Characterization of Foliar Macro- and Micronutrient Concentrations and Ratios in Loblolly Pine Plantations in the Southeastern United States

Janine M. Albaugh, Leandra Blevins, H. Lee Allen, Timothy J. Albaugh, Thomas R. Fox, José L. Stape, and Rafael A. Rubilar

ABSTRACT

Foliar nutrient concentration data collected from pretreatment foliage samples in regional trials extending across the southeastern United States provided a large data set useful for characterizing baseline loblolly pine nutrition for the native range of this species. The range and distribution of the foliar nutrient concentrations and their ratios to nitrogen (N) were characterized using descriptive statistics and frequency distributions. Data were collected from a total of 2,663 measurement plots from 110 studies. Manganese (Mn) was the most variable element (coefficient of variation [CV] = 52%), and N exhibited the least variability (CV = 11%). Nitrogen, phosphorus (P), potassium (K), magnesium (Mg), sulfur (S), copper (Cu), and the ratios P:N, K:N, calcium (Ca):N, Mg:N, S:N, and zinc (Zn):N were normally distributed. Calcium, Mn, Zn, boron (B), and the ratios Mn:N, B:N, and Cu:N were significantly non-normal, with positively skewed distributions. Baseline N, P, and S concentrations and the P:N and S:N ratios were considered potentially limiting to growth, as only the upper quartile of studies achieved the currently accepted adequate values for loblolly pine. Boron could be interpreted as being in sufficient supply or potentially limiting to growth, depending on the adequate value used for comparison. The remaining elements and their ratios to N were within the range of sufficiency reported for other conifers. Target concentrations for S and B and their ratios to N require further investigation, as the recommended values for loblolly pine may be too high.

Keywords: *Pinus taeda,* foliar nutrient concentrations, nutrient ratios

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Studies on pine species in the southeastern United States have shown that leaf area and consequently wood production are below potential levels (Fox et al. 2006), with low nutrient availability being the primary cause (e.g., Vose and Allen 1988, Colbert et al. 1990, Albaugh et al. 1998). Nitrogen (N) and phosphorus (P) are the nutrients most commonly limiting the growth of loblolly (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.) plantations in the South (Fox et al. 2007). Favorable biological and economic responses to nutrient additions displayed in these stands have led to extensive operational fertilization in the southeastern United States (Colbert and Allen 1996), with over 6.5 million ha of pine forests fertilized from 1969 to 2004 (Albaugh et al. 2007). Over the period 1999–2004, fertilizer was applied to more than 500,000 ha of southern pine plantations on an annual basis (Albaugh et al. 2007). Cost-effective fertilizer application requires accurate identification of stands that will respond to additional nutrients (Colbert and Allen 1996). Given the recent high and fluctuating fertilizer prices (Albaugh et al. 2007), information that can be used to correctly identify sites likely to respond to additional nutrients would enable forest managers to prioritize fertilizer applications, thereby targeting stands likely to generate large biological responses, potentially yielding substantial economic returns (Albaugh et al. 2009).

Foliar analysis has traditionally been used to assess the nutrient status of forest stands (Adams and Allen 1985). Foliage tests provide an integrated index of soil nutrient supply and stand demand (Ulrich and Hills 1967, Richards and Bevege 1972, Needham et al. 1990, Jokela et al. 1991), and as such are based on the concept that the tree, not the soil, may be the best indicator of soil nutrient availability (Brockley 2001a). This technique can be used as a diagnostic tool to identify stands requiring fertilization (Leaf 1973, Wells and Allen 1985, Will 1985, Hockman and Allen 1990) or as a predictive tool to estimate the response to nutrient additions (Wells et al. 1973, van den Driessche 1974, Brockley 2000).

The use of foliar analysis to diagnose the nutrient status of forest trees is well documented. When objectives are clearly defined (Lambert 1984) and analyses are correctly interpreted, this technique has proved to be a reliable method that is used extensively in many parts of the world, for example, Sweden (Linder 1995), Australia (Lambert 1984, Turner and Lambert 1986, Judd et al. 1996), New Zealand (Will 1978, 1985), Canada (Timmer and Stone 1978, Brockley 2001a), South Africa (Schönau 1983, Herbert 1996, Campion and Scholes 2007), and the United States (Wells et al. 1973, Wells and Allen 1985, Hockman and Allen 1990).

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This article uses metric units; the applicable conversion factors are: millimeter (mm): 1 mm = 0.039 in.; centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; cubic meters (m^3): 1 m^3 = 35.3 ft^3; hectares (ha): 1 ha = 2.47 ac; milligram (mg): 1 mg = 0.015 grain; kilograms (kg): 1 kg = 2.2 lb.

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Foliar analysis information can be used to monitor postfertilization uptake of applied nutrients (Richards and Bevege 1972, Will 1985) and foliar nutrient balance (Brockley 2001a). The use of nutrient ratios has shown promise in identifying deficient sites (Comerford and Fisher 1984, Hockman and Allen 1990, Valentine and Allen 1990) and in gaining a better understanding of response to fertilization (Schönau 1982, Schönau and Herbert 1983, Adams and Allen 1985). It is common to express nutrient concentrations in terms of ratios, as overall maximum yield is achieved with an optimum concentration and balance of all nutrients (van den Driessche 1974). According to Marschner (1986), nutrient ratios may be especially important if one or both of the elements are near deficiency levels. Linder (1995) used an optimum ratio approach to detect and correct nutrient imbalances and maintain optimal nutrient status in Norway spruce (*Picea abies* L. Karst.) trees in Sweden. Linder (1995) defined an optimal N status in the foliage and then set target values for each nutrient element relative to N on the basis of results obtained from laboratory studies and long-term forest nutrition experiments, in which plant nutrient requirements were established. According to foliar analysis and predicted growth response, the quantities of nutrients to be applied were estimated in relation to the target value (Linder 1995).

Loblolly pine is the leading timber species in the United States, predominating on more than 13.4 million ha of southern forestland and accounting for half the total volume of southern pine growing stock (Schultz 1997). Borders and Bailey (2001) present results showing that intensive management practices using improved genetic stock, mechanical site preparation, complete control of competing vegetation, and annual fertilization can increase the productivity of loblolly pine in the southeastern United States two to four times more than conventional plantation silviculture, enabling growth rates comparable to other parts of the world. However, intensive management practices, coupled with rapid growth rates and increased nutrient demand, may induce multiple nutrient limitations, particularly during the early stages of stand development (Jokela et al. 1991, Jokela 2004). Consequently, fertilization with multiple elements may be needed in southern pine stands, and Jokela (2004) suggested that further research on nutrient balance, especially for elements other than N and P, will be required to support management applications. Despite the importance of this species, a lack of nutrient concentration data exists in the literature. It is important to monitor the foliar nutrient status of this widely planted species and to have baseline (pretreatment) information on the range of nutrient concentrations found in loblolly pine plantations throughout the native species range. This baseline information is a necessary requirement to evaluate the nutrient status of loblolly pine, and it will provide value to both forest managers and the scientific community. In addition to their use in monitoring the effectiveness of fertilizer applications by assessing postfertilization uptake of applied nutrients and nutrient balance, baseline foliar values can serve as a basis for comparison to determine the effects of silvicultural practices that have the potential to manipulate nutrient resource availability, for example, vegetation control, thinning operations, and prescribed burning.

A series of region-wide trials was established by the Forest Nutrition Cooperative (FNC), previously known as the North Carolina State Forest Nutrition Cooperative, over the period 1984 to 2009. These trials cover the range of soil, site, and stand conditions for loblolly pine found in the southeastern United States. The region-wide studies were established to address a broad range of research objectives, focused mainly on resource manipulation, including determining the response of loblolly pine plantations to fertilization and/or vegetation control, identifying optimal rates and frequencies of nutrient application, and managing density to optimize value in fertilized stands. These trials provided a unique opportunity to establish an extensive database of foliar nutrient concentrations representative of loblolly pine plantations in the southeastern United States.

The specific objectives of this analysis were as follows:

1. To compile a comprehensive data set of baseline foliar macronutrient (N, P, potassium [K], calcium [Ca], magnesium [Mg], and sulfur [S]) and micronutrient (manganese [Mn], zinc [Zn], boron [B], and copper [Cu]) concentrations from studies across the planted region of loblolly pine in the southeastern United States,
2. To characterize the range and distribution of these foliar nutrient concentrations and their ratios to N using descriptive statistics and frequency distributions, and
3. To compare the foliar nutrient concentrations and their ratios to N with currently accepted adequate levels for loblolly pine.

Materials and Methods

Study Site Location and Description

Data were obtained from studies installed in loblolly pine plantations across the southeastern United States (Figure 1). These studies include six region-wide trial series established from 1984 to 2009 over a range of soil and site types and climatic conditions. The data presented in this article were collected from all plots at the time of study establishment, immediately prior to treatment application.

The study locations were distributed across the southern United States in 11 physiographic regions spanning 11 states, extending from Florida to Tennessee, northward to Virginia, and west to Texas. The study site locations were concentrated in Alabama and Georgia, followed by North and South Carolina; consequently, most of the studies were located on the Upper Gulf Coastal Plain, followed by the Lower Atlantic Coastal Plain and the Piedmont. A total of 69 soil series, ranging from very poorly to excessively drained, were represented. The majority of the studies were on well-drained soils, located mainly on the Upper Gulf Coastal Plain and Piedmont. Poorly drained sites were located in the Lower Atlantic Coastal Plain, and excessively drained sites were those established on the Sandhills of North and South Carolina.

Data Collection

Plot Selection

The studies included in the foliar nutrient database are representative of a range of operational conditions: A range of genetic material was used, from first-generation improved seedlings and beyond. All stands were site-prepared and received competing vegetation control. In some studies, fertilizer (mainly P, at a rate of 50 kg ha^{-1}) was applied at planting, and the data presented were obtained from both thinned and unthinned stands.

Data were collected from a total of 2,663 measurement plots from 110 study sites. The number of measurement plots across the studies ranged from 8 to 64, with plots containing between 16 and 186 measured trees. Plot size ranged from 0.02 to 0.14 ha, with an average of 0.04 ha. Diameter at breast height (dbh) and total height (H) were measured on all trees in each plot during the dormant season immediately prior to treatment. Site index at base age 25

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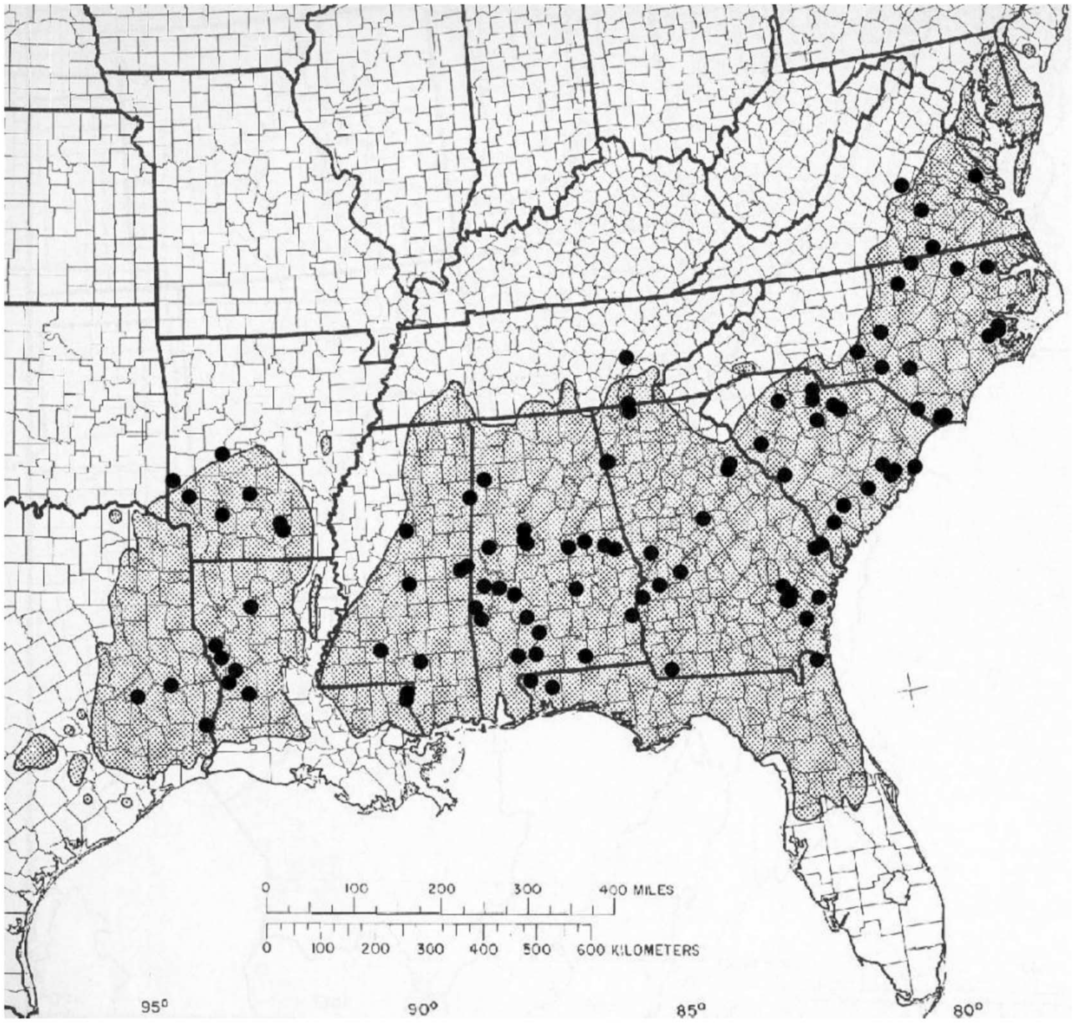

Figure 1. Locations of the study sites, with shaded areas representing the natural range of loblolly pine.

Table 1. Summary of the initial stand characteristics at the time of installation for studies included in the foliar nutrient database.

Stand characteristic	Average	Minimum	Maximum	Number of studies	Standard error
Age (years)	11	2	25	110	0.48
Stand density (stems ha^{-1})	1,261	312	2,246	110	40.99
Diameter at breast height (cm)	13.0	0.9	22.2	108	0.51
Height (m)	9.7	1.4	18.3	110	0.41
Site $index_{25}$ (m)	18.9	6.3	25.9	110	0.35
Basal area (m^2 ha^{-1})	16.7	0.1	32.4	108	0.80
Volume (m^3 ha^{-1})	97.2	6.4	244.2	108	5.30

years was calculated using the Clutter and Lenhart (1968) equation. Individual tree volumes (V) were calculated using the Shelton et al. (1984) equation for total outside bark volume ($V = 0.00748 + 0.0000353 \times dbh^2H$). Individual tree basal areas and volumes were summed on a per-plot basis to provide stand-level estimates.

Initial Stand Characteristics

Initial stand characteristics for all trials, where collected at the time of study installation, are summarized in Table 1. Descriptive site characteristics for individual studies, including geographic location, physiographic region, planting date and stand age at time of study establishment, soil series, and drainage class, are included in the Appendix.

Stand age ranged from 2 to 25 years, with the majority of the studies installed in midrotation plantations. Tree density ranged from 312 stems per hectare in thinned stands to 2,246 stems per hectare in unthinned stands. The average diameter and height values were 13.0 cm and 9.7 m, respectively. The selected studies exhibited site indices ranging from 6 to 26 m at age 25 years, with stand basal areas and volumes of 16.7 m^2 ha^{-1} and 97.2 m^3 ha^{-1}, respectively (Table 1).

Foliar Sampling and Nutrient Concentration Determinations

Foliar nutrient concentration values are based on samples collected prior to treatment, at the time of study establishment. Foliage samples were collected during the dormant season from December

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Table 2. Nutrient concentration determination methodology for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), manganese (Mn), zinc (Zn), copper (Cu), and boron (B) for foliage samples collected from 1984 to 2009.[a]

Element(s)	Year samples collected	Digestion procedure	Reagents	Determination procedure	References
N, P	1984–1985	Wet digestion	Sulfuric acid + hydrogen peroxide	Colorimetric (Technicon AutoAnalyzer)	Parkinson and Allen (1975), Forest Research Institute (1984)
N, P	1986–1996	Wet digestion	Sulfuric acid + hydrogen peroxide	Colorimetric (LaChat QuikChem FIA; LaChat Instruments)	Parkinson and Allen (1975), Forest Research Institute (1984)
N	1997	Wet digestion	Sulfuric acid + hydrogen peroxide	Colorimetric (LaChat QuikChem FIA; LaChat Instruments)	Parkinson and Allen (1975), Forest Research Institute (1984)
N	1998–2009	N/A	N/A	CHN Elemental Analyzer (CE Instruments NC 2100 Soil Analyzer)	CE Instruments (1997)
P	1997–2009	Wet digestion	Nitric acid	ICP (Varian Liberty II ICP-AES)	Huang and Schulte (1985)
K, Ca, Mg	1984–1996	Wet digestion	Sulfuric acid + hydrogen peroxide	AA (Perkin-Elmer 560 Spectrophotometer)	Perkin-Elmer (1976)
K, Ca, Mg	1997–2009	Wet digestion	Nitric acid	ICP (Varian Liberty II ICP-AES)	Huang and Schulte (1985)
S	1990–1996	Wet digestion	Nitric acid	ICP (Perkin-Elmer Corp.)	Perkin-Elmer (1976)
S	1997–2009	Wet digestion	Nitric acid	ICP (Varian Liberty II ICP-AES)	Huang and Schulte (1985)
Mn, Zn, Cu	1990–1996	Dry ash (500°C, 10 hours)	6N HCl	ICP (Perkin-Elmer Corp.)	Perkin-Elmer (1976)
Mn, Zn, Cu	1997–2009	Wet digestion	Nitric acid	ICP (Varian Liberty II ICP-AES)	Huang and Schulte (1985)
B	1990–1996	Wet digestion	Nitric acid	ICP (Perkin-Elmer Corp.)	Perkin-Elmer (1976)
B	1997–2009	Wet digestion	Nitric acid	ICP (Varian Liberty II ICP-AES)	Huang and Schulte (1985)

[a] FIA, flow injection analyzer; N/A, not applicable; CHN, carbon, hydrogen, nitrogen; ICP, inductively coupled argon plasma emission spectrometry; AA, atomic absorption.

to February. Twenty fascicles from the first flush of the most recent growing season were collected from the terminal of a primary lateral branch in the upper one-third of the live crown on each of five dominant or codominant trees per measurement plot. Individual samples were combined by plot, oven-dried to a constant weight at 65–70°C, ground to pass through a 1.0-mm screen, digested, and analyzed for nutrient concentration. Foliar samples were not routinely analyzed for S and micronutrient concentrations, i.e., of the 110 studies, foliar S, Cu, and the remaining micronutrients (Mn, Zn, and B) were determined for 44, 47, and 48 studies, respectively, whereas macronutrient (N, P, K, Ca, and Mg) concentrations were analyzed for all studies (see Table 1, column "Number of samples"). The methodology used to determine foliar nutrient concentrations is outlined in Table 2.

Statistical Analysis

All statistical analyses were performed on mean site values, i.e., parameters were averaged across all plots within a study. Descriptive statistics and frequency distributions were developed to characterize the range and distribution of foliar nutrient concentrations and their ratios to N. All statistical analyses and plotting of frequency histograms were performed using the Univariate procedure (proc. Univariate; SAS 2000). This procedure uses the Shapiro-Wilk *W* statistic to test for normality and reports measures of skewness and kurtosis that can also be used to determine whether data are normally distributed. Statistical significance was defined as $\alpha \leq 0.05$. Skewness provides a measure of the asymmetry of a distribution around its mean. A symmetrical distribution, such as the normal curve, has a skewness of zero (SAS 2009). Kurtosis is a measure of whether data are peaked or flat relative to a normal distribution. A normal distribution has a kurtosis of zero. Positive kurtosis indicates a distribution that is more peaked than the normal curve, whereas negative kurtosis demonstrates a flatter distribution than the normal curve (SAS 2009). Quantile values were calculated for the foliar nutrients and their ratios to N, and these values were used to classify the number of studies with low or adequate nutrition on the basis of currently accepted foliar guidelines.

Results

Macronutrient Concentrations and Ratios to N

Foliar N, S, and the S:N ratio were the least variable (coefficient of variation [CV] ≤ 12%), compared with Ca and the Ca:N ratio, which exhibited the highest variability (CV > 22%; Table 3). The macronutrient ranking from most to least variable was Ca > K > Mg > P > S > N, and for ratios was Ca:N > Mg:N > K:N > P:N > S:N. The frequency distributions for N, P, K, Mg, S, and the ratios P:N, K:N, Ca:N, Mg:N, and S:N were normally distributed (Figures 2 and 3). Foliar Ca was positively skewed (skewness = 0.57; Shapiro-Wilk statistic $W = 0.97$; $P = 0.01$) and peaked (kurtosis = 1.36) relative to the normal curve (Table 3, Figure 2).

Micronutrient Concentrations and Ratios to N

The most variable micronutrient was Mn (CV = 52%), followed by B (CV = 40%), Zn (CV = 22%), and Cu (CV = 20%; Table 3). The ranking for micronutrient ratio variability followed the same order, i.e., Mn:N > B:N > Zn:N > Cu:N.

Foliar Mn, Zn, and B and ratios Mn:N, B:N and Cu:N were not normally distributed, being positively skewed and more peaked than the normal curve (Figures 4 and 5). In particular, B and the B:N ratio were the most asymmetrical and peaked of all the distributions, demonstrated by the highest levels of skewness (2.72 and 2.41 for B and B:N, respectively) and kurtosis (9.64 and 6.81 for B and B:N, respectively; Table 3). The long right tails in the frequency distributions for these elements and ratios reflect this strong skewness and were due to a small number of studies with high values (Figures 4 and 5). Foliar Zn also exhibited a distribution more peaked than the normal curve with a relatively high kurtosis value of 2.55 (Table 3).

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Table 3. Descriptive statistics and Shapiro-Wilk test for normality for foliar nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), manganese (Mn), zinc (Zn), boron (B), and copper (Cu) concentrations and their ratios to N averaged across all study sites. CV, coefficient of variation.

						Shapiro-Wilk test		
Nutrient element or ratio to N	Mean	Standard deviation	CV (%)	Skewness	Kurtosis	*W* statistic	*P* value	Number of samples
Macronutrient concentrations (%)								
N	1.13	0.13	11.3	0.05	−0.50	0.99	0.53	110
P	0.11	0.02	15.0	−0.40	0.86	0.98	0.16	110
K	0.42	0.08	19.7	0.36	0.58	0.98	0.17	110
Ca	0.18	0.04	22.3	0.57	1.36	0.97	0.01	110
Mg	0.10	0.02	17.8	−0.14	0.74	0.98	0.25	110
S	0.09	0.01	11.9	−0.19	−0.67	0.97	0.42	44
Ratios (%)								
P:N	9.3	1.2	13.3	−0.50	0.96	0.98	0.12	110
K:N	37.8	7.0	18.5	0.38	0.29	0.99	0.48	110
Ca:N	16.5	3.9	23.6	0.47	1.11	0.98	0.10	110
Mg:N	8.8	1.9	21.1	0.22	−0.19	0.99	0.35	110
S:N	8.0	0.8	10.5	0.84	0.74	0.95	0.06	44
Micronutrient concentrations (mg kg^{-1})								
Mn	386.0	200.6	52.0	0.77	0.37	0.95	0.04	48
Zn	36.4	8.0	21.9	0.75	2.55	0.93	0.01	48
B	11.4	4.6	40.2	2.72	9.64	0.73	<0.01	48
Cu	3.2	0.6	19.7	0.66	0.43	0.95	0.06	47
Ratios (%)								
Mn:N	3.3	1.7	52.3	0.74	0.14	0.95	0.03	48
Zn:N	0.31	0.07	21.3	0.55	0.28	0.98	0.46	48
B:N	0.10	0.04	39.9	2.41	6.81	0.75	<0.01	48
Cu:N	0.03	0.00	18.1	0.86	0.48	0.94	0.02	47

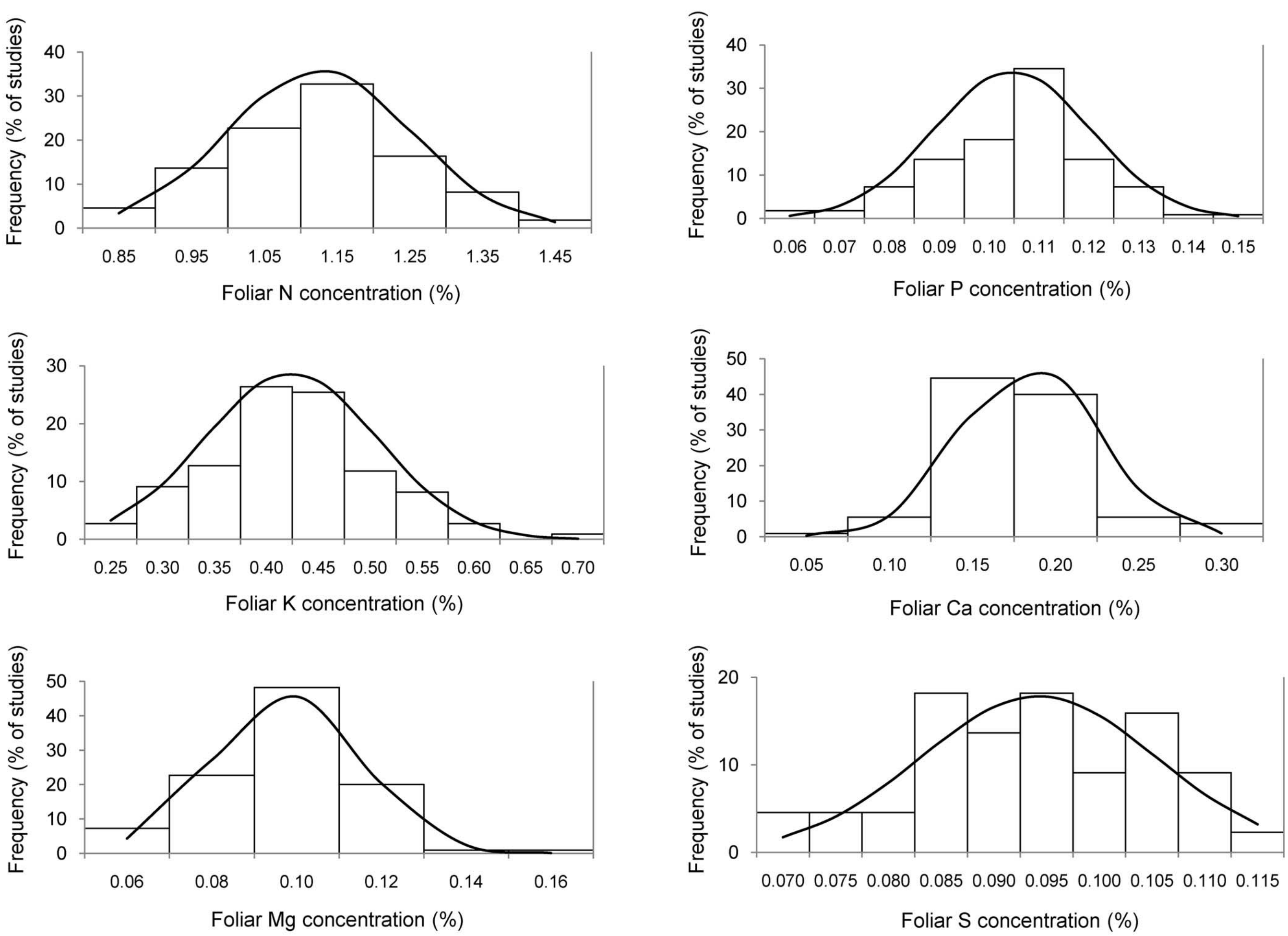

Figure 2. Frequency distributions of foliar nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) concentrations, with a superimposed normal curve for each distribution.

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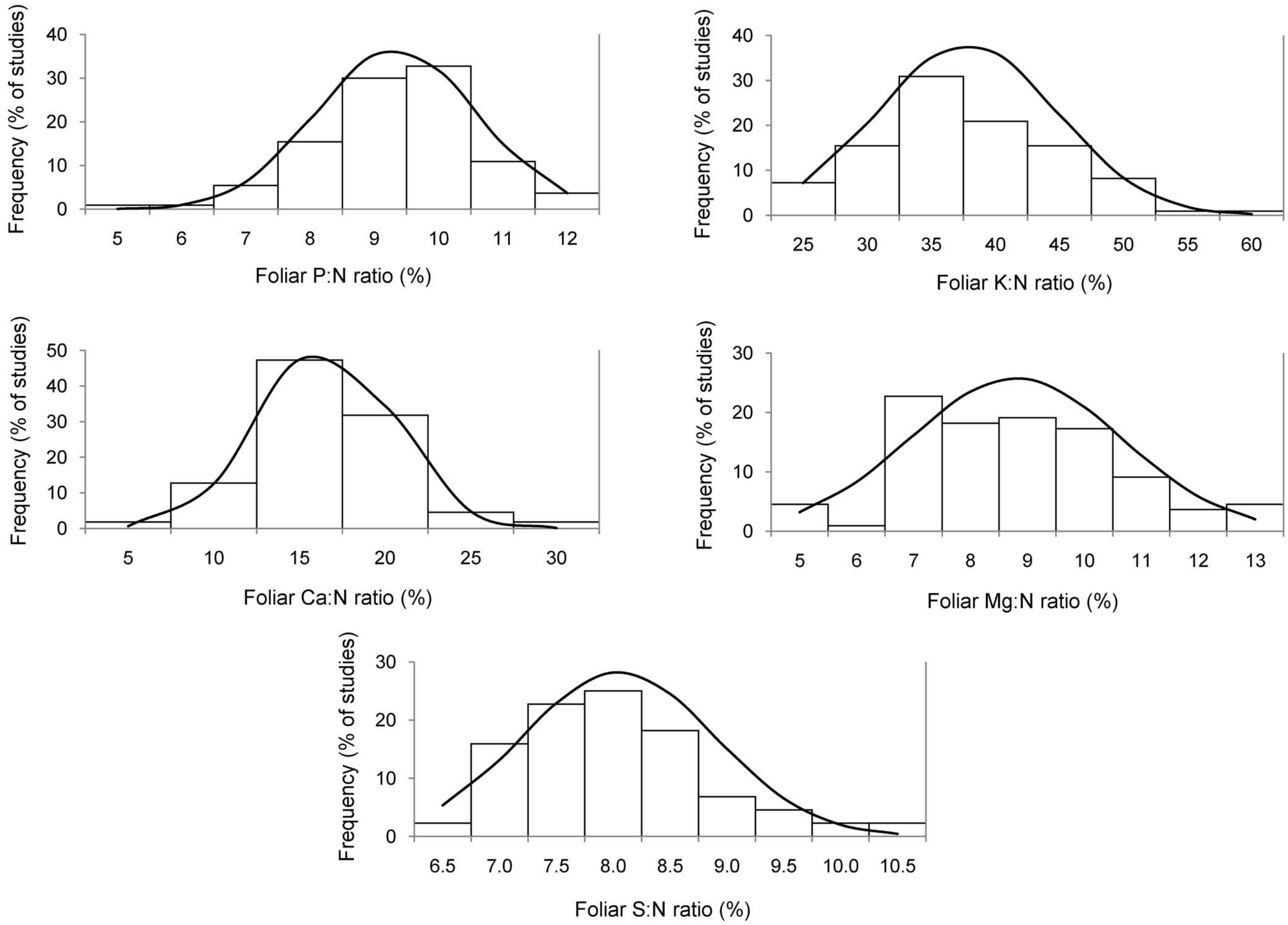

Figure 3. Frequency distributions of foliar phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) to nitrogen (N) ratios, with a superimposed normal curve for each distribution.

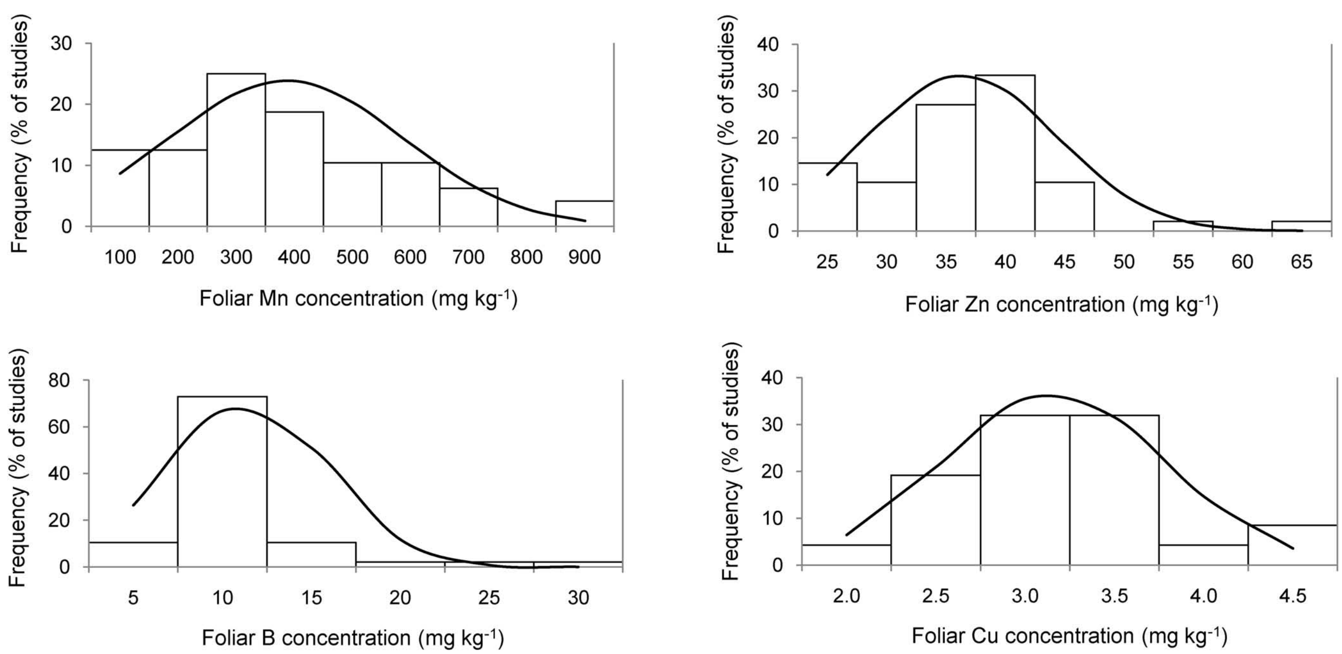

Figure 4. Frequency distributions of foliar manganese (Mn), zinc (Zn), boron (B), and copper (Cu) concentrations, with a superimposed normal curve for each distribution.

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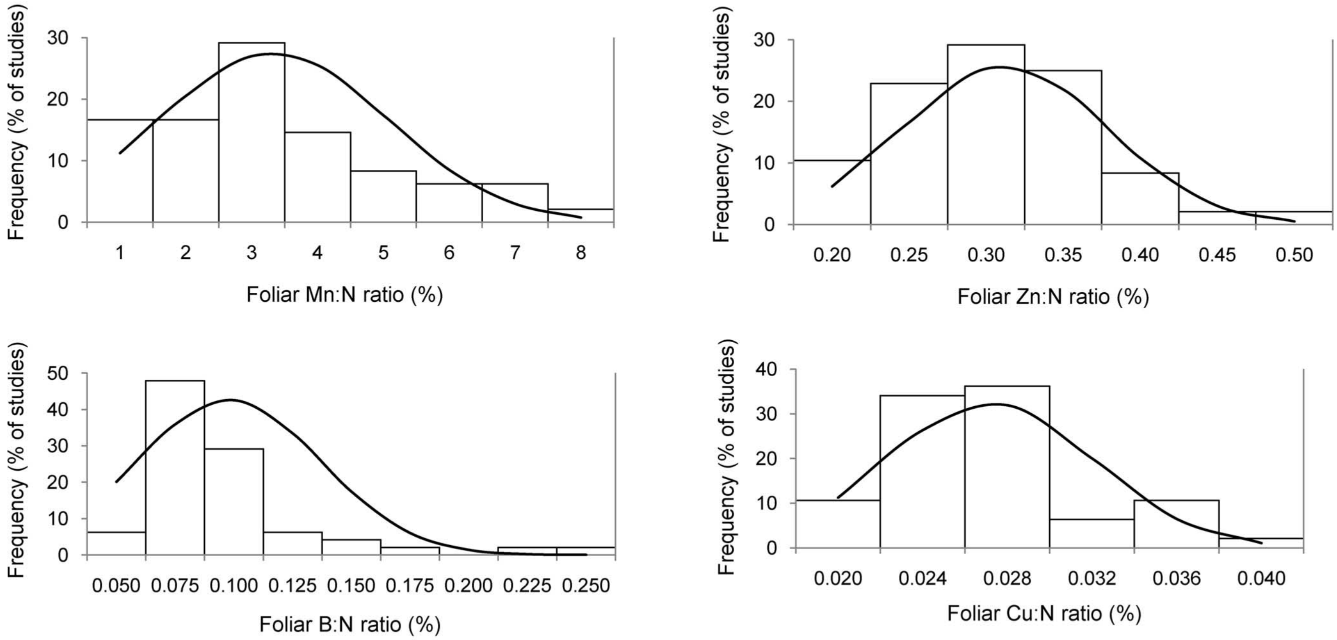

Figure 5. Frequency distributions of foliar manganese (Mn), zinc (Zn), boron (B), and copper (Cu) to nitrogen (N) ratios, with a superimposed normal curve for each distribution.

Table 4. Foliar nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), manganese (Mn), zinc (Zn), boron (B), and copper (Cu) concentrations and their ratios relative to N at the 0 (minimum value), 25, 50 (median), 75, and 100 (maximum value) percentiles, and currently accepted adequate values for loblolly pine. n.d., not determined.

Nutrient element or ratio to N	Minimum value	25%	Median	75%	Maximum value	Adequate levels or ranges
Macronutrient concentrations (%)						
N	0.87	1.03	1.14	1.21	1.43	1.20[a,b,c]
P	0.06	0.10	0.11	0.11	0.15	0.12[a,b,c]
K	0.24	0.38	0.42	0.47	0.71	0.35[d]–0.40[c]
Ca	0.07	0.16	0.18	0.21	0.31	0.15[b,c]
Mg	0.05	0.09	0.10	0.11	0.15	0.08[b,c]
S	0.069	0.086	0.094	0.105	0.114	0.10[b]–0.12[c]
Ratios (%)						
P:N	5.1	8.7	9.4	10.2	12.4	10[c]
K:N	22.9	33.1	37.0	42.5	60.5	35[c]
Ca:N	6.2	13.7	16.4	18.8	29.5	12[c]
Mg:N	4.6	7.3	8.7	10.0	13.1	6[c]
S:N	6.7	7.4	7.9	8.6	10.5	10[c]
Micronutrient concentrations (mg kg^{-1})						
Mn	83.9	257.8	344.5	484.5	915.9	20–40[b]
Zn	22.7	31.3	37.3	39.9	64.9	10–20[b]
B	6.2	8.7	10.4	12.0	32.1	4–8[b], 12[c]
Cu	2.1	2.8	3.1	3.5	4.7	2–3[b]
Ratios (%)						
Mn:N	0.7	2.2	3.3	4.1	7.9	n.d.
Zn:N	0.18	0.26	0.31	0.35	0.50	n.d.
B:N	0.05	0.08	0.09	0.10	0.25	0.10[c]
Cu:N	0.019	0.024	0.026	0.029	0.041	n.d.

[a] Wells and Allen (1985).
[b] Jokela (2004).
[c] FNC (2009).
[d] Allen (1987).

The distributions for Cu and Zn:N approximated a normal bell-shaped curve (Figures 4 and 5).

Percentile Values and Foliar Nutrient Guidelines

Macronutrient Concentrations and Ratios to N

Foliar N, P, and S concentrations and consequently the ratios P:N and S:N indicated a potential limitation to growth in almost all of the stands sampled as only the upper quartile of studies reached the minimum reported threshold values of 1.20, 0.12, 0.10, 10, and 10%, respectively (Table 4). Foliar K, Ca, and Mg were regarded as adequate for growth, as only the lower quartile of studies had concentrations lower than the sufficiency levels. Median K, Ca, and Mg ratios to N were above the recommended levels.

Micronutrient Concentrations and Ratios to N

Average Mn and Zn concentrations were higher than the currently recommended levels (Tables 3 and 4). In fact, the respective minimum values of 83.9 and 22.7 mg kg^{-1} exceeded the maximum

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reported values of 40 and 20 mg kg^{-1} considered adequate for Mn and Zn (Table 4). Jokela (2004) tabulated foliar B concentration guidelines for loblolly pine ranging from 4 to 8 mg kg^{-1}; the corresponding value used by the FNC (2009) is 12 mg kg^{-1} (Table 4). When comparing foliar concentrations with the sufficiency levels recommended by Jokela (2004), B would be classified as adequate, as the lower quartile of studies corresponded to these guideline values (Table 4). Furthermore, the mean B concentration (11.4 mg kg^{-1}; Table 3) exceeded this range. However, if the values are compared with the FNC (2009) sufficiency levels, foliar B is considered potentially limiting to growth; only the upper quartile of studies reached the threshold values of 12 mg kg^{-1} and 0.10% for B and B:N, respectively. Foliar Cu was regarded as adequate for growth, as the median value of 3.1 mg kg^{-1} corresponded closely to the range of 2–3 mg kg^{-1} suggested by Jokela (2004) (Table 4).

Discussion

Given the extensive range of site and stand conditions sampled, the distribution of foliar nutrient concentrations should be representative of site-prepared, genetically improved loblolly pine plantations without recent fertilization in the Southeast. The wide range in nutrient levels observed was not surprising considering the diversity among study sites in geographic region, age, the year samples were collected, soil type, drainage class, and initial stand characteristics, such as stem density, diameter, and height.

In general, the macronutrient concentrations and their ratios to N exhibited less variability (lower CV) than the micronutrient concentrations and ratios (Table 3). This may be related to the larger sample size used to determine macronutrient as opposed to micronutrient concentrations. Precision in estimating the mean and standard deviation increases with increasing sampling size, as larger samples tend to be more representative of the population than smaller samples (Gregoire and Barrett 1979). Consequently, the estimates of CV are also more precise for larger samples (Gregoire and Barrett 1979).

Some areas of the natural range of loblolly pine (Figure 1) are not well represented in our database, such as the Lower Atlantic and Gulf Coastal Plain of Florida extending into the south of Georgia, the northern parts of Mississippi and Alabama, and areas of Texas, including the "lost pines" disjunct population described by Schultz (1997). Future sampling should focus on these regions, and analyses should be conducted on the full set of elements (including S and micronutrients) to better represent the native range in foliar nutrient concentrations for this species. There were four studies lying near the boundary or outside the natural loblolly pine range (Figure 1). Two of these studies were located on well-drained sites in the Ouachita Mountains of Arkansas (132804 and 132805; see Appendix), one on a well-drained site on the Cumberland Plateau in Tennessee (132701), and one (195501) on the Piedmont in Virginia. For these sites outside the natural range of loblolly pine, all nutrient concentrations and their ratios to N fell within the distribution observed at sites within the natural range, with the exception of N at the Tennessee site. At that site, foliage N was lower than that observed at all other sites (0.87%; Table 4).

The adequate levels or ranges presented in Table 4 can be used to identify potentially responsive stands; sites with levels below these threshold values have been shown to be generally responsive to fertilizer application. Note that although critical foliar nutrient concentrations have been published for southern pines, according to Jokela (2004), these are not known with any exactness, especially for elements other than N and P, and are therefore used principally as qualitative guides. Foliar N, P, and S were classified as potentially limiting to growth compared with the currently accepted adequate values. The ratios P:N and S:N were also considered low as only the upper quartile of studies reached the threshold values. Depending on which recommended value is used, B could be classified as being in sufficient supply (according to Jokela [2004]), or considered as potentially limiting to growth if the levels are compared with those used by the FNC (2009). The remaining elements and their ratios to N were regarded as adequate, as they were within or higher than the currently recommended levels for loblolly pine.

It is apparent that the foliar nutrient concentrations and ratios currently accepted as adequate may require further examination, particularly for S and B. Sypert (2006) used critical foliar levels to diagnose the nutrient status in established loblolly pine plantations at four study sites across the southern United States. Although this technique proved effective in identifying deficiencies of N, P, and K, foliar Cu, S, and B levels appeared to be available in sufficient quantities even though concentrations of these elements were below the published critical levels (Sypert 2006). In our database, the mean Cu concentration and its ratio to N were 3.2 mg kg^{-1} and 0.03%, respectively (Table 3). The critical foliar Cu concentration recommended by Brockley (2001b) for lodgepole pine (*Pinus contorta* Dougl. var latifolia Engelm.) is 3 mg kg^{-1}, a value that closely approximates the range of 2–3 mg kg^{-1} suggested by Jokela (2004). According to Turner and Lambert (1986), a concentration of 2 mg kg^{-1} foliar Cu is considered to be critical in radiata pine, and Linder (1995) suggested a Cu:N ratio of 0.02% for Norway spruce. These recommended levels coincide with the minimum values in the loblolly pine database (Table 4), suggesting sufficiency levels. Furthermore, none of the studies exhibited symptoms of Cu deficiency (twisting of branches and stems).

In the study conducted by Sypert (2006), concentrations of S were especially low ($<$ 0.06%; S:N ratio = 4) and were not increased by fertilization, leading this author to conclude that the critical level (0.12%) is too high and should be reevaluated. In the current study, foliar S (0.09%) and its ratio to N (S:N = 8) (Table 3) were considered low relative to the currently accepted adequate levels for loblolly pine. However, the studies did not exhibit S deficiency symptoms (chlorosis of older needles), and the foliar levels appear to be within the range of sufficiency reported for other conifers: Turner and Lambert (1986) suggested 0.08% foliar S for radiata pine (*Pinus radiata* D. Don) in Australia, Linder (1995) recommended a value of 5 for S:N in Norway spruce trees in Sweden, and Brockley (2001b) proposed a threshold value of 7 for S:N in lodgepole pine growing in Canada.

Foliar values considered adequate for B are 4–8 mg kg^{-1} (Jokela 2004) for loblolly pine in the United States, 12 mg kg^{-1} for radiata pine in New Zealand (Will 1978, 1985) and loblolly pine in the United States (FNC 2009), and 12–15 mg kg^{-1} for lodgepole pine in Canada (Brockley 2001b). Linder (1995) suggested a B:N ratio of 0.05 for Norway spruce, compared with a value of 0.10 that is currently used by the FNC (2009). The loblolly pine database values for B and B:N are considered potentially limiting to growth compared with levels recommended by Will (1978, 1985), Brockley (2001b), and the FNC (2009); only the upper quartile of studies reached the threshold values of 12 mg kg^{-1} and 0.10% for B and B:N, respectively (Table 4). However, this element is regarded as being adequate when using values suggested by Linder (1995) and Jokela (2004). The studies included in our database did not show tip

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or shoot dieback, which indicate B deficiency. Although nutrient demand varies between species, these comparisons indicate that the target concentrations for S and micronutrients such as B and their ratios to N may require further investigation for loblolly pine.

The percentile values presented in Table 4 provide a cumulative quantitative distribution of each nutrient and are a useful tool for forest managers, who can relate the foliar nutrient concentrations of their individual stands to this regional distribution. This baseline information is a prerequisite for determining the nutrient status of loblolly pine and can be used for comparative purposes to test for nutritional changes that may result from silvicultural practices that are likely to alter nutrient availability (such as vegetation management, thinning, and prescribed burning) and to assess postfertilization nutrient uptake and balance.

Of all the diagnostic tools available for selecting responsive stands to fertilization, foliar analysis appears to have the most potential because it can provide an integrated index of site supply as well as stand demand for a nutrient (Allen 1987). However, recent work suggests that leaf area is also a good indicator of current nutrient deficiencies and growth (Allen et al. 2005), and for some elements, specifically N and P, it has proved superior to foliar nutrient analysis. Significant research conducted by Vose and Allen (1988), Albaugh et al. (1998), and Rojas (2005) found leaf area index measurement to be the preferred method to determine the likelihood of response to N and P additions. In midrotation pine stands in the southern United States, a leaf area index of 3.5 has been established as indicative of stands with adequate N and P nutrient supply (Fox et al. 2007). For those managers considering the application of N and P fertilizer, leaf area index measurements should be used to determine the likelihood of a response to these elements.

Additional foliar sampling is recommended under high-intensity management regimes to protect against nutrient imbalances that may limit expected response (North Carolina State Forest Nutrition Cooperative 2000). Where multiple N and P applications will be carried out, monitoring of other elements using foliar analysis is recommended, as there are concerns that as macronutrient limitations are ameliorated through widespread operational fertilization programs, other elements, particularly micronutrients, may become limiting (Stone 1990). With the standard operational practice of N and P fertilization in the southeastern United States and the application of more intensive management systems, rapid growth rates and consequently an increased nutrient demand can result in induced deficiencies of elements such as K (Grant 1991, Jokela et al. 1991), B, Cu, Mn, Zn (Jokela 2004, Allen et al. 2005), and Ca (Kyle et al. 2005, Fox et al. 2007). In 1994, application of elements other than N and P to loblolly stands in the Southeast, including K, B, Mg, Cu, and Mn, began in response to newly available research results (Albaugh et al. 2007). Furthermore, negative interactions between elements have been reported for other species; for example, S deficiencies, either induced or aggravated by N fertilization, have been implicated in limiting the effectiveness of added N in lodgepole pine stands in British Columbia, Canada (Brockley 2001a). Similarly, in Australia, high foliar S levels are required to obtain a response from radiata pine to N fertilization without inducing a S deficiency (Turner and Lambert 1986). Stone (1990) discusses macronutrient-induced B deficiencies in forest trees, and Brockley (2001a) reports on N-induced B deficiencies following operational fertilization in Canada.

Current evidence suggests that the target concentrations for S and B and their ratios to N may require further investigation for loblolly pine. We have no evidence to suggest that the currently recommended values for K, Ca, Mg, Mn, Zn, and Cu are incorrect. If foliar nutrient data are near or below the threshold values (Table 4) for these elements and fertilization with N and P is planned, it is likely that the response to added N and P may be lower than expected if other elements are not present in sufficient supply.

Conclusions

Macronutrient concentrations and their ratios to N in this loblolly pine foliar data set were less variable and more normally distributed than micronutrient concentrations and their ratios, which exhibited the highest variability and were positively skewed. Baseline N, P, and S concentrations were classified as potentially limiting to growth, and the ratios P:N and S:N were considered low compared with the currently accepted adequate values for loblolly pine. There is a wide range in the currently accepted sufficiency levels for B. Depending on which value is used, this element can be classified as being potentially limiting to growth or in sufficient supply. Further research into testing the proposed foliar adequacy levels and calibrating responses with field trials is warranted, particularly for S and B, as recommended concentrations may be too high. The remaining elements and their ratios to N were regarded as being sufficient, as they were within or higher than the recommended levels for loblolly pine and were within the range of sufficiency reported for other conifers. However, deficiencies of these elements may be induced under intensive management regimes, including repeated fertilizer applications. In addition to sampling those areas not well represented in the database (e.g., Florida, South Georgia, northern Mississippi and Alabama, and areas of Texas), continued monitoring of foliar nutrient status, particularly micronutrient concentrations, would add valuable information to the existing data set. It would be prudent to analyze nutrient balance where fertilizer has been applied by comparing the presented baseline values with postfertilization samples. To better determine the source of variation in foliar nutrient levels, we recommend additional studies examining the extent to which foliar nutrient concentrations vary with physiographic region, geology, soil drainage class, previous land use history, soil nutrient concentrations, and other stand factors.

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Appendix. Details of the region-wide studies included in the foliar nutrient database, showing the number of plots per study, the location and physiographic province (region), the planting date, stand age at study installation (year 0), soil series, and drainage class.

		Location						
Study	Number of plots	County	State	Region[a]	Planting date	Year 0	Soil series	Drainage class[b]
130101	48	Lancaster	SC	PIED	1973	1985	Pacolet	WD
130102	24	York	SC	PIED	1972	1986	Appling	WD
130401	24	King and Queen	VA	UACP	1971	1986	Suffolk	WD
130402	24	Amelia	VA	PIED	1968	1987	Durham	WD
130501	48	Hampton	SC	LACP	1969	1985	Lynchburg	SPD
130502	48	Bienville	LA	UGCP	1970	1986	Susquehanna	SPD
130701	24	Lincoln	MS	UGCP	1972	1985	Saffell	WD
130702	24	Decatur	GA	UACP	1974	1986	Wagram	WD
130703	48	Georgetown	SC	LACP	1977	1987	Bladen	SPD
130801	60	Craven	NC	LACP	1975	1984	Bayboro	VPD
130802	64	Craven	NC	LACP	1970	1984	Leaf	PD
130901	24	Brunswick	NC	LACP	1971	1985	Goldsboro	MWD
130902	48	Brunswick	NC	LACP	1971	1986	Pantego	VPD
130903	24	Cumberland	NC	LACP	1973	1987	Torhunta	VPD
131101	24	Colleton	SC	LACP	1972	1984	Lynchburg	SPD
131102	48	Georgetown	SC	LACP	1971	1985	Bladen	SPD
131103	24	Berkeley	SC	LACP	1973	1986	Pantego	VPD
132101	24	Marengo	AL	UGCP	1969	1986	Ruston	WD
132102	47	Dallas	AL	UGCP	1969	1987	Savannah	MWD
132201	24	Williamsburg	SC	LACP	1969	1985	Rains	PD
132401	48	Conecuh	AL	UGCP	1971	1985	Fuquay	WD
132402	24	Conecuh	AL	UGCP	1973	1986	Orangeburg	WD
132403	24	Covington	AL	UGCP	1975	1986	Dothan	WD
132601	24	Wayne	GA	LACP	1970	1984	Olustee	PD
132602	24	Wayne	GA	LACP	1972	1984	Pelham	PD
132603	24	MacIntosh	GA	LACP	1973	1985	Wahee	SPD
132604	50	Effingham	GA	LACP	1976	1986	Stilson	MWD
132605	24	Bertie	NC	LACP	1977	1987	Leaf	PD
132701	48	Rhea	TN	CUMB	1972	1984	Lonewood	WD
132702	24	Bradley	TN	MTS	1974	1986	Fullerton	WD
132801	60	Kemper	MS	UGCP	1973	1984	Wilcox	PD
132802	60	Howard	AR	UGCP	1974	1984	Blevins	WD
132803	30	Monroe	MS	UGCP	1973	1985	Ruston	WD
132804	30	Garland	AR	MTS	1974	1985	Carnasaw	WD
132805	30	Polk	AR	MTS	1974	1985	Sherwood	WD
132901	24	Sumter	AL	INFL	1970	1985	Wilcox	PD
133001	48	Washington	LA	UGCP	1970	1984	Malbis	WD
133002	24	Lamar	MS	UGCP	1971	1985	Malbis	MWD
133101	24	Vernon	LA	UGCP	1967	1985	Glenmora	MWD
133102	24	Vernon	LA	UGCP	1972	1986	Lucy	WD
133103	24	Sabine	LA	UGCP	1972	1987	Sacul	WD
133104	24	Aiken	SC	UACP	1972	1986	Ailey	WD
133105	24	Greenwood	SC	PIED	1973	1987	Cecil	WD
141501	12	Floyd	GA	RAV	1994	1997	Wolftever	MWD
143202	14	Santa Rosa	FL	LGCP	1986	1991	Troup	ED
144501	12	Wilcox	AL	UGCP	1994	1997	Malbis	MWD
150101	20	Union	SC	PIED	1979	1991	Cecil	WD
150102	20	Fairfield	SC	PIED	1981	1992	Cecil	WD
150103	9	Kershaw	SC	SAND	1982	1995	Lakeland	ED
150901	16	Columbus	NC	LACP	1975	1993	Lynchburg	SPD
151301	12	Scotland	NC	SAND	1985	1994	Wakulla	ED
151302	9	Vance	NC	PIED	1982	1994	Cecil	WD
152201	12	Jones	GA	PIED	1970	1995	Hiwassee	WD
152601	12	Effingham	GA	UACP	1978	1989	Coosaw	MWD
152602	15	Wayne	GA	UACP	1975	1989	Leefield	SPD
152603	24	Appling	GA	UACP	1975	1990	Olustee	PD
152604	12	Appling	GA	LACP	1975	1990	Olustee	PD
152701	20	Whitfield	GA	RAV	1977	1992	Montevallo	WD
153201	9	Monroe	AL	LGCP	1981	1992	Orangeburg	WD
153202	12	Escambia	FL	LGCP	1980	1992	Tifton	WD
153301	20	Choctaw	AL	UGCP	1975	1990	Smithdale	WD
153401	8	Trinity	TX	UGCP	1975	1993	Colita	SPD
153501	12	Barbour	AL	UGCP	1982	1994	Springhill	WD
153601	12	Montgomery	MS	UGCP	1985	1996	Smithdale	WD
153901	16	Bibb	AL	UGCP	1977	1995	Smithdale	WD
153902	16	Greene	AL	UGCP	1979	1996	Sacul	MWD
154202	12	Appling	GA	LACP	1984	1996	Fuquay	MWD
154301	9	Chambers	AL	PIED	1983	1996	Cecil	WD
154302	16	Macon	GA	UACP	1981	1996	Vaucluse	WD
154401	16	Bradley	AR	UGCP	1976	1997	Stough	SPD

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Appendix. Continued.

Study	Number of plots	Location: County	State	Region[a]	Planting date	Year 0	Soil series	Drainage class[b]
154402	16	Pike	AR	UGCP	1981	2000	Prescott	MWD
171201	16	Coosa	AL	PIED	1987	1999	Pacolet	WD
171301	12	Durham	NC	PIED	1984	1998	Cecil	WD
172601	18	Tallapoosa	AL	PIED	1986	1996	Cecil	WD
172602	20	Halifax	NC	PIED	1986	1999	Lenoir	SPD
173001	16	Washington	LA	UGCP	1981	1999	Ruston	WD
173901	16	Bibb	AL	UGCP	1980	1998	Smithdale	WD
174001	16	Chester	SC	PIED	1975	1997	Appling	WD
174301	20	Stewart	GA	UACP	1983	1997	Orangeburg	WD
175101	31	Chatham	NC	PIED	1984	2001	Nanford-Badincomplex	WD
180101	14	Kershaw	SC	SAND	1997	2000	Blanton	WD
180301	16	Oglethorpe	GA	PIED	1993	2000	Iredell	MWD
180601	40	Brunswick	VA	PIED	1993	1999	Cecil	WD
180701	18	Dallas	AR	UGCP	1997	2001	Smithdale	WD
180801	40	Craven	NC	LACP	1992	1998	Leaf	PD
181001	16	Marion	AL	UGCP	1994	2000	Saffell	WD
181101	44	Berkeley	SC	LACP	1994	1999	Lynchburg	SPD
181201	18	Coosa	AL	PIED	1996	2002	Louisa	WD
181502	18	Floyd	GA	RAV	1998	2001	Townley	MWD
181503	18	Angelina	TX	UGCP	2000	2003	Kurth	MWD
182201	18	Wilkes	GA	PIED	1997	2000	Appling	WD
182401	16	Nassau	FL	LACP	1994	1999	Meggett	PD
183101	16	Sabine	LA	UGCP	1993	1999	Sacul	MWD
183102	16	Vernon	LA	LGCP	1994	2000	Mayhew	MWD
183601	18	Kemper	MS	UGCP	1996	2000	Smithdale	WD
183901	18	Marengo	AL	UGCP	1998	2001	Lenoir	SPD
184001	16	Sumpter	AL	UGCP	1995	1999	Wilcox	SPD
184201	16	Brantley	GA	LACP	1994	1998	Seagate	SPD
184202	16	Brantley	GA	LACP	1995	1998	Pelham	PD
184301	18	Marion	GA	LGCP	1996	2000	Troup	WD
184302	18	Talbot	GA	PIED	1997	2003	Cecil	WD
184401	16	Bradley	AR	UGCP	1996	2000	Stough	SPD
184501	16	Marengo	AL	UGCP	1996	2000	Brantley	WD
184801	18	Newton	TX	LGCP	1999	2001	Evadale	PD
185201	18	Montgomery	NC	PIED	1999	2003	Herndon	WD
185301	18	Montgomery	MS	UGCP	1997	2003	Shubuta	WD
193901	32	Tuscaloosa	AL	APP	1991	2007	Sipsey	MWD
194001	32	Marion	SC	LACP	1995	2008	Cantey	PD
194201	32	Crenshaw	AL	UGCP	1991	2008	Arundel	WD
195501	32	Buckingham	VA	PIED	1995	2009	Littlejoe	WD

[a] UACP, Upper Atlantic Coastal Plain; LACP, Lower Atlantic Coastal Plain; UGCP, Upper Gulf Coastal Plain; LGCP, Lower Gulf Coastal Plain; PIED, Piedmont; RAV, Ridge and Valley; CUMB, Cumberland Plateau; MTS, Mountains; SAND, Sandhills; INFL, Inland Flatwoods; APP, Appalachian Plateau.
[b] ED, WD, MWD, SPD, PD, and VPD represent excessively drained, well drained, moderately well drained, somewhat poorly drained, poorly drained, and very poorly drained soils, respectively.

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