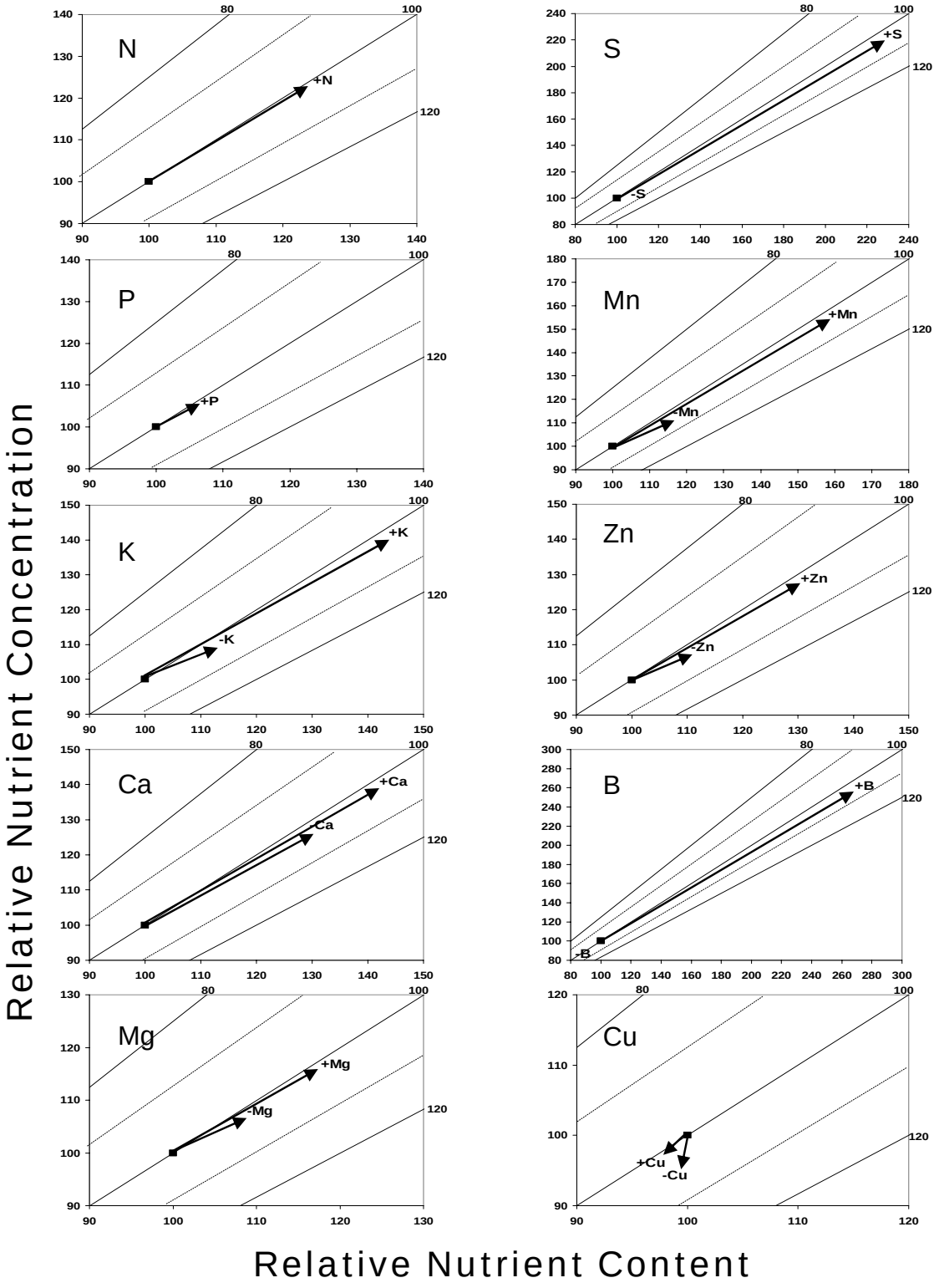

Figure 9: Vector Diagrams of the GA Site. All values are normalized to control values set at 100, represented by the closed square. Treatments where specified nutrients were applied were averaged and are represented by a (+) while treatments that lack the nutrient were averaged and are represented by a (-). Note differences in axis scales.

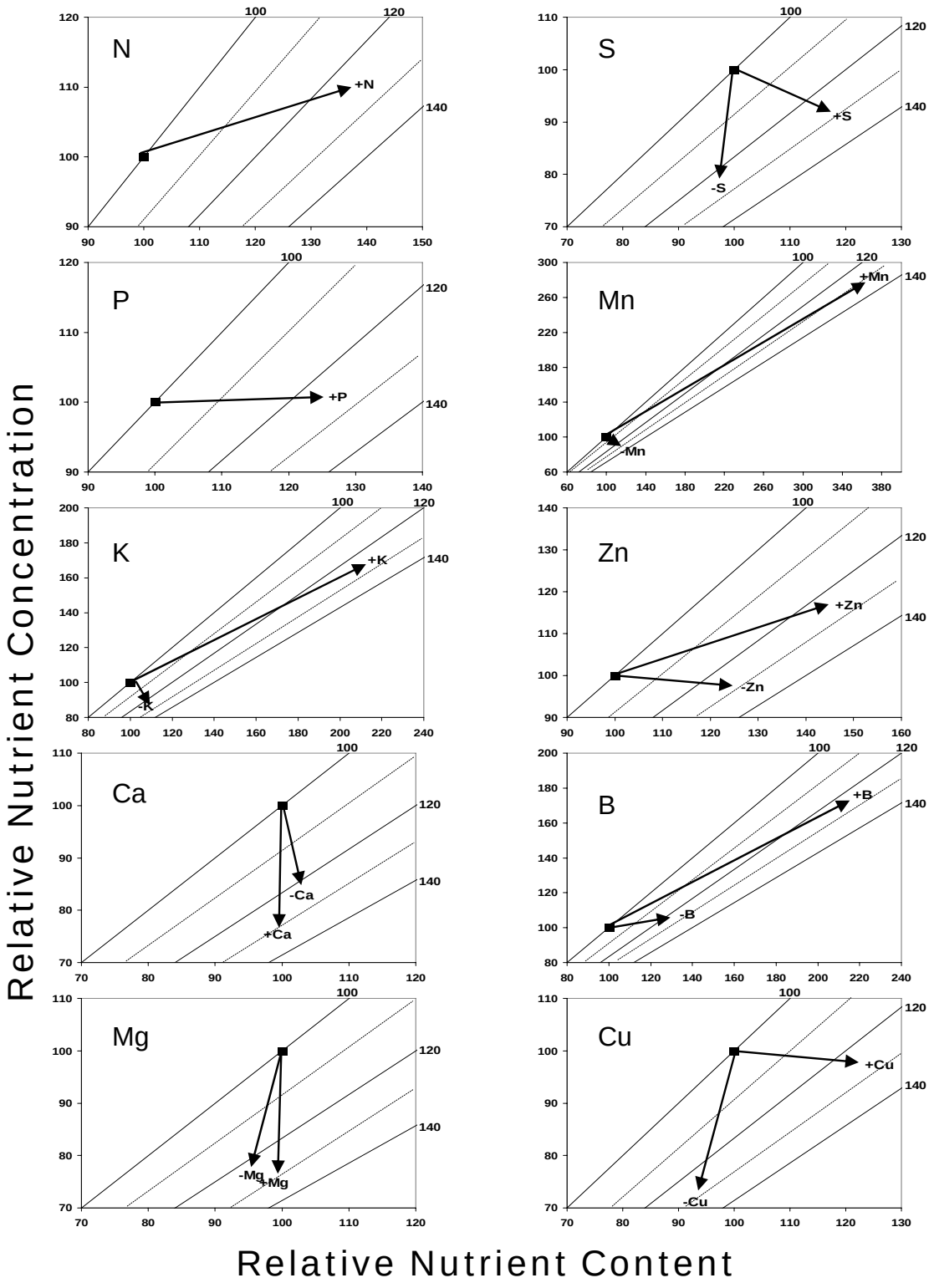

Figure 10: Vector Diagrams of the SC Site. All values are normalized to control values set at 100, represented by the closed square. Treatments where specified nutrients were applied were averaged and are represented by a (+) while treatments that lack the nutrient were averaged and are represented by a (-). Note differences in axis scales.

Total Branch Foliage Mass, Area, and Nutrient Content

Measures of projected leaf area have been used successfully to diagnose nutrient deficiencies in loblolly pine (Allen et. al, 2001). Supplying deficient nutrients has increased leaf area index (LAI) (Albaugh et. al., 1998), and a LAI of 3.5 has been established as indicative of stands with adequate nutrient supply (Fox et. al., 2006). Cost and complications associated with the measure of LAI have lead to the investigation of using fascicle mass as a surrogate of LAI, and resulting positive responses of fascicle mass have been correlated with long term volume responses (FNC, 2005b). However, the indeterminate growth habit of loblolly pine has cast doubt on the reliability of using individual fascicle mass as a predictive measure. Due to the indeterminate growth habit of loblolly pine, an individual tree may respond to fertilization by producing more and not necessarily bigger foliage. Mass of all current year flushes on a single lateral branch was measured in a subset of the treatments in this study to test this hypothesis. Foliage area of each flush was calculated using equations developed by Murthy and Dougherty (1997b). Total nutrient content of the foliage on each branch was calculated from the nutrient concentrations of the first flush. Graphical representations of response in branch foliage mass and area can be found in appendix 4.

Texas

Total branch foliage area and branch foliage mass, like individual fascicle mass, were not significantly affected by fertilizer treatments at the TX site (Table 17). Total branch foliage mass only ranged 4.96 grams, with values evenly ordered around the control. Branch foliage content of N, P, or K also did not significantly increase in any treatment (Table 17). Branch foliage content of B and Mn were increased over control levels in treatments where they were applied (Table 17).

Table 17: Impact of fertilization on branch foliage mass, area, and nutrient content of loblolly pine at the TX, AL, GA, and SC sites. P values indicate the results of ANOVA conducted for each nutrient. LSD at α=0.05 was conducted for those nutrients with treatment effects significant at P<0.05. Foliar mass is reported in grams (g) while nutrient contents are reported in milligrams (mg). Highlighted values are significantly different from controls.

		Foliar Area	Foliar Mass	N	P	K	Ca	Mg	S	Mn	Zn	B	Cu
		cm^2	--- g ---	---------- mg ----------									
TEXAS	P>F	0.8539	0.8686	0.5906	0.1444	0.7136	0.3379	0.6486	0.5308	0.0025	0.4721	<.0001	0.0425
	LSD	None	None	None	None	None	None	None	None	2.60	None	0.28	0.04
	1 - Control	3508	26.21	344.1	19.0	112.2	34.6	27.2	11.2	3.88	0.85	0.27	0.07
	2 - NP	3517	27.16	427.7	28.2	114.0	38.4	25.5	11.4	5.14	0.75	0.34	0.05
	5 - NPKB	3456	27.40	424.4	27.8	127.9	33.6	23.8	12.2	5.75	0.89	0.72	0.05
	6 - NPKBCaMgS	2969	23.89	408.7	23.9	127.4	24.4	21.0	12.9	4.12	0.87	0.55	0.06
	10 - Complete	3700	28.83	439.3	27.3	144.7	44.0	27.8	14.9	7.74	1.07	0.95	0.09
ALABAMA	P>F	0.1132	0.5746	0.4147	0.8613	0.2964	0.9516	0.4677	0.6095	0.5189	0.8143	0.0007	0.9103
	LSD	None	None	None	None	None	None	None	None	None	None	0.34	None
	1 - Control	4657	36.12	580.2	43.6	202.8	68.1	29.8	16.3	13.11	1.45	0.32	0.12
	2 - NP	5250	40.81	679.5	48.7	233.6	76.4	35.8	17.2	11.14	1.38	0.39	0.14
	5 - NPKB	6593	44.52	760.3	52.1	302.3	76.4	30.6	19.5	15.31	1.64	0.91	0.13
	6 - NPKBCaMgS	5871	39.90	625.5	46.0	249.0	76.3	35.0	19.0	12.75	1.37	0.74	0.13
	10 - Complete	6642	40.77	658.6	46.1	266.8	68.9	28.0	20.3	15.47	1.52	0.81	0.11
GEORGIA	P>F	0.0277	0.0376	0.0039	0.0417	0.0004	<.0001	0.0019	<.0001	0.0032	0.0185	<.0001	0.3022
	LSD	1171	12.74	157.0	13.1	55.4	35.0	19.1	17.9	3.06	0.54	0.76	None
	1 - Control	4256	30.10	317.4	32.4	79.1	53.0	41.4	12.0	5.15	0.92	0.46	0.07
	2 - NP	4657	31.72	419.3	37.6	93.9	64.6	44.3	13.3	5.87	1.04	0.33	0.08
	5 - NPKB	5211	36.91	477.9	41.9	134.4	69.8	49.6	14.9	5.95	1.13	1.63	0.08
	6 - NPKBCaMgS	5828	44.46	576.3	50.7	150.4	105.5	68.8	34.6	8.21	1.46	1.49	0.10
	10 - Complete	5967	40.39	494.4	43.5	151.6	104.8	65.9	32.8	10.73	1.60	1.22	0.09
SOUTH CAROLINA	P>F	0.6917	0.0165	0.0102	0.0226	<.0001	0.4029	0.3173	0.0166	<.0001	0.0165	0.0017	0.1059
	LSD	None	9.79	151.9	11.3	81.8	None	None	5.1	5.39	0.34	0.52	None
	1 - Control	4787	35.36	461.3	42.7	102.6	50.8	31.7	17.5	2.55	0.84	0.46	0.09
	2 - NP	4900	34.82	515.3	43.2	94.7	49.3	26.2	12.2	1.72	0.75	0.54	0.06
	5 - NPKB	5646	45.15	643.5	54.0	220.2	35.0	24.4	17.9	2.66	0.95	1.25	0.06
	6 - NPKBCaMgS	5196	47.40	696.3	60.7	217.6	52.7	31.0	21.2	2.45	1.09	0.98	0.07
	10 - Complete	4914	43.60	613.2	49.5	184.4	49.7	29.3	17.4	8.05	1.20	1.06	0.10

Alabama

There were no significant differences in branch foliage mass or branch foliage area at the AL site (Table 17). The only significant differences in total branch nutrient content occurred for B. Total branch foliar B content more than doubled in treatments where B was applied (Table 17).

Georgia

Total branch foliage area at the GA site was significantly greater than the control level of 4256 cm^2 in treatments 6 (macros +B) and 10 (complete), where increases of 1572 cm^2 and 1711 cm^2 were seen, respectively (Table 17). Treatment 6 also resulted in a significant total branch foliar mass response of more than 14 g over the 30.10 g seen in the control (Table 17). Total branch foliar content of all nutrients except Cu was significantly increased following fertilization (Table 17). However, N and P did not increase until K, B, Ca, Mg, and S were added in addition to the basic N+P treatment. Total branch K, Ca, Mg, and S were all increased significantly when they were applied. The GA site was the only site in the study to display a positive response to S (Table 17). It was interesting that total branch content of Mn and Zn were increased in treatment 6 when these nutrients were not added (Table 17).

South Carolina

Total branch foliage mass at the SC site significantly increased over control levels of 35.36 g by 9.79 g and 12.04 g in treatments 5 (NBKB) and 6 (macros +B), respectively (Table 17). In contrast, total branch foliage area did not increase due to fertilization. As at the GA site, total branch content of N and P did not increase when only N and P were applied. N and P content did increase along with total branch content of K and B when N, P, K, and B were applied in treatment 5 (Table 17). Total branch foliar content of K and B were significantly increased in all treatments where they were applied (Table 17). Branch foliar content of K was increased by more than 100 mg in treatments 5 and 6. Additions of Ca, Mg, and S did not result in increased total branch foliar content of these nutrients (treatment 6), while application of Mn and Zn in the complete treatment (treatment 10) did increase total branch content of Mn and Zn.

Vector Analysis – Branch Foliage Mass

Vector analysis with branch foliage mass as the associated biomass production variable may reduce problems with vector analysis in non-determinate species such as loblolly pine. Interpretation of vector diagrams produced from concentration, content, and foliage mass data representing the entire growing season may better characterize loblolly pine's responses to fertilization. Foliar concentrations and contents were significantly altered at all sites while individual fascicle mass was only increased at 1 site. Total branch foliage mass was significantly increased at 2 sites and increased by more than 20% at 3 sites. Vector diagrams were created by plotting the average nutritional response to fertilization of each element when it was (+) and was not applied (-). As with vector analysis with individual fascicle mass, interpretations of vectors were based on the procedure outlined by Timmer and Stone (1978) (Table 2). Interpretation of vector diagrams produced by specific elements in specific treatments using the vector matrix can be found in the appendix 5.

Texas

Using total branch foliage properties, vector analysis at the TX site indicated luxury consumption of N, P, K, S, Mn, B, and Cu (Fig. 11). Vectors of Mg indicated a dilution effect in all treatments regardless of application. Ca was diluted when added, but taken up as luxury consumption when it was not (Fig. 11). Unlike individual fascicle vector analysis, the vectors of branch foliage variables did not indicate sufficiency of non-applied nutrients as often. Dilution and luxury consumption were more common.

Alabama

Vectors derived from total branch foliage variables identified K and B as deficient at the AL site (Fig. 12). By far, the vector of B had the greatest magnitude and indicated a greater deficiency as compared to other elements. No other elements resulted in identified deficiencies. Vectors of N, Mn, and S indicated sufficiency, while vectors of applied and non-applied P, Ca, Mg, Zn, and Cu indicated dilution (Fig. 12).

Georgia

Vector analysis of total branch foliage variables at the GA site indicated deficiencies of N, K, Ca, Mg, S, Mn, Zn, and B (Fig. 13). The magnitude of S and B vectors were greater than those of other nutrients identified as deficient. P and Cu were found in sufficient quantities with or without application. Despite increases in fascicle weight, no applied or non-applied nutrients were diluted. Vectors of non-applied vectors indicated a deficiency of K and Ca and sufficiency of Mg, S, Mn, and Zn (Fig. 13).

South Carolina

Vectors of total branch foliage at the SC site indicated deficiencies of N, K, Mn, Zn, and B. The indicated magnitude of K, Mn, and B deficiencies were greater than those of N and Zn (Fig. 14). When K and Mn were not applied, low magnitude vectors indicating a slight dilution were created while vectors of non-applied B still revealed a deficiency. Vectors of Ca, Mg, S, and Cu indicated dilution despite application. P was shown sufficient when applied and had foliar concentrations virtually unchanged from control levels (Fig. 14).

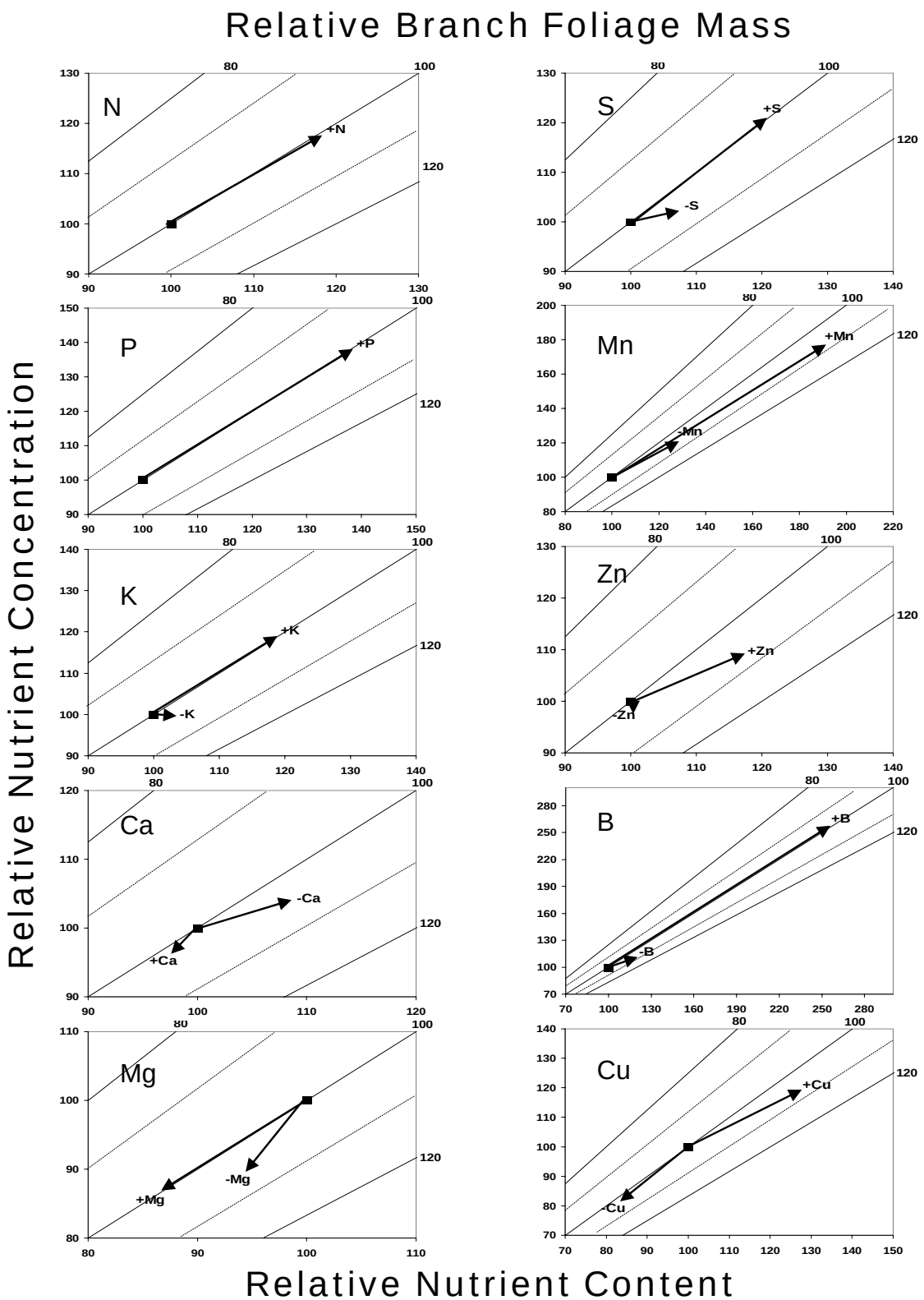

Figure 11: Vector Diagrams of the TX Site (total branch weight). All values are normalized to control values set at 100, represented by the closed square. Treatments where specified nutrients were applied were averaged and are represented by a (+) while treatments that lack the nutrient were averaged and are represented by a (-). Note differences in axis scales.

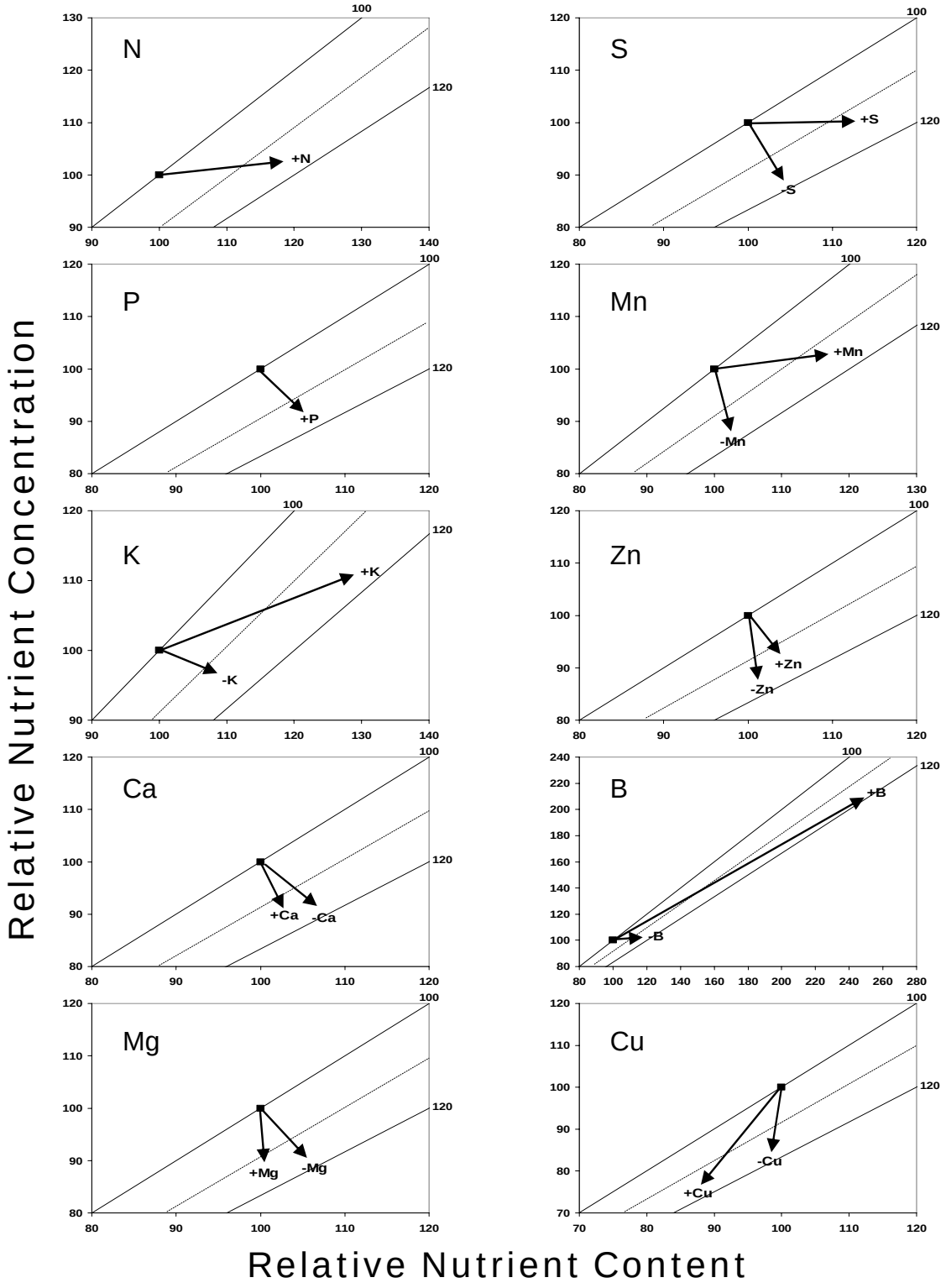

Figure 12: Vector Diagrams of the AL Site (total branch weight). All values are normalized to control values set at 100, represented by the closed square. Treatments where specified nutrients were applied were averaged and are represented by a (+) while treatments that lack the nutrient were averaged and are represented by a (-). Note differences in axis scales.

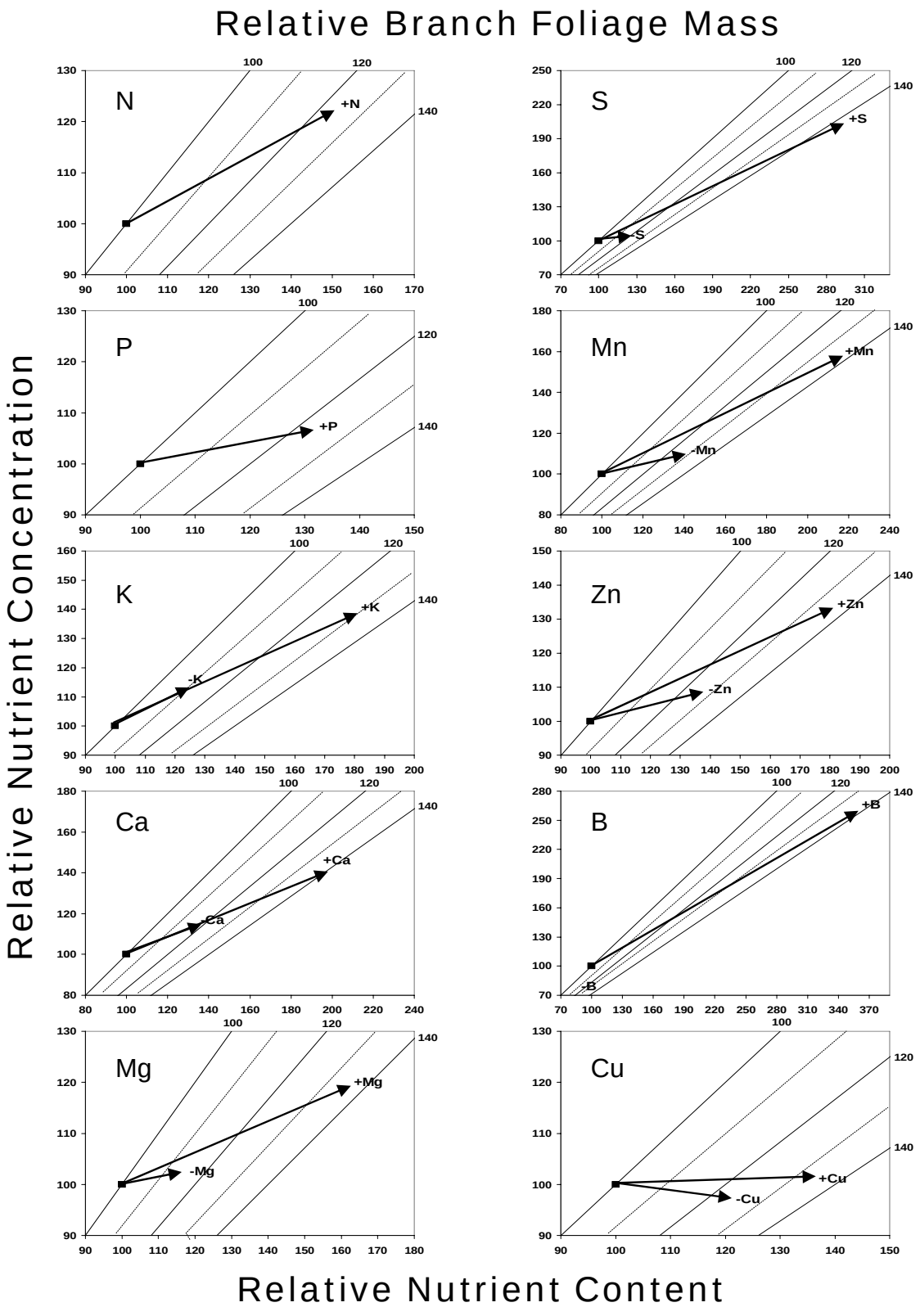

Figure 13: Vector Diagrams of the GA Site (total branch weight). All values are normalized to control values set at 100, represented by the closed square. Treatments where specified nutrients were applied were averaged and are represented by a (+) while treatments that lack the nutrient were averaged and are represented by a (-). Note differences in axis scales.

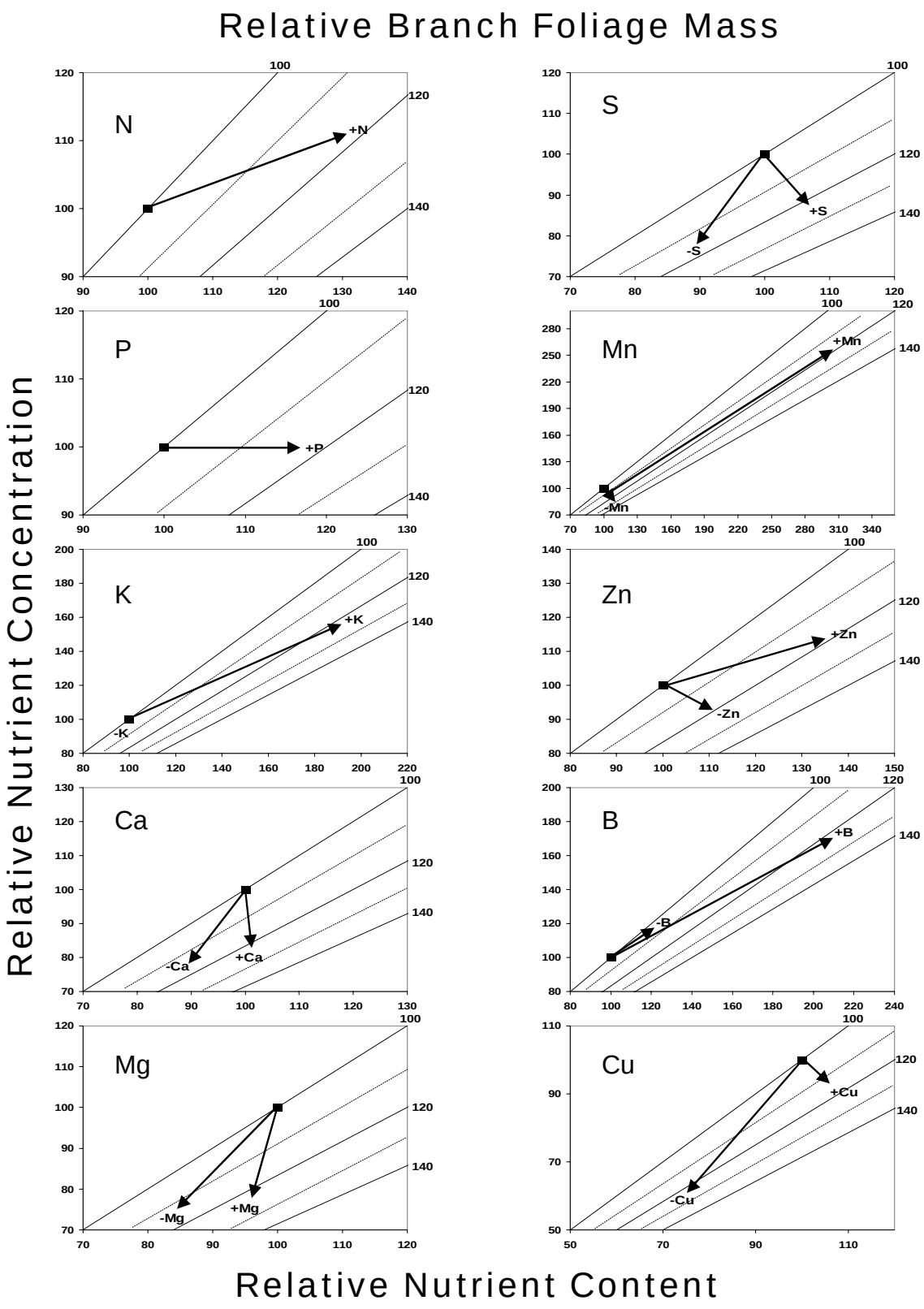

Figure 14: Vector Diagrams of the SC Site (total branch weight). All values are normalized to control values set at 100, represented by the closed square. Treatments where specified nutrients were applied were averaged and are represented by a (+) while treatments that lack the nutrient were averaged and are represented by a (-). Note differences in axis scales.

DISCUSSION

Deficiency Interpretation

Texas

Deficiency of P at the TX site was identified by all techniques involving foliar concentration and content, but P fertilization failed to produce significant responses in individual fascicle or branch foliage mass (Table 18). Because insignificant individual fascicle mass responses ($P > 0.1226$) occurred following P fertilization, additional data are needed to determine if the P deficiencies were limiting growth. Valentine and Allen (1990) determined that changes in fascicle mass following P fertilization in loblolly pine were poor predictors of tree response, resulting in type II errors. Vector analysis at the TX site also predicted P deficiencies. However, vector analysis confirmed the predictions based on critical concentrations or foliage mass changes. The increased complexity of vector analysis did not provide any marginal benefit over the simpler techniques. Similarly, Valentine and Allen (1990) reported vector analysis provided no benefit in predicting responses over foliage mass increases alone since P content and concentration were always increased in their study.

Identification of P deficiencies were expected at the TX site because soils of the Catahoula geologic formation are frequently P deficient (FNC, 2006). The Catahoula formation was the site of a previous study in the FNC RW15 that had the lowest pre-treatment foliar P levels (0.6 g/kg) in the entire study (FNC, 2004). Ngono and Fisher (2001) also found P limited diameter growth more often than N or K in east Texas counties where soils of the Catahoula formation are common. Evedence that naturally high levels of arsenate in the soils of the Catahoula formation were interfering with P nutrition (FNC, 2006) were not substantiated at the TX site. Arsenic concentrations in Mehlich I extracts of surface and subsurface soil were below detection limits.

Table 18: Predicted nutrient deficiencies at each site based on the foliar diagnostic tools listed.

		Critical Level	Nutrient Ratios	DRIS	Fascicle Vector Analysis	Branch Foliage Vector Analysis	Responsive Fascicle Mass	Responsive Branch Foliage Mass	Responsive Branch Foliage Area
TEXAS	N				**X**		**X**		
	P	**X**	**X**	**X**	**X**		**X**		
	K				**X**		**X**		
	Ca		**X**						
	Mg		**X**						
	S	**X**	**X**	**X**					
	Mn								
	Zn								
	B		**X**	**X**	**X**				
	Cu	**X**			**X**				
ALABAMA	N								
	P								
	K					**X**			**X**
	Ca								
	Mg		**X**						
	S	**X**	**X**	**X**					
	Mn								
	Zn								
	B	**X**	**X**	**X**		**X**			**X**
	Cu			**X**					

- **X** indicates that the diagnostic technique identified a nutrient deficiency

Table 18: Continued

		Critical Level	Nutrient Ratios	DRIS	Fascicle Vector Analysis	Branch Foliage Vector Analysis	Responsive Fascicle Mass	Responsive Branch Foliage Mass	Responsive Branch Foliage Area
GEORGIA	N	**X**				**X**		**X**	**X**
	P	**X**						**X**	**X**
	K	**X**		**X**		**X**		**X**	**X**
	Ca					**X**		**X**	**X**
	Mg					**X**		**X**	**X**
	S	**X**	**X**	**X**		**X**		**X**	**X**
	Mn					**X**			
	Zn					**X**			
	B			**X**		**X**		**X**	**X**
	Cu	**X**							
SOUTH CAROLINA	N				**X**	**X**		**X**	
	P							**X**	
	K	**X**	**X**	**X**	**X**	**X**	**X**	**X**	
	Ca								
	Mg		**X**						
	S	**X**	**X**	**X**					
	Mn			**X**	**X**	**X**			
	Zn				**X**	**X**			
	B		**X**	**X**	**X**	**X**		**X**	
	Cu	**X**							

- Critical range and DRIS (southwide) diagnosis are based on deficiencies indicated in the control treatment (Table 13, 15)
- Diagnosis based on nutrient ratio were made when ratios unbalanced enough to be considered biologically important (Table 14)
- Vector analysis diagnosis is based on vector diagram interpretations of individual elements (Fig. 8-15)
- All applied elements were considered deficient when their application increased foliage mass or area significantly at the 0.15 alpha level (Table 16, 17)

Alabama

Fewer deficiencies were predicted at the AL site than at any other (Table 18). The only significant responses in foliar nutrient concentration or content occurred following B fertilization. B concentrations in the control were 9.1 mg/kg, below the 10.0 mg/kg critical level, but increases to 18 mg/kg were measured following B additions (Table 13). B deficiencies in loblolly pine (Albaugh et. al., 1998) and radiata pine (Hopmans & Flinn, 1983) are seen on deep, sandy soils where B is easily leached. Responses to B at the AL site were counterintuitive in that surface and subsurface soils contained high kalonitic clay fractions and a high percentage of total carbon, indicating adequate exchange capacity and nutrient holding. In fact, surface soil B concentrations were higher than other sites (Table 3). The only characteristic of the AL site associated with B deficiency was the moderately well drained soil. At pH < 7.0, B requires ample water and H^+ carriers to facilitate root uptake (Moraghan & Mascagni, 1991).

Whether the insignificant (P>.1132) total branch foliar area responses to B fertilization at the AL site will result in future volume responses is yet to be seen. B deficiency corrections are considered solely responsible because no other elements had concentrations or contents increased by fertilization (Tables 13, 15). B applications increase the length of terminal leaders in B deficient, N sufficient Douglas-fir (Carter and Brockley, 1990). B fertilization is also suggested when the intention is to prevent terminal leader death in trees fertilized with N (Brockley, 1990). B fertilization that results in increased branch elongation or reduced branch elongation loss could result in greater total branch foliage area due to its inclusion in the flush area equation by Murthy and Daugherty (1997b). The likelihood of B limiting branch foliar area production at the AL site is small due to the high levels of total branch foliar area growth in the control plots relative to the other sites (Table 17).

Georgia

Unlike the other sites, the critical level approach indicated more nutrient deficiencies than either optimum nutrient ratios, or DRIS methodology at the GA site (Table 18). N, P, and K levels in the control plot were below the critical level. DRIS and nutrient ratios

predicted fewer nutrient deficiencies because the capability of these techniques is reduced when many nutrients are outside the sufficiency range (Soltanpor et. al., 1995). The pre-treatment concentrations of N, P, and K were above critical levels, but were below the critical levels in the control stands after treatment. Large seasonal variations in foliar nutrient concentrations make diagnosis of nutrient deficiencies problematic. Concentrations of the mobile elements N, P, and K decrease in aging loblolly pine foliage, while concentrations of the immobile elements, Ca and Mg, increase due to retranslocation (Adams et. al. 1987). Retranslocation efficiency is decreased for N, P, and K following fertilization (Winborne, 2001). Powers (1984) reported that current-year foliar N concentrations in ponderosa pine (*Pinus ponderosa* Laws.) increased from below to above critical level following the senescence of the oldest needles at the end of the growing season. Nutrient uptake also occurs during the "dormant" season when soil conditions are suitable for root activity which Comerford et. al. (1987) reported for N, P, and K in slash pine growing in south Georgia and north Florida. Weather conditions perhaps affected the pre-treatment foliar nutrient concentrations at the GA site where soil temperatures are high enough to allow nutrient to be mineralized from organic matter and subsequently taken up.

Multiple deficiencies exist at the GA site, so diagnosis by the foliage mass/area method was poor. Additions of N, P, and K increased foliar concentrations but total branch foliar mass/area only increased when S was applied in treatment 6 (Table 17). The ramped fertilization scheme in the current study resulted in the prediction of P and Mg deficiencies that were not identified as deficient without foliar analysis (Table 18). This and work by others (Hockman and Allen, 1990; Gregorie and Fisher, 2004) indicated that when using foliage mass, applying suites of elements identifies more deficiencies than when adding them singularly.

S deficiencies were predicted at all sites, but only the GA site indicated a response to S fertilization with the measurements made to date (Table 18). Significant foliage mass increases at the GA site were only measured when N, P, K, and S deficiencies were corrected together in treatment 6 (Table 17). Lodgepole pine stands in interior British

Columbia respond to added S when foliar SO_4^{-2} concentrations are <0.6 g/kg and N/S ratios are >13 (Brockley, 2000). All sites in the current study had total S concentrations in the control plots of <0.6 g/kg with N/S ratios approaching 35 (Table 13, 14). Jokela (2004) stated that critical levels for elements other than N and P were suspect and probably unreliable, so previous notions of loblolly pine's requirements for S may need more study, especially since foliage production at the AL and SC sites was not hampered by low S concentrations (Tables 16, 17).

South Carolina

K deficiencies were identified by all diagnostic techniques tested at the SC site excluding total branch foliage area (Table 18). K fertilization in treatments 4-10 produced significant responses in individual fascicle and total branch foliage mass. Stands in the Lower Atlantic Coastal Plain were implicated as K deficient (Xiao et. al. 2003) and as having foliage mass responsive to K additions (FNC, 2005b). Foliage mass responses are due to the specific mechanism of K within plant cells. K^+ is required as an osmoticum and maintains turgor pressure. When deficient K^+ is supplied, cell expansion occurs at a greater rate leading to increased cell division and foliar biomass production (Marschner, 1986).

Increases in foliage mass following K fertilization in treatments 4-10 lead to dilution of non-deficient nutrients including Ca, Mg, Mn, Zn, and Cu (Table 13). Dilution of Ca and Mg to sub-acute deficiency levels were reported in other K deficient stands where fertilization resulted in increased fascicle mass (Xiao et. al. 2003). Following K fertilization in the current study, these nutrients were reduced to below critical levels but nutrient contents were unaffected. This indicated that K did not hinder nutrient uptake and availability was not affected.

Soil properties of the SC site did not indicate that K deficiencies were likely. Deficiencies of K are found on deep, sandy soils (Albaugh et. al., 1998) where the K^+ ion is easily leached (Will, 1985). The soils of the SC site were loamy sands or sandy loams

with high concentrations of total carbon (Table 3) which indicates K^+ should have an adequate ability to be held within the soil profile without leaching. However, K deficiency was suspected at the SC site due to widespread response to K fertilization in north Florida, southeast Georgia, and southern South Carolina (Albaugh et. al., 1998; Xiao et. al. 2003; FNC, 2004) The SC site was also located on the K limiting Wicomico geologic formation (FNC, 2006). K^+ uptake is reduced by competition from other divalent cations such as Ca^{+2} and Mg^{+2} (Marschner, 1986); however, soil concentrations of Ca and Mg were not high (Table 3). Concentrations of total soil N were high (Table 3), and a sufficient portion of the total N fraction as NH_4^+ would lead to increased competition for soil exchange and plant uptake resulting in K deficiencies (Phillips, 2004).

Diagnostic Technique Interpretations

Critical Levels / Nutrient Ratios

Deficiencies of S were consistently indicated by the critical level method (Table 18) but S application seldom resulted in increased nutrient concentrations or foliage mass/area responses (Table 13, 14, 16, and 17). Allen (1987) suggests a critical level of 1.2 g/kg for S, but concentrations at the TX, AL, and SC sites only reached 0.7 g/kg with S applications. Brockley (2000) describes S responsive lodgepole pine stands in interior British Columbia with foliar concentrations higher than those seen in this study. Lack of S responses in this study was a result of unbalanced N and S concentrations evidenced by ratios approaching 35 (Table 14). Pre-treatment N concentrations at the TX, AL, and SC sites were above the critical levels but displayed concentration increases with N applications. Resulting N concentrations were much higher than the GA site which was responsive to S and had N/S ratios of 13 in some treatments. N and S balance is important to determine the response to applications of both (Turner et. al. 1979), but the current study indicated that excess N does not lead to increased S uptake and lower N/S ratios. Cu was implicated as deficient by critical levels (3.0 mg/kg) but failed to be detected by other diagnostics. South et. al. (2004) found healthy loblolly pine seedlings with foliar Cu concentrations as low as 2.8 mg/kg while visually deficient trees had

concentrations of 0.0 mg/kg. These results indicate that some minor nutrient critical concentrations may require more study to be reliable.

The high degree of replication in the current study resulted in statistical power to identify nutrient ratios as different from established optimums, so inference was based solely on what was considered biologically important. The purposeful selection of stands with deficiencies and unbalanced nutrition resulted in poor diagnosis by nutrient ratios because the utility of a ratio is reduced in cases where the comparison elements are outside the sufficiency range (Soltanpor et. al., 1995). Optimal nutrient ratios with N were difficult to obtain when N fertilization increased foliar concentrations at most sites (Table 14). The increased uptake of N came at the expense of other nutrients such as Ca, Mg, and S which resulted in their dilution and unbalanced nutrient ratios (Table 13, 14). Similar difficulties were seen with the maintenance of N/Mg ratios in the presence of N applications (Albaugh et. al., 1998). Results of deficiency diagnosis may have been more accurate if pre-treatment nutrient ratios were used to adjust fertilizer applications (Albaugh et. al., 1998) rather than as a response variable to pre-determined treatments.

Diagnosis and Recommendation Integrated System (DRIS)

Results from this study agree with those found by Gregorie and Fisher (2004) who determined that southwide, rather than regional norms would provide more interpretable and consistent diagnosis. The use of micro-nutrients, particularly Mn, in DRIS diagnosis has created problems in the past due to the often high variances seen in foliar concentrations and correlation between Mn concentrations and Mn indices (Rathfon and Burger, 1991). The same could be said in the current study where Mn fertilization increased Mn concentrations and Mn indices, but Mn indices were neutralized by the effects of increases of all concentrations in the full treatment (TX and SC). B concentrations were also not correlated with DRIS indices because increasing elemental additions in treatments 6-10 mediated the effects of consistently doubled foliar B concentrations (TX, GA, and SC) on B indices (Table 15). Basic DRIS tenants assume that nutrient balance is improved as limiting factors are reduced and stand/tree productivity approaches an optimum (Fig. 4) (Beaufils, 1971). Previous studies have

verified DRIS diagnosis by fertilizer responses to stand level variables such as basal area and volume production (Gregoire and Fisher, 2004; Hockman and Allen, 1990). However, the current study did not have a response variable available to confirm the DRIS diagnosis, and thus no indication of whether failures to correct nutrient balance were from poor DRIS norm synthesis or actually more unballanced mineral nutrition.

Vector Analysis

Vector analysis was conducted with individual fascicle mass and nutrient content and total branch foliar mass and nutrient content to test the assumption that vector analysis is best applied in species with determinate growth. Vector analysis works well in balsam fir (Timmer and Stone, 1978) and lodgepole pine (Weetman and Fournier, 1982) because needle numbers are set in the previous year's terminal bud and fertilization affects the weight but not the number of fascicles. In non-determinate species such as loblolly pine, improved nutrition from fertilization can affect the number and the mass of fascicles (Kozlowski and Pollardy, 1997). The two approaches to vector analysis produced inconsistent results in this study. Vector analysis using total branch foliage mass predicted deficiencies at 3 stands (AL, GA, and SC) while vector analysis using individual fascicle mass only identified deficiencies at 2 stands (TX and SC). Lack of detection was due to non-responsive foliage mass because nutrient concentration and content of fascicles and total branch foliage were increased for at least one element at every site (Table 13, 16, 17). Other users of vector analysis in loblolly pine have seen consistent individual fascicle mass responses, positive or negative, to added fertilizer (Valentine and Allen, 1990; Xiao et. al., 2003; Gregorie and Fisher, 2004). Individual fascicle mass at AL and GA and total branch foliage mass at TX was totally non-responsive to fertilizer treatments, often resulting in identified luxury consumption.

Vector diagrams were produced by plotting the average nutritional status of an element when it was (+) and was not (-) applied in a treatment. This modification of standard techniques reduced the limitations and inaccuracies of interpreting non-applied nutrients seen by others (Valentine and Allen, 1990; Ngono and Fisher, 2001). Nutritional status of non-applied nutrients was shifted with lower magnitude and more unpredictably than

applied nutrients. Averaging the nutrient status of elements across treatments that did not contain them identified dilution of non-applied elements at SC (Fig. 11, 15) and simultaneous uptake of the cations Ca, Zn, and Mn with other cation applications at the TX (Fig. 8) and GA (Fig. 10, 14) sites. Other attempts to display generalities in vector diagrams have eliminated insignificant vectors (Imo and Timmer, 1987) or grouped like vectors (Chappell and Bennett, 1993). The current study maintained all treatment means as part on an overall mean and statistical significance of vectors is explained in appendix 3 and 5.

Foliage Weight/Area

Fertilization induced increases in LAI display strong positive relationships with stand volume production (Vose and Allen, 1988) and can be used to predict fertilizer response (Fox et. al., 2006). Response of individual fascicle mass has also been acceptable in predicting 4-year volume growth response (FNC, 2005b). Previous research with loblolly pine has quantified growth and fascicle mass correlations with sporadic success (Valentine and Allen, 1990; Wells et. al. 1793; FNC, 2005b) because responses to fertilization may result in more rather than larger foliage. The current study went beyond where previous research has fallen short by developing techniques that compensate for the indeterminate nature of loblolly pine growth. Summations of individual current year flush areas (Murthy and Dougherty, 1997b) and the weights of those flushes were used to measure total current year foliage production.

K fertilization increased total branch foliage mass and individual fascicle mass at the SC site and the correction of multiple deficiencies increased total branch foliage mass/area at the GA site (Table 16, 17). Differences in significant responsive variables seen at these sites indicate that efforts to improve sampling techniques in loblolly pine were not effective. As stated earlier, examining correlations between individual fascicle mass and long term growth response has shown limited success in loblolly pine, but correlations are assumed to be better in determinate species (Valentine and Allen, 1990). The technique has shown successes in Jack pine (*P. banksiana* Lamb.) (Timmer and Morrow, 1984) and lodgepole pine (Yang, 1998) where correlations of R^2=0.88 and R^2=0.91 were

seen, respectively. Loblolly pine has recently indicated correlations with R^2=0.75 (FNC, 2005b). Other studies with lodgepole pine have only found correlations of R^2=0.19 (Weetman et. al. 1988) and R^2=0.33 (Brockley, 2000). The current study had one site that displayed first year individual fascicle mass response. Examining fascicle mass, total branch foliar mass, and total branch foliar area resulted in at least one significant variable (P>0.1500) at each site. However, refinement is needed to determine which variable will be suitable across all candidate sites or which variable is best suited to individual sites.

Failure at the TX and AL sites to produce significant foliage mass responses following correction of P and B deficiencies, respectively, could be due to a time lag in response to fertilization. Time lags following P fertilization were seen on P deficient soils in FNC trials when volume responses in years 0-2 were insignificant while responses in years 2-4 were highly significant (NCSUFNC, 1988). Similarly, the first year following fertilization may have been needed to assimilate P and B in foliage before truly significant increases in mass/area could be realized in the future. Lack of foliage production due to drought is not suspected because the 2005 growing season (March through October) in Jasper Co., TX only experienced a 20% reduction in total rainfall (87.79 cm vs. 69.45cm) while Lamar Co. AL actually experienced rainfall 20% greater than normal (96.15 cm vs. 121.11 cm) during the same period (N.O.A.A., 2006). Furthermore, improved water availability in loblolly pine increases volume production by increasing growth efficiency, not photosynthetic area (Albaugh et. al. 1998). Non-responsive foliage mass and area at these sites may also indicate that the factor most limiting growth was not corrected by even the complete fertilizer treatment.

Diagnostic Technique Comparison

Deficiency diagnosis by critical level, nutrient ratios, and DRIS differed in the number of elements identified (Table 18). Nutrient ratios and DRIS identified more minor nutrient (Ca, Mg, S, Mn, Zn, B, and Cu) deficiencies than the critical level and many more than by increases in foliage mass. Similarly, Ngono and Fisher (2001) and Gregorie and Fisher (2004) found that DRIS deficiency predictions included more elements than the critical level method. Except S and Cu, the current study seldom indicated that Ca, Mg,

S, Mn, Zn, B, and Cu were below their critical levels (Table 13). Significant volume and stem form responses to additions of Mg (Mitchell et. al. 2003), Cu (Stone et. al., 2004; Dell and Bywaters, 1989), B (Hunter et. al., 1990), and Zn (Boardman and McGuire, 1990b) are seen following the onset of physical deficiency symptoms with subsequent foliar analysis revealing nutrient concentrations well below the critical levels used in this study. Therefore, it is unlikely that sub-acute deficiencies, detectable by identifying concentrations just below the critical level, will lead to significant increases in volume production. This study did show foliar responses to N, P, and K fertilization is likely when they are found below their critical levels. Critical levels of K (4.0 g/kg) confirmed by identifying responsive stands that had foliar concentrations elevated to or slightly above this level.

Vector diagrams developed with total branch foliage mass and nutrient content detected deficiencies with more sensitivity than individual fascicle mass and nutrient content. Haase and Rose (1995) warned that vector diagnosis utilizing a specific number of needles (individual fascicle analysis) requires a species with determinate growth habits. Regardless of the foliar mass variable used, vector analysis predicted more deficiencies than would actually produce growth responses. Averaging applied nutrients across a ramped treatment design resulted in deficiency diagnosis of elements that had, in reality, only experienced luxury consumption following foliar mass responses due to N, P, and K additions. Thelin et. al. (1999) came to the conclusion that singly applied micro-nutrients, and in particular B and Mn, were not capable of producing foliage mass increases needed to be identified as deficient by vector analysis. This study found macro-nutrients to be responsible for foliage mass increases. With this knowledge, decisions regarding macro-nutrient deficiency prediction will be just as easily made by identifying significant responses in foliar mass. The same conclusions were reached by Valentine and Allen (1990) when foliar concentrations and contents of N and P were increased across all examined sites and vector analysis gave no additional power of deficiency prediction over increases in foliar mass.

The ability of the foliage mass method to quickly detect single nutrient deficiencies makes it similar to the critical level method which has inference lost in cases of multiple deficiencies (Bates, 1971; Mead, 1984). Singular K deficiencies were identified by the critical level and foliar mass response methods at the SC site just as other K responsive sites in the FNC's RW18 (FNC, 2005b). Where more than one element was deficient, diagnosis by examining foliar mass responses required accompanying concentration data to provide accurate interpretation. Deficient concentrations of N, K, Ca, and S were determined by the critical level method before fertilization at the GA site, but foliage mass was not increased until the nutrients were added together in treatment 6. Diagnosis by foliage mass would have identified all elements included in treatment 6 as deficient, and fertilizer prescriptions would waste resources with applications of P and Mg. Any trial utilizing the foliage mass response method and ramped fertilizer applications has to accept limitations between individual elemental diagnosis and inclusion of all possible deficient nutrients. Some singularly applied nutrients are not capable of producing increases in foliage mass. N and P are influential in producing individual increases in foliage mass (Valentine and Allen, 1990; FNC, 2005b), but responses due to singly applied Ca, Mg (Timmer and Stone, 1978), and S (Brockley, 2000) have been refuted.

SUMMARY and CONCLUSIONS

Examining pre-fertilization critical concentrations of N, P, and K were adequate to detect deficiencies of these elements across all sites. Neither DRIS nor nutrient ratios provided more power of deficiency prediction beyond this simple initial step. K deficiencies seem to be easily predicted on many Lower Atlantic Coastal Plain sites by examining increases in individual fascicle and total branch foliage mass. This method may require base applications of N and P because responses from singular K applications were not substantiated in this study. The use of vector analysis for examination of N, P, and K status is not more effective than examining the individual responses in nutrient concentration and foliage mass used to create vector diagrams.

Critical levels of foliar S concentrations need to be reevaluated because stands in the current study showed no response to added S even with concentrations below the

suggested 1.2 g/kg. Maintenance of a N/S ratio below 13 has been suggested for lodgepole pines (Brockley, 2000). However, this benchmark was never achieved, even by the S responsive GA site where N/S ratios were above 14 following S additions. If actual S deficiencies are expected, they may be confirmed by total branch foliage mass increases following a base application of N, P, and K.

Application of deficient B (AL) and Cu (TX, GA, and SC) did not always correct the deficiencies or produce responses in foliage mass or area. The correction of the non-severe deficiencies may not produce volume growth responses. B fertilization is suggested to prevent stem damage and not stimulate growth responses (Stone, 1990), and major growth and stem form responses to Cu (South et. al., 2004; Dell and Bywaters, 1989), Zn (Dell and Dapling, 1995; McGrath and Robson, 1984) and Mn (Jokela et. al. 1991) in loblolly pine and other species are only seen at foliar concentrations well below the critical levels utilized in this study. Due to the geographically localized effects of micro-nutrient deficiencies, single-year foliar effects may not be useful in diagnosing deficiencies. Long term responses in height, DBH, or volume may be required to identify deficient stands.

Nutrient deficiency detection in loblolly pine stands should first include methods to identify deficits of N, P, and K. These nutrients are most likely to produce growth and foliage mass responses and can be identified by assessments of foliar concentrations relative to the critical level. Deficiencies of K can be quickly identified by examining foliar mass increases following K additions when N and P application decision criteria are already established. This may be important in Lower Atlantic Coastal Plain sites where K deficiencies are implicated. The current study did not indicate that the S, B, or Cu were detectable by the critical level method. The current study indicated that volume and foliage production responses may only be seen when concentrations are lower than the critical concentrations used in this study. Furthermore, DRIS and vector analysis provided no further power to identify truly deficient sites. Deficient S was taken up when N was also deficient indicating an interaction between the two. Further interactions may also be seen when N, P, and K fertilization increase growth to the point of dilution of

other nutrients. On the best sites, the costs of blanket applications of complete treatments may actually be offset by the prevention of deficiencies and growth reduction following N, P, and K additions and visual micro-nutrient deficiency symptoms. On poorer sites, variables requiring a more long-term sampling period such as height, DBH, or volume improvement may be needed to identify truly responsive stands. Repeated measurement of the trees in this study may find significant response in these variables, and be able to correlate those tree growth attributes to first year foliage responses.

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APPENDIX

Appendix A - DRIS Analysis by Regional Norms

The high-yielding populations chosen from the FNC's RW18 fertilizer trial were selected based on each stands superior volume growth relative to controls during the previous year. Due to these criteria, nutrient concentration data were not always what would intuitively indicate high growth rates. Often nutrient concentrations were well above or below the critical level. Also, the study design of RW18 did not contain a large number of replicates leading to a high yielding population that had nutrient concentrations and ratios with high variances. These characteristics lead to regional indices of the study sites that indicated excesses and deficiencies that were of such great magnitude, they were of little use. Furthermore, the NBI rarely indicated that major deficiencies had been corrected (e.g. phosphorus at TX and potassium at SC). When the nutrient concentrations from each of the four high-yielding populations were pooled to create one south-wide data set, outlying nutrient concentrations were neutralized and variances were reduced. The resulting norms of the south-wide population produced nutrient indices of the study sites that were more neutral, but still representative of real nutrient deficiencies and excesses. For example, South-wide DRIS norms were able to produce indices that identified large improvements of P concentration in TX, S concentration in GA, and K concentration in SC. Regional diagnosis is discussed here due to their inconsistencies, and each discussion results from a comparison of study sites and a single, high-performing matched stand.

Texas

Severity of negative indices in the control stand based on regional norms were in the order S>>P>K>Ca=B>Mn while positive indices were in the order Mg>>Zn>N>>Cu (Table 19). P concentrations barely above the critical level following high P application rates in treatment 11 were identified as excessive, while other treatments that had lower concentrations were more neutral (Table 19). K deficiency was indicated despite concentrations above the critical range at TX because the site matched with TX had average K concentrations of 0.78%. Indices indicating K deficiencies were slightly

corrected, but K uptake could not reach the level of the matched stand. Near neutral levels of B were made excessive especially when N, P, and B were added alone in treatment 3 (Table 19). DRIS did not indicate that S and Mg were affected in any way by fertilization as their indices maintained their position as the most deficient and excessive elements, respectively (Table 19). Sufficient levels of Cu were maintained by Cu treatments 8 and 10, but indices indicated deficiencies when treatments without Cu were added. No clear trends of the NBI could be identified. The high P rate in treatment 11 lead to an NBI greater than the other treatments despite the correction of an obvious P deficiency.

Alabama

Severity of negative indices in the control stand based on regional norms were in the order S>B while positive indices were in the order Mn=Zn>Cu>N>Ca>Mg>K (Table 19). Negative B indices were maintained where B was not applied but made positive by B applications (Table 19). The negative S indices were not improved with S application in treatments 6-10 (Table 19). Positive indices of Zn were slightly reduced by other elemental applications in treatments 2-10, but still remained quite high (Table 19). P was maintained at near neutral levels until K and B were added together in treatments 5-10. P indices were then turned sharply negative (Table 19). NBI was reduced from control levels by almost all treatments, but was never reduced to neutral levels.

Georgia

Severity of negative indices in the control stand based on regional norms were in the order S>B>K while positive indices were in the order Mg>Zn>P>Ca>Cu>N (Table 19). Indices of Mn were not calculated for regional norms at the GA site due to very low concentrations (8 ppm) in the high-yielding reference stand that were possibly due to dilution. Extremely negative S indices were greatly corrected by S applications in treatments 6-10 but remained negative (Table 19). Very negative B indices were also greatly increases by those treatments containing B (Table 19). Negative K indices were not corrected by fertilizer treatments. Significantly increases S concentrations (Table 13) improved the balance of all nutrients and lead to a NBI much lower than the control in treatments 6-10 (Table 19)

South Carolina

Severity of negative indices in the control stand based on regional norms were in the order S>>Cu=P>N=Ca while positive indices were in the order Mn>Mg>B>Zn>K (Table 19). Low K concentrations in the control plot did not result in negative indices and application worsened the nutrient balance by indicating an even more positive K index (Table 19). Neutral indices of Cu in the control trees were made negative by treatments that did not contain Cu (Table 19). Fertilization proved to worsen the unbalanced nutrition of the SC site in all treatments. Mn applications in treatment 9 created the most unbalanced situation when the NBI was increases to more than 700 (Table 19).

Table 19: DRIS indices indicating deficient or excessive nutrient status based on regional norms. Lower Nutrient balanced indices (NBI) indicate more balanced nutrient concentrations.

		DRIS Indices										
		N	P	K	Ca	Mg	S	Mn	Zn	B	Cu	NBI*
TEXAS	1 - Control	31	-22	-16	-12	70	-74	-3	33	-12	5	277
	2 - NP	49	8	-18	-1	58	-85	1	15	-5	-22	262
	3 - NPB	39	4	-33	-10	50	-86	0	8	52	-23	305
	4 - NPK	35	11	-9	-19	40	-65	-6	21	-3	-5	215
	5 - NPKB	35	1	-17	-17	42	-77	3	23	28	-20	263
	6 - NPKBCaMgS	36	-10	-14	-32	37	-58	-2	29	18	-4	240
	7 - " + Zn	29	-7	-13	-17	34	-57	-3	17	22	-4	203
	8 - " + Cu	29	-2	-17	-19	39	-74	0	16	26	1	224
	9 - " + Mn	19	-7	-14	-27	43	-58	3	26	19	-4	221
	10 - Complete	21	-14	-21	-11	33	-73	5	22	34	4	238
	11 - NPK	39	16	-9	16	41	-81	4	25	-17	-34	283
ALABAMA	1 - Control	19	0	2	11	9	-103	50	50	-64	25	333
	2 - NP	39	-1	8	18	19	-115	34	35	-50	12	332
	3 - NPB	20	-4	5	8	-1	-118	51	38	-4	4	254
	4 - NPK	36	5	7	15	6	-118	58	33	-51	9	338
	5 - NPKB	28	-10	16	-5	-13	-127	52	32	13	13	309
	6 – NPKBCaMgS	18	-13	8	6	9	-106	37	27	8	6	237
	7 - " + Zn	20	-15	-1	13	13	-95	39	28	1	-4	228
	8 - " + Cu	16	-16	12	-2	-1	-106	58	28	3	9	250
	9 - " + Mn	29	-11	-4	17	-9	-107	54	16	7	8	262
	10 - Complete	19	-17	12	-1	-9	-98	54	32	4	3	249
GEORGIA	1 - Control	25	40	-38	30	68	-127	N.A.	51	-71	22	473
	2 - NP	45	39	-36	38	69	-130	N.A.	54	-97	18	525
	3 - NPB	47	36	-45	38	54	-152	N.A.	34	7	-18	431
	4 - NPK	42	30	-21	41	69	-147	N.A.	50	-78	12	490
	5 - NPKB	33	25	-18	24	39	-145	N.A.	36	14	-9	342
	6 - NPKBCaMgS	-1	-6	-45	30	47	-26	N.A.	31	-1	-29	218
	7 - " + Zn	-11	-17	-29	25	40	-15	N.A.	32	0	-25	195
	8 - " + Cu	11	-14	-42	28	42	-29	N.A.	29	-13	-13	220
	9 - " + Mn	-7	-17	-28	25	33	-14	N.A.	25	-1	-15	165
	10 - Complete	-10	-19	-31	30	43	-23	N.A.	40	-17	-13	227
SOUTH CAROLINA	1 - Control	-2	-3	4	-2	15	-67	25	10	13	-3	144
	2 - NP	2	8	2	11	16	-107	18	14	41	-32	251
	3 - NPB	0	0	-10	6	8	-121	17	0	109	-31	303
	4 - NPK	-3	0	42	-16	0	-110	37	25	17	-9	258
	5 - NPKB	-1	-8	66	-43	-17	-124	29	1	120	-43	454
	6 - NPKBCaMgS	0	4	42	-7	6	-95	22	11	73	-79	339
	7 - " + Zn	-1	-11	44	-40	-8	-112	19	25	73	-2	336
	8 - " + Cu	-1	-9	38	-12	-5	-95	16	16	47	-4	244
	9 - " + Mn	-13	-15	50	-136	-27	-107	218	2	84	-80	731
	10 - Complete	-11	-19	28	-38	-16	-138	117	19	61	-21	468

Appendix B - Individual Fascicle Mass

The first year response to fertilization in foliage mass may serve as a quick predictor of future volume response because strong correlations between the two have been found (FNC, 2005b). The current study only indicated that the SC site had individual fascicle mass significantly increased by fertilization. The significant increases at the SC site were seen in conjunction with K applications in treatments 4-10 (Fig. 16). No response was seen at the AL site but foliage mass was consistently higher than any other site possibly indicating ample nutrition. These results tend to confirm the fact that non-determinate species such as loblolly pine may produce more, rather than bigger needles in response to fertilization.

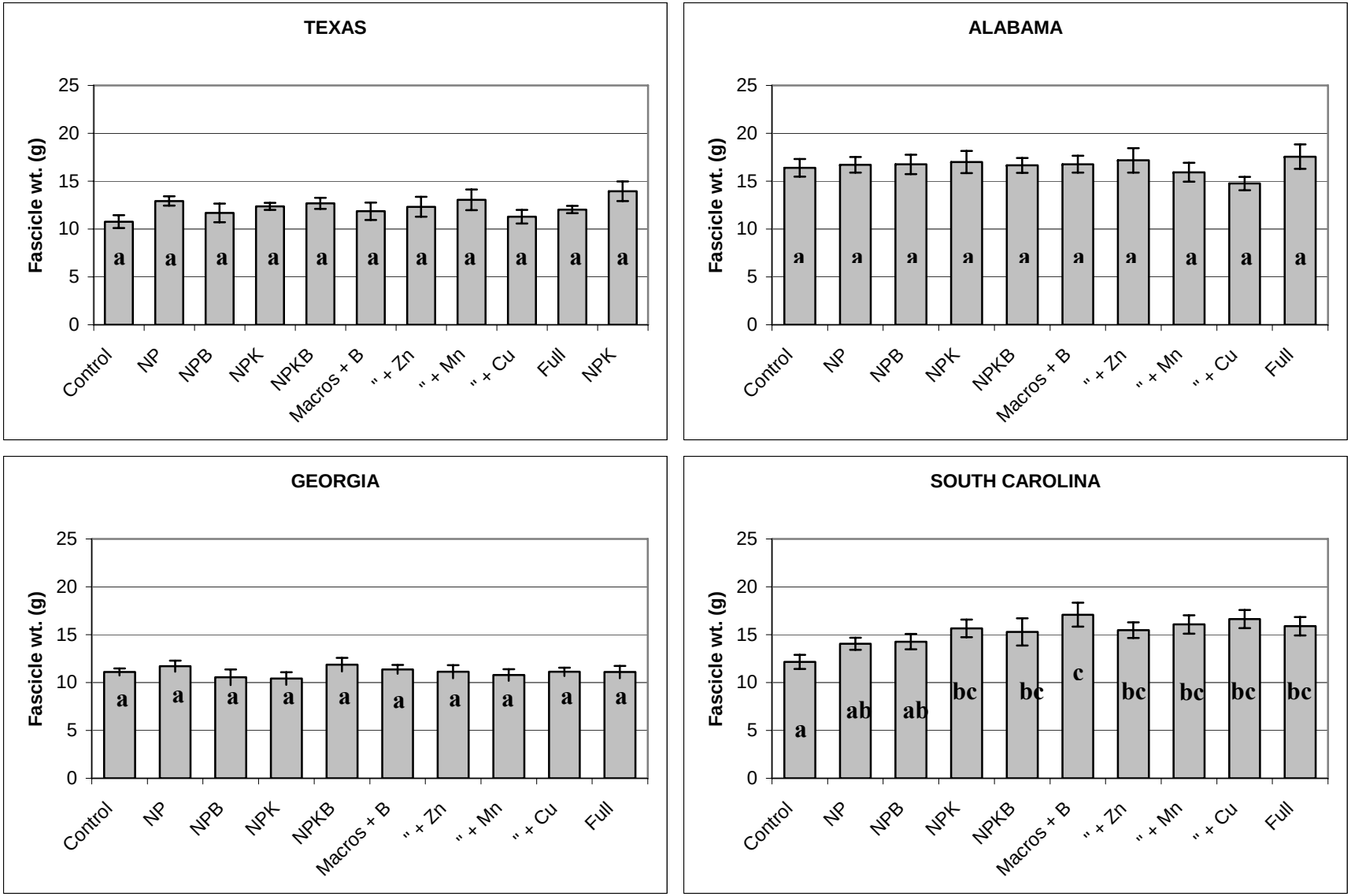

Figure 15: Weight of 100 individual fascicles from the 1st flush following fertilization. Error bars are standard errors. Bars with the same letter are not significantly different at P<0.05.

Appendix C - Vector Analysis – Individual Fascicle Mass

Vector analysis was utilized to bridge the gap between diagnosis and interpretation of nutrient status by integrating measures of concentration, content, and fascicle mass. Fertilization always created at least slight shifts in foliar nutrition from control levels, so a matrix was created to provide meaningful delineation between vector shifts and facilitate interpretation of individual treatment by element effects (Fig. 6). The intention to simplify the diagnosis of vector shifts without loosing site of meaningful changes in pine nutrition. To be interpreted as changed from control levels, a treatment must have had foliage mass, nutrient concentration, or nutrient content changed by at least 10% from control levels. Interpretation with the matrix allowed treatment by element effects to be categorized into 1 of 7 possible interpretations of nutritional shifts based on the generalizations of Timmer and Stone (1978). This preliminary diagnosis was followed by mean separation of nutrient concentration, nutrient content, and foliage mass to be used along with the interpretation matrix to provide further insight into truly significant shifts in nutrition from the control plot. Unfortunately, diagnosis in this manor was found to be harder to interpret due to the often unexpected and unfounded changes in the interpretation of individual treatment by element vectors without application. Graphical interpretation of elemental vectors averaged by application and non-application were sufficient to provide adequate diagnosis (Fig. 8-15).

Texas

Interpretation of vectors of N, P, and K revealed that these 3 elements were often deficient (Table 20). B and Mn were also indicated as deficient in many situations, but lack of foliage mass responses resulted in these elements being identified as increasing only due to luxury consumption in treatments 3 and 9 (Table 20). Mg was diluted in foliage of all treatments despite Mg applications in treatments 6-10 (Table 20). Treatment 10, the full treatment, indicated that all the applied elements except Mg were slightly deficient, and that foliage mass was increased from control levels by more than 10% (Fig. 17).

Alabama

No vectors indicating deficiency were interpreted at the AL site (Table 20). Dramatic uptake of B was consistently interpreted as luxury consumption due to the lack of any response in foliage weight (Table 20). Treatments 8 and 9 actually had foliage mass that was reduced below the level of the control resulting in antagonistic and toxic effects of P, K, Ca, Mg, S, Mn, Zn, B, and Cu (Table 20). Many of the effects of fertilization were so minor that resulting nutritional shifts could only be identified as unchanged. Zn and Cu were the exceptions in that all treatments regardless of whether they contained a Zn or Cu were interpreted as dilution or antagonism (Table 20). Treatment 10 displayed that B uptake was much greater than other nutrients but that fertilization was not responsible for a foliage weight increase (Fig. 17).

Georgia

Vectors of N, K, Ca, Mg, S, Zn and B were consistently identified as increasing due to luxury consumption (Table 20). P and Cu were especially unresponsive and applications resulted in no change from control levels in the majority of treatments (Table 20). Vectors of treatment 10 all indicate luxury consumption at the GA site. Nutrient concentration and content responses of S and B were of much greater magnitude than other elements (Fig. 17).

South Carolina

Consistent foliage mass increases and increased nutrient concentration produced statistically significant vectors indicating deficiencies of K in treatments 4-10 (Table 20). Vectors of N were also indicated as deficient in several treatments; however, N was also shown to be sufficient following K additions. P was not limiting and was shown to be consistently sufficient, independent of any fertilizer applications (Table 20). Dilution of Ca and Mg was indicated even following fertilizer additions in treatment s 6-10 (Table 20). Vectors of B were interpreted as significantly deficient in some treatments when it was applied with K (Table 20). Similarly, applications of Mn produced large increases in nutrient concentration and content that resulted in interpretation of statistically significant deficient vectors (Table 20), but the significant increase in foliage mass was more likely a

result of accompanying K fertilization. Treatment 10 indicated a large response in foliage mass and primary deficiencies of B, K, and Mn (Fig. 17).

Table 20: Vector shift interpretation of nutrition of individual fascicles. Bold and highlighted values indicate that shifts in foliar weight and nutrient concentration and content were significantly changed from controls in accordance to patterns of interpretation similar to those provided by Timmer and Stone (1978) (Table 2).

		N	P	K	Ca	Mg	S	Mn	Zn	B	Cu
TEXAS	1 - Control	CON	CON	CON	CON	CON	CON	CON	CON	CON	CON
	2 - NP	DEF	DEF	SUF	SUF	NONE	SUF	DEF	DIL	DEF	DIL
	3 - NPB	LUX	LUX	NONE	DEF	NONE	SUF	LUX	DIL	LUX	DIL
	4 - NPK	DEF	DEF	DEF	NONE	DIL	SUF	DEF	NONE	DEF	DIL
	5 - NPKB	DEF	DEF	DEF	SUF	DIL	SUF	DEF	SUF	DEF	DIL
	6 - NPKBCaMgS	DEF	DEF	DEF	DIL	DIL	DEF	DEF	SUF	DEF	NONE
	7 - " + Zn	SUF	DEF	DEF	SUF	DIL	DEF	DEF	NONE	DEF	SUF
	8 - " + Cu	DEF	DEF	DEF	SUF	DIL	SUF	DEF	SUF	DEF	SUF
	9 - " + Mn	SUF	LUX	LUX	SUF	DIL	LUX	LUX	NONE	LUX	NONE
	10 – Complete	DEF	DEF	DEF	DEF	DIL	DEF	DEF	SUF	DEF	DEF
	11 – NPK	DEF	DEF	DEF	DEF	DIL	SUF	DEF	SUF	SUF	DIL
ALABAMA	1 – Control	CON	CON	CON	CON	CON	CON	CON	CON	CON	CON
	2 – NP	NONE	NONE	NONE	NONE	NONE	DIL	DIL	DIL	NONE	DIL
	3 – NPB	NONE	NONE	NONE	NONE	DIL	NONE	NONE	NONE	LUX	DIL
	4 – NPK	NONE	NONE	NONE	NONE	NONE	DIL	NONE	DIL	LUX	DIL
	5 – NPKB	NONE	NONE	LUX	NONE	DIL	DIL	DIL	DIL	LUX	DIL
	6 – NPKBCaMgS	NONE	NONE	NONE	DIL	NONE	NONE	NONE	DIL	LUX	DIL
	7 - " + Zn	SUF	NONE	SUF	NONE	LUX	LUX	SUF	NONE	LUX	DIL
	8 - " + Cu	NONE	ANT	LUX	ANT	ANT	NONE	ANT	ANT	LUX	ANT
	9 - " + Mn	NONE	ANT	ANT	NONE	ANT	ANT	ANT	ANT	TOX	ANT
	10 – Complete	NONE	DIL	LUX	DIL	DIL	NONE	SUF	NONE	LUX	DIL
GEORGIA	1 – Control	CON	CON	CON	CON	CON	CON	CON	CON	CON	CON
	2 – NP	LUX	LUX	LUX	LUX	SUF	SUF	LUX	LUX	DIL	SUF
	3 – NPB	LUX	NONE	NONE	LUX	LUX	NONE	NONE	NONE	LUX	ANT
	4 – NPK	LUX	NONE	LUX	LUX	LUX	NONE	LUX	LUX	NONE	NONE
	5 – NPKB	LUX	SUF	LUX	LUX	NONE	SUF	SUF	SUF	LUX	NONE
	6 – NPKBCaMgS	LUX	SUF	LUX	LUX	LUX	LUX	LUX	LUX	LUX	NONE
	7 - " + Zn	LUX	NONE	LUX	LUX	LUX	LUX	LUX	LUX	LUX	ANT
	8 - " + Cu	LUX	NONE	LUX	LUX	NONE	LUX	LUX	LUX	LUX	ANT
	9 - " + Mn	LUX	NONE	LUX	LUX	LUX	LUX	LUX	NONE	LUX	NONE
	10 – Complete	LUX	NONE	LUX	LUX	NONE	LUX	LUX	LUX	LUX	NONE
SOUTH CAROLINA	1 – Control	CON	CON	CON	CON	CON	CON	CON	CON	CON	CON
	2 – NP	DEF	SUF	NONE	SUF	DIL	DIL	DIL	DIL	DEF	DIL
	3 – NPB	DEF	SUF	DIL	SUF	DIL	DIL	DIL	DIL	DEF	DIL
	4 – NPK	SUF	SUF	DEF	DIL	DIL	DIL	DEF	SUF	SUF	DIL
	5 – NPKB	SUF	SUF	DEF	DIL	DIL	DIL	DIL	DIL	DEF	DIL
	6 – NPKBCaMgS	DEF	SUF	DEF	DIL	DIL	DIL	DIL	SUF	DEF	DIL
	7 - " + Zn	DEF	SUF	DEF	DIL	DIL	DIL	DIL	DEF	DEF	SUF
	8 - " + Cu	SUF	SUF	DEF	DIL	DIL	SUF	DIL	DEF	DEF	SUF
	9 - " + Mn	SUF	SUF	DEF	DIL	DIL	SUF	DEF	SUF	DEF	DIL
	10 - Complete	SUF	SUF	DEF	DIL	DIL	DIL	DEF	DEF	DEF	DIL

CON, control; SUF, sufficiency; DEF, deficiency; LUX, luxury consumption; TOX, toxicity; ANT; antagonism; DIL, dilution; NONE, no response.

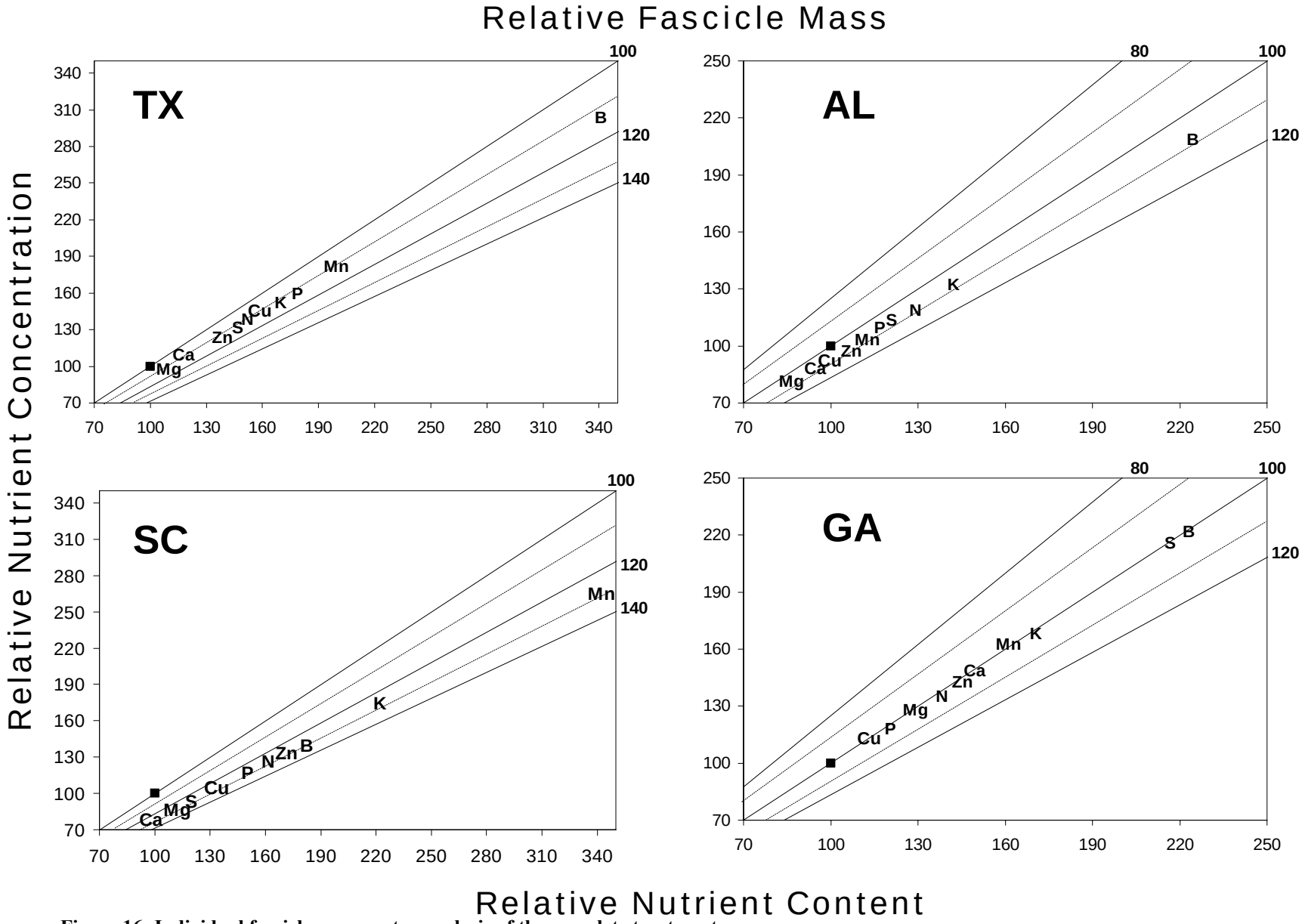

Figure 16: Individual fascicle mass vector analysis of the complete treatment.

Appendix D – Total Branch Mass and Area

Measures of projected leaf area have been successful in diagnosing nutrient deficiencies in loblolly pine (Allen et. al. 2001). Supplying deficient nutrients has proven to increase leaf area index (LAI) (Albaugh et. al., 1998), and a LAI of 3.5 has been established as representative of stands with adequate nutrient supply (Fox et. al., 2006). Cost and complications associated with the measure of LAI have lead to the investigation of using fascicle mass as a surrogate of LAI, and resulting positive responses of fascicle mass have been correlated with long term volume responses (FNC, 2005b). However, the indeterminate growth habit of loblolly pine has cast doubt on the reliability of using individual fascicle mass as a predictive measure. An individual loblolly pine tree may respond to fertilization by producing more and not necessarily bigger foliage. Mass of all current year flushes on a single branch was measured in a subset of the treatments. Foliage area of each flush was calculated using equations developed by Murthy and Dougherty (1997b).

It is shown here that branch foliar mass was significantly affected ($P<0.05$) at 2 sites (Fig. 18) while branch foliar area was significantly affected at only 1 site (Fig. 19). Foliage mass was at the GA site was slightly affected by K and B, but the combined effects of S, Ca, and Mg applications created truly significant effects (Fig. 18). K and B applications were primarily responsible for the foliage mass increases at the SC site, with further elemental applications not creating any further increases (Fig. 18). Branch foliage area was increased over control levels by the combined effects of an application of macronutrients and B in treatment 6 (Fig. 19). The full treatment, including all of the micronutrients did not create further foliage area gains.

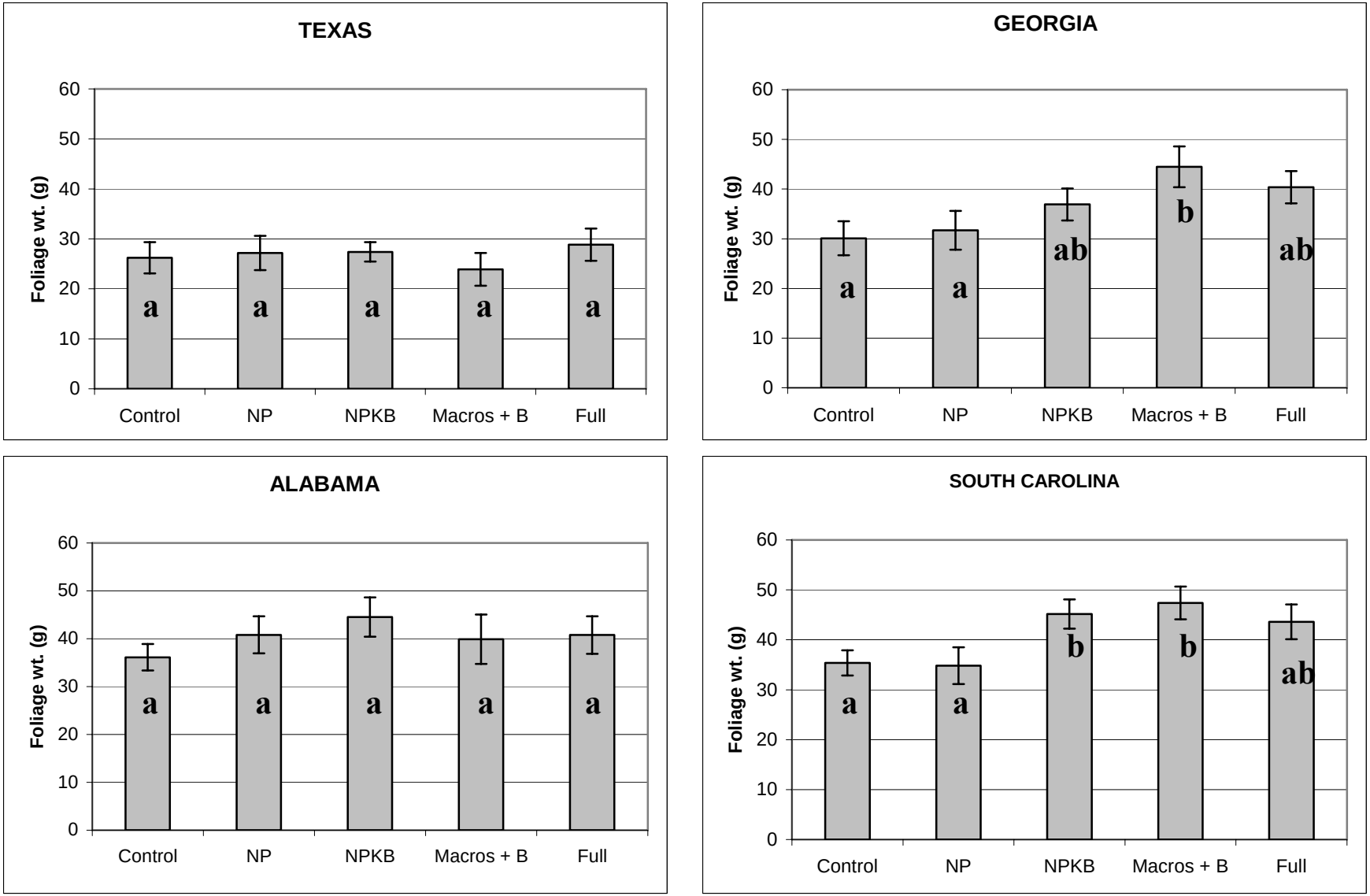

Figure 17: Weight of entire current year of foliage following fertilization. Error bars are standard errors. Bars with the same letter are not significantly different at P<0.05.

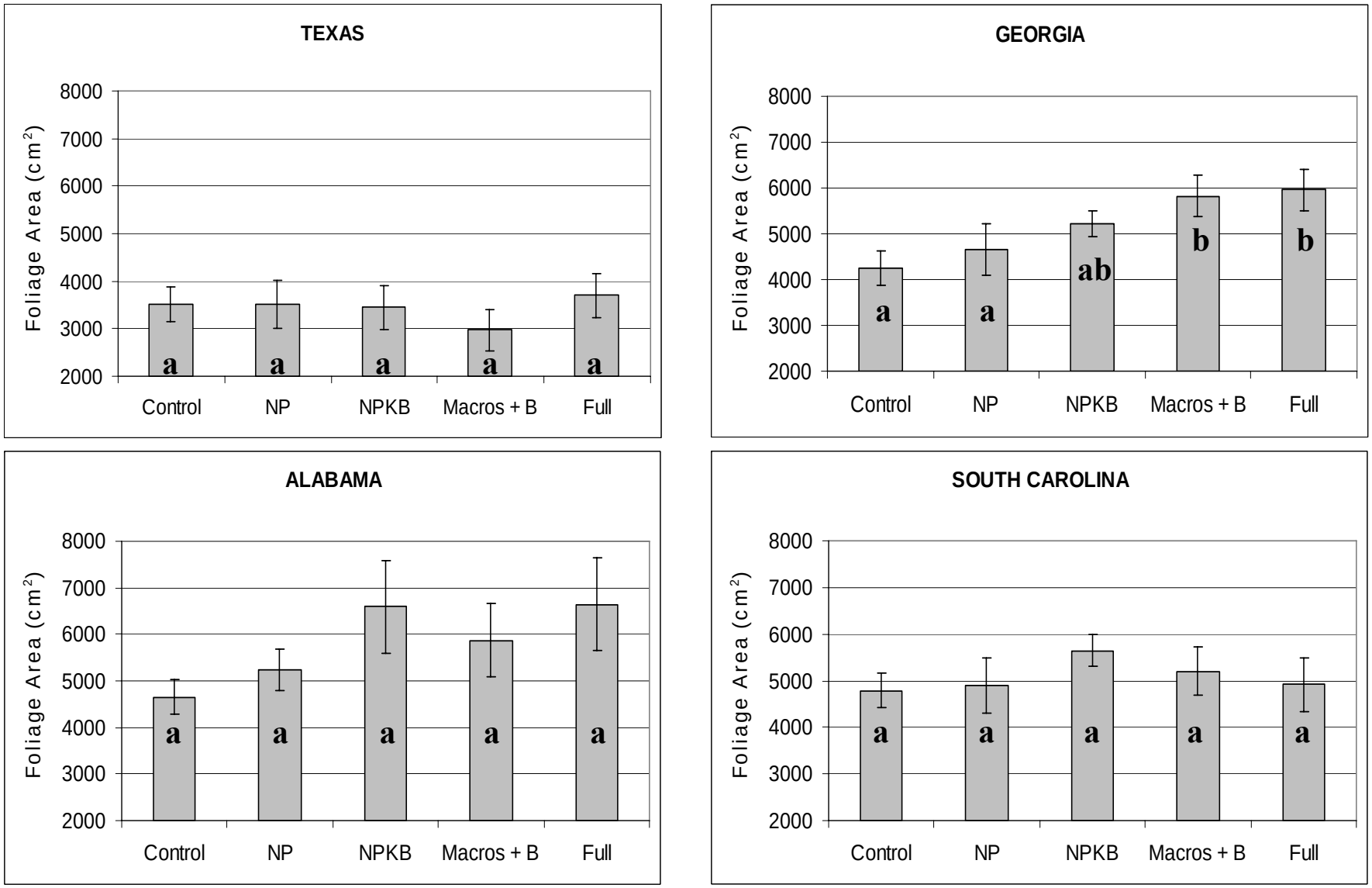

Figure 18: Area of entire current year of foliage following fertilization. Error bars are standard errors. Bars with the same letter are not significantly different at P<0.05.

Appendix E - Vector Analysis – Branch Foliage mass

Vector analysis with branch mass as the associated biomass production variable may reduce problems with vector analysis in non-determinate species such as loblolly pine. Interpretation of vector diagrams produced from concentration, content, and foliage mass data representing the entire growing season following fertilization may better characterize loblolly pine's responses to fertilization. In the current study, foliar concentrations and contents were significantly altered at all sites while individual fascicle mass was only increased at 1 site. Branch foliage mass was significantly increased at 2 sites and increased by more than 20% at 3 sites, and therefore may be a better predictive tool. Vector diagrams were interpreted by overlaying a matrix with distinct breaks separating different vector shifts into 1 of 7 possible interpretations based on the procedure outlined by Timmer and Stone (1978) (Table 2). Mean separation of total branch foliage mass and nutrient concentration and content in statistically significant treatments further identified truly identifiable shifts in foliar nutrition from those that were only shifted slightly.

Texas

Treatments 2, 5, and 6 resulted in little branch foliage mass gain and subsequently identified nutritional shifts of many elements as increasing due to luxury consumption (Table 23). Treatment 10 (complete) had branch foliage mass, concentration, and branch foliage content increased sufficiently to identify deficiencies of N, P, K, Ca, S, Mn, B, and Cu (Table 21). A reduction in foliage mass from control levels in treatment 6 resulted in antagonistic and toxic effects of Ca, Mg, and Cu (Table 21). The vector diagram of treatment 10 indicated that B and Mn uptake was of a much greater magnitude than other elements including P which was identified as deficient by other methods (Fig. 18).

Alabama

Vector diagrams of treatments 5 and 10 at the AL site identified deficiencies of B and K (Table 21). N was found to be consistently sufficient across all treatments while the other macronutrients, P, Ca, Mg, and S, were often found to be unchanged or only slightly diluted. Cu was consistently diluted despite application in treatment 10. By far, the

vector of B had the greatest magnitude in treatment 10 indicating a greater deficiency as compared to other elements (Fig. 18).

Georgia

Vector analysis utilizing branch foliage mass resulted in the interpretation of statistically significant deficiencies of N, K, Ca, S, and B where these elements were all applied together in treatments 6 and 10 (Table 21). Uptake of N and P in treatment 2 without the other associated deficient nutrients resulted only in luxury consumption. Cu was consistently found sufficient regardless of application (Table 21). Vectors of treatment 10 indicated that deficiencies of S and B had the greatest magnitude, but that many elements also had associated substantial deficiencies (Fig. 18).

South Carolina

Vector analysis with branch foliage mass variables indicated statistically significant deficiencies of N, K, and B when they were applied together (Table 21). Vectors of N were affected by K applications in treatment 6 as N vectors were changed from displaying luxury consumption to a deficiency following K application. Vectors of Ca, Mg, S, and Cu were diluted in the treatments with K and B due to resulting branch foliage mass increases (Table 21). Vectors of P additions were consistently identified as sufficient (Fig. 18). The magnitude of the vector of Mn in treatment 10 indicated that it was the most deficient element at the SC site (Fig. 18).

Table 21: Vector shift interpretation of nutrition of the entire amount of current year foliage. Bold and highlighted values indicate that shifts in foliar weight and nutrient concentration and content were significantly changed from controls in accordance to patterns of interpretation similar to those provided by Timmer and Stone (1978) (Table 2).

		N	P	K	Ca	Mg	S	Mn	Zn	B	Cu
TEXAS	1	CON	CON	CON	CON	CON	CON	CON	CON	CON	CON
	2	LUX	LUX	NONE	SUF	NONE	NONE	LUX	DIL	LUX	DIL
	5	LUX	LUX	LUX	NONE	DIL	SUF	LUX	NONE	LUX	DIL
	6	LUX	LUX	LUX	ANT	ANT	LUX	LUX	NONE	LUX	ANT
	10	DEF	DEF	DEF	DEF	DIL	DEF	DEF	SUF	DEF	DEF
ALABAMA	1	CON	CON	CON	CON	CON	CON	CON	CON	CON	CON
	2	SUF	NONE	NONE	NONE	SUF	DIL	DIL	DIL	SUF	DIL
	5	SUF	SUF	DEF	DIL	DIL	DIL	SUF	DIL	DEF	DIL
	6	SUF	NONE	SUF	NONE	NONE	NONE	DIL	DIL	DEF	DIL
	10	SUF	DIL	DEF	DIL	DIL	SUF	SUF	NONE	DEF	DIL
GEORGIA	1	CON	CON	CON	CON	CON	CON	CON	CON	CON	CON
	2	LUX	LUX	LUX	LUX	SUF	SUF	LUX	LUX	DIL	SUF
	5	DEF	SUF	DEF	DEF	SUF	SUF	SUF	SUF	DEF	SUF
	6	DEF	SUF	DEF	DEF	DEF	DEF	DEF	DEF	DEF	SUF
	10	DEF	SUF	DEF	DEF	DEF	DEF	DEF	DEF	DEF	SUF
SOUTH CAROLINA	1	CON	CON	CON	CON	CON	CON	CON	CON	CON	CON
	2	LUX	NONE	NONE	NONE	ANT	ANT	ANT	ANT	LUX	ANT
	5	SUF	SUF	DEF	DIL	DIL	DIL	DIL	DIL	DEF	DIL
	6	DEF	SUF	DEF	DIL	DIL	DIL	DIL	SUF	DEF	DIL
	10	SUF	SUF	DEF	DIL	DIL	DIL	DEF	DEF	DEF	DIL

CON, control; SUF, sufficiency; DEF, deficiency; LUX, luxury consumption; TOX, toxicity; ANT; antagonism; DIL, dilution; NONE, no response

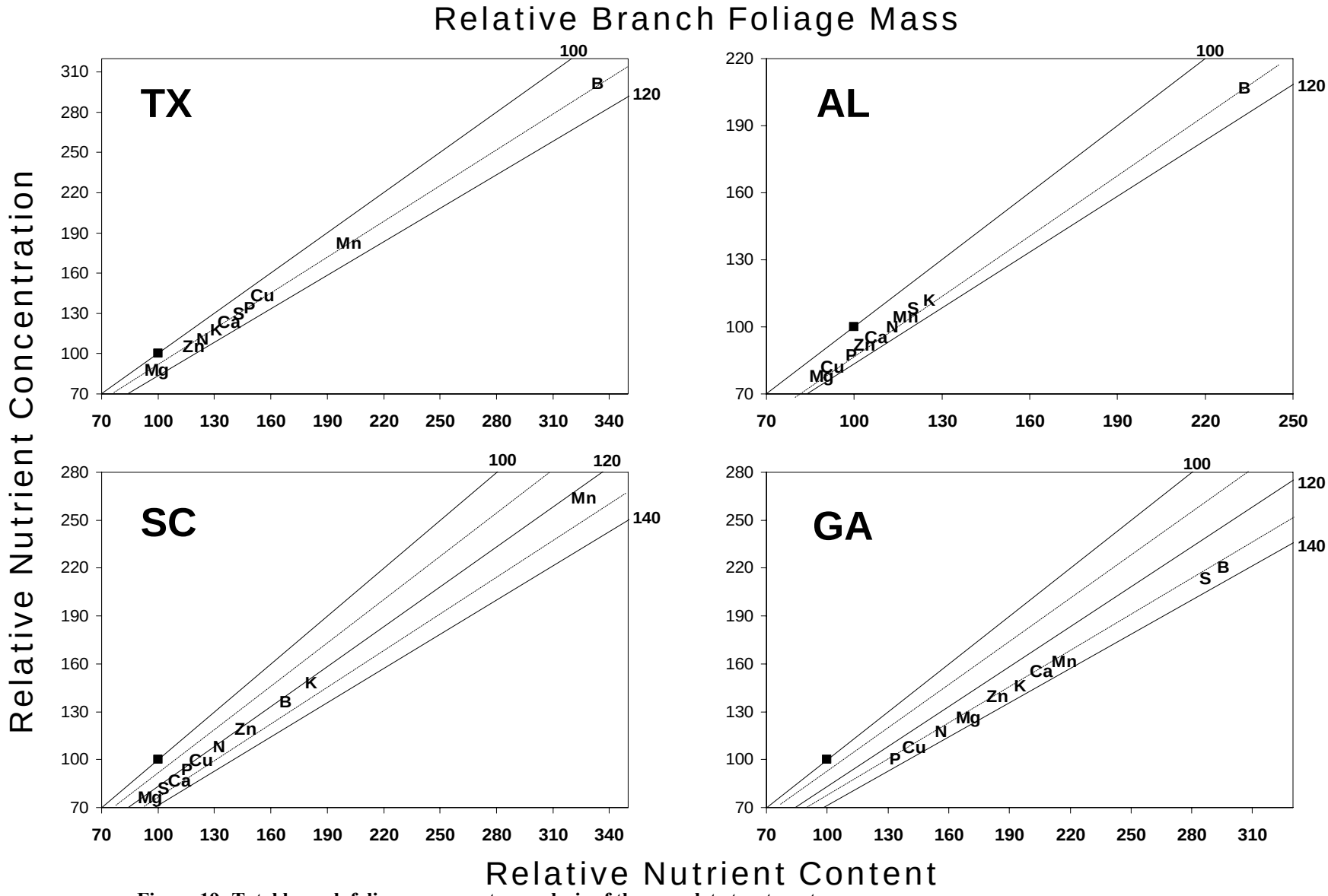

Figure 19: Total branch foliage mass vector analysis of the complete treatment.