

ABSTRACT

BARRETT, THOMAS BOONE. Soil Boron in Loblolly Pine Plantations of the Southeastern United States. (Under the direction of D. L. Kelting.)

Boron (B) is not well understood in intensively managed pine plantations across the Southeastern United States. Forest fertilizer research has focused primarily on N and P applications, with essentially no research being conducted on micronutrients such as B. The objectives of this study were to quantify soil B fractions and to identify relationships that may exist between soil B fractions and soil and site properties. Soil samples from 50 sites scattered across 11 states were used to provide a wide range of soil and site properties. Soil properties including total carbon, pH, exchangeable acidity, exchangeable base cations, effective cation exchange capacity, and particle size were determined. Site properties such as 30-year average annual precipitation, drainage class, soil taxonomic information, and parent material were used for the analysis. Three B fractions were chosen for analysis due to their relative quantities and overall contribution to the B pool. The readily soluble B fraction was determined by boiling a 2:1 solution of 0.02 M CaCl_2 and soil. This fraction ranged from 0.00 to 1.35 mg B kg^{-1} , with a mean value of 0.28 mg B kg^{-1} . The specifically adsorbed plus oxide bound fraction was determined using a sequential extraction procedure with 0.2 M acidic ammonium oxalate. The oxide bound B fraction ranged from 3.8 to 30.5 mg B kg^{-1} soil and the mean was 11.7 mg B kg^{-1} soil. The organically bound fraction was extracted with 0.02 M nitric acid (HNO_3) and 5-mL of 30% hydrogen peroxide (H_2O_2). The organically bound B

fraction ranged from 5.1 to 650.6 mg B kg⁻¹ soil, with a mean value of 75.5 mg B kg⁻¹ soil.

The readily soluble fraction was significantly and positively ($r = 0.57$) correlated with 30-year average annual precipitation. The specifically adsorbed plus oxide bound fraction was significantly and positively correlated with the effective cation exchange capacity ($r = 0.62$) and exchangeable base cations ($r = 0.75$). The organically bound fraction was significantly and positively correlated with total carbon ($r = 0.60$) and exchangeable acidity ($r = 0.60$).

Organically bound B contained the highest overall levels of B. Organically bound B from poorly drained soils were approximately triple that of well-drained soils. Poorly drained soils contained nearly twice as much total carbon as well drained soils. The readily soluble fraction contained the lowest levels of B followed by the oxide bound fraction. Soils derived from marine sediments contained the highest levels of B across all fractions.

Results from this work should provide the groundwork for understanding B in forest soils through the characterizations of B outlined in this study.

**SOIL BORON IN LOBLOLLY PINE PLANTATIONS OF THE
SOUTHEASTERN UNITED STATES**

by

Thomas Boone Barrett

A thesis submitted to the Graduate Faculty of
North Carolina State University
In partial fulfillment of the
Requirements for the Degree of
Master of Science

DEPARTMENT OF FORESTRY

Raleigh

2004

APPROVED BY:

Chair of Advisory Committee

BIOGRAPHY

The author was born March 1, 1972 in Roanoke Rapids, N.C. He attended Roanoke Rapids High School where he was active in football, track, and golf. He graduated in 1990 and continued his education at North Carolina State University. While at North Carolina State University, the author worked with the North Carolina Forest Nutrition Cooperative. In the spring of 1995, he received a Bachelor of Science in Forestry. Following his bachelor's degree, the author worked for a year at the Weyerhaeuser Research Station in New Bern, North Carolina. In the fall of 1996, he enrolled at East Carolina University in the Environmental Health program. He received a M. S. in Environmental Health in December 1997. In January of 2000, the author returned to North Carolina State University to enroll in the Master of Science program in Forestry, where he minored in Soil Science.

The author enjoys a wide variety of activities including fly-fishing, hunting, mountain biking, and working in his yard. He has a strong interest in forest soils and enjoys working with students. The author hopes this research will provide a basis for understanding boron in forest soils and assist in making adequate silvicultural decisions in the years to come.

ACKNOWLEDGEMENTS

The author would like to thank Dr. Dan Kelting who served as the chairman of my Graduate Advisory Committee. His help and guidance during the entire process is very much appreciated. A special thanks goes to Drs. Allen and Campbell, who have help guide my course for many years. The author would like to express his gratitude to Denise Pauliac for her help during the laboratory phase of this research. The author would also like to thank Ian Winborne for his help and commentary during the time we worked together. Contributions from all team members at the North Carolina State Forest Nutrition Cooperative are gratefully acknowledged.

The author would like to thank Ellis Edwards for the use of the Soil Science Department's soil grinding facilities on Reedy Creek Road. The author would also like to thank Dr. Chuck Davey for his interesting stories and his interest in boron.

The author would like to thank his mother and his in-laws, who have been there when he needed them for help and guidance.

Finally, the author is glad to have a wife who has patience and understanding and has allowed him to complete this undertaking. The author dedicates this research to his wife Katie and his daughter Hanna.

TABLE OF CONTENTS

LIST OF TABLES	V
LIST OF FIGURES.....	VI
INTRODUCTION	1
METHODS.....	6
STUDY SITES.....	6
SAMPLE COLLECTION AND PREPARATION	6
LABORATORY ANALYSIS	9
STATISTICAL ANALYSIS.....	11
RESULTS	12
SOIL PROPERTIES	12
B FRACTIONS.....	13
B FRACTIONS AND SOIL PROPERTIES	17
DISCUSSION	27
B FRACTIONS.....	27
B FRACTIONS AND SOIL PROPERTIES	30
CONCLUSIONS	36
LITERATURE CITED	38
APPENDICES	45

LIST OF TABLES

Table 1. Descriptive statistics for soil and site properties and B fractions from surface horizons soil samples of 50 studies	13
Table 2. Pearson correlation coefficients for boron fractions and soil properties	16
Table 3. Boron fractions by drainage class and textural family	25
Table 4. Boron fractions by mineralogical family	26
Table 5. Boron fractions by geological grouping	26
Table 6. Total B content for selected geologic materials	32

LIST OF FIGURES

Figure 1. Soil sample locations in the Southeastern United States	8
Figure 2. Frequency distributions for the soluble (a), specifically absorbed (b), and organically bound (c) boron fractions determined for 50 sites	15
Figure 3. Readily soluble boron as a function of 30-year average annual precipitation for surface horizon soils	20
Figure 4. Specifically adsorbed boron as a function of ECEC for surface horizon soils	21
Figure 5. Specifically adsorbed boron as a function of base saturation for surface horizon soils	22
Figure 6. Organically bound boron as a function of total carbon for surface horizon soils.....	23
Figure 7. Organically bound boron as a function of exchangeable acidity for surface horizon soils.....	24

INTRODUCTION

Boron (B) deficiency has been suggested to be the most widespread micronutrient problem in soils and plants of the United States (Purvis, 1939; Jordan and Powers, 1946; Berger, 1962; Sparr, 1970; Goldberg, 1997). B has been intensively researched in agricultural soils (Berger and Truog, 1945; Gupta, 1979, 1993) since the early part of the twentieth century and was found to play an important role in plant growth and development. However, little research has focused on forest soils of the Southeastern United States.

Loblolly pine (*Pinus taeda* L.) is the dominant pine species on some 12 million hectares of pine plantations in the Southeast, where it is considered the most economically important pine species (Burns and Honkala, 1990). Fertilization of pine plantations with nitrogen (N) and phosphorus (P) has dramatically increased from 50,000 hectares in 1980 to 600,000 hectares in the year 2000 in response to the increasing value of wood products (NCSFNC, 2001).

Recent evidence has suggested that repeated applications of N and P fertilizers in pine plantations can lead to deficiencies in other nutrients such as B (NCSFNC, 1994). Tree growth response to N and P fertilization may be reduced by the limitations of B. Stone (1990) hypothesized that increased use of macronutrients would induce B deficiencies over time. B deficiency symptoms in the Southeast are not as apparent as the ones in Chile, Colombia, Australia, or New Zealand and fertilization is a necessity in order to have a viable timber product (Tollenaar, 1969; Flores, 2000; Urrego, 2000; Lambert et. al., 1997; Olykan, 1995). Tree diseases and other macronutrient deficiencies sometimes mask B deficiency symptoms in

pinus of the Southeast. Therefore, a better understanding of the role of B in forest soils of is needed in the Southeastern United States.

The Ultisol order covers the majority of the loblolly pine range and is characterized by its low base saturation, extremely acid to moderately acid conditions, and its high degree of weathering (Buol et al., 1997; Foth and Ellis, 1997; Pritchett and Fisher, 1987). B deficient areas are generally comprised of acidic, highly leached, and coarse-textured soils (Troeh and Thompson, 1993; Barber, 1984).

Stone (1990) reported that soil properties were essential to understanding occurrences of B deficiencies in forest stands. Furthermore, Stone (1990) predicted that changes to these soil properties through erosion (loss of surface layers), site preparation, fire, and macronutrient fertilization would contribute to B deficiency. Soil properties such as texture (Kubota et al., 1948; Wilson et al., 1951; Wear and Patterson, 1962; Adriano, 1986; Gupta 1993), pH (Goldberg, 1997; Gupta, 1993; Elrashidi and O'Connor, 1982; Peterson and Newman, 1976) organic matter (Berger and Truog, 1945; Parker and Gardner, 1982; Mortvedt et al., 1991; Hou et al., 1994) and cation exchange capacity (Jin et al., 1987; Hou et al., 1994) have been related to indices of B availability, as have site properties such as precipitation (Hobbs and Bertramson, 1949; Page and Paden, 1954; Pais and Jones, 1997; Xu et al., 2001) and underlying geology (Adriano, 1986).

The majority of B found in soils can be traced to either geologic material such as tourmaline (3 to 4% B), or seawater (4.6 mg kg^{-1}) (Stone, 1990). However, tourmaline is extremely resistant to weathering and literally unavailable due to its

slow dissolution, which is comparable to diamond. Seawater contributes to B cycle through its contact with sediments and through ocean sprays. To better understand the contribution of B from soils, we must first review the B fractions that contribute the greatest to the B cycle.

Work by Jin et. al. (1987) outlined a variety of extractions of soil B fractions, revealing their relative levels of magnitude. The ability of certain B fractions to contain and to release B within days, months, or years makes them highly valuable in terms of supplying B to pines. Identifying specific B fractions that may contain high levels of B and can subsequently release it so that is bio-available would be of key importance.

The readily soluble fraction is the B fraction is the one most available to plants. This fraction is the conduit through which all other B sources must flow in order to be taken up by plants. However, this fraction generally contains the lowest levels of B at anytime. Other B fractions such as the oxide bound and organically bound have shown to contain relatively high levels of B (Hou et. al., 1994; Jin et. al., 1987). B in these fractions also has the ability to be released quickly through weathering processes and by decomposition, making its characteristics ideal for supply to plants.

Within the B cycle, fractions are competing for B constantly. B may be released from the one fraction and be bound by another fraction. This process may go on many times before the readily soluble fraction is able to obtain it and release it to the plant. A variety of processes may need to take place in order for B to release and to find its way into the plant.

A number of methods have been used to extract various B fractions from soils. The most common fraction extracted is the readily soluble, commonly extracted with boiling water or a calcium chloride solution (Berger and Truog, 1939, 1944; Dible et al., 1954; Gupta, 1967; Cartwright et al., 1983; Mahler et al., 1984; Shuman et al., 1992); however, not all methods are suitable for acidic forest soils. Certain methods contain chemicals that actually negate the extraction procedures in acidic soils and are more suitable for alkaline soils (Aitken et al., 1987; Novozamsky et al., 1990). The hot-water soluble method of Parker and Gardner (1981) provides a fast, reliable method, especially when utilizing an inductively coupled plasma atomic emission spectrometer system (ICP-AES) described by Spiers et al. (1990). The use of ICP-AES reduces interferences and increases precision (Sah and Brown, 1997).

The readily soluble fraction has been used almost exclusively for site recommendations, although very little is understood about the role of this other B fractions in B availability (Gupta, 1979, 1993; Keren and Bingham, 1985). The readily soluble fraction works well as an indicator for agriculture crops, which are generally grown on an annual basis. Pine plantations may require different indicators to predict long-term B availability since most rotation lengths generally exceed two or three decades. Since the readily soluble fraction only represents a portion of the total B supply, understanding other B fractions may indicate how much each fraction contributes to the B cycle and the potential availability of B in forest soils.

Two of the lesser-understood and rarely extracted fractions, the oxide and the organically bound, have strong affinities to bind with Fe and Al hydroxides and organic matter, respectively. Since large quantities of these soil constituents are present in Southeastern forest soils, desorption and mineralization may provide these fractions with a release mechanism to become available to the potentially bio-available B pool.

Jin et al. (1987) developed methods for extracting oxide bound B. These methods employed both sequential and separate extraction procedures. Hou et al. (1996) utilized a single oxide bound extraction procedure. The work of Jin et al. (1987) showed that significant quantities of B were found in the oxide bound B fraction (8.7 to 73.4 mg B kg⁻¹ soil), which is nearly 100 times greater than the quantities found in the readily soluble fraction for the same study.

Organically bound extractions have been used for other trace elements, but no other researcher had utilized these methods to analyze organically bound B prior to Hou et al. (1994, 1996) and Lambert et al. (1997). Research by Hou et al., (1996) provided a chemical fractionation method for B. Earlier work by Hou et al. (1994) provides some idea of the quantities of B found in this fraction, where B ranged from 0 to 22.97 mg B kg⁻¹ soil across all extractions. However, Lambert et al. (1997) using a slightly different extraction procedure found quantities in the organic B fraction from 15.0 to 60.8 mg B kg⁻¹ soil.

Their relative quantities and the rate at which they may become available to the overall B cycle, suggests that the readily soluble, oxide bound, and organically

bound fractions are the most important to consider when estimating long-term B availability.

With little work focusing on B in forest soils of the Southeast and recent evidence suggesting that deficiencies may arise, an investigation was undertaken with the following objectives: (1) to quantify B fractions across the chemical and physical property range of loblolly pine and (2) to identify relationships between B fractions and soil and site properties.

METHODS

Study Sites

The North Carolina State Forest Nutrition Cooperative (NCSFNC) has an extensive number of fertilizer field trials throughout the Southeast. Soil samples collected from 50 sites from NCSFNC field trials were used in this investigation. These sites were selected to obtain a broad range of soil and site conditions from the native range of loblolly pine (Figure 1).

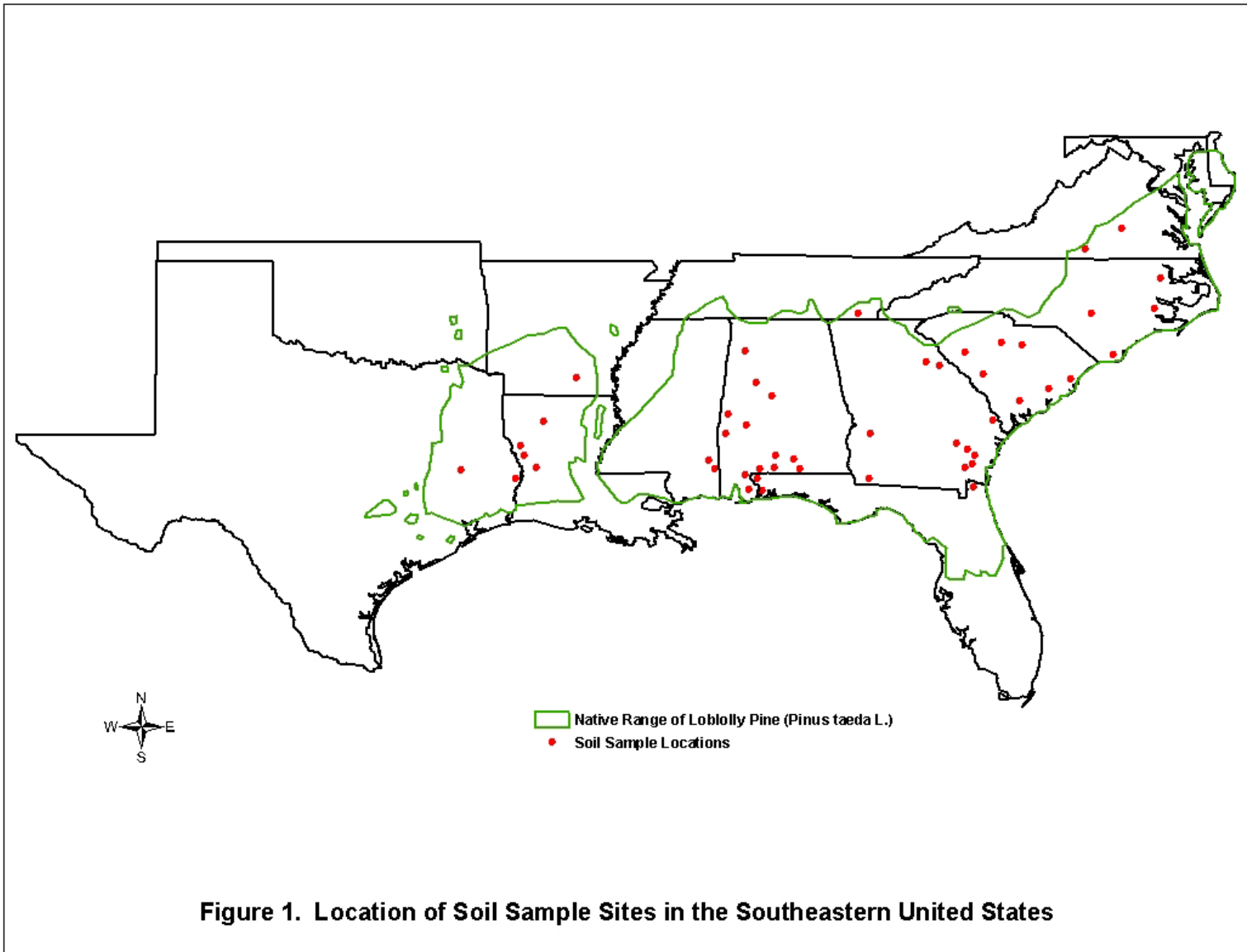
Soil samples used in this study represented 5 soil orders and 33 different soil series. The drainage class ranges from poorly to well drained with textures extending from fine to coarse. Soil samples utilized in this study had previously been collected, air-dried, ground, and stored for up to 20 years in some cases.

Sample Collection and Preparation

Soil samples were collected across 16 plots (4 treatments x 4 repetitions), which constituted the NCSFNC field trial. Soil samples were obtained within each

plot by depth or horizon. Soil samples were taken prior to the application any silvicultural treatment and represent the background levels of the site.

Soil samples from the field trials were air-dried and passed through a 2.0-mm (No. 10) mesh sieve. A composite sample was then made for each site by depth or horizon by using equal quantities of soil from each individual sample. The composite samples were thoroughly mixed to insure a homogeneous sample. An adequate quantity of soil was prepared to complete all analyses and to retain a portion for archive purposes. The composite samples were then ground and passed through a 0.250-mm (No. 60) mesh sieve. Each sample was properly labeled and stored for analysis.



Laboratory Analysis

Soil Properties

A 10-g sub-sample was selected from each composite sample and dried at 105°C for 24 hours to determine moisture content on an oven-dry basis according to the methods described by Klute et. al., (1986). Soil pH was determined in a 1:1 soil/H₂O solution, following equilibration the pH was determined by using a Mettler DL12 Titrator pH probe while simultaneously vortexing the sample (Sparks, 1996). Exchangeable acidity was determined by extracting 10:1 solution/soil sample in 1 N potassium chloride (KCl) for 1 hour, followed by titrating the supernatant to a pH endpoint of 8.2 (Carter, 1993). The samples were then centrifuged and filtered through a 2.5- μ m Whatman glass fiber filter and analyzed using the Mettler DL12 Autotitrator. Exchangeable base cations were determined from a 10:1 solution/soil sample extracted in 1 M ammonium chloride (NH₄Cl), the solution was then centrifuged and analyzed for calcium, potassium, magnesium, and sodium (Ca, K, Mg, and Na) using the Varian Liberty Series // inductively coupled plasma atomic emission spectrometer (ICP-AES) (Klute, 1986). Total carbon (C) was determined via dry combustion of 0.250-mm sieved soil in an NC 2100 Soil Carbon/Hydrogen/Nitrogen (CHN) analyzer made by CE instruments. Samples were corrected for moisture content following analyses. Duplicates, internal standards, and National Bureau of Standards (NBS) were used to ensure quality control and quality assurance throughout all analyses.

Particle size analysis was determined on each composite sample utilizing the hydrometer method outlined by Klute et al. (1986). Sand, silt, and clay fraction

percentages were then used to determine the USDA texture with the USDA textural triangle. Precipitation data for the sites was obtained from the National Climatic Data Center (NCDC) website (NCDC, 2001).

Boron Fractions

The readily soluble B fraction (solution plus non-specifically adsorbed) was extracted by using the hot-water soluble method of Sparks (1996). This method involved adding 40-mL of 0.02 M calcium chloride (CaCl_2) to a 250-mL flat bottom flask containing 20-g of soil. The solution was then heated until boiling. At the point of boiling, a glass funnel was inserted into each flask to reflux the soil solution. The solution was allowed to boil under this reflux condition for 5 minutes. The flasks were promptly removed from the heat at the end of the boiling period and allowed to cool, and filtered through Whatman No. 42 filter paper into a 50-mL Nalgene sample bottle. The extracted solution was analyzed directly with ICP-AES using the methods outlined by Spiers et al. (1990).

The specifically adsorbed plus oxide bound fraction was determined using a sequential extraction procedure (Hou et al., 1994). This involved adding 20-mL of 0.2 M acidic ammonium oxalate to 1-g of soil in a 50-mL centrifuge tube. The solution was shaken for 4 hours, removed from the shaker, centrifuged for 15 minutes, and the supernatant was poured into a 50-mL Nalgene sample bottle. The residual soil was retained for use on the next phase of the sequential procedure.

The organically bound fraction was obtained by utilizing the soil from the previous extraction. The soil residue was extracted by adding 3-mL of 0.02 M nitric acid (HNO_3) and 5-mL of 30% hydrogen peroxide (H_2O_2) to each centrifuge tube

(Hou et al., 1994). The solution was loosely capped and maintained at 85°C in a water bath for 2 hours with intermittent shaking. The samples were removed from the water bath, where 3-mL of 30% H₂O₂ was added to the centrifuge tube. The centrifuge tubes were then returned to the water bath where they remained for 3 hours. The tubes were removed from the water bath and allowed to cool. A 5-mL aliquot of 3.2 M ammonium acetate in 20% v/v nitric acid was added to the cooled solution. The solution was then diluted to 20-mL with deionized distilled water on a weight basis. The solution was shaken for 30 minutes and then centrifuged for 15 minutes. The supernatant was poured into a 50-mL Nalgene sample bottle. The solution was clarified using 0.25 g activated charcoal that had been previously washed in 3.2 M ammonium acetate in 20% v/v nitric acid.

Activated charcoal (0.25 g) was added to each solution to remove color from oxides and humic substances. The charcoal was thoroughly washed with respective extracting solutions prior to clarifying each sample solution. Tests conducted prior to actual analyses showed that adding 0.25 g of charcoal did not alter B concentrations in known solutions. Samples were then prepared following the Azomethine-H procedure described by Sparks, (1996); Wolf, (1971, 1974). The samples were allowed to develop color for 2 hours and then loaded directly into 4.5-mL polystyrene cuvettes, absorbance was read at 420 nm on a spectrophotometer (Bausch & Lomb Spectronic-100).

Statistical Analysis

Descriptive statistics were described for all soil properties and B fractions. Relationships were explored using simple correlation analysis between pH, total

carbon, clay content, sand content, exchangeable acidity, base saturation, ECEC, 30-year average annual precipitation, and B fractions. Results were summarized by mineralogical and textural families, geologic groups, and by drainage classification. Taxonomic and geologic information were determined from county soil surveys and state geologic maps and not from specific characterization. All of the statistical analyses were performed using the SAS[®] system.

RESULTS

Soil Properties

The pH ranged from 3.6 to 5.8 with a mean of 4.6 (Table 1). Total carbon content varied widely from 0.05 to 1.18 g C kg⁻¹ soil with a mean of 0.26 g C kg⁻¹ soil. Exchangeable acidity ranged 0.04 to 5.21 cmol_c kg⁻¹ soil with a mean of 1.34 cmol_c kg⁻¹ soil. Base saturation covered a range from 0.06 to 9.48 cmol_c kg⁻¹ soil with a mean of 1.44. The effective cation exchange capacity (ECEC) had a mean of 2.78 cmol_c kg⁻¹ soil and ranged from 0.93 to 10.58 cmol_c kg⁻¹ soil. These values reflect the low cation exchange capacity (CEC) status of the Ultisol order (Buol et al., 1997), which comprises >70% of this dataset. Clay content ranged from 26 to 336 g clay kg⁻¹ soil, with a mean content of 166 g clay kg⁻¹ soil. Sand content covered a wider range from 245 to 885 g sand kg⁻¹ soil and had a mean content of 669 g sand kg⁻¹. Silt content ranged from 0 to 517 g silt kg⁻¹, with a mean of 166 g silt kg⁻¹. The 30-year average annual precipitation ranged from 1103 to 1763 mm yr⁻¹, with a mean of 1372 mm yr⁻¹.

Table 1. Descriptive statistics for soil and site properties and B fractions from surface horizons of 50 studies.

Property	Units	Mean	Std. Dev.	Min	Max
pH		4.6	0.6	3.6	5.8
Total C	g kg ⁻¹	0.26	0.23	0.05	1.18
Ex. Acidity	cmol _c kg ⁻¹	1.34	1.34	0.04	5.21
Base Sat.	cmol _c kg ⁻¹	1.44	1.83	0.06	9.48
ECEC	cmol _c kg ⁻¹	2.78	2.04	0.93	10.58
Clay	g kg ⁻¹	166	76	26	336
Sand	g kg ⁻¹	669	150	245	885
Silt	g kg ⁻¹	166	117	0	517
Precipitation	mm	1372	177	1103	1763
Readily Soluble B	mg kg ⁻¹	0.28	0.27	<0.00	1.35
Oxide Bound B	mg kg ⁻¹	11.7	4.8	3.8	30.5
Organically Bound B	mg kg ⁻¹	75.5	122.7	5.1	650.6

B Fractions

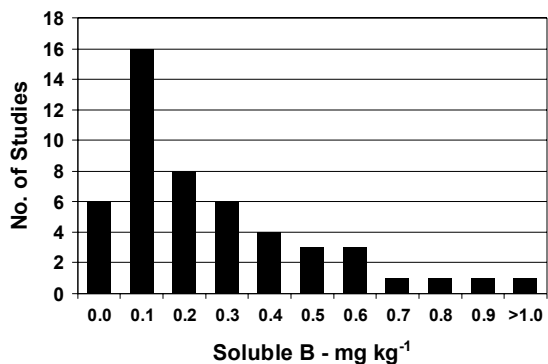
The readily soluble B fraction ranged from below the detection limit to 1.35 mg B kg⁻¹ soil with a mean of 0.28 mg B kg⁻¹ soil. The readily soluble B fraction was skewed toward the lower values, with greater than 90% of the studies containing less than 0.60 mg B kg⁻¹ soil (Figure 2a.). Only one soil exceeded 1.0 mg B kg⁻¹ level for the readily soluble B fraction.

The oxide bound B fraction ranged from 3.8 to 30.5 mg B kg⁻¹ soil and the mean was 11.7 mg B kg⁻¹ soil. The oxide bound B was more normally distributed compared to the readily soluble B fraction (Figure 2b.). Forty-nine of the fifty studies analyzed contained values below 22.0 mg B kg⁻¹ soil. One study exceeded the 30.0 mg B kg⁻¹ soil.

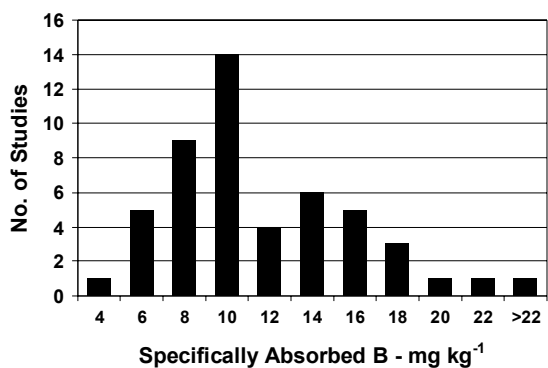
The organically bound B fraction ranged from 5.1 to 650.6 mg B kg⁻¹ soil, with a mean value of 75.5 mg B kg⁻¹ soil. This range represents 2 orders of magnitude in variation among the studies. Approximately 42% of the studies analyzed contain values less than or equal to 20.0 mg B kg⁻¹ soil (Figure 2c.). Ten studies exceeded 100.0 mg B kg⁻¹ soil.

The readily soluble fraction represented less than 0.5% of the sum of the three fractions. The oxide bound B fraction comprised the second largest portion (16.6%) and contained approximately 40 times more B than the readily soluble B fraction. The organically bound B fraction was 83% of the three B fractions. No significant simple linear correlations existed between the three B fractions (Table 2).

a.



b.



c.

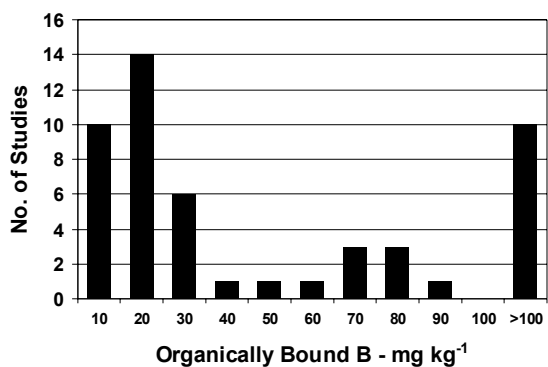


Figure 2. Frequency distributions for the readily soluble (a), specifically absorbed (b) and organically bound (c) boron fractions for surface horizons from 50 studies.

Table 2. Pearson correlation coefficients for boron fractions and soil properties (n = 50).

	Sol. B	Ox. B	Org. B	pH	Tot. C	Clay	Sand	Ex. Acid	Base. Sat	ECEC	Precip.
Sol. B	-										
Ox. B	-0.04	-									
Org. B	0.04	-0.17	-								
pH	0.01	0.24*	-0.40**	-							
Tot. C	0.09	-0.01	0.60***	-0.57***	-						
Clay	-0.06	0.20	0.24*	-0.36**	0.44***	-					
Sand	-0.11	-0.36**	-0.28*	0.04	-0.27*	-0.68***	-				
Ex. Acid.	0.09	-0.08	0.60***	-0.73***	0.79***	0.46***	-0.38**	-			
Base Sat.	0.02	0.75***	-0.17	0.38**	-0.10	0.39***	-0.53***	-0.20	-		
ECEC	0.08	0.62***	0.25*	-0.14	0.43***	0.65***	-0.73***	0.48***	0.77***	-	
Precip.	0.57***	0.02	-0.18	0.19	-0.21	-0.30*	0.02	-0.12	0.02	-0.06	-

*Significant at probability level 0.1.

**Significant at probability level 0.01.

***Significant at probability level 0.001.

B Fractions and Soil Properties

The readily soluble B fraction was significantly and positively correlated ($r = 0.57$) with 30-year average annual precipitation (Table 2 and Figure 3). No other linear correlations or apparent trends were found between soil properties and the readily soluble B fraction. The oxide bound B fraction was significantly and positively correlated with ECEC ($r = 0.62$) and base saturation ($r = 0.75$), which were the strongest simple correlations found between a B fraction and a soil property (Figures 4 and 5). The organically bound B fraction was significantly and positively correlated with total carbon ($r = 0.60$) (Figure 6). Several data points were located outside the range of the other data. Organically bound B fractions was also significantly and positively and exchangeable acidity ($r = 0.60$) (Figure 7).

Well-drained soils contained slightly higher levels of readily soluble B ($0.30 \text{ mg B kg}^{-1} \text{ soil}$) as compared with poorly drained soils ($0.24 \text{ mg B kg}^{-1} \text{ soil}$) (Table 3). The highest levels of the readily soluble B for poorly drained soils were found in very fine-textured soils ($0.51 \text{ mg B kg}^{-1} \text{ soil}$), whereas well-drained soils with sandy textures contained $0.62 \text{ mg B kg}^{-1} \text{ soil}$. Oxide bound B contained equal quantities of B across poorly and well-drained soils. The highest quantities of oxide bound B were found in the finer textured soils across both drainage classes. Organically bound B extracted from poorly drained soils ($124.4 \text{ mg B kg}^{-1} \text{ soil}$) contained nearly triple that of well-drained soils ($45.6 \text{ mg B kg}^{-1} \text{ soil}$). Fine-loamy textures contained the highest levels of organically bound B in poorly drained soils ($215.2 \text{ mg B kg}^{-1}$) soil while fine-textured soils were found to contain the highest levels in well-drained soils ($54.0 \text{ mg B kg}^{-1} \text{ soil}$).

The highest levels of B for the readily soluble B fraction were found in the kaolinitic mineralogical family (0.37 mg B kg⁻¹ soil) (Table 4). The siliceous and mixed mineralogical families contained the lowest quantities of readily soluble B with 0.21 and 0.22 mg B kg⁻¹ soil, respectively. The highest quantities of oxide bound B were found in the smectitic mineralogical family (21.7 mg B kg⁻¹ soil). The lowest B values were found in the kaolinitic and siliceous mineralogical families with 9.7 and 10.6 mg B kg⁻¹ soil, respectively. All mineralogical families contained substantial portions of B in the organically bound B fraction. The organically bound B was highest in the siliceous mineralogical family (81.6 mg B kg⁻¹ soil), and lowest in the kaolinitic mineralogical family (35.9 mg B kg⁻¹ soil).

Soils derived from shale and fine marine sediments contained the highest levels of readily soluble B (0.35 mg B kg⁻¹ soil) across the range of geologic materials (Table 5). Readily soluble B samples collected from soils derived from sedimentary rocks and marine sediments contained an average of 0.27 mg B kg⁻¹ soil as compared with samples from soils overlying metamorphic rocks which contained an average of 0.17 mg B kg⁻¹ soil. Oxide bound B levels were found to be the highest in soils resulting from mafic metamorphic rocks (21.8 mg B kg⁻¹ soil). B extracted from shale and limestone (sedimentary rocks) resulted in the lowest values for the oxide bound B fraction with 7.6 and 5.9 mg B kg⁻¹ soil, respectively. Organically bound B was found to be the highest in marine sediments with an average concentration of 64.6 mg B kg⁻¹ soil. Organically bound B was also higher in limestone-derived soils (55.8 mg B kg⁻¹ soil). Soils derived from mafic

metamorphic rocks contained the lowest value for organically bound B (5.6 mg B kg⁻¹ soil).

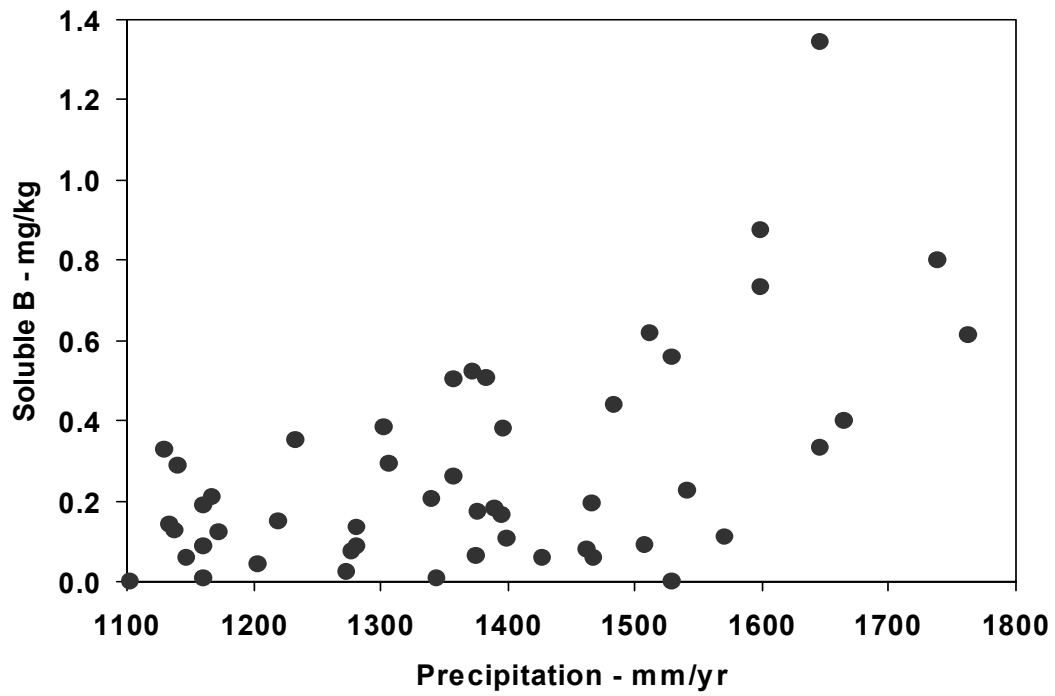


Figure 3. Readily soluble boron as a function of 30-year average annual precipitation for surface horizon soils.

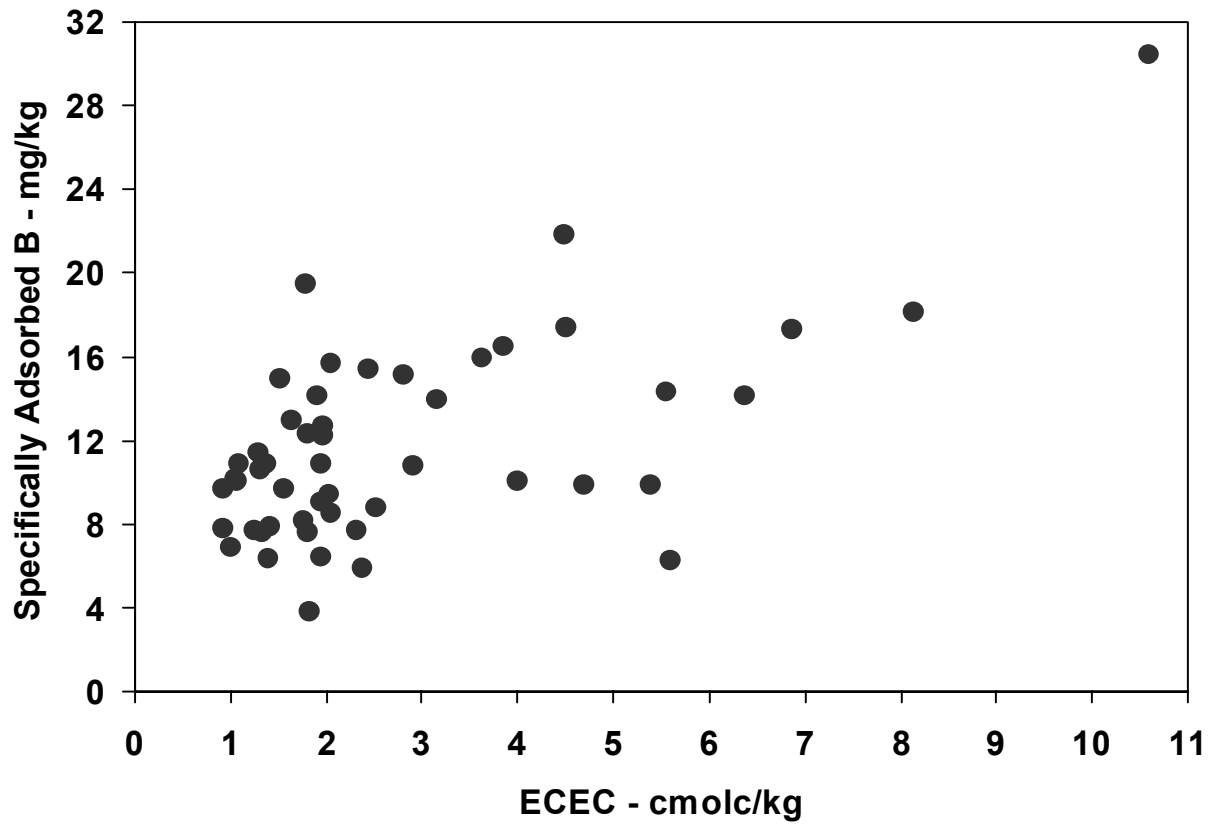
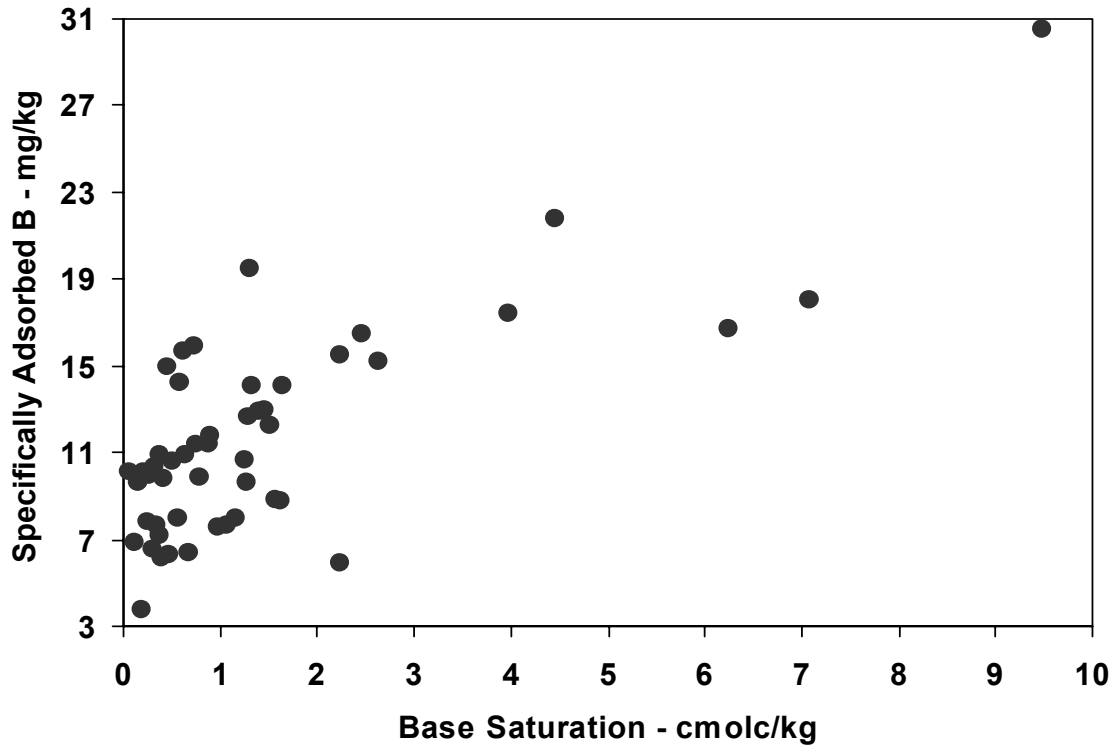


Figure 4. Specifically adsorbed boron as a function of ECEC for surface horizon soils.



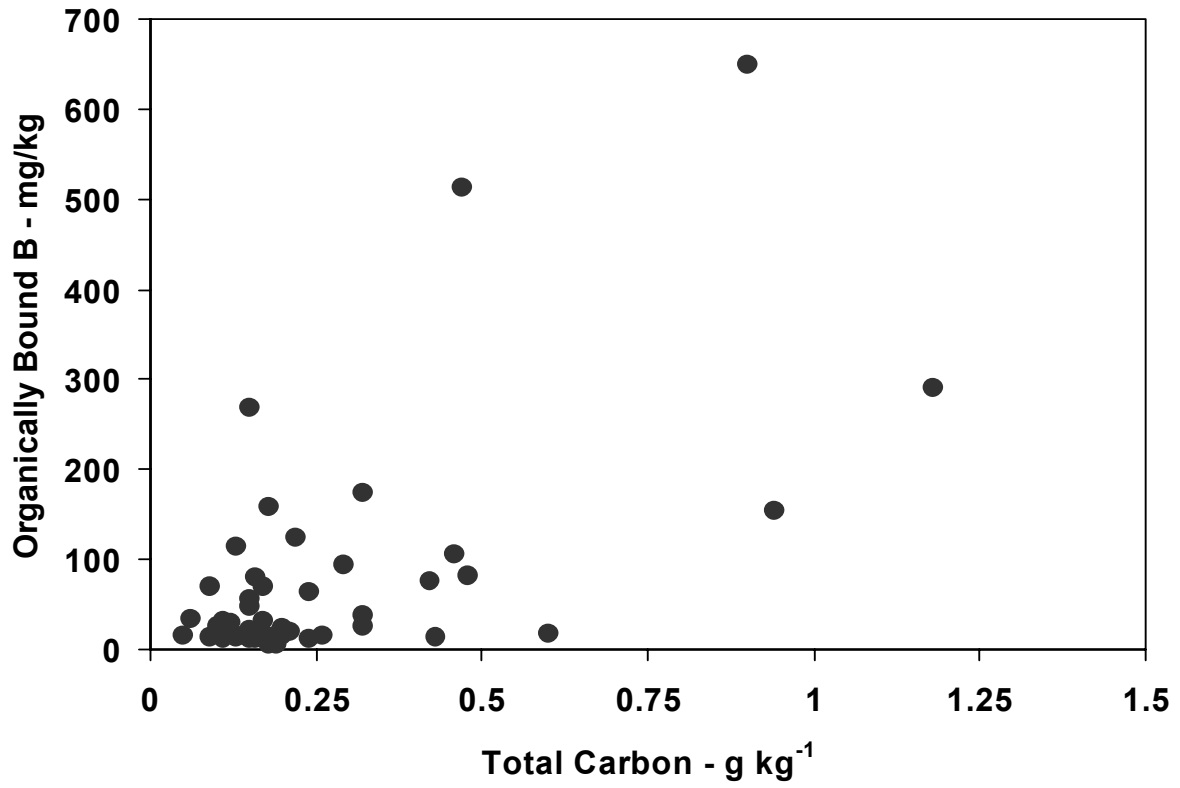


Figure 6. Organically bound boron as a function of total carbon for surface horizon soils.

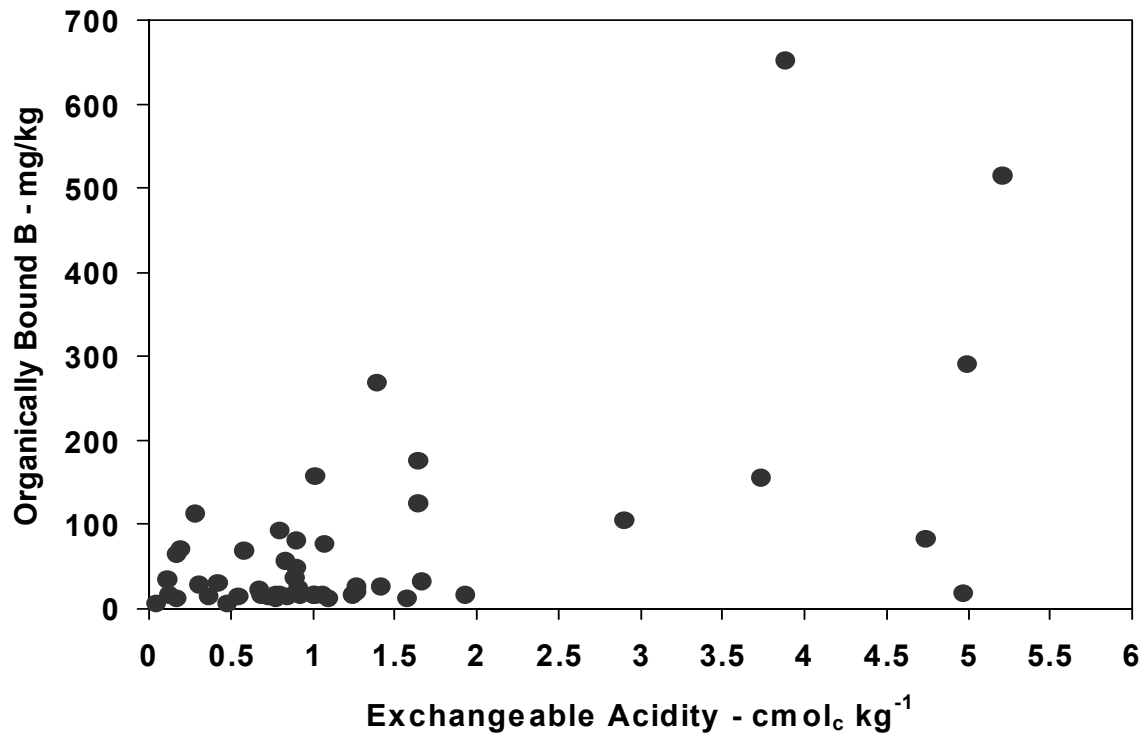


Figure 7. Organically bound boron as a function of exchangeable acidity for surface horizon soils.

Table 3. Boron fractions by drainage class and textural family (n=50).

Drainage Class	Textural Family	No. of Studies	Readily Soluble	Boron Fraction	
				Oxide Bound	Organically Bound
				----- mg kg ⁻¹ -----	
Poorly	Very fine	1	0.51	30.5	11.3
Poorly	Fine	5	0.26 (0.06)†	13.6 (2.0)	130.6 (95.6)
Poorly	Clay loam	2	0.12 (0.01)	11.2 (1.1)	91.9 (62.7)
Poorly	Fine-loam	5	0.30 (0.07)	10.5 (1.6)	215.2 (125.5)
Poorly	Loam	3	0.26 (0.15)	6.5 (1.3)	68.9 (53.2)
Poorly	Sand	3	0.10 (0.05)	7.8 (1.2)	77.3 (40.6)
Poorly	Average	19	0.24 (0.04)	11.4 (1.4)	124.4 (41.2)

Well	Fine	15	0.34 (0.08)	12.9 (3.9)	54.0 (16.7)
Well	Fine-loam	10	0.34 (0.10)	11.8 (1.3)	48.1 (13.7)
Well	Loam	5	0.03 (0.01)	10.7 (1.5)	30.4 (11.8)
Well	Sand	1	0.62	10.1	13.3
Well	Average	31	0.30 (0.06)	11.9 (0.70)	45.6 (9.5)

† Mean value with standard error in parentheses.

Table 4. Boron fractions by mineralogical family (n=50).

Mineralogy	No. of Studies	Boron Fraction		
		Readily Soluble	Oxide Bound	Organically Bound
----- mg kg ⁻¹ -----				
Kaolinitic	18	0.37 (0.09)†	10.6 (0.8)	35.9 (7.9)
Mixed	10	0.22 (0.04)	14.5 (1.3)	55.7 (23.7)
Siliceous	19	0.21 (0.04)	9.7 (0.7)	81.6 (18.8)
Smectitic	3	0.31 (0.10)	21.7 (4.4)	53.7 (40.4)

† Mean value with standard error in parentheses.

Table 5. Boron fractions by geological grouping (n=50).

Geological Grouping	No. of Studies	Boron Fraction		
		Readily Soluble	Oxide Bound	Organically Bound
----- mg kg ⁻¹ -----				
<i>Marine Sediments</i>				
Fine	18	0.35 (0.08)†	13.5 (1.3)	49.8 (14.7)
Medium	14	0.30 (0.07)	11.1 (1.0)	88.5 (23.4)
Coarse	10	0.17 (0.07)	9.2 (0.9)	55.5 (17.8)
<i>Metamorphic Rocks</i>				
Felsic	5	0.18 (0.06)	12.1 (1.5)	29.3 (13.0)
Mafic	1	0.15	21.8	5.6
<i>Sedimentary Rocks</i>				
Limestone	1	0.18	7.6	55.8
Shale	1	0.35	5.9	16.5

† Mean value with standard error in parentheses.

DISCUSSION

B Fractions

The readily soluble B fraction in this study represented a relatively narrow range, which is remarkably consistent with literature from many geographic areas of the world. Values obtained for the readily soluble B fraction were consistent with results presented by Jin et al., (1987, 1988); Hou et al., (1994); Lambert et al., (1997); Datta et al., (1998); Rahmatullah et al., (1999); and Xu et al., (2001). Readily soluble B extracted by Ratto de Miguez et al., (1999) covered a larger range (0.20 to 2.60 mg B kg⁻¹ soil) than our values. Soil samples analyzed by Lombin (1985) found a much narrower range of readily soluble B values (0.18 to 0.36 mg B kg⁻¹ soil).

These relatively narrow ranges of readily soluble B suggest that only small quantities of B can be held in this fraction. This may be due to the immediate demand by plants for B and the highly sensitive nature of this fraction to environmental changes. Precipitation and drought are two key environmental changes that regulate the readily soluble B fraction via mass flow.

The oxide bound B fraction covered a sizeable range in the current dataset (3.8 to 30.5 mg B kg⁻¹ soil). Literature containing oxide bound B fractions contained a wide range of values. Jin et al., (1987, 1988) and Rahmatullah et al., (1999) reported oxide bound values of 8.7 to 73.4 and 15 to 30 mg B kg⁻¹ soil, respectively. Conversely, oxide bound B values from my research were nearly 10 times greater than the results of Hou et al., (1994) (0.00 to 1.69 mg B kg⁻¹ soil) and over 100 times greater than those of Xu et al., (2001) (<0.01 to 0.70 mg B kg⁻¹ soil).

The agricultural soils used by Hou et al., (1994) were relatively young, sedimentary soils from Ontario, Canada, that have undergone considerably less weathering in comparison to the highly weathered soils of the Southeastern United States (Evans, 1987, 2002). This lack of soil development may suggest that with minimal weathering, B has not been released into biogeochemical cycle of Canadian soils to the extent it has in the Southeast. Lambert and Ryan (1990) found that good soil development helped improve B availability even on parent materials low in B.

The Chinese soils of Xu et al., (2001) contained soils of similar taxonomy; however, high precipitation areas likely increased the weathering of the parent materials and the soil development, whereby releasing more B to the soil solution. Low precipitation areas will limit weathering and soil development, which in turn may decrease the availability of B in the soil solution via mass flow.

Although clay contents were quite similar for the oxide bound B studies presented above, the specific type of clay mineral found in has the greatest effect on soil B content. Phyllosilicate minerals have a wide range of surface areas, with kaolinitic minerals having relatively low surface areas, while smectitic minerals have much higher surface areas (Sparks, 1995). These higher surface area minerals such as smectite may provide more adsorption sites for B to bind.

The organically bound B fraction ranged from 5.1 to 650.6 mg B kg⁻¹ soil. Hou et al., (1994) and Lambert et al., (1997) are the only authors that had reported organically bound B values in the literature prior to this study. The values obtained in the current research contained a significantly wider range of B values than the two studies presented. The organically bound B fraction values for the Australian soils of

Lambert et al. (1997) ranged from 15.7 to 60.8 mg B kg⁻¹ soil. These values were nearly considerably lower than the values found in the current research. The methods of Lambert et al. (1997) also utilized slightly different extraction methods than that of the current study, which were adapted from Hou et al. (1994). Hou et al. (1994) found values ranging from 0.00 to 11.03 mg B kg⁻¹ soil with a mean of 3.57 mg B kg⁻¹ soil. The values of Hou et al. (1994) were an order of magnitude less than the current research.

Lambert et al. (1997) selected soils to coincide with a range of geologic materials found in forests of Australia. The Canadian soils of Hou et al. (1994) developed under a significantly different set of conditions than those found in the Southeastern US and Australian forests. The crop being grown is one significant difference between the soils of Hou et al. (1994) and the Australian and US soils. Agricultural crops are harvested annually, which significantly reduces the inputs from the above-ground biomass. Pine forests generally have a litterfall every year, which contributes considerable quantities of needles and subsequently B through the cell wall material. The high levels of B found in the organically bound fraction in this study may suggest that B is bio-accumulating in the soil organic fraction from annual litterfall deposits. Gurlevik et al. (2003) determined that approximately 40 percent of the B contained in the forest floor was released through decomposition the first year. The loss of this critical B input could explain the differences in organically bound B levels between forest and agricultural soils.

Although no direct correlations existed among B fractions in this study, only simple linear correlations were tested. More complex relationships inevitably exist

among the fractions. These complex relationships among the fractions are possibly controlled by changes in site conditions and differences in soil properties as well as land use history. Limited knowledge of these fractions hinders the overall understanding of their relationships and the ability to predict B availability.

B Fractions and Soil Properties

Readily Soluble

Interestingly, soil samples stored up to 20 years in some instances, showed a significant positive relationship with 30-year average annual precipitation. This relationship possibly depicts the results of long-term weathering and release of B into the soil solution. Unlike our study, other researchers found precipitation to be negatively correlated with readily soluble B (Page and Paden, 1954; Xu et al., 2001). Xu et al. (2001) attributed this inverse relationship to greater leaching in areas with higher precipitation and the influence of soil properties such as texture. Page and Paden (1954) indicate that B deficiency occurs as a result of high rainfall and the subsequent leaching of B through the soil profile. Hobbs and Bertramson (1949) found a relationships between B deficiency symptoms and precipitation in which they theorized that B deficiencies were a result of low soil moisture conditions and not necessarily low levels of B in the soil.

The simple positive relationship found in the current study between precipitation and the readily soluble B fraction may be indirectly related to water's influence on soil and geologic materials. Weathering processes include dissolution, hydration, hydrolysis, oxidation, reduction, and carbonation (Kabata-Pendias and Pendias, 1984). These processes require the presence or absence of water to

complete their chemical reaction. This necessity for water alludes to the possible link between precipitation and the inherent levels of readily soluble B in the soil. Regardless of this explanation is difficult to pinpoint an apparent reason for this relationship.

Well-drained soils contained higher levels of the readily soluble B when considering drainage class across all textural classes. Within drainage classes, well-drained, coarse-textured soils and fine-textured, poorly drained soils yielded the highest levels of readily soluble B.

Sedimentary rocks of marine origin contained the highest levels of readily soluble B in the current dataset (Table 5). According to Fairbridge (1972) most parent materials are relatively poor in B, with the exception of marine sediments.

Igneous rocks generally contain the lowest levels of total B (5 to 10 mg kg⁻¹) with metamorphic rocks following close behind, with an average of 5 to 50 mg kg⁻¹) (Table 6). Sedimentary rocks, especially those of marine origin contain between 50 and 500 mg kg⁻¹ of total B. The high levels of B in marine sedimentary rocks have a strong bearing on soils derived from these parent materials and stress the importance of knowing the geology of a particular site.

Table 6. Total B content in selected geologic materials.

Geologic Material	B (mg kg ⁻¹)	Reference
<i>Igneous Rocks</i>	5-10	Goldschmidt (1958) and Fairbridge (1972)
Acid Rocks	3-30	Barber (1984), Kabata-Pendias and Pendias (1984), and Walker (1975)
Basic Rocks	1-5	Barber (1984) and Walker (1975)
Granites	10-15	Goldschmidt (1958), Adriano (1986), and Sparks and Evans (1983)
Basalts	0.1 –6	Marshall and Fairbridge (1999) and Goldschmidt (1958), and Adriano (1986)
<i>Metamorphic Rocks</i>	5-50	Barber (1984) and Walker (1975)
Gneiss	10	Walker (1975)
Slate	2-50	Walker (1975)
<i>Sedimentary Rocks</i>	20-100	Krauskopf (1979) and Sparks and Evans (1983)
Shales	100-130	Kabata-Pendias and Pendias (1994), Krauskopf (1979), and Walker (1975)
Sandstones	30-35	Kabata-Pendias and Pendias (1984), Krauskopf (1979)
Limestones	20-30	Kabata-Pendias and Pendias (1984) and Sparks and Evans (1983)
Marine sediments	100-500	Kabata-Pendias and Pendias (1984) and Marshall and Fairbridge (1999)
Marine clay sediments	50-500	Goldschmidt (1958)
Non-marine clay sediments	5-10	Goldschmidt (1958)

Specifically Adsorbed

The oxide bound fraction was significantly positively correlated with ECEC and base saturation. The ECEC relationship suggests that with an increasing number of adsorption sites, more B may be sorbed. Surface area may prove to be a surrogate for ECEC, since an increase in surface area generally coincides with a larger number adsorption sites. These adsorption sites are essential to retaining as much B within the soil profile, thus maintaining a B pool for future plant needs.

The relationship with base saturation is very similar to that of ECEC, since base saturation is a component of ECEC total. This increase in base saturation will also provide more adsorption sites.

Poorly and well-drained soils contained similar levels of oxide bound B across textural classes. Fine-textured soils contained the highest levels of oxide bound B within drainage class possibly due to the type of extraction method and the binding affinity of clay particles. Keren and Bingham (1985) and Keren (1996) theorized that B is adsorbed on clay mineral edges rather than planar surfaces, as did De Bussetti et al., (1995) who theorized that most B adsorption sites are located on the rough edges of clay particles. Clay particles generally have higher surface areas than coarse particles, which may provide a greater number of binding sites for B. The high levels of B found were found in the smectitic mineralogical family. Goldberg and Glaubig (1985), found that materials with high surface areas had the highest B adsorption. Smectites formed from micas are likely to contain the highest levels of boron (Dixon and Weed, 1977).

Organically Bound B

Not surprisingly, the organically bound B fraction was significantly positively correlated with total carbon. Three data points fell outside of the range of the other data. These points contained the highest levels of organically bound B and are all from the Aquic suborder, which indicates that they have poorly drained characteristics and generally more organic matter. These sites have been reported to be some of the most productive pine plantations in the Southeast (Allen, 2004; Campbell, 2004).

The high binding affinity of humic substances may explain the relationship with organic B fraction and the majority of B being found in this fraction. Parks and White (1952) were the first to indicate the importance of humic substances as a sink for B. Lambert, Turner, and Knott (1997) and Yerimayahu (2001) reaffirm the importance of organic matter as the primary sink for maintaining B in soils.

Humic substances are comprised of varying degrees of humic and nonhumic constituents. Different structural compositions of organic matter may have different binding effects with B. Research by Hou et al. (1996) found that no significant relationship existed between humic acid and organically bound B. Lambert et al., (1997) extracted organically bound B by humic fraction and found that the fulvic acid fraction contained the highest levels of B. The work of Lambert et al. (1997) provides some indication that fulvic acids may play an important role in binding and subsequently releasing B. According to Stevenson (1982), forest soils contain humic substances that are dominated by fulvic acids. Fulvic acids are easily degraded by microbial activity and acidic conditions (Brady, 1990; Sparks and

Evans, 1983), which may suggest that greater quantities of B can be released in the acidic, forest soils of the Southeast.

Yerimayahu et al., (1988, 2001) suggests that organic matter's capacity to bind with B is at least 4 to 7 times greater than that of clays and soils on a weight basis, which is consistent the results of my study. Although, this capacity of organic matter to bind with B has been suggested, only recently have mechanisms for this adsorption been investigated. The mechanism for B adsorption in the presence of organic matter is likely to be ligand exchange (Yerimayahu et al., (1988); Gu and Lowe, 1990). The boric acid molecule and the borate anion can complex with hydroxycarboxylic acids, dicarboxylic acids, and diol groups depending on the pH of the solution (Schmitt-Koplin et al., 1998). Schmitt-Koplin et al., (1988) also present findings showing B binding as bidentate monoesters and tridentate diesters.

The relationship between organically bound B and exchangeable acidity is significantly and positively correlated ($r = 0.60$). This relationship involves pH, where the decrease in exchangeable acidity will subsequently raise pH. Since rising pH is known to negatively affect the availability of B (Gupta, 1997), exchangeable acidity can be viewed as possible surrogate for pH, where it indirectly affects the outcome.

Organically bound B for poorly drained soils was found to be nearly triple that of well-drained soils. Poorly drained soils in this study contained twice as much organic matter as the well-drained soils. These higher levels of organic matter may provide more opportunities for complexation of B. Poorly drained soils may also contain organic matter that has a different overall makeup than that of well-drained soils, which may suggest different binding capabilities. The high binding affinity of

organic matter and the elevated levels of organic matter suggest higher levels of organically bound B. Levels of organically bound B presented by Hou et al. (1994) in poorly drained soils were nearly twice that of well-drained soils, supporting the trend of the current dataset.

All mineralogical families contained substantial portions of organically bound B; however, the siliceous mineralogy contained the highest overall levels (Table 5). In the Southeast, the siliceous mineralogy is normally related marine sediments and poorly drained soils. Since poorly drained soils contained nearly double that of well-drained soils, this may provide an explanation for the increased levels of B. Marine sediments contain the highest overall level of organically bound B. This is due to the high levels of B found in the ocean (4.6 mg B L^{-1}).

CONCLUSIONS

The organically bound fraction contained the highest levels of B amongst the three fractions analyzed. Simple linear relationships were found for all three fractions with soil and site properties; however, no simple linear relationships were found among the three B fractions. Drainage class was critical to differentiating the readily soluble and organically bound fractions. The organically bound B fraction contained the highest overall quantities of B. Poorly drained soils contained the highest levels of the organically bound B fraction. Marine sedimentary rocks were found to contain the highest levels of B across all fractions.

The characterization of B across Southeastern forests should begin to shed some light into the available quantities of B in the soil fractions and provide the initial work to better manage southern forests for this important micronutrient.

Future work should focus on combining foliar and tree growth data to further explain the relationships of B in intensively managed forests. A more involved study of organically bound B and its release to subsequent fractions may provide some indication of the available B supply in the soil.

LITERATURE CITED

- Adriano, D.C. 1986. Trace Elements in the Terrestrial Environment. New York, Springer-Verlag.
- Aitken, R.L., A.J. Jeffrey, and B.L. Compton. 1987. Evaluation of selected extractants for boron in some Queensland soils. *Aust. J. Soil Res.* 25:263-273.
- Allen, H.L. 2004. Personal communication.
- Barber, S.A. 1984. Soil Nutrient Bioavailability. John Wiley & Sons, Inc, New York, NY.
- Berger, K.C. 1962. Micronutrient deficiencies in the United States. *Agric. and Food Chemistry.* 10:178-181.
- Berger, K.C. and E. Truog. 1945. Boron Availability In Relation to Soil Reaction and Organic Matter Content. *Soil Sci. Soc. Am. Proc.*, 10:113-116.
- Berger, K.C. and E. Truog. 1944. Boron Tests and Determination for Soils and Plants. *Soil Science*, 57:25-36.
- Berger, K.C. and E. Truog. 1939. Boron Determination in Soils and Plants Using the Quinalizarin Reaction. *Industrial and Engineering Chemistry, Analytical Ed.*, 11:540-545.
- Brady, N.C. 1990. Nature and Properties of Soils 10th (ed.). MacMillan Publishing Company, New York, NY.
- Buol, S.W., F.D. Hole, R.J. McCracken, and R.J. Southard. 1997. Soil Genesis and Classification, 4th edition. Iowa State University Press, Ames, Iowa.
- Burns, R.M. and B.H. Honkala, tech. cords. 1990. Silvics of North America: 1. Conifers. Agricultural Handbook 654. U.S. Department of Agriculture, Forest Service, Washington, DC. Vol. 1, 675 p.
- Campbell, R.G. 2004. Personal communication.
- Carter, M.R. (ed.). 1993. Soil Sampling and Methods of Analysis, Soil Reaction and Exchangeable Acidity. Canadian Society of Soil Science. Lewis Publishers.
- Cartwright, B., K.G. Tiller, B.A. Zarcinas, and L.R. Spouncer. 1983. The Chemical Assessment of the Boron Status of Soils. *Aust. J. Soil Res.*, 21:321-332.

- Datta, S.P., P.B.S. Bhadoria, and S. Kar. 1998. Availability of Extractable Boron in Some Acid Soils, West Bengal, India. *Commun. Soil Sci. Plant Anal.*, 29 (15&16), 2285-2306.
- De Bussetti, S.G., E.A. Ferreiro, and A.K. Helmy. 1995. Sorption of Boron by Hydrous-Al Oxide. *Clays and Clay Minerals*, Vol. 43, No. 1, 58-62.
- Dible, W.T., E. Truog, and K.C. Berger. 1954. Boron Determination in Soils and Plants, Simplified Curcumin Procedure. *Analytical Chemistry*, Vol. 26, No. 2, 418-421.
- Dixon, J.B and S.B. Weed (ed.). 1977. *Minerals in Soil Environments*. Soil Science Society of America, Madison, Wisconsin.
- Elrashidi, M.A. and G.A. O'Connor. 1982. Boron Sorption and Desorption in Soils. *Soil Sci. Soc. Am. J.*, 46:27-31.
- Evans, L.J. 2002. Personal communication. July 29, 2002.
- Evans, L.J. 1987. Retention of Boron by Agricultural Soils from Ontario. *Can. J. Soil Sci.* 67:33-42.
- Fairbridge, R.W. (ed.) 1972. *The Encyclopedia of Geochemistry and Environmental Sciences*. Van Norstrand Reinhold Company, New York, NY.
- Flores, F.J. 2000. Personal communication.
- Foth, H.D. and B.G Ellis. 1997. *Soil Fertility* 2nd ed. Lewis Publishers, Boca Raton, FL.
- Goldberg, S. 1997. Reactions of Boron with Soils. *Plant and Soil*, 193:35-48.
- Goldberg, S. and R.A. Glaubig. 1985. Boron Adsorption on Aluminum and Iron Oxide Minerals. *Soil Sci. Soc. Am. J.*, 49:1374-1379.
- Goldschmidt, V.M. 1958. *Geochemistry*. Oxford University Press, London, England.
- Gu, B. and L.E. Lowe. 1990. Studies on the adsorption of boron on humic acids. *Can. J. Soil Sci.*, 70:305-311.
- Gupta, U.C. (ed.). 1993. *Boron and Its Role in Crop Production*. CRC Press, Boca Raton, Florida.
- Gupta, U.C. 1979. Boron Nutrition of Crops. *Adv. Agron.* 31:273-307.

Gupta, U.C. 1967. A Simplified Method for Determining Hot-Water-Soluble Boron in Podzol Soils. *Soil Sci.*, 103:424-428.

Gurlevik N., D.L. Kelting, and H.L. Allen. 2003. The effects of vegetation control and fertilization on net nutrient release from decomposing loblolly pine needles. *Can J. For. Res.* 33:(in press)

Hobbs, J.A. and B.R. Bertramson. 1949. Boron Uptake by Plants as Influenced by Soil Moisture. *Soil Sci. Soc. Am. Proc.*, 14:257-261.

Hou, J., L.J. Evans, and G.A. Spiers. 1994. Boron Fractions in Soils. *Commun. Soil Sci. Plant Anal.*, 25 (9&10), 1841-1853.

Hou, J., L.J. Evans, and G.A. Spiers. 1996. Chemical Fractionation of Soil Boron: I. Method Development. *Canadian J. Soil Sci.*, 76:485-491.

Jin, J., D.C Martens, and L.W. Zelanzny. 1988. Plant Availability of Applied and Native Boron in Soils with Diverse Properties. *Plant and Soil*, 105:127-132.

Jin, J, D.C Martens, and L.W. Zelanzny. 1987. Distributions and Plant Availability of Soil Boron Fractions. *Soil Sci. Soc. Am. J.*, 51:1228-1231.

Jordan, J.V. and W.L. Powers. 1946. Status of Boron in Oregon Soils and Plant Nutrition. *Soil Sci. Soc. Am. Proc.*, 11:324-331.

Kabata-Pendias, A. and H. Pendias. 1984. Trace Elements in Soils and Plants. CRC Press, Inc., Boca Raton, FL.

Keren, R. 1996. Boron. In *Methods of Soil Analysis. Part 3. Chemical Methods—SSSA Book Series No. 5.*

Keren, R. and F.T. Bingham. 1985. Boron in Water, Soils, and Plants. *Adv. Soil Sci.* 1:229-276.

Klute, A. (ed.). 1986. *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, 2nd Ed.* Soil Science Society of America and American Society of Agronomy. Madison, WI.

Krauskopf, K.B. 1979. *Introduction to Geochemistry 2nd ed.* McGraw-Hill, Inc., New York, NY.

Kubota, J., K.C Berger, and E. Truog. 1948. Boron Movement in Soils. *Soil Sci. Soc. Am. Proc.*, 13:130-134.

- Lambert, M.J., J. Turner, and J Knott. 1997. Boron nutrition of radiata pine plantations in Australia. In *Boron in Soils and Plants. Proceedings.* Eds. R.W. Bell and B. Berkasem. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 83-88.
- Lambert, M.J. and P.J. Ryan. 1990. Boron Nutrition of *Pinus radiata* in Relation to Soil Development and Management. *Forest Ecology and Management*, 30:45-53.
- Lambert, M.J. and J. Turner. 1977. Dieback in High Site Quality *Pinus radiata* Stands—The Role of Sulphur and Boron Deficiencies. *New Zealand Journal of Forest Science*, 7(3):333-348.
- Lombin, G. 1985. Micronutrient Soil Tests for the Semi-Arid Savannah of Nigeria: Boron and Molybdenum. *Soil Sci. Plant Nutr.*, 31 (1), 1-11.
- Mahler, R.L., D.V. Naylor, and M.K. Fredickson. 1984. Hot Water Extraction of Boron From Soils Using Sealed Plastic Pouches. *Commun. Soil Sci. Plant Anal.*, 15(5):479-482.
- Marshall, C.P. and R.W. Fairbridge. 1999. *Encyclopedia of Geochemistry.* Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Mortvedt, J.J., F. R. Cox, L.M. Shuman, and R.M. Welch Eds. 1991. *Micronutrients in Agriculture 2nd ed.* Soil Science Society of America, Inc.: Madison, WI.
- National Climatic Data Center (NCDC). 2001. World Wide Web. <http://www.ncdc.noaa.gov/oa/ncdc.html>
- NCSFNC. 2001. North Carolina State Forest Nutrition Cooperative Thirtieth Annual Report. Department of Forestry. North Carolina State Univ., Raleigh, NC. 17p.
- North Carolina State Forest Nutrition Cooperative (NCSFNC). 1994. Response to Nitrogen, Phosphorus, and Potassium Fertilization in Midrotation Loblolly Pine Plantations. NCSFNC Report No. 32. College of Forest Resources. North Carolina State Univ., Raleigh, NC.
- Novozamsky, I., L.L. Barrera, V.J. G. Houba, J.J. Van der Lee, and R. van Eck. 1990. Comparison of a Hot-water and Cold 0.01 M CaCl₂ Extraction Procedures for the Determination of Boron in Soil. *Commun. Soil Sci. Plant Anal.*, 21 (17&18), 2189-2195.
- Olykan, S. T., Adams, J. A., Nordmeyer, A. H., and McLaren, R. G. 1995. Micronutrient and Macronutrient Uptake by *Pinus radiata*, and soil boron fractions, as Affected by Added Nitrogen and Boron. *New Zealand Journal of Forest Science*, 25(1): 61-72.

Page, N.R. and W.R. Paden. 1954. Boron-Supplying Power of Several South Carolina Soils. *Soil Sci.*, 77:427-434.

Pais, I. and J.B. Jones, Jr. 1997. *The Handbook of Trace Elements*. St. Lucie Press (CRC Press), Boca Raton, Florida.

Parker, D.R. and E.H. Gardner. 1982. Factors Affecting the Mobility and Plant Availability of Boron in Some Western Oregon Soils. *Soil Sci. Soc. Am. J.*, 46:573-578.

Parker, D.R. and E.H. Gardner. 1981. The Determination of Hot-Water Soluble Boron in Some western Oregon Soils Using a Modified Azomethine-H Procedure. *Commun. In Soil Sci. Plant Anal.*, 12(12): 1311-1322.

Parks, W.L. and J.L. White. 1952. Boron Retention by Clay and Humus Systems Saturated with Various Cations. *Soil Sci. Soc. Am. Proc.*, 16:298-300.

Peterson, L.A. and R.C. Newman. 1976. Influence of Soil pH on the Availability of Added Boron. *Soil Sci. Soc. Am. J.*, 40:280-282.

Pritchett, W.L. and R.F. Fisher. 1987. *Properties and Management of Forest Soils*, 2nd edition. John Wiley and Sons, New York.

Purvis, E.R. 1939. The Present Status of Boron in American Agriculture. *Soil Sci Soc. Am. Proc.*, 4:316-321.

Rahmatullah, Badr-uz-zaman, M. Salim. 1999. Plant Utilization and Release of Boron Distributed in Different Fractions in Calcareous soils. *Arid Soil Research and Rehabilitation*, 13:293-303.

Ratto de Miguez, S., C. Diggs, and C. Ras. 1999. Effect of Some Soil Properties on Extractable Boron Content in Argentine Pampas Soils. *Commun. Soil Sci. Plant Anal.*, 30(15&16), 2083-2100.

Sah, R.N. and P.H. Brown. 1997. Techniques for Boron determination and their Applications to the Analysis of Plant and Soil Samples. *Plant and Soil*, 193:15-33.

Shuman, L.M., V.A. Bandel, S.J. Donohue, R.A. Isaac, R.M. Lippert, J.T. Sims, and M.R. Tucker. 1992. Comparison of Mehlich-1 and Mehlich-3 Extractable Soil Boron With Hot-Water Extractable Boron. *Commun. Soil Sci. Plant Anal.*, 23(1&2):1-14.

Schmitt-Koplin, Ph., N. Hertkorn, A.W. Garrison, D. Freitag, and A. Kettrup. 1988. Influence of Borate Buffers on the Electrophoretic Behavior of Humic Substances in Capillary Zone Electrophoresis. *Anal. Chem.*, (70) 3798-3808.

Sparks, D.L. 1995. Environmental Soil Chemistry. Academic Press. San Diego, CA.

Sparks, D.L. (ed). 1996. Methods of Soil Analysis. Part 3. Chemical Methods---SSSA Book Series No. 5. Soil Science Society of America and American Society of Agronomy, Madison, WI.

Sparks, D.L. and C.M. Evans. 1983. On the Chemistry and Mineralogy of Boron in Pure and in Mixed Systems: A Review. Commun. Soil Sci. Plant Anal., 14(9): 827-846.

Sparr, M.C. 1970. Micronutrient Needs – Which, Where, On What – In The United States. Commun. Soil Sci. Plant Anal., 1(5):241-262.

Spiers, G.A., L.J. Evans, S.W. McGeorge, H.W. Moak, and C. Su. 1990. Boron Analysis of Soil Solutions and Plant Digests using a Photodiode-array equipped ICP Spectrometer. Commun. Soil Sci. Plant Anal., 21 (13-16), 1645-1661.

Stevenson, F. J. 1982. Humus Chemistry—Genesis, Composition, Reactions. John Wiley & Sons, Inc. New York, NY.

Stone, E.L. 1990. Boron Deficiency and Excess in Forest Trees: A Review. Forest Ecology and Management, 37:49-75.

Tollenaar, H. 1969. Deficiencia de boro en plantaciones de pino en la zone central de Chile. Agric. Tech., 29:85-88.

Troeh, F.R. and L.M. Thompson. 1993. Soils and Soil Fertility, 5th ed. Oxford University Press, New York, NY.

Urrego, J.B. 2000. Personal communication.

Walker, C.T. (ed.). 1975. Geochemistry of Boron, Benchmark Papers in Geology Volume 23. Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania:

Wear, J.I. and R.M. Patterson. 1962. Effect of Soil pH and Texture on the Availability of Water-Soluble Boron in the Soil. Soil Sci. Soc. Am. Proc., 26:344-346.

Wilson, C.M., R.L. Lovvorn, and W.W. Woodhouse, Jr. 1951. Movement and Accumulation of Water-Soluble Boron within the Soil Profile. Agron. J., 43:363-367.

Wolf, B. 1971. The Determination of Boron in Soil Extracts, Plant Materials, Composts, Manures, Water, and Nutrient Solutions. Soil Science and Plant Analysis, 2(5), 363-374.

Wolf, B. 1974. Improvements in the Azomethine-H Method for the Determination of Boron. *Commun. Soil Sci. Plant Anal.*, 5(1), 39-44.

Xu, J.M., K. Wang, R.W. Bell, Y.A. Yang, and L.B. Huang. 2001. Soil Boron Fractions and Their Relationship to Soil Properties. *Soil Sci. Soc. Am. J.*, 65:133-138.

Yerimayahu, U., R. Keren, and Y. Chen. 1988. Boron Sorption on Composted Organic Matter. *Soil Sci. Soc. Am. J.*, 52:1309-1313.

Yerimayahu, U., R. Keren, and Y. Chen. 1995. Boron Sorption by Soil in the Presence of Composted Organic Matter. *Soil Sci. Soc. Am. J.*, 59:405-409.

Yerimayahu, U., R. Keren, and Y. Chen. 2001. Effect of Composted Organic Matter on Boron Uptake of Plants. *Soil Sci. Soc. Am. J.*, 65:1436-1441.

APPENDICES

Appendix A. Descriptions of soils used for boron analyses.

Soil Series	Subgroup	Mineralogy Family	Textural Family	No. of Studies
Ailey	Arenic Kanhapludults	Kaolinitic	Loamy	1
Appling	Typic Kanhapludults	Kaolinitic	Fine	1
Bladen	Typic Albaquults	Mixed	Fine	1
Blanton	Grossarenic Paleudults	Siliceous	Loamy	1
Brantley	Ultic Hapludalfs	Mixed	Fine	1
Cecil	Typic Kanhapludults	Kaolinitic	Fine	3
Colita	Typic Glossaqualfs	Siliceous	Fine-loamy	1
Cowarts	Typic Kanhapludults	Kaolinitic	Fine-loamy	1
Dothan	Plinthic Kandiudults	Kaolinitic	Fine-loamy	1
Durham	Typic Hapludults	Siliceous	Fine-loamy	1
Eustis	Psammentic Paleudults	Siliceous	Sandy	1
Evadale	Typic Glossaqualfs	Smectitic	Fine	1
Fullerton	Typic Paleudults	Kaolinitic	Fine	1
Fuquay	Arenic Plinthic Kandiudults	Kaolinitic	Loamy	1
Greenville	Rhodic Kandiudults	Kaolinitic	Fine	1
Iredell	Oxyaquic Vertic Hapludalfs	Mixed	Fine	1
Leaf	Typic Albaquults	Mixed	Fine	2
Lynchburg	Aeric Paleaquults	Siliceous	Fine-loamy	2
Marlboro	Typic Paleudults	Kaolinitic	Fine	1
Meggett	Typic Albaqualfs	Mixed	Fine	1
Olustee	Ultic Alaquods	Siliceous	Sandy	2
Orangeburg	Typic Kandiudults	Kaolinitic	Fine-loamy	3
Pantego	Umbric Paleaquults	Siliceous	Fine-loamy	2
Pelham	Arenic Paleaquults	Siliceous	Loamy	2
Sacul	Aquic Hapludults	Mixed	Fine	3
Seagate	Typic Haplohumods	Siliceous	Sandy	1
Smithdale	Typic Hapludults	Siliceous	Fine-loamy	2
Stilson	Arenic Plinthic Paleudults	Siliceous	Loamy	1
Stough	Fragiaquic Paleudults	Siliceous	Coarse-loamy	1
Susquehanna	Vertic Paleudalfs	Smectitic	Fine	1
Sweatman	Typic Hapludults	Mixed	Fine	1
Tifton	Plinthic Kandiudults	Kaolinitic	Fine-loamy	1
Torhunta	Typic Humaquepts	Siliceous	Coarse-loamy	1
Troup	Grossarenic Kandiudults	Kaolinitic	Loamy	1
Wagram	Arenic Kandiudults	Kaolinitic	Loamy	1
Wilcox	Chromic Dystruderts	Smectitic	Very-fine	1

Appendix B. Summary of Boron Fraction Analyses for Surface Horizon Soils.

Study	Location	Horizon	Drainage Class	Readily* Soluble	Oxide Bound	Organically Bound
130402	Amelia, VA	A	W	0.00	10.6	15.6
130502	Bienville, LA	A	P	0.23	18.1	15.4
130702	Decatur, GA	A	W	0.06	13.0	65.1
130902	Brunswick, NC	A	P	0.50	9.8	290.3
130903	Cumberland, NC	A	P	0.12	10.0	154.6
131101	Colleton, SC	A	P	0.07	10.9	12.8
131102	Georgetown, SC	A	W	0.38	14.3	17.6
131103	Berkeley, SC	A	P	0.29	9.9	650.6
132402	Conecuh, AL	A	W	0.06	10.9	14.8
132403	Covington, AL	A	W	0.00	9.7	12.8
132601	Wayne, GA	A	P	0.01	10.1	157.5
132602	Wayne, GA	A	P	0.09	3.8	175.3
132604	Effingham, GA	A	W	0.04	6.3	15.4
132605	Bertie, NC	A	P	0.21	6.2	513.6
132702	Bradley, TN	A	W	0.18	7.6	55.8
133103	Sabine, LA	A	W	0.17	15.2	12.0
133104	Aiken, SC	A	W	0.01	7.8	16.8
133105	Greenwood, SC	A	W	0.14	8.8	80.8
142401	Escambia, AL	A	W	0.33	8.5	21.0
142402	Baldwin, AL	A	W	0.73	9.1	24.7
142403	Covington, AL	A	P	0.56	7.9	15.6
143201	Escambia, FL	A	W	0.61	7.7	17.1
143301	Baldwin, AL	A	W	0.80	7.7	16.4
143302	Escambia, AL	A	W	1.35	8.2	93.3
143303	Greene, MS	A	W	0.62	10.1	13.3
143304	Greene, MS	A	P	0.40	14.0	15.3
150102	Fairfield, SC	A	W	0.33	10.9	14.2
152603	Appling, GA	A	P	0.19	6.9	48.2
153202	Escambia, FL	A	W	0.88	12.2	124.9
153301	Choctaw, AL	A	W	0.11	9.4	34.9
153401	Trinity, TX	A	P	0.35	5.9	16.5
153901	Bibb, AL	A	W	0.44	9.7	113.6
153903	AL various	A	W	0.53	14.1	69.5
180101	Kershaw, SC	A	W	0.06	15.0	76.0
180301	Oglethorpe, GA	A	W	0.15	21.8	5.6
180601	Halifax, VA	A	W	0.29	17.4	13.9
180801	Craven, NC	A	P	0.38	14.1	82.9
181001	Marion, AL	A	W	0.09	19.5	5.1
181101	Berkeley, SC	A	P	0.26	15.9	105.7
182201	Wilkes, GA	A	W	0.13	12.7	22.2
182401	Nassau, FL	A	P	0.06	15.7	25.9
183101	Sabine, LA	A	W	0.17	15.5	70.7
183102	Vernon, LA	A	W	0.08	10.7	33.0
184001	Sumter, AL	A	P	0.51	30.5	11.3
184201	Brantley, GA	A	P	0.09	6.4	26.2
184202	Brantley, GA	A	P	0.14	7.7	15.9
184301	Webster, GA	A	W	0.02	11.4	31.1
184401	Bradley, AR	A	P	0.11	12.3	29.1
184501	Marengo, AL	A	W	0.21	17.3	37.2
184801	Newton, TX	A	W	0.19	16.5	269.1

* Units for boron fractions (mg B kg⁻¹ soil)