ASSESSMENT OF THE POTENTIAL ROLE OF ATMOSPHERIC ACIDIC DEPOSITION IN THE PATTERN OF SOUTHERN PINE BEETLE INFESTATION IN THE NORTHWESTERN COASTAL PLAIN OF GEORGIA, 1992-95

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96-4131

Prepared in cooperation with the
GEORGIA FORESTRY COMMISSION

Cover photograph by Richard Jernigan, Georgia Forestry Commission, showing southern pine beetle infestation in a loblolly pine forest near Providence Canyon State Park, Lumpkin, Georgia.

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Atlanta, Georgia
1996

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS, ACRONYMS AND ABBREVIATIONS, AND VERTICAL DATUM

CONVERSION FACTORS

Multiply	by	to obtain
	Length	
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
centimeter (cm)	0.3937	inch
micrometer (µm)	1	micron
	Weight and Rate	
gram (g)	3.52×10^{-2}	ounce (avdp)
kilogram (kg)	2.205	pound
megagram (Mg)	1.102	ton
milligram per kilogram (mg kg^{-1})	1	part per million
microgram (µg)	3.52×10^{-8}	ounce (avdp)
nanogram (ng)	3.52×10^{-11}	ounce (avdp)
kilogram per hectare (kg ha^{-1})	0.893	pound per acre
	Area	
hectare (ha)	2.471	acre
	Volume	
liter (L)	0.2642	gallon
milliliter (mL)	3.38×10^{-2}	ounce (fluid)
	Concentration	
nanoliter per liter (nL L^{-1})	1.28×10^{-7}	ounce (fluid) per gallon
centimole positive charge per kilogram ($cmol_c$ kg^{-1})	1.0	milliequivalent per 100 gram
	Flow	
cubic meter per second (m^3 s^{-1})	35.31	cubic foot per second
cubic meter per hour (m^3 h^{-1})	9.81×10^{-3}	cubic foot per hour

Temperature

Temperature, in degrees Celsius (° C) can be converted to degrees Fahrenheit (° F)] as follows:

$$° F = (9/5\ ° C) + 32$$

ACRONYMS AND ABBREVIATIONS

EPA	U.S. Environmental Protection Agency
EPD	Georgia Department of Natural Resources, Environmental Protection Division
GFC	Georgia Forestry Commission
GIS	Geographic Information System
NADP	National Acid Deposition Program
NAPAP	National Acid Precipitation Assessment Program
NCE	Net-Canopy Exchange
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resource Conservation Service (formerly called Soil Conservation Service)
NTN	National Trends Network
ODWT	Oven-dry, 105 ° Celsius constant weight
PMRW	Panola Mountain Research Watershed
ppb(v)	Parts per billion by volume
SCS	Soil Conservation Service (now called Natural Resource Conservation Service)
SPB	Southern pine beetle
STATSGO	State Soil Geographic Database
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

VERTICAL DATUM

Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

ASSESSMENT OF THE POTENTIAL ROLE OF ATMOSPHERIC ACIDIC DEPOSITION IN THE PATTERN OF SOUTHERN PINE BEETLE INFESTATION IN THE NORTHWESTERN COASTAL PLAIN OF GEORGIA, 1992–95

By *Thomas G. Huntington*

ABSTRACT

In response to unexplained chronic outbreaks of southern pine beetle in loblolly pine forests in Stewart and Chattahoochee Counties, Georgia, the U.S. Geological Survey and the Georgia Forestry Commission conducted a 3-year study to determine whether acidic deposition could explain the pattern of infestation. There were no significant differences in total acidic deposition between areas of high infestation in Stewart County and low infestation in adjacent Marion County. The annual rate of total atmospheric sulfur deposition in the highly infested area was 6.0 kilograms per hectare per year. This rate represents significant pollutant loading; however, it is somewhat lower than previously published estimates for the southern Piedmont and Coastal Plain physiographic provinces. There is no indication of significant local point sources. The annual rate of total atmospheric nitrogen deposition in the highly infested area was 5.9 kilograms per hectare per year which is comparable to previously published estimates.

Ambient air-quality measurements indicated that sulfur dioxide and ozone concentrations were comparable to typical values in rural areas of the southeastern United States. Ozone concentrations were high enough to constitute a chronic stress on sensitive loblolly genotypes. However, the limited data available do not indicate that there is a spatial correlation between ozone concentration and southern pine beetle infestation. Comparisons of soil properties that could be influenced by chronic acidic deposition between paired, infested and uninfested plots in Stewart County indicated that there were no significant differences that could explain susceptibility to infestation. Site conditions throughout the study area are marginal for economic production of loblolly pine because of low soil fertility and a tendency towards conditions of drought because of the common occurrence of sandy surface soils. County general soil maps indicate that the area of highest infestation contains a higher abundance of soils containing a subsurface horizon that is partially cemented and restrictive to rooting, when compared with areas of low infestation. Loblolly pine in the study area is growing under multiple, interacting stresses; and it is hypothesized that cumulative effects of these stresses are greater in the most highly infested areas.

INTRODUCTION

In 1992, unexplained chronic infestations of southern pine beetle (SPB), *Dendroctonus frontalis* Zimm. (Coleoptera: Scolytidae), infestations in loblolly pine (*Pinus taeda* L.) in Stewart and Chattahoochee Counties, Georgia (fig. 1), caused concern to commercial and private foresters. Infestations of SPB are common throughout the range of indigenous and planted loblolly pine in the southeastern United States; however, the pattern of persistence and severity in the northwestern Coastal Plain Province of Georgia was unprecedented in 1992.

Commercial and private foresters requested assistance from the Georgia Forestry Commission (GFC) to determine whether acidic deposition was related to the SPB infestations. The GFC was conducting an ongoing statewide Forest Health

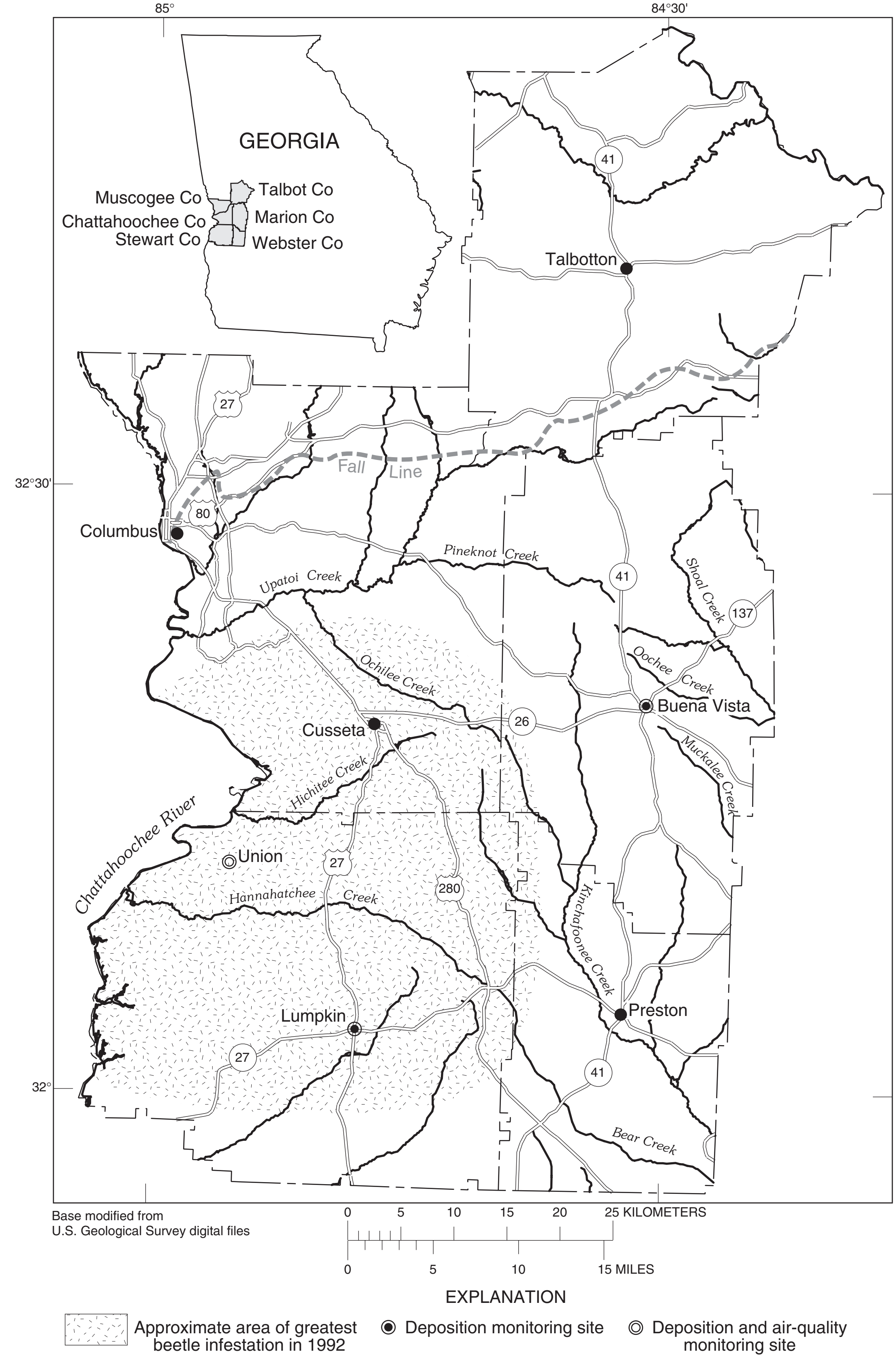


Figure 1. Counties in the study area, area of greatest southern pine beetle infestation (modified from Price and others, 1991), and location of deposition monitoring sites and air-quality monitoring sites.

Monitoring Program that included the development of hazard and risk assessments concerning the health of forests in Georgia. The U.S. Geological Survey (USGS) and the Georgia Forestry Commission then began a cooperative investigation in 1992 to examine the relation between various environmental factors and the geographic distribution of SPB infestations.

The area of greatest SPB infestation during much of the 1980's and the early 1990's was centered in southern Chattahoochee and Stewart Counties (Price and others, 1991; Joel Robertson, Champion International, written commun., 1992). Timber company land managers and landowners expressed concern that emissions from wood pulp processing facilities might be involved in the SPB problem.

Purpose and Scope

This report assesses the potential relation between atmospheric acidic deposition and geographic distribution of southern pine beetle infestation in the northwestern Coastal Plain Province of Georgia (fig. 1). Muscogee, Chattahoochee, Stewart, Talbot, Marion and Webster Counties were selected for study because they include areas of highest SPB infestation, as well as adjacent areas of lower infestation. The report includes a literature review, a comparison of total acidic deposition between areas of high and low infestation, an evaluation of ambient concentrations of sulfur dioxide and ozone, a comparison of soil properties and soil-water chemistry between adjacent infested and uninfested forest stands, and a comparison of stream-water chemistry between areas of high and low infestation.

The literature review includes previous investigations on the epidemiology of SPB, factors controlling outbreaks of SPB, the interaction between environmental stress and loblolly pine resistance to SPB attack, and effects of selected environmental stressors on loblolly pine. Total acidic deposition was measured during 1992–94 at a heavily-infested site in Stewart County and at a lightly-infested site in Marion County. Ambient concentrations of sulfur dioxide and ozone were monitored at one site in Stewart County in 1993–94. Soil properties including exchangeable cations, extractable sulfate, and soil organic matter were compared between adjacent infested and uninfested forest stands in Stewart and Webster Counties. Soil-water chemistry was evaluated by leaching field-moist samples collected from adjacent infested and uninfested forest stands with simulated acidic precipitation. Stream-water chemistry was compared between streams in areas of high and low infestation.

Acknowledgments

The author acknowledges technical support and advice by various personnel of the Georgia Forestry Commission, including Terry Price, John Horton, Todd Bell, Richard E. Jernigan, Neal Hendrix, and William Bagley. Special thanks also to Rosa Prior, Mr. and Mrs. Kenneth Slay, and Meade Coated Board, who gave access to their properties for the collection of throughfall samples and for ambient air-quality measurements.

The author wishes to thank Peter Lorio, Jr., U.S. Department of Agriculture, Forest Service, for his technical review and advice on portions of this report involving resistance of loblolly pine to SPB attack. Joel Robertson, Champion International, provided valuable background data on the historical pattern of SPB infestation in Stewart County, Ga., and collected some preliminary surface-water samples. Rafael Ballagus, Kathy Yeart, Mike Whigam, and Victor Barr of the Georgia Department of Natural Resources, Environmental Protection Division, Air Quality Branch, provided the loan, maintenance, and calibration of air-quality monitoring equipment. Victor Shelburne, Clemson University, loaned air-quality sampling equipment.

DESCRIPTION OF STUDY AREA

The study area (fig. 1) is located in the extreme northwestern Coastal Plain Province of Georgia. The area having the most extensive SPB infestation through much of the 1980's and until 1992 included most of Stewart and Chattahoochee Counties (fig. 1). During this period, relatively few incidences of infestation occurred in Marion County, immediately to the east of Chattahoochee County. Persistent and extensive infestations were first detected in Chattahoochee County in the early 1980's; however, the infestation spread progressively toward the south until, by 1992, all of Stewart County was affected (Joel Robertson, Champion International, unpublished data, 1992). Marion County was included to provide a relatively uninfested area having similar soils, geology, land use, forest type, topography, and climate for comparison with the more heavily infested areas in Stewart and Chattahoochee Counties.

Elevation ranges from about 70 meters (m) above sea level along the Chattahoochee River on the western border of Stewart County to about 180 m on ridges in Marion County. The area is highly dissected (fig. 2) with relief of 20 to 50 m common between ridges and stream valleys. Stewart and Chattahoochee Counties have somewhat steeper slopes than Marion County (fig. 3).

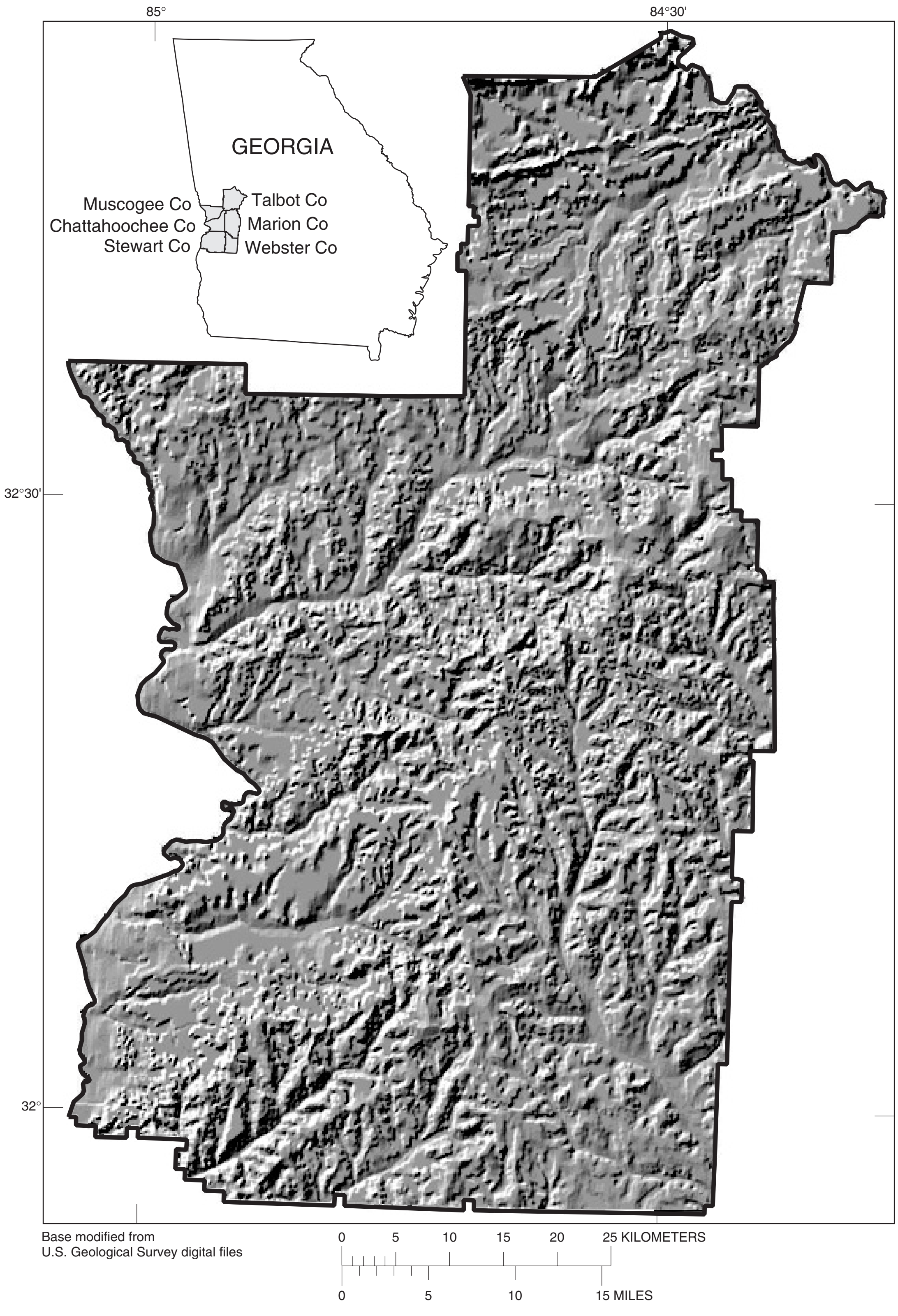


Figure 2. Shaded relief of the study area.

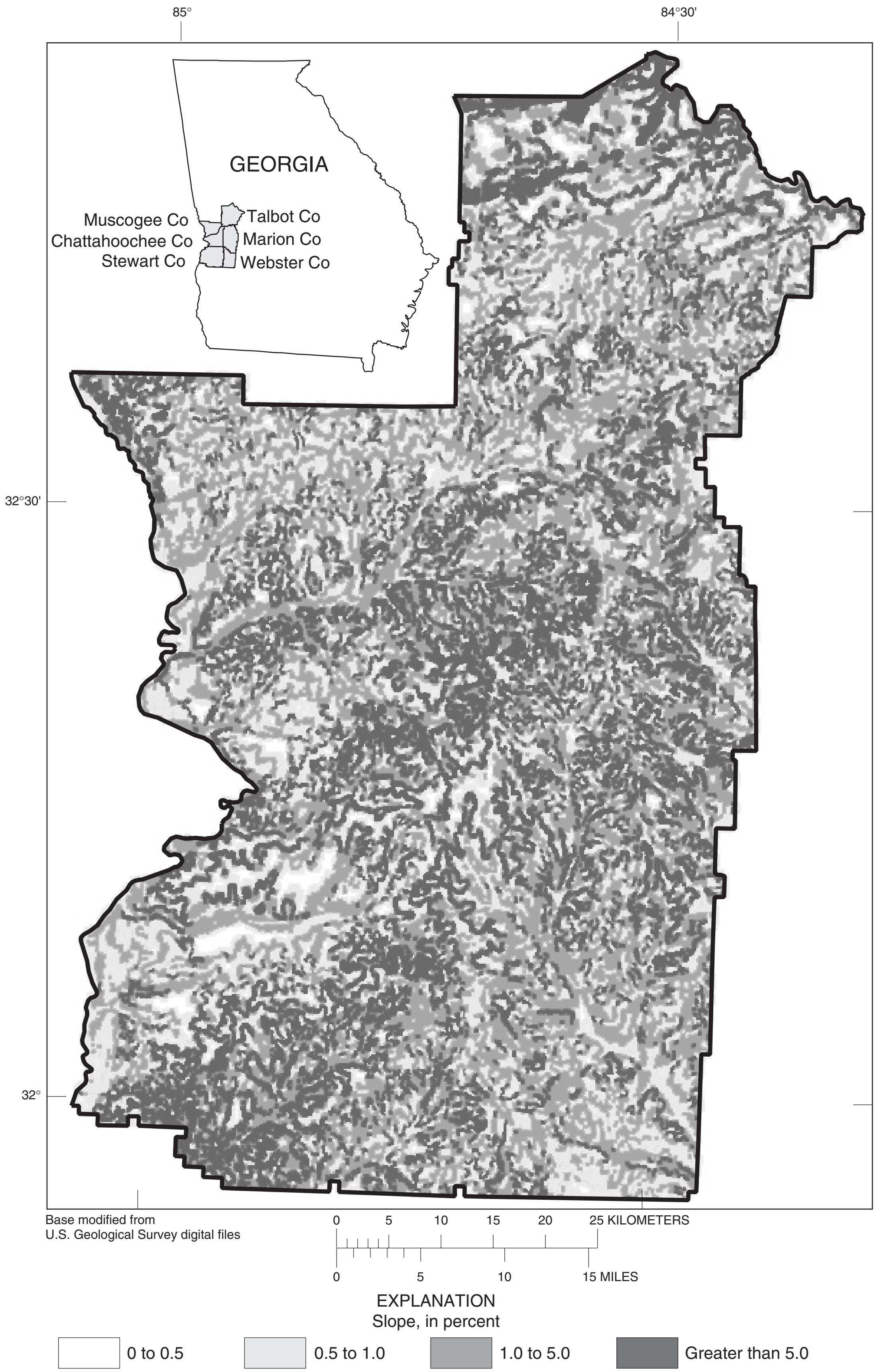


Figure 3. Slope, in percent, of the study area.

Climate

The climate of the area is classified as warm, temperate subtropical with a mean-annual temperature of 18 ° C (Hodler and Schretter, 1986). Annual precipitation averages 127 centimeters (cm) and is relatively evenly distributed throughout the year. There are large variations in total annual rainfall and in intra-annual rainfall distribution. Occasional low rainfall during the growing season combined with relatively high potential evapotranspiration results in periodic drought conditions in this area. Actual annual evapotranspiration averages 91.5 cm (Hodler and Schretter, 1986); therefore, annual water flux through surface soils (runoff plus recharge) averages about 35.5 cm.

Land Use

Stewart County was first settled by Europeans in 1827 after displacement of the Creek Indians (Dixon, 1975). Judging from records published by Dixon (1975) Stewart County was settled rapidly, and by 1850, the population was about 16,000. By 1850, 20 grist mills and 15 saw mills were in operation and there were about 59,000 hectares of improved land. Corn and cotton were the major agricultural crops in the region. The population fluctuated between the years 1850 and 1990 (table 1) in response to changes in viability of agriculture in the region.

Table 1. Population of Stewart County, Georgia

Year	Population
1/1850	16,000
1/1900	5,856
1/1910	13,437
2/1970	6,511
2/1980	5,896
2/1990	5,654

1/ From Dixon (1975).

2/ From Akioka (1994)

Much of the area now forested was once under agricultural land use. Extensive erosion is evident throughout the steeper parts of the study area. A particularly spectacular example is the Providence Canyon State Park, near Lumpkin, in Stewart County, Ga., where some gullies are more than 30 m deep.

Land use, derived from (1988–90) Landsat Thematic Mapper imagery (fig. 4), was similar in Stewart and Marion Counties with the exception that there was somewhat more cultivated agricultural land in Marion County than in the heavily infested area of Stewart County. In the northern part of Marion County, a higher proportion of land was coniferous forest than in Stewart and Chattahoochee Counties. The larger proportion of coniferous forest probably is indicative of a higher density of plantation pine in that area, as opposed to with more naturally regenerated mixed forest type in Chattahoochee and Stewart Counties.

Forestry is very important for the local economy throughout the study area. All six counties had more than 50 percent in forest land; and Chattahoochee, Stewart, Marion, and Talbot all had more than 75 percent in forest land managed for timber production (Hodler and Schretter, 1986). Predominant forest land ownership varied substantially between counties (based on 1982 data from Hodler and Schretter, 1986). In Muscogee and Chattahoochee Counties, the predominant ownership was public. In Marion and Webster Counties, the predominant ownership was forest industry. In Stewart and Talbot Counties, the predominant ownership was private. The proportion of private and public forest lands that are managed by the timber industry is not known.

Geology

Surficial geologic units in the study area generally consist of various igneous and regional metamorphic rock types in the northwestern quarter of the area (Muscogee and Talbot Counties), and various sedimentary rock types in the remainder of the area (Chattahoochee, Marion, Stewart, and Webster Counties). In the northwestern quarter of the area, igneous and metamorphic rocks occur in northeast-trending outcrop bands (fig. 5). The petrology of this complex of rocks is extremely variable and is beyond the scope of this report.

Geologic units in the southeastern three quarters of the study area generally consist of Upper Cretaceous to lower Tertiary marine and restricted marine sands, interbedded with silty clay beds of variable thickness (Reinhardt and Gibson, 1980; Reinhardt and others, 1994). These strata generally were deposited along a southeast-regressing shoreline; many of the formations contain abundant marine fossils (Reinhardt and Gibson, 1980; Reinhardt and others, 1994). Marine and restricted marine sands vary in texture from coarse to fine and may be glauconitic, micaceous, or calcareous in nature (Reinhardt and Gibson, 1980). Chattahoochee and Marion Counties, and all but the extreme southeastern portion of Stewart County, have similar spatial distribution of surficial geologic units being predominantly Providence Sand, Ripley Formation, Cusseta Sand, and Blufftown Cretaceous formations (fig. 5).

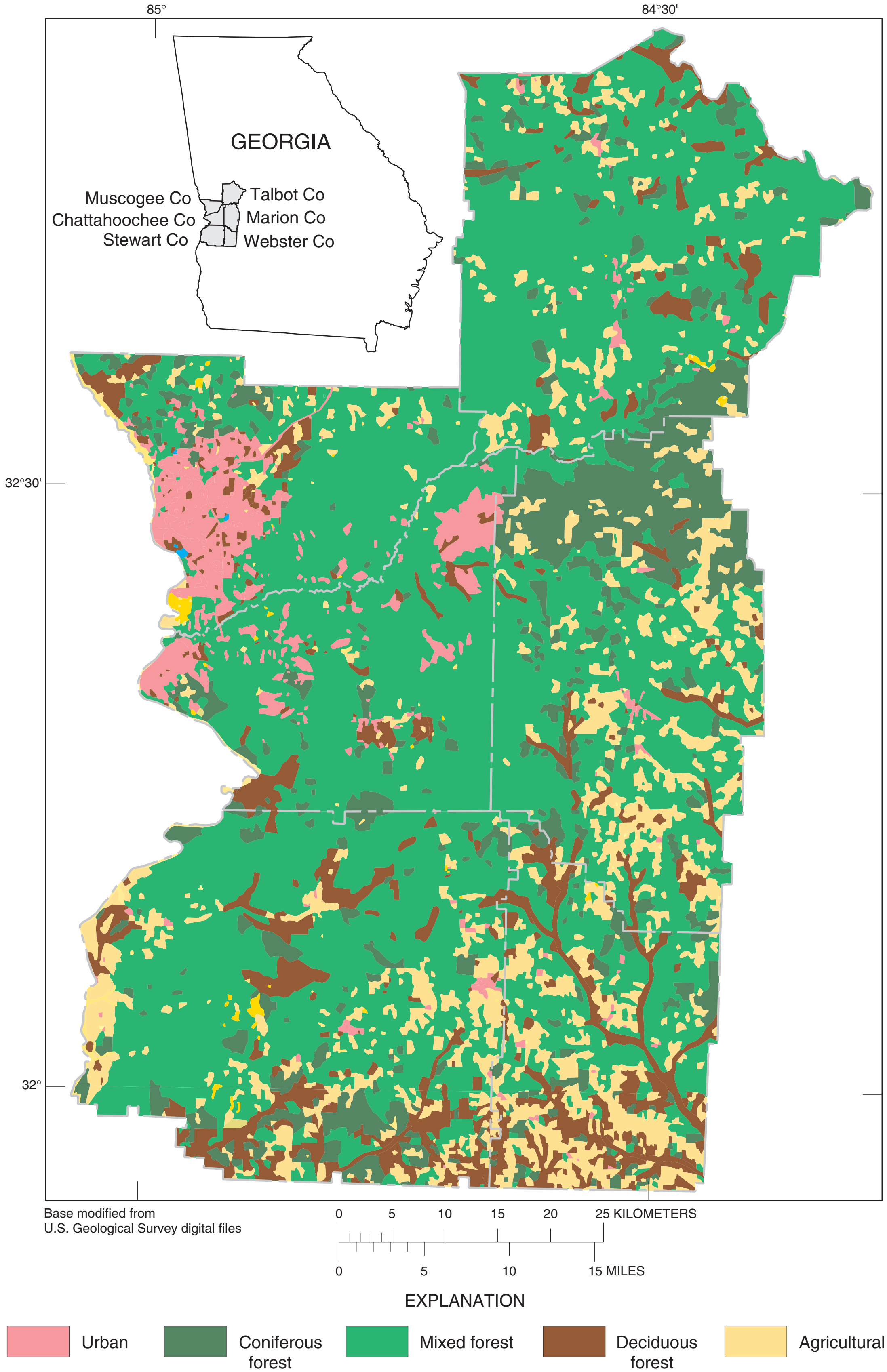
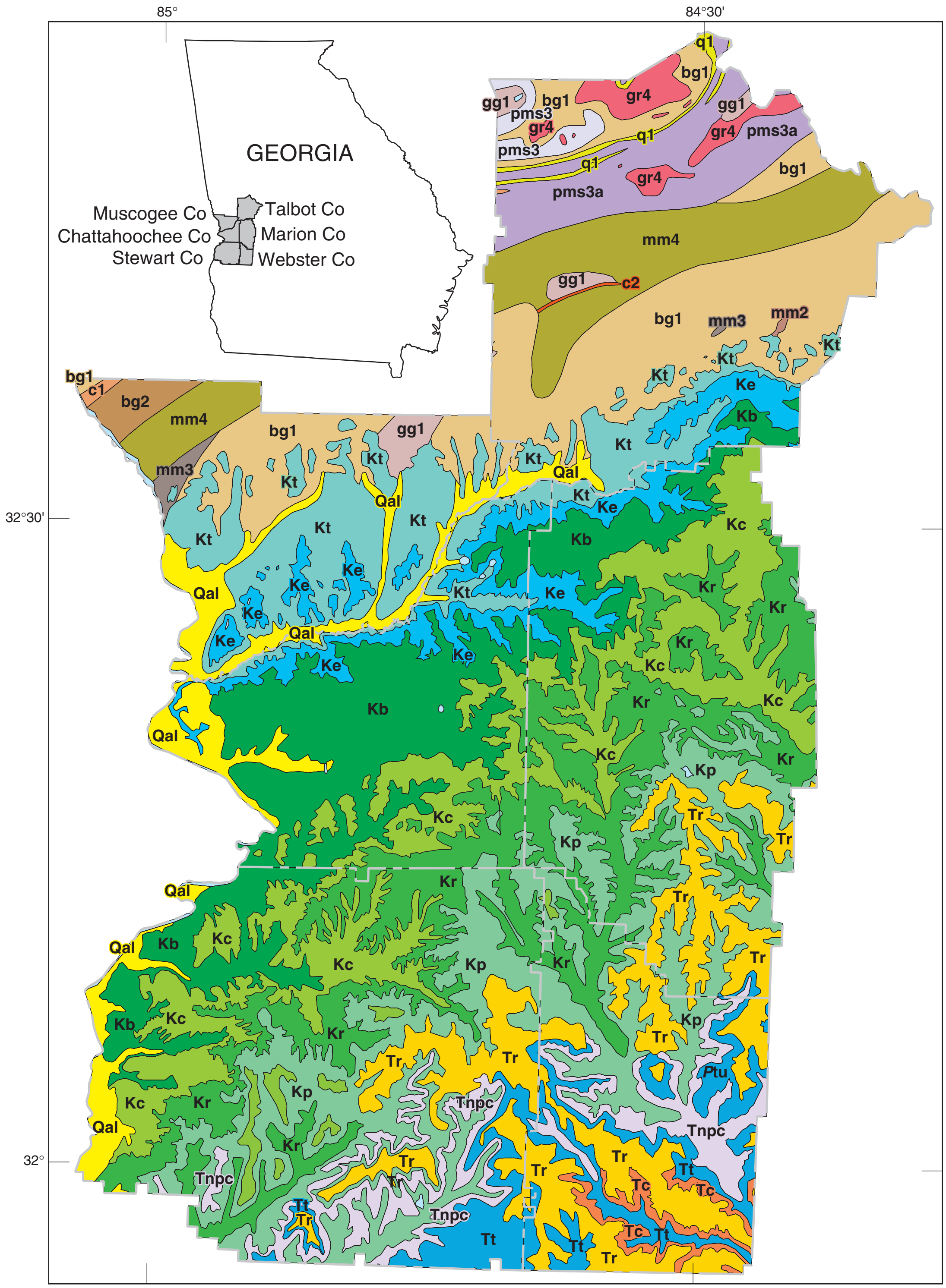


Figure 4. Land use in the study area (land-cover classification from digital files of the Georgia Departments of Natural Resources, and Community Affairs; as interpreted by ERDAS, Inc., Atlanta, Georgia, from 1988–90 LANDSAT Thematic Mapper Satellite imagery, spatial resolution 100 feet x 100 feet).



Base modified from
U.S. Geological Survey digital files

0 5 10 15 20 25 KILOMETERS

0 5 10 15 MILES

(SEE EXPLANATION ON FACING PAGE)

Figure 5. Surficial geology of the study area (modified from Georgia Geologic Survey, 1976).

EXPLANATION (Figure 5)

Sedimentary Deposits and Rocks of the Coastal Plain Province

Period	Symbol	Description
Quaternary	Qal	Stream alluvium and local undifferentiated terrace deposits (Holocene)
Tertiary	Tr	Residuum, undifferentiated (Oligocene and Eocene)
	Tc	Claiborne Formation (Eocene)
	Tt	Tuscahoma Formation (Paleocene)
	Tnpc	Nanafalia Formation, Porters Creek Clay, and Clayton Formation, undifferentiated (Paleocene)
Cretaceous	Kp	Providence Sand
	Kr	Ripley Formation
	Kc	Cusseta Sand
	Kb	Blufftown Formation
	Ke	Eutaw Formation
	Kt	Tuscaloosa Formation

Igneous and Metamorphic Rocks of the Piedmont Province

Era	Symbol	Description
Paleozoic	gr4	Charnockite
	gg1	Granite gneiss
	bg1	Biotite gneiss
	mm2	Hornblende gneiss
	mm3	Hornblende gneiss and amphibolite
	mm4	Hornblende gneiss, amphibolite, and granite gneiss
	pms3	Mica schist and gneiss
	pms3a	Mica schist, gneiss, and amphibolite
	q1	Quartzite
	c1	Mylonite and ultramylonite
	c2	Flinty crush rock

——— Geologic contact, approximately located

In ascending order, this vertical sequence of strata consists of Tuscaloosa, Eutaw, and Blufftown Formations, Cusseta Sand, Ripley Formation, and Providence Sand (all Upper Cretaceous). Lower Tertiary units consist of the Clayton Formation, Porters Creek Clay, Nanafalia and Tuscahoma Formations (all Paleocene), and the Claiborne Formation (Eocene) (fig. 5; Georgia Geologic Survey, 1976). These strata generally dip to the south and southeast at about 6 to 9 meters per kilometer (Reinhardt and Gibson, 1980) and become younger to the south and southeast. The relations (stratigraphy, dip, surficial expression) of selected formations in the western part of the study area are shown diagrammatically in figure 6. Locally, formations are overlain by Eocene and Oligocene residuum, and by Quaternary alluvium (fig. 5).

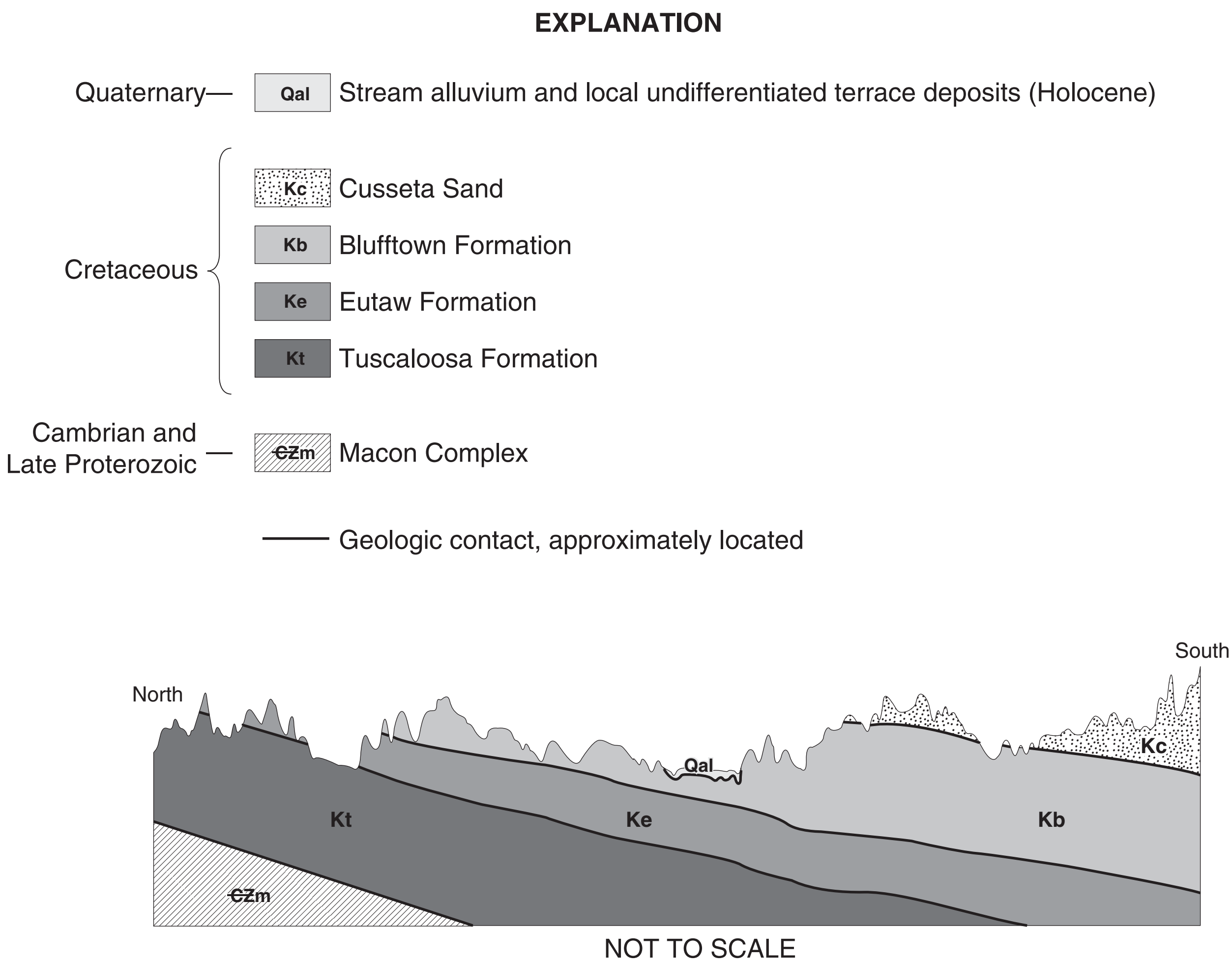


Figure 6. Diagrammatic geologic section showing the stratigraphy and surficial expression of geologic formations in the upper Coastal Plain of Georgia (modified from Reinhardt, 1994).

Soils

Soils in Chattahoochee, Stewart, Marion, and Webster Counties were derived from marine sedimentary Cretaceous sand and loamy parent materials. The predominant soil order in these counties is Ultisols, although substantial amounts of Entisols, particularly Lakeland soils are present in Marion County (fig. 7, table 2). Ultisols are highly weathered, low in cation exchange capacity, organic matter, and base saturation, acidic, and contain an argillic (clay rich) horizon (Perkins and others, 1973; Woods and Smith, 1983). The argillic horizon in these soils can be of variable thickness and occurs at widely varying depths below land surface. Ultisols in the study area also tend to have a sandy surface horizon of variable thickness. The principal Entisols in the study area are Quartzipsamments that are extremely sandy, very low in cation exchange capacity, and do not contain an argillic horizon (Perkins and others, 1973; Woods and Smith, 1983).

Soils of the study area tend to be very low in native fertility, low in organic matter, droughty, and sandy textured in the A horizon (Perkins and others, 1973). Loblolly pine is only moderately productive because soils are low in fertility, droughty, and relatively shallow (Woods and Smith, 1983). Another distinctive feature is the presence of a dense, brittle, partially cemented layer of soil occurring more commonly in some Ultisol soils in Stewart and Chattahoochee Counties than in Ultisol soils in Marion County. Descriptions of these soils are published in the Natural Resource Conservation Service (NRCS), formerly U.S. Department of Agriculture, Soil Conservation Service (SCS), Soil Survey of Dooly and Macon Counties, Ga. (Woods and Smith, 1983); these counties are near the study area and are in the Coastal Plain. Soils in the study area having partially cemented layers do not meet the diagnostic criteria for fragipans; however, they are thought to be effective in restricting the depth of rooting (Lawrence West, University of Georgia, oral commun., 1994).

Figure 7 is a soil-association map derived from NRCS county general soil maps. Presently, Muscogee County is the only county for which the general soil map is published. The other counties in the study area have been mapped and copies of the current maps may be obtained from the NRCS, Athens, Ga. Soil-association maps must be interpreted with caution because map units represent an aggregation of many different soil types and are named for predominant soils. The map units cannot be used to identify specific soil types or soil properties at specific locations (U.S. Department of Agriculture, Soil Conservation Service, 1991).

Table 2. Predominant soil series in the study area, taxonomic classifications, and distinctive features

Soil series	Taxonomic classification	Distinctive features
Ailey	loamy, siliceous, thermic Arenic Fragiudult	thick sandy surface horizon, subsoil is sandy clay loam which may be firm and brittle, and slightly hard and cemented below 1 meter
Cowarts	fine-loamy, siliceous, thermic Typic Hapludults	shallow (less than 1 meter), particularly eroded phases, substratum is firm, compact and may restrict rooting
Esto	clayey, kaolinitic, thermic Typic Paleudults	firm, clayey, slowly permeable subsoil; more clay in subsoil than Vaucluse
Faceville	clayey, kaolinitic, thermic Typic Paleudults	loamy surface horizon, clayey subsoil
Lakeland	thermic, coated Typic Quartzipsamments	excessively well drained; sandy throughout
Nankin	clayey, kaolinitic, thermic Typic Hapludults	sandy clay loam surface horizon, clayey subsoil, substratum is sandy loam
Orangeburg	fine-loamy, siliceous, thermic Typic Paleudults	sandy surface horizon, sandy clay loam subsoil
Troup	loamy, siliceous, thermic Grossarenic Paleudults	loamy sand from the surface to about 2 meters, substratum is sandy clay loam
Redbay	fine-loamy, siliceous, thermic Rhodic Paleudult	sandy loam surface horizon, sandy clay loam subsoil, no restrictions to rooting
Vaucluse	fine-loamy, siliceous, thermic Typic Hapludults	loamy subsoil that is mainly cemented and brittle, restricts rooting

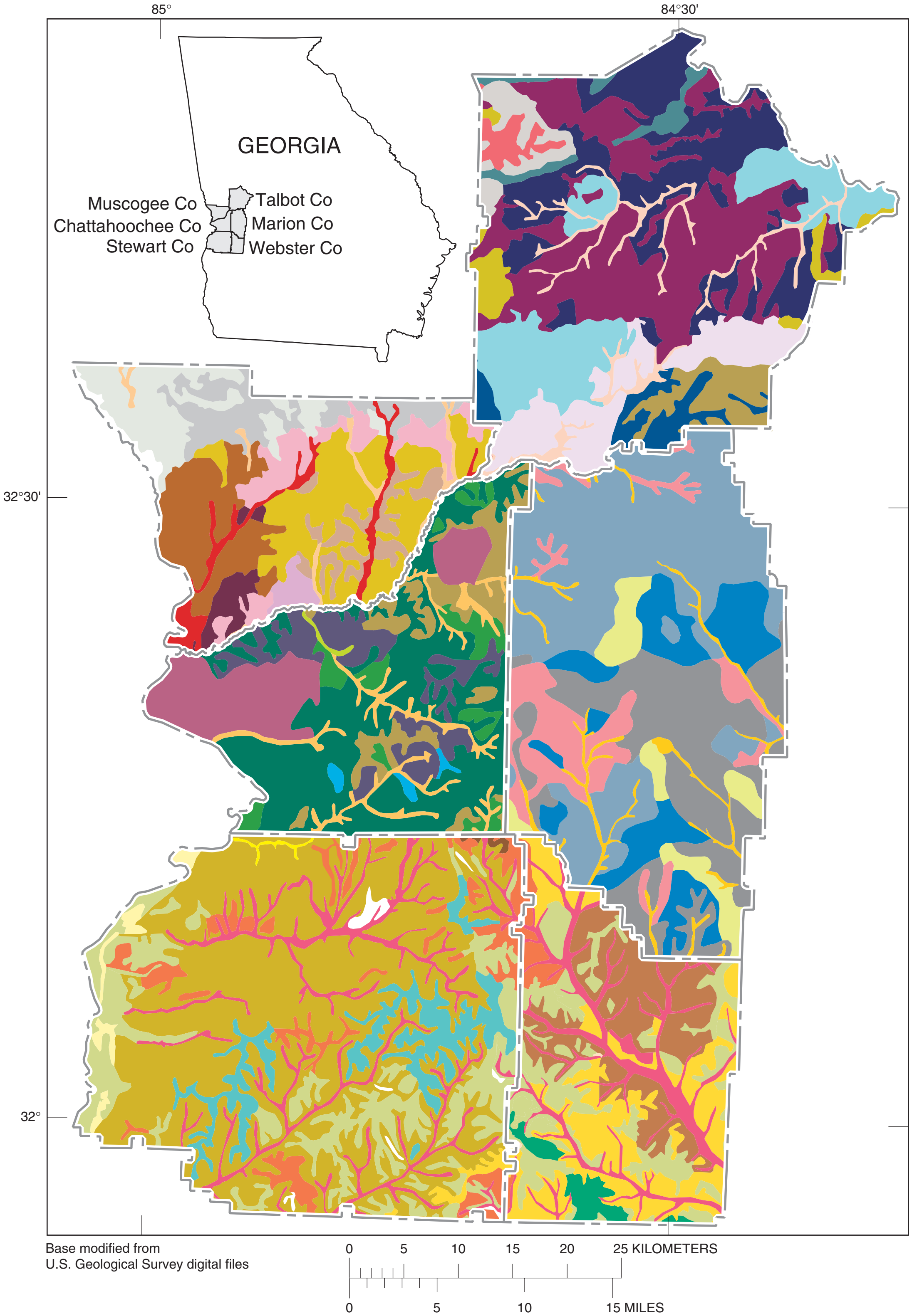


Figure 7. Soil associations in the study area. Soil classification based on county general soils maps produced by the Natural Resource Conservation Service (NRCS). The general soils map for Muscogee County is published in the soil survey for that county (Johnson, 1983). Soils maps for the other five counties in the study area were obtained from NCRS offices in Georgia (Alfred J. Green and Jerald Pilkinton, written communication, 1992–94).

EXPLANATION (Figure 7)

SOIL ASSOCIATIONS, FROM COUNTY DATA

Talbot County

- Appling-Pacolet-Cecil
- Chewacla-Bibb
- Cecil-Pacolet
- Fuquay-Dothan-Troup
- Gwinnett-Pacolet-Cecil
- Hiawassee-Gwinnett-Pacolet
- Lakeland-Cowarts-Ailey
- Louisburg-Zion-Pacolet
- Musella-Allen
- Pacolet-Louisburg-Zion
- Troup-Lakeland-Cowarts

Muscogee County

- Ailey-Troup-Vancluse
- Bibb-Toccoa-Pelham
- Chewacla-Dogue
- Dothan-Orangeburg-Esto
- Esto-Troup
- Pacolet-Cecil-Wedowee
- Pacolet-Wedowee
- Troup-Vaucluse-Pelion
- UrbanLand-Dothan-Enola

Chattahoochee County

- Bibb-Iuka-Chastain
- Lucy-Fuquay-Dothan
- Nankin-Cowarts-Vaucluse
- Nankin-Troup-Ailey
- Troup-Cowarts-Lakeland
- Troup-Lakeland-Cowarts
- Urban-Impacted
- UrbanLand-Orangeburg-Esto

Marion County

- Bibb-Iuka
- Cowarts-Vaucluse-Troup
- Lucy-Dothan-Fuquay
- Orangeburg-Greenville-Redbay
- Troup-Cowarts-Lakeland
- Troup-Lakeland-Ailey

Stewart and Webster Counties

- Cowarts-Troup
- Greenville-Faceville-Orangeburg-Redbay
- Greenville-Faceville-Tifton
- Izagord-Wahee-Grady
- Kingston-Bibb
- Orangeburg-Redbay-Greenville-Faceville
- Troup
- Troup-Lucy-Americus
- Vaucluse-Nankin-Esto
- Vaucluse-Troup
- Unmapped

SOUTHERN PINE BEETLE INFESTATION AND ENVIRONMENTAL STRESSORS—PREVIOUS INVESTIGATIONS

Epidemiology of Southern Pine Beetle

Southern pine beetle infestations are common throughout the range of indigenous and planted loblolly pine and have increased in frequency, severity, and distribution in the last 30 years (Belanger and others, 1993). Forest inventories (conducted from 1952–85) show that loblolly pine and other softwoods have increased significantly throughout the southeastern United States (U.S. Department of Agriculture, Forest Service, 1988). Belanger and others (1993) suggested that changes in forest structure, including increases in stand age and volume of saw timber, appeared to be related to the increases in SPB infestations and that appropriate management strategies could minimize timber losses from SPB. Infestations of SPB in loblolly pine of the extreme northwestern Coastal Plain of Georgia during 1979–92 were unprecedented in their persistence (Price and others, 1991) and were not explained by stand structure, climatic, silvicultural, or other known factors. Once SPB infestations have reached epidemic proportions within a given area, it is frequently very difficult to determine whether past management practices were a cause of the infestations.

In the normal epidemiology of SPB within a given area, outbreaks are of short duration (typically two to three years), the beetle then virtually disappears, only to recur several years later (Payne, 1980). This pattern has led to the common belief that beetle activity is sporadic, following some irregular and unpredictable cycle. The most remarkable aspect of the infestations in the northwestern Coastal Plain of Georgia was the persistence or recurrence of the pest at levels resulting in substantial economic losses during most years from 1979–92 (Price and others, 1991; Joel Robertson, Champion International, oral commun., 1992). Economic losses occur both from direct damage to merchantable timber and losses in harvesting efficiency, resulting from need to alter normal management schedules to accommodate salvage cutting.

Factors Controlling the Outbreak of Southern Pine Beetle

Factors controlling the outbreak and biology of SPB have been studied for decades and much has been learned about beetle-conifer-pathogen interactions and relations between environmental stress, tree physiology, and invading organisms (Thatcher and others, 1980; Lorio and Sommers, 1986; Schowalter and Filip, 1993; Lorio and others, 1995). Trees under acute stress are thought to be more susceptible to SPB infestation because of decreased oleoresin defenses (see review by Reeve and others, 1995; Berryman, 1972) and trees damaged by lightning frequently are attacked by SPB and killed (Paine and Baker, 1993; Hodges and Pickard, 1971; Coulson and others, 1986). Severe water deficits lower the potential amount and duration of resin flow from wounds, thus enhancing attack success of SPB (Lorio and Hodges, 1977; Lorio and others, 1995). Severe water deficits also reduce oleoresin pressure in pines (Vité, 1961; Lorio and Hodges, 1968). It is important to note that oleoresin pressure and flow are not directly correlated and that oleoresin flow is considered a superior method of estimating relative resistance of trees to SPB attack (Lorio, 1993). Trees under prolonged waterlogged conditions have reduced resistance to SPB (Lorio and Hodges, 1968). Hicks (1980) and Paine and Stephen (1987a) studied the influence of site and stand conditions on resistance to attack by SPB. Blanche and others (1983) and Paine and Stephen (1987b) studied the influence of host condition on resistance to attack by SPB.

Lorio and others (1995) reviewed several publications in which a wide array of abiotic and biotic factors such as weather, lightning, natural enemies, site and stand conditions, and host conditions were identified as important to SPB population dynamics. Lorio and others (1995) further noted that in recent years, investigations focused on the potential susceptibility to SPB infestation because of host condition as affected by environment, tree physiological stage, and the role of mutualistic fungi. Based on a review of this literature, Lorio and others (1995) stated that "detailed studies of tree conditions provide few data to link host conditions to population dynamics of colonizing bark beetles." Lorio and others (1995) concluded that tree resistance to SPB attack, even in the absence of experimentally applied stresses, is a dynamic process requiring studies of physiological changes associated with ontogeny of trees that affect tree susceptibility to forest insects. Complex factors influence interactions between SPB, its predators and pathogens, and potential hosts that ultimately control SPB population density (Reeve and others, 1995).

Despite several decades of research and many advancements in understanding SPB infestations, little progress has been made in understanding or controlling biological and environmental factors that apparently are associated with outbreaks and subsequent economic losses. As early as the 1920's, several reports concluded that fluctuations in beetle populations were driven by drought or temperature extremes (Turchin and others, 1991). Turchin and others (1991), however, analyzed a 30-year record of beetle activity in eastern Texas and concluded that, in contrast to previous analyses, SPB outbreaks were driven by some unknown population process in a delayed density-dependent manner, and not by stochastic fluctuations of weather. Fundamental questions about the factors that trigger, control the size, and control the persistence or recurrence of outbreaks within a given geographic area have not been resolved.

Environmental Stress and Loblolly Pine Resistance to Southern Pine Beetle Attack

Lorio (1986) and Lorio and others (1990) proposed application of plant growth-differentiation balance principles (Loomis, 1932; 1953) toward understanding SPB interaction and providing a framework for developing testable hypotheses for research. Because moderate stress reduces growth more than it does photosynthesis, proportionately greater differentiation (for example, carbohydrate partitioning to oleoresin) can occur under moderate stress, thus resulting in greater resistance to SPB attack. In another example of this principle, in the initial response to fertilization trees can partition more photosynthate to growth and less to oleoresin synthesis, thus resulting in greater susceptibility to attack by bark beetle in the short term.

Oleoresin synthesis and yield is the primary conifer defense mechanism from bark beetle attack (Hodges and others, 1979). As the degree of cumulative stress increases beyond some threshold, growth and differentiation may be limited and the tree will become more susceptible to SPB attack. Lorio (1986) proposed that trees are more susceptible early in the growing season when a greater proportion of photosynthate is used for growth than for production of defensive compounds. The relation between cumulative stress and oleoresin yield (which is directly related to the proportion of energy partitioned into defensive compounds) is shown graphically in figure 8.

Experimentally induced moderate water deficits (Lorio and Sommers, 1986; Reeve and others, 1995) and nutrient limitations (Peter Lorio, U.S. Department of Agriculture, Forest Service, oral commun., 1995) have been shown to result in greater oleoresin flow than observed in unstressed loblolly pine treatments. Lorio and others (1995) suggested that moderate water deficits occurring after the transition from earlywood to latewood formation apparently increase partitioning of energy to oleoresin synthesis and provide resistance to SPB attack. Results of another recent study (Birk and Matson, 1986) comparing site fertility and seasonal carbon reserves in loblolly pine also are consistent with the growth-differentiation balance principles. Birk and Matson (1986) showed that foliar carbon reserves accumulated in trees during the growing season under lower nutrient conditions, indicating a weaker sink strength than under more optimal soil-fertility conditions.

Environmental Stressors

Loblolly pine trees growing in the study area may be subject to multiple interacting stressors including air pollutants, ultraviolet-B radiation, and low soil fertility aggravated by acidic-deposition-induced cation leaching. The primary air pollutants that could have direct effects on plant metabolism are sulfur dioxide and ozone. When sulfur and nitrogen oxides are deposited on foliar surfaces, and subsequently remobilized as sulfate and nitrate in rainfall, nutrient cations may be leached from leaves and pose an additional stress on loblolly pine.

Sulfur Dioxide

Sulfur dioxide is a primary air pollutant that, in sufficiently high concentrations, will have adverse effects on plant growth involving alterations in carbohydrate allocation (Winner and others, 1985; Miller and McBride, 1975; Mohren and others, 1992). Kress and others (1982) demonstrated significant height growth reduction in loblolly pine with 6-hour exposures to 140 nL L^{-1} SO_2 in one loblolly pine family but not another. Trees weakened by industrial air pollution, including SO_2, may be predisposed to attack by certain insects (Sierpinski, 1977; Dahlsten and Rowney, 1980; Kozlowski, 1985). Foliar uptake of sulfur dioxide can decrease photosynthesis and increase respiration in Douglas fir trees; these physiological effects are dependent upon temperature and generally are reversible (Kropff and others, 1990). The physiological effects of sulfur dioxide on forest growth also are strongly influenced by soil moisture availability (Mohren and others, 1992).

Sulfur dioxide concentrations in air usually are at or near detection limits of 2.5 nL L^{-1} throughout the rural southeast, with the exception of areas immediately downwind from point sources (Lefohn, 1990). Although SO_2 can be transported long distances, in the

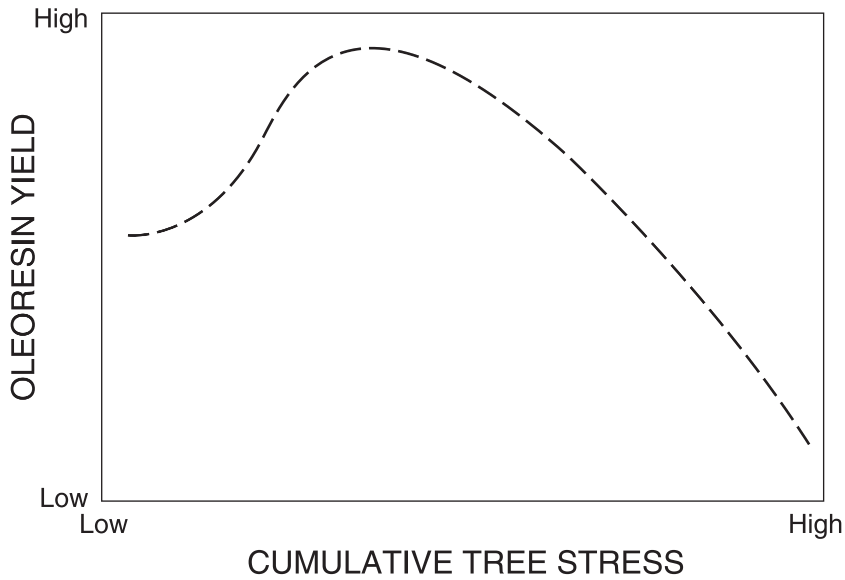


Figure 8. Theoretical relation between cumulative tree stress and yield of oleoresin for loblolly pine.

southeastern United States at distances greater than 100 km from large source areas, less than 50 percent of the locally deposited sulfur is derived from those sources (Venkatram and others, 1990). Where regional air-quality data have been evaluated within the context of published dose-response relations, sulfur dioxide and nitrogen dioxide are not regarded as significant threats to crop productivity, either acting alone or interacting with ozone (Lefohn and others, 1987). The impacts of sulfur dioxide as a pollutant that could affect forests in the southeastern United States generally are viewed as being indirect effects resulting in leaching of nutrient cations from soils and foliage.

Sulfur and nitrogen oxides can be converted either into sulfuric and nitric acid vapors or liquids in the atmosphere and on foliar surfaces, and potentially are stressful to loblolly pine trees. Enhanced foliar leaching of base cations is the primary mechanism by which these acids can directly affect trees (Johnson and Lindberg, 1992; Parker, 1990). Field and laboratory experiments have shown that acidic precipitation can cause leaching of base cations from tree foliage (Scherbatskoy and Klein, 1983; Cappellato and others, 1993; Turner and van Broekhusizen, 1992; Johnson and Taylor, 1989). However, studies have shown that exposure to acidic precipitation (pH between 3.0 and 5.0) does not alter foliar nutrient content or concentration in loblolly pine and other conifers (Edwards and others, 1995). Turner and van Broekhusizen (1992) demonstrated that the majority of cation leaching in response to acid precipitation originates from the apoplast rather than the symplast. Leaching from the apoplast indicates that foliar leaching increases the rate of biological cycling of base cations, but probably does not affect plant growth directly. The available evidence suggests that the effects of acidic precipitation on nutrient losses from foliage are small; however, additional experimentation to determine possible effects of long-term exposures and chronic nutrient losses is warranted (Parker, 1990).

Ozone

Ozone is a secondary air pollutant, a product of photochemical reactions involving various natural and anthropogenic hydrocarbon and nitrogen oxide compounds that accumulate in stagnant air masses; however, it is readily scavenged from the atmosphere by rainfall. Ozone is a strong oxidant that causes physiological damage to leaf tissues and creates a metabolic drain because the leaf must produce antioxidants (for example, superoxide dismutase and peroxidases) to repair damage (Polle and Rennenberg, 1993; Mansfield and Pearson, 1993). The precise mechanisms by which ozone damages leaves are not entirely understood (Polle and Rennenberg, 1993); however, ambient ozone concentrations typical of the eastern United States generally are thought to adversely affect photosynthesis and growth of a wide range of crop and forest species (Reich, 1987). Allen (1992) concluded that ozone has a pronounced negative effect on loblolly pine foliage longevity, but not on foliage production in seedling and branch chamber experiments, and that the effects on mature trees is uncertain. Allen (1992) also demonstrated that ozone at concentrations of 1.3 to 1.7 multiplied times ambient (where ambient concentrations were 31 nL L^{-1}) had an adverse effect on growth for some loblolly pine families. McLaughlin and Downing (1995) concluded that growth of mature loblolly pine was significantly and negatively correlated with ambient ozone levels and increasing soil moisture deficit.

Ozone is of particular concern because ambient concentrations presently typical of rural forested areas in the Southeast (Pinkerton and Lefohn, 1988; Lefohn and Pinkerton, 1988; Taylor and others, 1992) have been shown to have adverse effects on sensitive species such as loblolly pine (Taylor, 1994; McLaughlin and others, 1994, McLaughlin and Downing, 1995; Wright and others, 1991; Edwards and others, 1990; Edwards and others, 1992; Richardson and others, 1992; Pye, 1988; Adams and others, 1988; Chappelka and others, 1992). Recent controlled-exposure experiments showed large genotypic variation of loblolly pine in response to ozone (Taylor, 1994; McLaughlin and others, 1994); these experiments generally have concluded that most trees exhibit growth reductions at ambient or sub-ambient ozone levels (about 40 to 50 nL L^{-1} for 6- to 12-hour mean concentrations). In one recent study involving ambient ozone exposures to mature loblolly pine, McLaughlin and Downing (1995) determined that ozone concentrations in excess of 40 nL L^{-1} reduced circumference growth. There also has been suggestion of a positive interaction between bark-beetle infestation and ozone (Stark and others, 1968; Cobb and Stark, 1970) in the case of ozone damage to ponderosa pine in the San Bernadino Mountains, Calif. (Miller and others, 1989). In these oxidant-damaged ponderosa pines, oleoresin exudation pressure was observed to be reduced gradually as disease severity increased (Cobb and others, 1968). Ozone also has been shown to adversely affect induced host resistance of slash pine (*Pinus elliotii* Engelm); and thereby, make the trees more susceptible to attack by secondary agents (Johnson and others, 1992).

Ultraviolet-B Radiation

Another potential environmental stressor is ultraviolet-B (UV-B) radiation. Atmospheric pollutants have caused a continuing depletion of stratospheric ozone concentrations at a current estimated rate of about 4 to 5 percent per decade over northern mid-latitudes (Kerr, 1991). This rate of ozone depletion could correspond to a 7- to 10-percent increase in UV-B radiation flux in northern mid-latitudes (Naidu and others, 1993). Depletion of stratospheric ozone is a concern because increased penetration of UV-B (UV-B, 290–320 nanometer) radiation results in damage to sensitive plant species. Investigations conducted with loblolly pine seedlings suggest that it is one of many species sensitive to moderate increases in UV-B radiation (Kossuth and Biggs, 1981; Sullivan and Terramura, 1989; Naidu and others, 1993). In a recent study involving field-grown loblolly pine seedlings, Naidu and others (1993) observed that enhanced UV-B (corresponding to a 25-percent reduction in stratospheric ozone) resulted in a 20-percent reduction in total plant biomass. Biomass reductions were thought to primarily result from a decrease in foliar surface area.

Low Soil Fertility and Acidic Deposition-Induced Cation Leaching

Soils in the study area generally are extremely low in exchangeable nutrient cations because they are highly weathered and have low cation exchange capacity. Evidence suggests that soil calcium stores in aggrading forests on formerly cultivated lands in the southeastern United States are being steadily depleted through biomass uptake and soil leaching (Johnson and Todd, 1990; Johnson and others, 1988a, 1988b; Binkley and others, 1989; Knoepp and Swank, 1994; Richter and others, 1994; Wells and Jorgensen, 1975; Huntington and others, 1994b). Forest ecosystems normally do not receive fertilizer inputs to replace nutrients lost through timber harvesting and soil leaching.

Southern commercial pines generally accumulate less calcium than do hardwoods; however, harvest removals are still substantial (Wells and Jorgensen, 1979; Marion, 1979). Lower calcium concentrations in wood and bark of southern commercial pines are partially offset by faster growth rates and shorter rotations. Younger trees have a higher proportion of biomass in branches and bark (Saucier, 1979) and faster rates of calcium uptake (Alban, 1979). Timber harvesting also has been shown to accelerate calcium losses through increased leaching and erosion of topsoil (McColl and Grigal, 1979; Federer and others, 1989). Timber harvesting temporarily disrupts the biological cycling that maintains higher levels of calcium in the forest floor and surface soil horizons than would be present under the cumulative effects of long-term leaching. In addition, the potential for replenishment of soil-exchangeable calcium by weathering mineral sources is very low, because soils in this study area typically are largely depleted of calcium-bearing minerals.

Current levels of acidic deposition contribute to the leaching losses of exchangeable soil calcium by providing a mobile anion (sulfate and nitrate) (Galloway and others, 1983; Reuss and Johnson, 1986; Johnson, 1992). Acidic deposition also can increase the mobility of reactive aluminum which, in turn, displaces soil-exchangeable calcium, resulting in accelerated calcium leaching (Lawrence and others, 1995). Ultisol soils in the southeastern United States retain a large proportion of atmospherically deposited sulfate (Huntington and others, 1994a; Rochelle and others, 1987; Shriner and Henderson, 1978); however, a substantial amount of sulfate is leached (Huntington and others, 1994a; Johnson and Van Hook, 1989; Swank and Crossley, 1988). Acidic deposition accelerates the rate of cation leaching loss because base cations accompany a portion of the sulfate that is transported out of the rooting zone. Sulfur emissions in the southeastern United States generally decreased by about 9 percent between 1975–88 (Kohut and others, 1990); however, Georgia was an exception, where sulfur emissions increased by about 88 percent over the same time period, primarily because of increases from coal-fired power plants and other industrial sulfur-emission sources (Placet and Streets, 1987).

The pattern and temporal trends in calcium deposition further contribute to the chronic decline in soil fertility resulting from harvest removals and cation leaching. Forest soils in the southeastern United States generally receive lower inputs of calcium in wet deposition than does most of the eastern United States, with the exception of the coastal New England states (Sisterson, 1990; Appendix 1, this report). Calcium deposition also has been declining in recent years throughout the eastern United States (Hooper and Peters, 1989; Aulenbach and others, 1996; Swank and Waide, 1988; Hedin and others, 1994; Lynch and others, 1995). At an intensively studied watershed near Atlanta, Ga. (described by Huntington and others, 1993), a marked decrease in calcium concentration in precipitation and wet deposition of calcium has been observed during the period 1986–95 (Appendix 1).

Few data exist on sustainability of forest productivity from a soil fertility perspective, because there have been only a few harvest rotations in the southeastern United States. There also are few data available on long-term changes in site quality and productivity under continuous silvicultural management. Increases in tree growth following calcium fertilization have not been reported (Wells and Jorgensen, 1979); however, there have been very few investigations involving calcium fertilization treatments (North Carolina State Forest Nutrition Cooperative, 1995). However, in one study, the site index (a measure of forest productivity) for loblolly pine was significantly correlated with exchangeable calcium in the A and B horizons (McKee, 1976). Typical silvicultural fertilization studies for loblolly pine, such as those conducted by the North Carolina State Forest Nutrition Cooperative, generally are based on expected responses to nitrogen and phosphorus only (North Carolina State Forest Nutrition Cooperative, 1995). In one ongoing study across the Southeast, potassium has been identified as limiting loblolly productivity and growth responses to nitrogen and phosphorus additions (North Carolina State Forest Nutrition Cooperative, 1995).

Loblolly pine trees growing in the study area may be subject to additional stressors including insect pests, pathogens, periodic drought, and hardwood competition. These stress factors may interact with air pollutants, UV-B, and infertile soils in complex ways; this makes it quite difficult to determine the incremental contribution of any individual stress factor. Another dimension to the problem of determining the role of any specific environmental stress factor to the health of loblolly pine and its resistance to SPB, is that the population dynamics and virulence of SPB and its pathogens and predators likely are to be influenced by one or more of these same factors.

METHODS OF INVESTIGATION

Atmospheric acidic deposition, air quality, and soil chemical properties were assessed during the period 1992–94 to determine any relation between these environmental factors and the spatial pattern of SPB infestation. Atmospheric acidic deposition was measured in Lumpkin, Stewart County (heavily infested); and Buena Vista, Marion County (lightly infested) (fig. 1) to determine whether pollutant loadings were related to the observed spatial pattern of SPB infestation. Air quality was monitored in Stewart County for ozone and sulfur dioxide concentrations to determine whether ambient levels of these gaseous air pollutants were within ranges generally considered to be stressful for loblolly pine.

Selected soil chemical properties were investigated from soil samples collected in paired, infested and uninfested forest plots in Stewart County to determine whether there were any associations between soil properties and the incidence of infestation. The soil properties investigated were those that generally are considered to be influenced by acidic deposition and that could play a role either in forest health or susceptibility to SPB. Soil-water chemistry was evaluated by leaching field-moist soil samples with simulated throughfall using a mechanical vacuum extractor in the laboratory.

Water-quality samples were collected from selected streams throughout the study area during baseflow conditions to determine whether the incidence of SPB infestation was related to stream-water chemistry.

Atmospheric Acidic Deposition

Atmospheric acidic deposition normally is partitioned into wet deposition (precipitation only) and dry deposition (gaseous, aerosol, and particulate forms of sulfur and nitrogen) components. Wet deposition can be measured directly from rainfall, but dry deposition must be estimated using indirect methods. In this study dry deposition was estimated by subtracting wet-only deposition from total atmospheric deposition. Total atmospheric deposition was estimated using throughfall. Throughfall is a measure of inputs to the forest floor integrating the interactions of rainfall with the forest canopy during storms. The key interaction that makes throughfall a good indirect measure of total acidic deposition is the “wash-off” of sulfur which has been “dry deposited” on foliar and canopy surfaces during antecedent dry periods (Joslin and Wolfe, 1992; Lindberg and Lovett, 1992).

Total Deposition (Throughfall)

The use of throughfall to estimate total deposition requires the following assumptions:

- soil derived, plant assimilated sulfate does not leach from stems or foliage into throughfall;
- sulfur compounds do not degas from leaf surfaces;
- sulfur compounds are not appreciably taken up and assimilated by the canopy during a period of measurement;
- sulfur dry deposition to the forest floor, sulfur compounds in stemflow, and coarse particulate deposition of sulfur are all relatively small components; and
- the number of samplers deployed is sufficient to overcome spatial variability in both throughfall chemistry and throughfall volume.

Several studies support the argument that foliar leaching of soil-derived sulfate and degassing of sulfur compounds following dry deposition are insignificant (Lindberg and Lovett, 1992; Lindberg and Garten, 1988; Cape, 1993). There is contradictory evidence regarding the third assumption that foliar uptake is insignificant. Throughfall measurements have been shown to closely correspond to independent estimates of wet-plus-dry deposition in several forests (Joslin and Wolfe, 1992; Lindberg and Garten, 1988; Johnson and Lindberg, 1992). However, indirect evidence from some studies indicates that canopy retention of dry-deposited sulfur dioxide might be significant, particularly in southern pines, suggesting that throughfall techniques underestimate dry-deposition fluxes. Results of the Integrated Forest Studies (IFS) that included isotopic exchange experiments (Lindberg and Lovett, 1992; Gay and Murphy, 1989) indicated that loblolly pine may retain between 20 and 70 percent of dry-deposited sulfur. However, Lindberg and Lovett (1992) acknowledged large uncertainties associated with the inferential eddy-correlation techniques (Meyers and others, 1991), and the computation of sulfate retention based on these techniques and measurements of throughfall and stemflow used in the IFS. Lindberg and Lovett (1992) concluded that, in most cases, reported net canopy retention may not be significantly different than zero. Furthermore, drought conditions during the IFS would have biased the inferential techniques and overestimated dry deposition (Lindberg and Lovett, 1992). Direct evidence, since the IFS program, has not supported significant net uptake of dry-deposited sulfur on a long-term (annual) basis (Steven Lindberg, Oak Ridge National Laboratory, Oak Ridge, Tenn., written commun., 1996).

Uncertainties inherent in the inferential measurements of dry deposition of sulfur are illustrated when sulfur mass-balance calculations are applied to published estimates of sulfur fluxes derived using these techniques (table 3). At three of the five sites considered, more dry-deposited sulfur was retained than required for plant growth. Such high proportions are clearly suspect, suggesting that the precision of the inferential technique is low and that this method may be less reliable than throughfall for estimating total atmospheric deposition. Although there is some evidence for net canopy sulfur uptake in loblolly pine, these data and the isotopic work reviewed by Lindberg and Lovett (1992) indicate that the absolute uptake must be quite small relative to total deposition.

Table 3. Sulfur fluxes and mass-balance calculations in loblolly pine forests in the southeastern United States
[kg ha^{-1} yr^{-1}, kilogram per hectare per year]

Study site	Dry deposition (kg ha^{-1} yr^{-1})	Net annual above-ground sulfur requirement[1/] (kg ha^{-1} yr^{-1})	Proportion of dry-deposited sulfur retained in canopy[2/] (in percent)	Dry-deposited sulfur retained in canopy (kg ha^{-1} yr^{-1})	Proportion of annual above-ground sulfur requirement derived from dry deposition (in percent)
Duke Forest, North Carolina[3/]	8.55	5.0	62	5.3	106
Oak Ridge, Tennessee—plot 1[3/]	7.25	6.1	27	1.95	32
Oak Ridge, Tennessee—plot 2[3/]	7.25	3.7	27	1.95	53
Panola Mountain, Georgia[4/]	11.5	3.2	54	6.21	197
B.F. Grant Forest, Georgia[3/]	6.53	[5/]3.5	74	4.83	138

[1/] Calculated as reported net-wood requirement plus total above-ground litter production.

[2/] Net-canopy exchange is annual flux in throughfall plus stemflow (total annual deposition to canopy). Amount retained in canopy is defined as net-canopy exchange over dry deposition where dry deposition was estimated by independent measurements of deposition velocity (Meyers and others, 1991).

[3/] From Johnson and Lindberg (1992).

[4/] From Cappellato and others (1993) and Rosanna Cappellato (U.S. Geological Survey, written commun., 1995).

[5/] For B.F. Grant Forest net annual above-ground sulfur requirement was estimated as 50 percent of total new biomass requirement to be consistent with other sites.

The fourth assumption is that dry deposition to the forest floor, stemflow, and coarse particulate deposition are all relatively small components of total deposition. These forms of deposition were not considered in this study because they are difficult and costly to measure however, a review of the evidence supports the assumption that their combined deposition is relatively small (Joslin and Wolfe, 1992). Dry deposition to the forest floor has been reported to be about 15 percent of total deposition (Meyers and Baldocchi, 1993), but is sensitive to surface wetness and proportions of gaseous, fine particulate, and coarse particulate forms. Stemflow sulfate flux also was not quantified in this study, but in loblolly pine forest stands, it generally has been reported to be small, and typically in the range of less than 1 to about 8 percent of throughfall sulfate flux (Johnson and Lindberg, 1992; Cappellato and others, 1993). Coarse particulate sulfate aerosol deposition at a site near Atlanta, Ga., was estimated using the method of Lindberg and Lovett (1985) to be about 10 percent of total atmospheric deposition during a two-year period (Cappellato and others, 1993).

The final assumption for the use of throughfall to estimate total deposition concerns the problems of spatial variability in throughfall chemistry and throughfall volume. Using 30 funnels normally is sufficient to overcome these problems of spatial heterogeneity (Joslin and Wolfe, 1992; Lindberg and Garten, 1988). Throughfall samples from individual samplers were composited so it was not possible to evaluate spatial variability in this study. Throughfall volume averaged 85 percent of rainfall volume as measured using an Aerochem Metrics, Inc., collector in a clearing adjacent to the site of throughfall collections.

In summary, the use of throughfall to estimate total deposition is justified from a scientific and experimental standpoint, although it is recognized that this method probably results in an underestimate of the actual acidic deposition primarily because of unmeasured inputs in the forms of dry deposition to the forest floor, coarse particulates, and stemflow. The degree of underestimation probably is similar at acidic deposition measurement sites, so it would not influence the interpretation of the data when comparing deposition between sites.

Arrays of funnels were established in forested plots near Lumpkin (September 1, 1992) and Buena Vista (November 2, 1992), Georgia, to estimate total atmospheric deposition using throughfall. Forest plots were selected in similar stands representing loblolly pine forests in the study area. Stands were selected for easy access. Stand age was estimated to be 25 to 35 years based on tree height and diameter. Stand composition was almost exclusively loblolly pine with closed canopies, estimated leaf area index greater than 5, and minimal understory vegetation. Forest stands were on level to very gently sloping (less than 3 percent) land. The forest stand near Buena Vista was cut, unexpectedly, in November of 1993; thus throughfall measurements were not conducted at this location after November 19, 1993. A new throughfall plot was established near Buena Vista on March 12, 1994. Throughfall measurements were discontinued in Buena Vista on November 3, 1994, and in Lumpkin on September 13, 1995. The period of record for total atmospheric deposition was substantially longer near Lumpkin than near Buena Vista.

In Lumpkin, the forest stand was immediately adjacent to the GFC field office and wet-fall precipitation collector. In Buena Vista, the first forest stand was located about 5 km east of the GFC field office and wet-fall precipitation collector. The second forest stand in Buena Vista was located about 5 km north of the GFC field office. Precipitation and throughfall volumes were more closely related at Lumpkin than at Buena Vista because of the proximity of the precipitation and throughfall sites in Lumpkin compared with Buena Vista. Only two measurements show large differences in volumes of recorded throughfall compared with rainfall at the Buena Vista sites and these differences can be explained by the occurrence of rainfall at one location and not at the other.

At the Lumpkin and Buena Vista field sites, 30 polyethylene funnels were attached to rods and randomly placed within 50-by-50 m plots under loblolly pine canopies. The funnels were positioned to permit weekly placement and retrieval of 1-liter polyethylene bottles beneath the funnels to collect throughfall samples. During each weekly collection, bottle contents were added to a 25-liter (L) graduated polyethylene container to form a composite sample. The total volume was recorded and a subsample was poured off into 250-milliliter (mL) polyethylene bottle and shipped to the USGS water-quality laboratory, Atlanta, Ga. Plastic mesh was placed within the funnels to minimize the amount of debris that fell into the bottles. Debris that collected in the funnels or in the bottles was routinely removed during sample collection and the bottles were replaced periodically to minimize the accumulation of algae.

Throughout the entire period of record there were six storms in which more than 25 L of throughfall were collected. On these occasions, two separate subsamples were obtained and a composite, volume-weighted subsample was analyzed. Individual bottles were tipped over or were overtopped because of very high throughfall volumes during less than 5 percent of all storms. On these occasions, concentrations were based on the collected sample and volumes were estimated from precipitation volume and a regression of precipitation volume and throughfall volume. In July 1994, storms associated with Tropical Storm Alberto occurred, resulting in more than 30 cm of rainfall at both sites. During this period, both wetfall and throughfall collector capacities were exceeded. Wetfall volumes for this period were estimated from independent rainfall records maintained by the GFC and throughfall records were based on 90 percent of estimated wetfall volume. Deposition during this period was computed from concentrations measured for the portion of rainfall or throughfall collected and from the estimated volumes.

In 1994, a throughfall plot was established near Union, in Stewart County, in a loblolly forest stand following similar procedures used in the plots instrumented in Lumpkin and Buena Vista. Stand age was assumed to be about 25 to 35 years based on average tree diameter and tree height. At the Union location, 24 funnels (6.8 cm diameter) were used. The funnels were inserted into stoppers and the stoppers were inserted into polyethylene bottles secured to wooden stakes. Smaller diameter funnels were used to permit much less frequent site visits because it was not practical for GFC staff to service this installation. Three collections were made at this site during the period March 29, 1994, through November 30, 1994. On each sampling date, between 3 and 10 funnels had been removed, presumably by wildlife. Variable numbers of funnels made calculation of deposition impractical. Samples from apparently undisturbed funnels at Union were collected and composited to compare major-solute concentrations with data collected at Lumpkin over the same time periods.

Wet Deposition (Precipitation)

Wet deposition was measured using Aerochem Metrics, Inc., Model 301 wetfall/dryfall automatic collectors located in clearings adjacent to GFC field offices in Lumpkin and Buena Vista. Precipitation collections were made by GFC staff on approximately weekly intervals. If no rainfall occurred during the preceding week, the buckets were left in place until the end of a subsequent week in which rainfall was collected. The collectors were equipped with moisture sensors that automatically trigger a movable lid to expose a collection bucket during storms. Precipitation and throughfall samples were collected on the same dates.

Precipitation volumes were determined by transferring the contents of the collector buckets into graduated cylinders or bottles, depending on sample volume. Precipitation amount (in cm) was computed based on the surface area of the bucket opening by multiplying sample volume in mL by the constant 0.00147. Subsamples were poured off into 250-mL polyethylene bottles and shipped to the USGS water-quality laboratory in Atlanta, Ga., for analysis. A small systematic bias occurs using the wetfall/dryfall automatic collectors because some rainfall must occur, which is not collected, in order to trigger the moisture sensor to move the lid and expose the sample bucket. However, this bias is small, illustrated by the cumulative-mean collector efficiency of 98 percent (range = 77 to 103 percent) for the 38 years of record at the Griffin, Bellville, and Tifton, Ga., sites (see Appendix 2).

Analytical Techniques

Anion concentrations in precipitation and throughfall were measured by ion chromatography and cations (except ammonium) by direct-coupled plasma optical emission spectroscopy. Ammonium was determined colorimetrically and pH was measured potentiometrically. Alkalinity (acid neutralizing capacity) was determined by an automated Gran titration. For water samples where pH was less than 5.0, alkalinity was computed as:

$$Ca+Mg+K+Na+NH_4+2Al-(SO_4+NO_3+Cl); \quad (1)$$

where units for all ions except aluminum were micro-equivalents per liter (μeq L^{-1}) and aluminum was micromoles per liter (μm L^{-1}). Bicarbonate was computed from pH and alkalinity using standard formulations (Stumm and Morgan, 1981). Estimates of precision and quality-assurance procedures are described in Huntington and others (1993). Wet-deposition elemental flux was calculated from the product of element concentration in precipitation or throughfall multiplied by the appropriate precipitation volume.

Statistical comparisons of acidic deposition between the two sites were performed using multiple pairwise mean-comparison tests (alpha = 0.05). Mean-comparison tests were analyzed for five periods (three-month seasons) for which complete records were available from both site.

Ambient Sulfur Dioxide and Ozone Concentrations

Ambient sulfur dioxide concentrations were measured with a Thermo Environmental Instruments Inc. (TEII), Franklin, Mass., Model 43A Pulsed Fluorescence Ambient SO_2 Analyzer calibrated by the U.S. Environmental Protection Agency (USEPA) Designated Equivalence Method Number EQSA-0486-060. Calibrations were made using a permeation tube system employing a TEII model 143 Multipoint Permeation Tube Calibrator and a VICI Metronics extended-life permeation tube (rate = 236 nanogram per minute ± 5 nanogram per minute at 35 ° C). The permeation tube is traceable to the National Institute of Standards and Technology. The SO_2 analyzer was operated and maintained in accordance with procedures described in the manufacturer's operating manual.

Ambient sulfur dioxide concentrations were measured at Union, Ga. Sulfur dioxide concentrations were measured and quality assured for periods during 1993–94 (table 4). Concentrations were measured continuously and the data were stored as 15-min average concentrations.

Table 4. Periods of continuous record for ambient atmospheric sulfur dioxide and ozone concentration measurements at Union, Georgia, 1993–94

Periods of continuous record			
Sulfur dioxide		Ozone	
Beginning date	Ending date	Beginning date	Ending date
08/18/93	12/10/93	07/23/93	01/27/94
12/12/93	01/27/94	02/10/94	06/16/94
02/10/94	03/11/94	07/22/94	11/30/94
04/08/94	06/16/94	not applicable	not applicable
07/22/94	11/30/94	do.	do.

Ambient ozone concentrations were measured with a TEII model 49 U.V. Photometric Ozone Analyzer calibrated by USEPA Designated Equivalence Method Number EQOA-0880-047. Calibrations were made using an ozone generator and TEII model 49PS ozone calibrator maintained and calibrated by the Georgia Department of Natural Resources, Environmental Protection Division, Air Quality Branch, in accordance with USEPA specified procedures (U.S. Environmental Protection Agency, 1979, Technical Assistance Document EPA600/4-79-057). The ozone analyzer was operated and maintained in accordance with procedures described in the manufacturer's operating manual.

Ambient ozone concentrations also were measured at Union, Ga. Siting and installation of gas handling equipment followed procedures approved by the USEPA and the Georgia Department of Natural Resources, Environmental Protection Division (EPD) and were comparable to procedures used at other EPD air-quality monitoring sites in Georgia. Teflon tubing, connectors, and filters were used for all gas handling because ozone reacts with most other materials. Ambient ozone data were collected and quality assured for the periods shown in table 4. Concentrations were measured continuously and the data were stored as 15-min average concentrations.

A data logger equipped with a storage module was used to acquire and store sulfur dioxide and ozone data. Data were retrieved during site visits when instrument checks and calibrations were conducted. It was not possible to detect problems immediately because of the remote nature of the site and the lack of real-time data acquisition; therefore, there were periods where data were not collected. Data are reported only for periods of continuous measurement that included beginning and ending calibration checks.

Soil Chemical Properties

Soil samples were collected in adjacent, paired infested and uninfested forest stands throughout Stewart County and in two locations in Webster County by GFC personnel to determine if there were systematic differences in properties between infestation status (fig. 9). Funding was not available to establish plots, sample soils, and analyze soil samples from Marion County. Soil-sampling sites were selected from a larger group of sites previously sampled by GFC personnel as part of a root pathogen survey. Statistical analyses (paired comparison t-tests) were conducted at the 95 percent confidence level to test the null hypothesis that there were no differences in soil properties between infested and uninfested forest stands.

The basis for comparisons between soil properties of infested and uninfested stands rests on the assumption that forest condition and resistance to attack by SPB are influenced by soil properties. Selected soil properties such as base saturation, availability of exchangeable calcium, and extractable sulfate are known to be adversely influenced by acidic deposition. Comparisons between soil properties of infested and uninfested stands were conducted to determine whether there was any association between infestation and soil quality that would be consistent with acidic deposition being a possible causal agent. For example, if stress related to low soil fertility were important in the susceptibility of loblolly pine to SPB, then it was expected that soils of infested forest stands would have lower exchangeable calcium, lower base saturation, and lower sulfate retention compared with soils of uninfested stands. It was considered that if there were differences in soil properties that could be associated with infestation status, such differences should be apparent throughout the study area.

The data collected in this study would not provide evidence for cause and effect, but would provide an association which could be further investigated. It should be recognized that differences in soil properties within Stewart County could be the result of natural spatial variation in parent materials or differences in prior agricultural or silvicultural practices. Therefore, even if differences in soil fertility were detected between plots of different infestation status, it would not be appropriate to conclude that acidic deposition was necessarily responsible for the observed differences.

Collection of Soil Samples

During 1994, soil samples were collected within 28 pairs of infested and uninfested plots; one infested and one uninfested plot constituted a pair of plots which were adjacent to each other (fig. 9). These paired plots provided the basis for the statistical analysis using paired comparison t-tests. At six randomly located points within each plot, soil was excavated with a 3-inch bucket auger. Depth-integrated samples were composited from the six samples collected at each of the three depth strata; 0–20, 20–60, and 60–100 cm soil depths. Subsamples were collected from each composite sample representing each of the three depth strata in both infestation categories for a total of 168 samples.

Infested plots were defined as those in which all trees had been killed by SPB. Uninfested plots were established in areas adjacent to the infested plots where loblolly pine forests had not been affected by SPB.

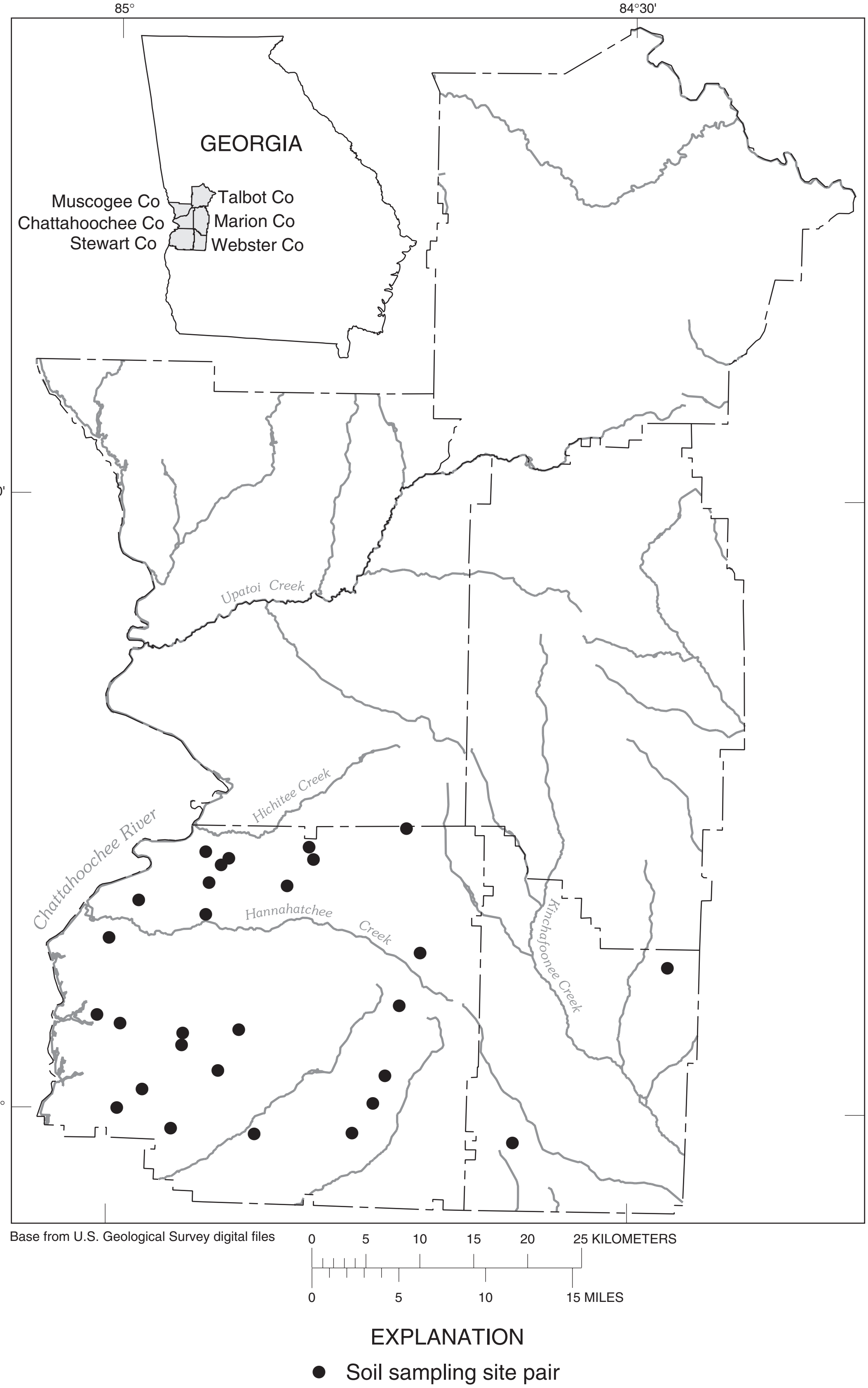


Figure 9. Soil sampling sites in the study area.

Field-moist soil samples were shipped to the USGS soil analysis laboratory in Atlanta, Ga., for analysis. Field-moist soil samples were subdivided into a fraction used for estimation of soil water chemistry and sulfate extraction and a fraction used for all other analyses. The former fraction was refrigerated and the sulfate extraction was air dried, sieved through 2-mm mesh, and stored at room temperature.

Exchangeable Cations

Exchangeable cations were determined by mechanical vacuum extraction using unbuffered N NH_4Cl as the extractant (Robarge and Fernandez, 1986; Holmgren and others, 1977; U.S. Department of Agriculture, Soil Conservation Service, 1992a; Huntington and others, 1990). In this method, 5 g of air-dry soil was extracted with 100 mL of extractant over 12 hours. Extract solutions were acidified, refrigerated, and analyzed within four weeks of extraction and results were reported on an oven-dry, 105 ° C constant weight (ODWT) basis. Exchangeable cation concentrations were determined by direct coupled plasma optical emission spectroscopy (DCP). Laboratory quality-assurance procedures are described in Huntington and others (1993). Determinations of cations by DCP were less precise in N NH_4Cl background than cited by Huntington and others (1993) for dilute aqueous solutions. Estimated precision averaged 0.2 micrograms per gram ($\mu g\ g^{-1}$) for aluminum and 1 to 5 $\mu eq\ L^{-1}$ for base cations. Error associated with determination of cation concentration in extracts equated to an average error of less than 5 percent for soil exchangeable cations expressed as centimoles positive charge per kilogram ($cmol_c\ kg^{-1}$).

Cation exchange capacity (CEC) was calculated as the sum of the individual exchangeable cations; sodium, potassium, calcium, magnesium, and aluminum determined using unbuffered N NH_4Cl. Percent base saturation was calculated as the sum of base cations (sodium, potassium, calcium, and magnesium) divided by CEC. Mean values reported for CEC and percent base saturation are based on the mean values of 28 separate ratios and not the ratio of the mean values reported for individual exchangeable cations.

Soil Organic Matter Concentration and Estimation of Bulk Density

Soil organic matter concentration (SOM) was determined by the loss-on-ignition method using a modification of this method described by Davies (1974). Soil samples in pre-weighed ceramic crucibles initially were brought to constant weight at 105 ° C and then weighed. Samples then were ashed at 500 ° C for 12 to 24 hours in a muffle furnace, allowed to cool to room temperature and reweighed. Soil organic matter was estimated as the difference in weight associated with combustion at 500 ° C. SOM was reported as a percent [(g SOM/g oven dry, 105 ° C, weight of soil)(100)]. Bulk density was estimated from SOM using a standard regression technique based on the inverse relation between SOM concentration and bulk density (Federer and others, 1993, Huntington and others, 1989). The equation used was

$$D_b = D_{bm}D_{bo}/[F_o\ D_{bm}+(1-F_o)D_{bo}] \qquad (2)$$

where F_o is the soil organic matter concentration, D_b is the bulk density, D_{bm} is the bulk density when F_o is 0, D_{bo} is the bulk density when F_o is 1. In this case, the measured SOM data were fit with D_{bm} = 1.928 and D_{bo} = 0.144 which provided the best fit for a broad range of soil types (Jeffrey, 1970).

Bulk density was used in the estimation of the soil-exchangeable calcium pool. The exchangeable calcium pool was estimated as the sum, over the three depth intervals sampled, of the products of exchangeable calcium multiplied by bulk density. For the purpose of this estimation of exchangeable calcium pool size, coarse fragment volume was assumed to be zero. The presence of coarse fragments results in an overestimation of exchangeable calcium pool size; therefore, this is a conservative assumption in the context of estimating calcium depletion.

Water- and Phosphate-Extractable Sulfate

Water-extractable sulfate was determined by mechanical vacuum extraction (MVE) using deionized water as the extractant, using a modification of the procedures described by Robarge and Fernandez (1986). Extraction with deionized water provides an estimate of the total amount of water-soluble sulfate in the soil. This fraction includes sulfate-S in the soil solution and readily soluble sulfate salts. A MVE (Holmgren and others, 1977) was used rather than a batch equilibration; analyses were performed on fresh rather than air-dried soils. The amount of soil and the extractant-to-soil ratio varied slightly among individual extractions; however, all data were reported based on ODWT basis. In general, 20 to 25 g of fresh soil was extracted with 50 mL deionized water during a 12-hour extraction. Sulfate concentrations in the extracts were determined by ion chromatography.

Phosphate-extractable sulfate was determined by MVE using 0.016 *M* NaH_2PO_4 as the extractant in a modification of the procedures described by Robarge and Fernandez (1986). Extraction with 0.016 *M* NaH_2PO_4 estimates the total amount of adsorbed sulfate-S retained on clay and iron and aluminum oxide surfaces. The amount of soil and the extractant to soil ratio varied slightly among individual extractions; however, all data were reported based on ODWT basis. In general, 20 to 25 g of fresh soil was extracted with 60 mL 0.016 *M* NaH_2PO_4 during a 3-hour extraction. Sulfate concentrations in the extracts were determined by ion chromatography.

Measurement of Soil-Water Chemistry

Soil-water chemistry was estimated by leaching field-moist soil in a mechanical vacuum extractor with a solution containing major ion concentrations typical of mean solute concentrations (except for sulfate) in throughfall measured from September 1992 through February 1994 in Lumpkin, Ga. (table 5). Sulfate concentrations in simulated throughfall were prepared to simulate the maximum rather than observed concentrations to differentiate soils based on sulfate-retention capacity. Field-moist soil samples used in this analysis were subsamples of those collected for chemical analyses described above.

In general, 20 to 50 g (mean=32 g) of fresh soil was leached with 60 mL of simulated throughfall in the MVE over a 12-hour period. Anion concentrations in leachate were measured by ion chromatography and cations (except ammonium) by direct-coupled plasma optical emission spectroscopy. The amount of sulfate retained by field-moist soils during leaching with simulated throughfall was calculated by subtracting the amount of sulfate measured in leachate from the amount of sulfate in the input simulated throughfall solution. The resulting sulfate retained was reported as mg S kg^{-1} ODWT of soil.

Anion concentrations in precipitation and throughfall were measured by ion chromatography and cations (except ammonium) by direct-coupled plasma optical emission spectroscopy.

Measurement of Surface-Water Chemistry

Surface-water samples were collected from selected streams throughout the study area (fig. 10) to compare water quality between areas having heavy and light SPB infestations under base-flow conditions. Surface-water samples were collected during several field trips between June 1992 and June 1994. Discharge was not measured during most collections; however, comparisons of sample-collection times with stream hydrographs suggests that water samples generally were collected during baseflow conditions. Surface-water samples collected from streams in the area of low infestation on March 30, 1993, were collected at relatively high streamflow based on Kinchafoonee Creek (USGS station ID 2350900) discharge but were not collected during peak flow (fig. 11). During storms, many constituent concentrations either increase or decrease substantially with increasing discharge; therefore, and samples collected during stormflow conditions may not be indicative of surface-water quality under baseflow conditions (Huntington and others, 1994a). However, constituent concentrations in surface water rapidly return to levels characteristic of baseflow conditions as streamflow recedes following peak stormflow.

Analysis of stream hydrographs for Upatoi Creek, draining parts of Chattahoochee, Muscogee, Talbot, and Marion Counties (fig. 12), and Kinchafoonee Creek, draining parts of Marion and Webster Counties and a small part of Stewart County (fig. 11) indicates that streamflow generally returns to near baseflow conditions within two days following storms. Surface water was sampled mostly following antecedent dry periods of two or more days. In the few instances where samples were collected less than two days following a storm, analysis of storm hydrographs for nearby Kinchafoonee and Upatoi Creeks indicated that sample-collection times did not correspond to times of high flow (figs. 11, 12).

Table 5. Measured concentrations of major inorganic constituents in simulated throughfall used to leach field-moist soil

[μeq L^{-1}, microequivalent per liter; concentrations based on mean solute concentrations for throughfall and maximum observed sulfate concentration measured in Lumpkin, Georgia, during the period September 1992 through February 1994]

Type	Property	Major inorganic constituents							
	pH (standard units)	Magnesium (μeq L^{-1})	Nitrate (μeq L^{-1})	Phosphate (μeq L^{-1})	Sulfate (μeq L^{-1})	Sodium (μeq L^{-1})	Potassium (μeq L^{-1})	Calcium (μeq L^{-1})	Ammonium (μeq L^{-1})
Simulated throughfall	4.90	39.5	5.45	2.64	195	40.0	59.1	37.9	66.9

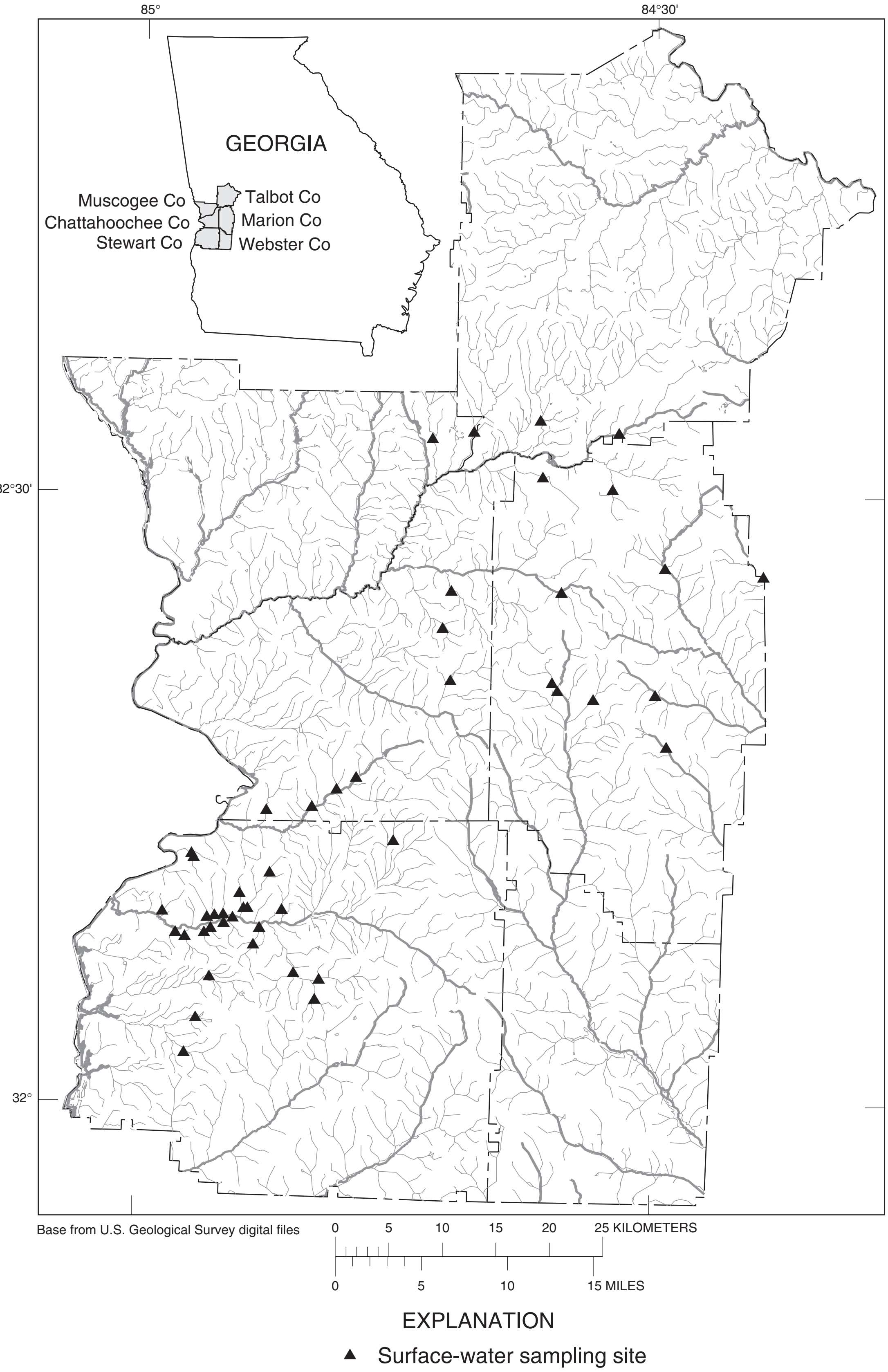


Figure 10. Surface-water sampling sites in the study area.

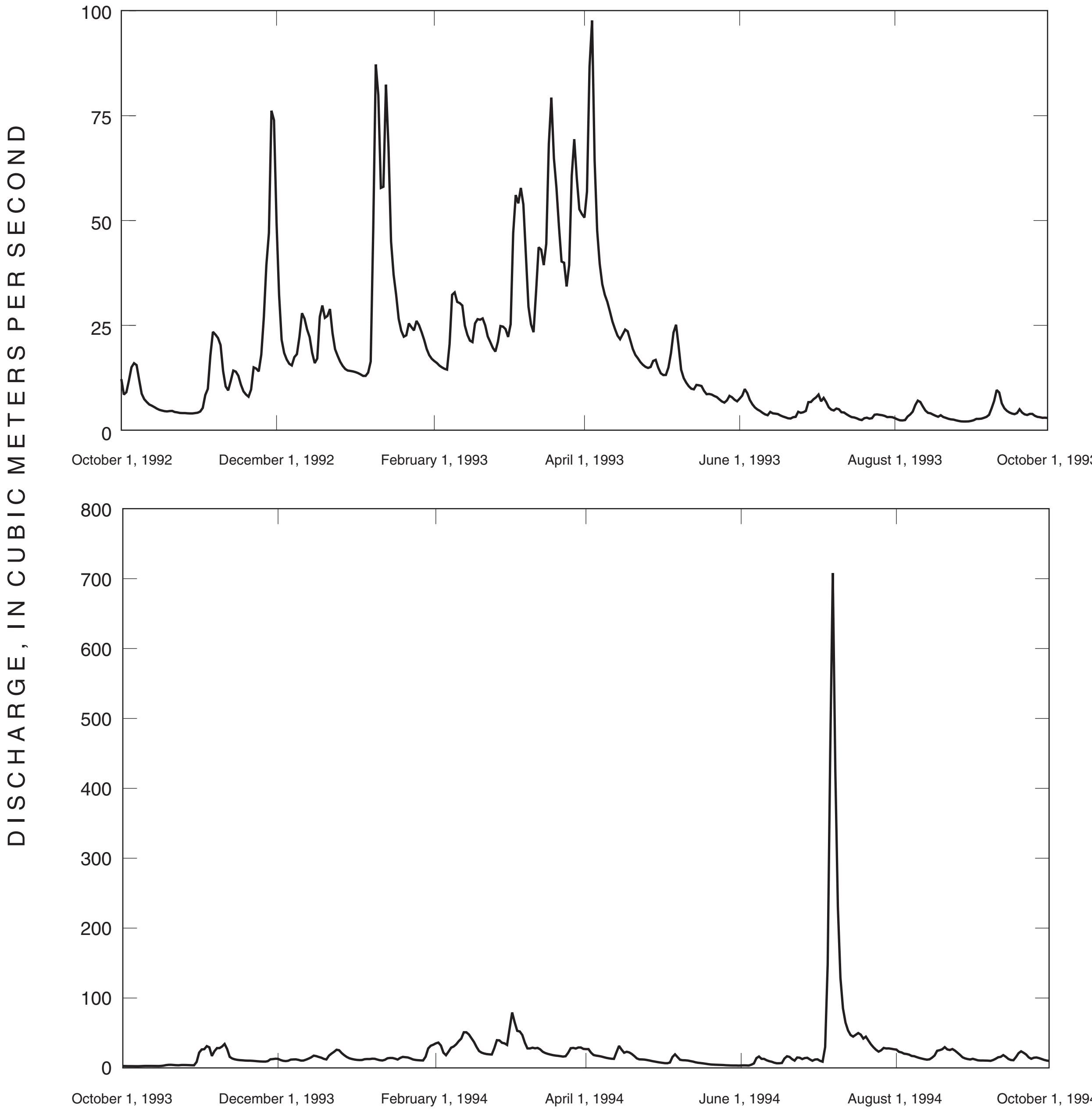


Figure 11. Discharge hydrograph for Kinchafoone Creek (USGS Station ID 02350900) 8.4 km northwest of Leesburg, Georgia, 1992–94.

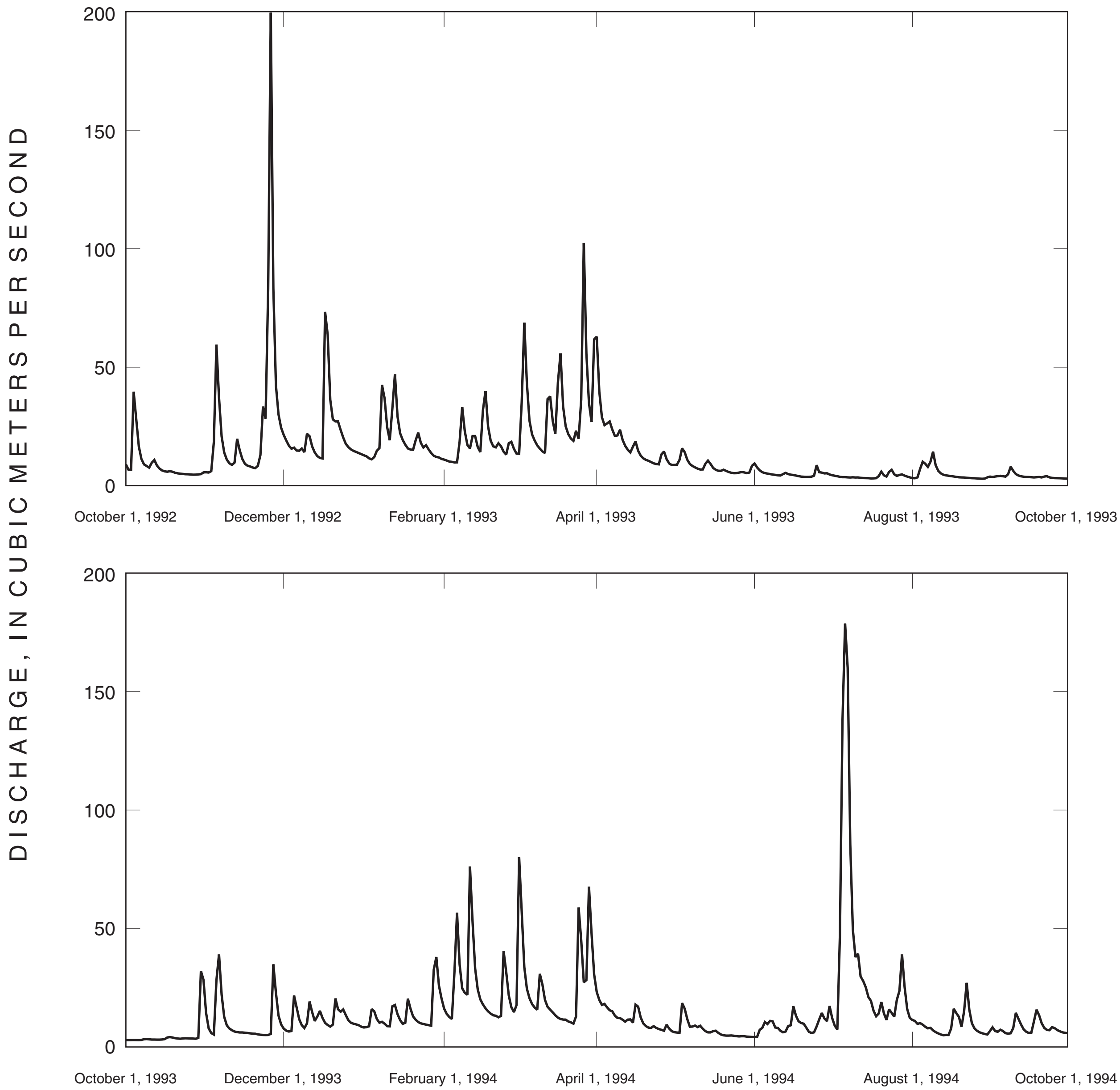


Figure 12. Discharge hydrograph for Upatoi Creek (USGS Station ID 02341800) 12.9 km southeast of Columbus Georgia, 1992–94.

POTENTIAL ROLE OF ATMOSPHERIC ACIDIC DEPOSITION AND OTHER STRESSORS

Loblolly pine in the study area is growing under complex, multiple interacting stresses. Cumulative effects of these stresses may be greater in the areas that are most highly infested by the SPB. This section of the report contains comparisons and discussions of atmospheric acidic deposition, ambient concentrations of sulfur dioxide and ozone, soil properties, soil-water chemistry, and stream-water chemistry relative to areas of high and low SPB infestation.

Atmospheric Acidic Deposition

Atmospheric acidic deposition of sulfur in both wet-only and throughfall deposition (wet-plus-dry deposition) was not significantly different (alpha = 0.05) between Lumpkin and Buena Vista, Ga., based on multiple pairwise mean-comparison tests between sites, paired for the periods where data were available for both sites (table 6). Although the period of overlapping record is short, data do not support the hypothesis that sulfur deposition is greater in the area of higher susceptibility to SPB infestation. The estimated annual rate of total sulfur deposition at Lumpkin was 6.0 kg S ha^{-1} yr^{-1}, based on two years of record. It was more difficult to estimate an annual rate for Buena Vista because of the limited and partial data. However, scaling the partial records using independent measurements of rainfall during the periods in which no throughfall samples were collected and summing seasonal averages for those seasons with records resulted in an estimate of 6.1 kg S ha^{-1} yr^{-1}.

Cumulative rainfall during the study period at the Lumpkin site and at the nearby National Weather Service First Order Station in Columbus, Ga., indicates a close agreement in amount and timing of precipitation recorded between these independent records (fig. 13). The exception to this agreement occurred during Tropical Storm Alberto (July 1994) when substantially more rainfall was recorded in Lumpkin than in Columbus. Agreement between these independent records supports the accuracy of the techniques used in this study to measure rainfall volume. The fact that there also was close agreement in the seasonal pattern of measured throughfall and rainfall volumes (data not shown) is further evidence supporting the validity of the estimates of throughfall volume.

Table 6. Seasonal and annual sulfur deposition in areas infested (Lumpkin, Georgia) and uninfested (Buena Vista, Georgia) by the southern pine beetle, 1992–95

[kg ha^{-1}, kilogram per hectare; nd, not determined]

Year	Seasonal sulfur deposition				Annual sulfur deposition (kg ha^{-1})
	Winter1/ (kg ha^{-1})	Spring2/ (kg ha^{-1})	Summer3/ (kg ha^{-1})	Fall4/ (kg ha^{-1})	
Buena Vista —Wet Deposition					
1992	no data	no data	no data	5/0.93	nd
1993	0.94	1.62	1.43	.73	4.72
1994	.81	.94	1.75	5/.46	nd
Buena Vista—Throughfall Deposition					
1992	no data	no data	no data	5/2.07	nd
1993	2.83	1.85	.96	no data	do.
1994	no data	.87	2.22	5/.82	do.
Lumpkin—Wet Deposition					
1992	no data	no data	no data	1.31	do.
1993	1.22	1.03	1.28	.73	4.26
1994	.87	1.46	1.54	.52	4.40
Lumpkin—Throughfall Deposition					
1992	no data	no data	no data	1.78	nd
1993	1.93	1.45	1.91	1.36	6.65
1994	1.36	1.74	1.43	.78	5.32
1995	.98	.61	6/1.01	no data	nd

1/ January through March.

2/ April through June.

3/ July through September.

4/ October through December.

5/ Estimated from partial records by scaling to total precipitation recorded during the period by independent measurements.

6/ Record through September 13, 1995 only.

Acidic sulfur deposition is relatively low in the study area and generally comparable to or lower than deposition estimated for this region during 1992–93 (Appendix 2). Sulfate deposition declined in Georgia and throughout the eastern United States from the late 1970's through the early 1990's, based on other assessments (Appendix 2) supported by the National Atmospheric Deposition Program (NADP) (Lynch and others, 1995), National Oceanic and Atmospheric Administration (NOAA), Integrated Forest Study-Electric Power Research Institute (IFS) (Lindberg and Lovett, 1992) and the Panola Mountain Research Watershed (PMRW) (Huntington and others, 1994a). There is strong evidence of declining sulfate deposition

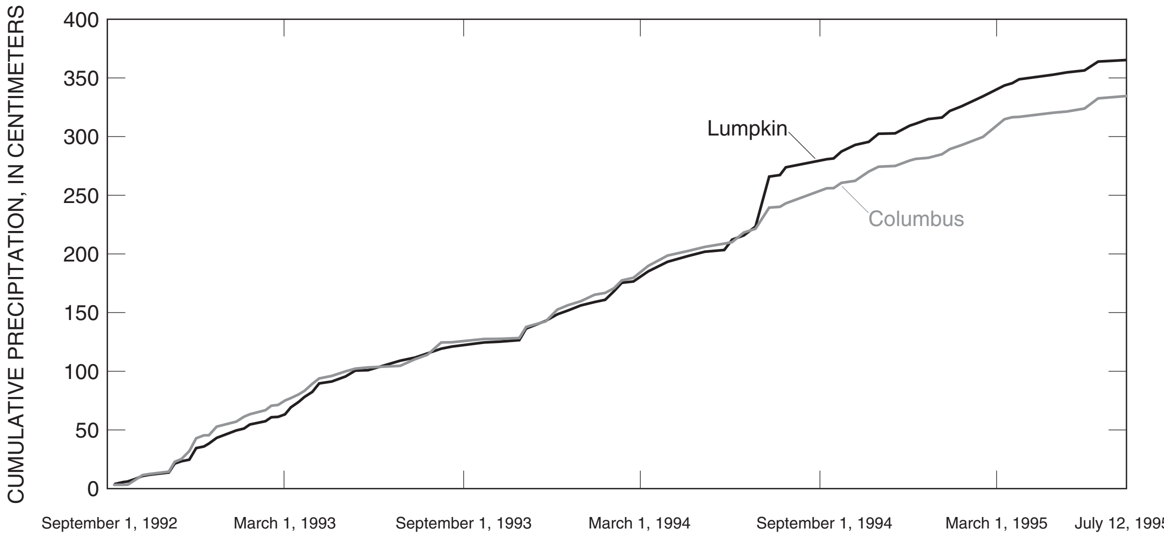


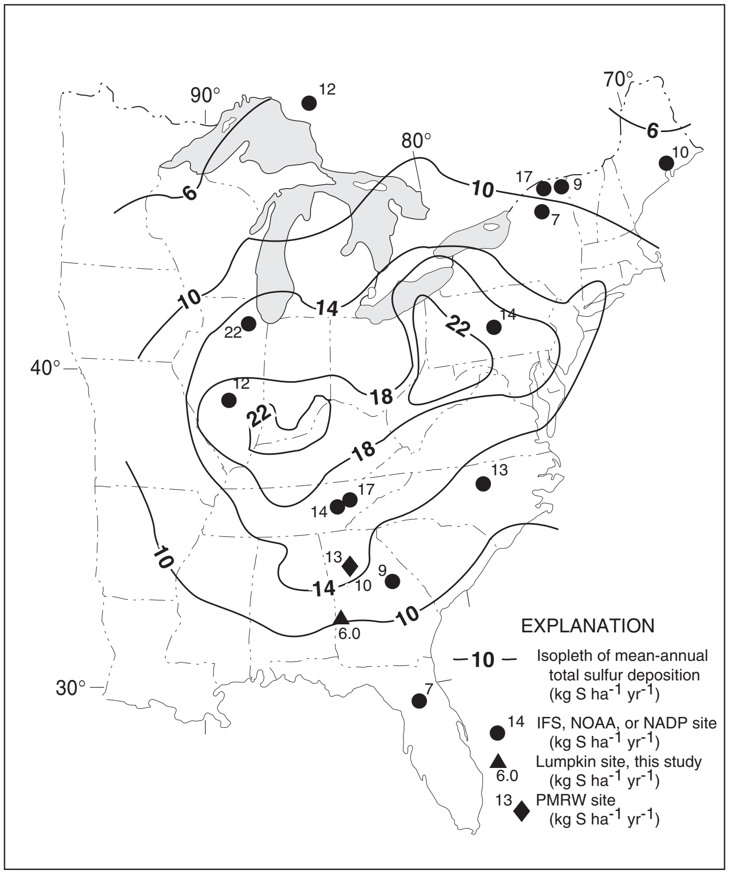
Figure 13. Cumulative rainfall recorded during the period September 1, 1992 through July 12, 1995 at Lumpkin and Columbus, Georgia.

at PMRW, near Atlanta, Ga., from the period October 1985 through September 1995, based on an observed rate of decrease of sulfate concentration in precipitation of 2.5 μeq L^{-1} yr^{-1} (Appendix 1). The relatively low levels of acidic deposition in the study area are a strong indication that there were no large local point sources during the measurement period. It is likely that sulfur deposition in the study area was higher during the 1980's, as it was throughout the region in general (Lynch and others, 1995); however, there are no known local point sources that were operating in the 1980's that would have effectively raised local deposition above regional levels.

The similarity in sulfur deposition measured at Lumpkin and Buena Vista does not support the hypothesis that sulfur deposition was greater in the more highly SPB-infested area than in the low SPB-infested area of the study area. It should be noted that the data represent only a short-term record; and therefore, higher sulfur deposition in the infested areas compared with the uninfested areas during the 1980's cannot be ruled out. However, there are two reasons why it is unlikely that elevated sulfur deposition played a role in the pattern of infestation over the study area. First, the absence of any known pollutant sources during the 1980's, but not during the study period, makes it unlikely that sulfur deposition was substantially higher in Lumpkin as compared with Buena Vista during this period. Second, longer-term records of sulfur deposition within the region (Appendix 2; Lynch and others, 1995) show declining trends, but do not show any periods of exceptionally high deposition in the region.

Levels of sulfur deposition measured in this study are lower than those in the Piedmont of Georgia (Huntington and others, 1994a); these levels generally are lower than those in more northerly latitudes across the eastern United States (figs. 14, 15), which are thought to be associated with the burning of fossil fuels for industry and power generation in the Midwest. The existence of wood pulp processing facilities which emit sulfur dioxide does not appear to elevate sulfur deposition across the study area above typical ambient levels of sulfur dioxide in the rural southeastern United States. Wood pulp processing facilities produce hydrogen sulfide in addition to sulfur dioxide. In spite of the fact that hydrogen sulfide has a very distinct odor, even at concentrations below 1 nL L^{-1}, emissions of hydrogen sulfide from such facilities generally are much lower than sulfur dioxide emissions, so that sulfur deposition from this source is small.

There was little difference seasonally in total sulfur deposition at the Lumpkin site (table 6). In contrast, at the majority of locations sampled by Meyers and others (1991), there was a distinct seasonal pattern in which dry and total sulfur deposition was highest in summer and lowest in winter. The sites reported by Meyers and others (1991) largely were dominated by deciduous vegetation having much lower leaf surface area in winter; whereas, the loblolly pines at the Lumpkin site maintain a nearly constant leaf surface area. Meyers and others (1991) used the inferential eddy correlation technique rather than the throughfall method to estimate dry deposition.



Base modified from U.S. Geological Survey digital data files

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Figure 14. Isopleths of mean-annual total sulfur deposition (kg S ha^{-1} yr^{-1}) in the eastern United States, based on an analysis completed in 1989 by Lindberg and Lovett (1992); and mean-annual total sulfur deposition determined for Integrated Forest Study (IFS), National Oceanographic and Atmospheric Administration (NOAA), or National Atmospheric Deposition Program (NADP) sites (Lindberg and Lovett, 1992), the Panola Mountain Research Watershed (PMRW) (Huntington and others,1994a), and this study.

At Lumpkin, dry deposition of sulfur as a fraction of total sulfur deposition (DD/TD) averaged 32 percent for the period October 1992 through December 1994, excluding summer 1994. In computing this fraction, the summer 1994 season was excluded because weather circumstances were highly unusual. As a result of very high rainfall (greater than 35 cm) at Lumpkin resulting from Tropical Storm Alberto, volume-weighted sulfate concentrations in throughfall were nearly identical with those in precipitation during the summer 1994 season. As is typical, the estimated throughfall volume for the summer 1994 season was lower than the precipitation volume because of stemflow and evaporation from the canopy. Nearly identical sulfate concentrations in throughfall and rainfall and lower throughfall volume than rainfall volume resulted in a slightly lower estimate for total atmospheric deposition than that for wet deposition during summer 1994.

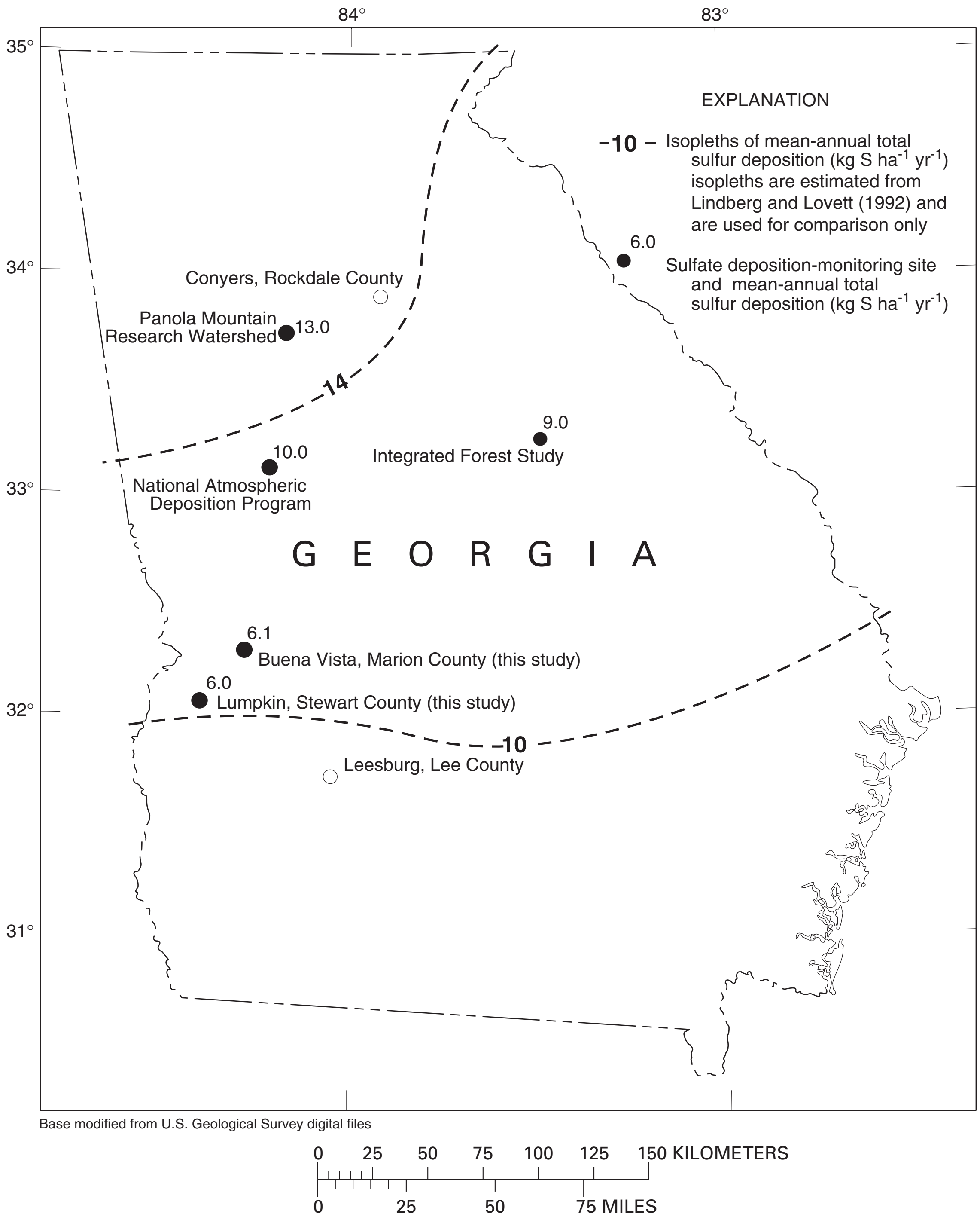

Figure 15. Isopleths of mean-annual total sulfur deposition (kg S ha^{-1} yr^{-1}) in Georgia, based on an analysis completed in 1989 by Lindberg and Lovett (1992); and mean-annual total sulfur deposition determined for sites of the Integrated Forest Study (Lindberg and Lovett, 1992), National Atmospheric Deposition Program (Lindberg and Lovett, 1992), the Panola Mountain Research Watershed (Huntington,1994a), and this study.

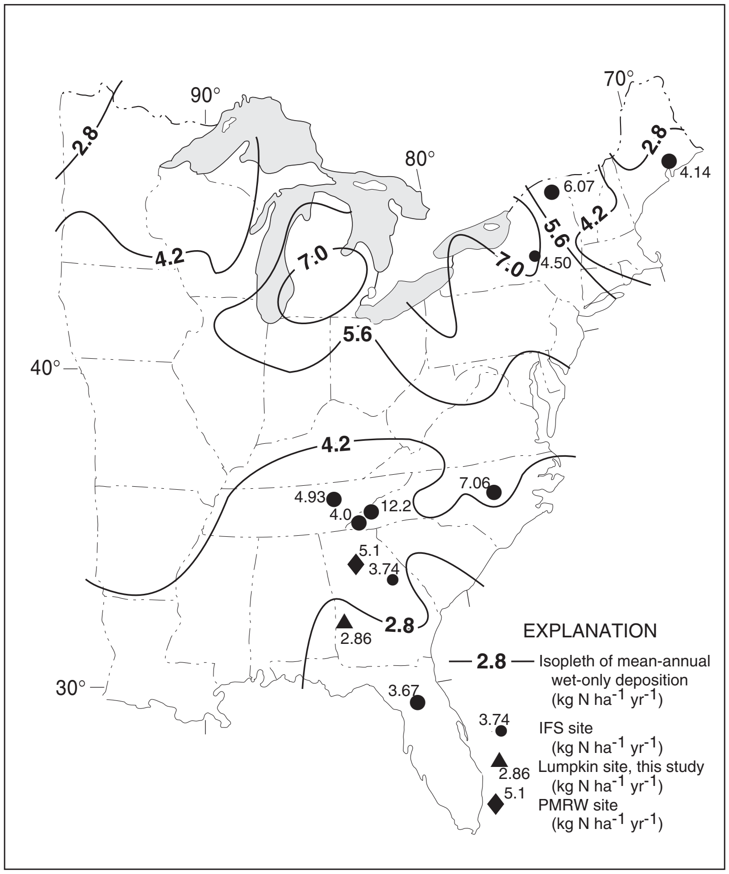

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Figure 16. Isopleths of mean-annual wet-only nitrogen ($NO_3^- + NH_4^+$) deposition (kg N ha^{-1} yr^{-1}) in the eastern United States determined for data collected from April 1986 through March 1989, modifed from Johnson and Lindberg (1992); and mean-annual wet-only nitrogen deposition determined for Integrated Forest Study (IFS) sites (Johnson and Lindberg, 1992), the Panola Mountain Research Watershed (PMRW) (Huntington,1995), and this study.

Similarly, there was no strong seasonal pattern in DD/TD at Lumpkin. This also was in contrast to most of the sites studied by Meyers and others (1991), including Panola Mountain in Georgia where DD/TD was higher in winter than in summer or fall. It is unexpected that this fraction would be higher in winter than in summer or fall because deposition velocities for SO_2 and SO_4^{2-} (based in part on leaf area index) are much higher in summer than in winter Meyers and others (1991).

During the short period of overlapping record, there was significantly greater wet deposition of nitrogen (P less than 0.05) at the Lumpkin site than the Buena Vista site based on multiple pairwise mean-comparison tests between sites, paired for the five seasons where data were available for both sites (table 7). Throughfall deposition of nitrogen was not significantly different between sites. Wet deposition of nitrogen (fig. 16) in Lumpkin, for which there were more than 2 years of record, was very similar to the regional norm (Johnson and Lindberg, 1992) and does not indicate an unusually high source of acidic deposition from nitrogen oxides. The level of nitrogen wet deposition measured at Lumpkin is lower than that at the B.F. Grant Forest, near Eatonton, Ga. (Johnson and Lindberg, 1992) and at Panola Mountain, near Atlanta, Ga. (Huntington, 1995). Lower nitrogen deposition in the study area was expected because it is more rural than the B.F. Grant Forest or Panola Mountain, which are closer to Metropolitan Atlanta.

Table 7. Seasonal and annual nitrogen deposition in areas infested (Lumpkin, Georgia) and uninfested (Buena Vista, Georgia) by the southern pine beetle, 1992–95

[kg ha^{-1}, kilogram per hectare; nd, not determined]

Year	Seasonal nitrogen deposition				Annual nitrogen deposition (kg ha^{-1})
	Winter[1/] (kg ha^{-1})	Spring[2/] (kg ha^{-1})	Summer[3/] (kg ha^{-1})	Fall[4/] (kg ha^{-1})	
Buena Vista—Wet Deposition					
1992	no data	no data	no data	[5/]0.39	nd
1993	0.59	0.55	0.15	.20	1.49
1994	.32	.17	.33	no data	nd
Buena Vista—Throughfall Deposition					
1992	no data	no data	no data	[5/].65	
1993	1.50	.58	.40	no data	do.
1994	no data	.25	3.12	no data	do.
Lumpkin—Wet Deposition					
1992	no data	no data	no data	1.36	do.
1993	1.60	.78	.87	.46	3.71
1994	.41	.89	.14	.27	1.71
Lumpkin—Throughfall Deposition					
1992	no data	no data	no data	2.43	nd
1993	2.82	1.61	.61	.42	5.46
1994	1.61	2.05	1.67	.97	6.31
1995	.41	5.77	.50	no data	nd

[1/] January through March.

[2/] April through June.

[3/] July through September.

[4/] October through December.

[5/] Estimated from partial records by scaling to total precipitation recorded during the period by independent measurements.

Nitrogen deposition probably does not contribute to increased leaching of nutrient cations, as does sulfur deposition because these forest ecosystems are thought to be nitrogen limited; and therefore, nitrate is taken up by vegetation and is not leached. In fact, current levels of nitrogen deposition probably have a positive, fertilization effect on these forests in a similar manner as has been indicated for forests in western Europe (van Breemen and others, 1995) and globally (Schindler and Bayley, 1993). However, in some montane forest ecosystems that receive higher nitrogen inputs than lower elevation forests nitrogen is not limiting and nitrate leaching does contribute to the loss of nutrient cations and the mobilization of aluminum (van Breemen and others, 1995).

Rainfall and Throughfall Chemistry

Volume-weighted mean concentrations of major solutes, along with pH and alkalinity in precipitation and throughfall at Buena Vista and Lumpkin, Ga., are shown in table 8. Sulfate concentrations in precipitation within the study area are about one half of the concentrations measured at a site in the Piedmont about 25 km southeast of Atlanta (Huntington and others, 1994a), which probably has elevated sulfate because of the concentration of coal-burning power plants and other industrial emission sources in the Metropolitan Atlanta area.

The volume weighted average pH of precipitation in Buena Vista (4.77) is slightly lower (more acidic) than that measured in Lumpkin (4.90). Ammonium and base cation concentrations in precipitation are higher at the Lumpkin site than at the Buena Vista site (table 8, fig.

Table 8. Volume-weighted mean concentrations of major inorganic constituents, pH, and alkalinity in precipitation and throughfall samples collected in areas infested (Lumpkin, Georgia) and uninfested (Buena Vista, Georgia) by the southern pine beetle, 1992–95

[µeq L^{-1}, microequivalent per liter]

Location	Sample type	Physical properties		Major inorganic constituents							
		pH (standard units)	Alkalinity (µeq L^{-1})	Sodium (µeq L^{-1})	Potassium (µeq L^{-1})	Magnesium (µeq L^{-1})	Calcium (µeq L^{-1})	Ammonium (µeq L^{-1})	Chloride (µeq L^{-1})	Nitrate (µeq L^{-1})	Sulfate (µeq L^{-1})
Buena Vista	precipitation	14.77	–21.34	17.84	12.59	2.20	13.83	12.61	17.93	15.09	122.19
	throughfall	4.89	40.33	17.17	39.92	26.10	44.24	16.97	23.39	7.26	40.58
Lumpkin	precipitation	4.90	–2.58	16.26	12.75	3.63	6.15	9.45	16.82	5.44	19.27
	throughfall	5.34	46.53	21.48	40.32	20.60	21.81	45.32	26.46	2.41	32.31

17). Throughfall is enriched in most anions and cations relative to precipitation because of dry deposition (which is more important for sulfate), foliar leaching (which is more important for potassium, calcium, and magnesium), and evaporative concentration (fig. 18). Nitrate is an exception because forest canopies generally retain (presumably by active uptake) about 40 percent of total inputs of inorganic nitrogen, thereby depleting throughfall relative to precipitation (Johnson and Lindberg, 1992; Cappellato and others, 1993). Nitrate concentration was higher in throughfall than in precipitation at Buena Vista, suggesting that nitrate was leached from the canopy; in contrast, at the Lumpkin site and at most other sites (Johnson and Lindberg, 1992; Cappellato and others, 1993), nitrate is retained.

Studies involving nutrient cycling and the potential impacts of atmospheric acidic deposition also should include an assessment of the deposition of base cations. Atmospheric deposition of base cations offsets or mitigates some proportion of the negative impacts of acid-induced cation leaching from soils and the loss of cations through vegetation uptake. Dry deposition of base cations was not assessed in this study because throughfall is not an appropriate surrogate. A substantial proportion of base cations measured in throughfall are derived from foliar leaching rather than dry deposition. Wet deposition of base cations was computed from measurements of precipitation volume and chemistry. Base cation deposition was higher at Lumpkin than at Buena Vista, based on the relatively short period of record in this study (table 9). Sodium and potassium were the dominant cations by weight, followed by calcium and magnesium.

Calcium wet deposition rates were somewhat higher than those reported by Sisterson (1990); however, the period of record for that study (1985–87) were drought years. Calcium in wet deposition at PMRW, near Atlanta, Ga., averaged 0.80 kg ha^{-1} yr^{-1} over the period October 1985 through September 1995, and showed strong evidence of declining, based on an observed rate of decrease in calcium concentration in precipitation of 0.22 μeq L^{-1} yr^{-1} (Appendix 1). The calcium wet deposition rate of 1.68 kg ha^{-1} yr^{-1} at Lumpkin is still relatively small when compared with average rates of removal in loblolly pine ecosystems through soil leaching and vegetation uptake (Johnson and Lindberg, 1992). The combination of low and declining inputs may be cause for concern regarding long-term maintenance of site productivity (Swank and Waide, 1988; Hooper and Peters, 1989; Hedin and others, 1994; Aulenbach and others, 1996). Low and declining inputs also may be of concern because of the arguments made for the potential role of calcium in maintaining an adequate supply of oleoresin and the role this defense mechanism plays in resistance to SPB.

The canopy neutralizes some acidity in precipitation so that throughfall has a higher pH than precipitation. The lack of charge balance indicated in figures 17 and 18 reflects unmeasured organic anions, small concentrations of phosphate, bromide, and fluoride, and analytical error.

Throughfall samples were collected between March 22 and November 30, 1994, in Union, Ga. Volume-weighted average concentrations of major solutes, with the exception of magnesium and nitrate, generally were somewhat higher in Union compared to Lumpkin, Ga. (table 10). There were insufficient data from the Union site to make statistical comparisons between sites or to compute rates of deposition. The limited data may suggest a possible spatial trend (decreasing sulfate concentration from west to east) within the more highly infested area; however, further analysis would be required to establish such a trend. Even if such a trend were demonstrated, the overall sulfur deposition rate would still be relatively low compared with other areas measured in the southeastern United States.

Table 9. Annual average wet-only deposition of base cations and total inorganic nitrogen from areas infested (Lumpkin, Georgia) and uninfested Buena Vista, Georgia) by the southern pine beetle, 1992–95

[kg ha^{-1} yr^{-1}, kilogram per hectare per year]

Location	Period of record	Major inorganic constituents				
		Sodium (kg ha^{-1} yr^{-1})	Potassium (kg ha^{-1} yr^{-1})	Magnesium (kg ha^{-1} yr^{-1})	Calcium (kg ha^{-1} yr^{-1})	Nitrogen (kg ha^{-1} yr^{-1})
Buena Vista	01/17/92 to 11/03/94	2.16	1.15	0.028	0.84	1.28
Lumpkin	09/01/92 to 01/24/95	5.17	6.81	.32	1.68	2.86

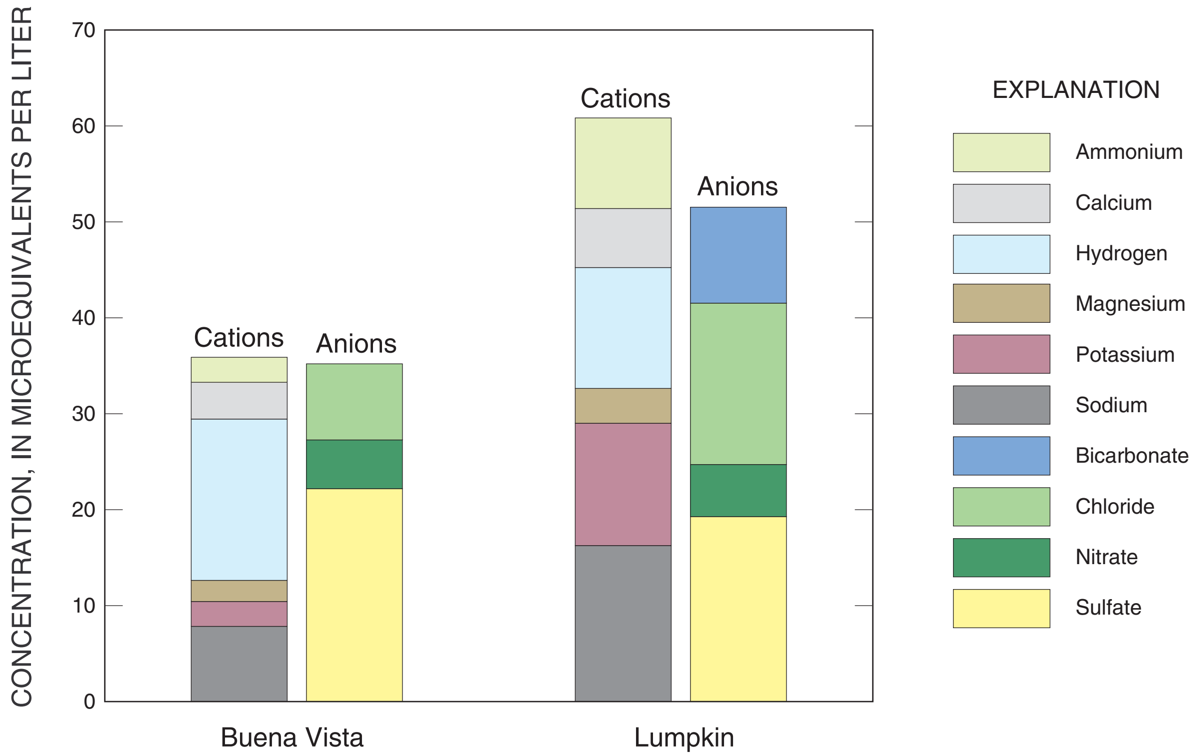

Figure 17. Major solute concentrations in precipitation at Lumpkin (September 1992 through January 1995) and Buena Vista (November 1992 through November 1994), Georgia.

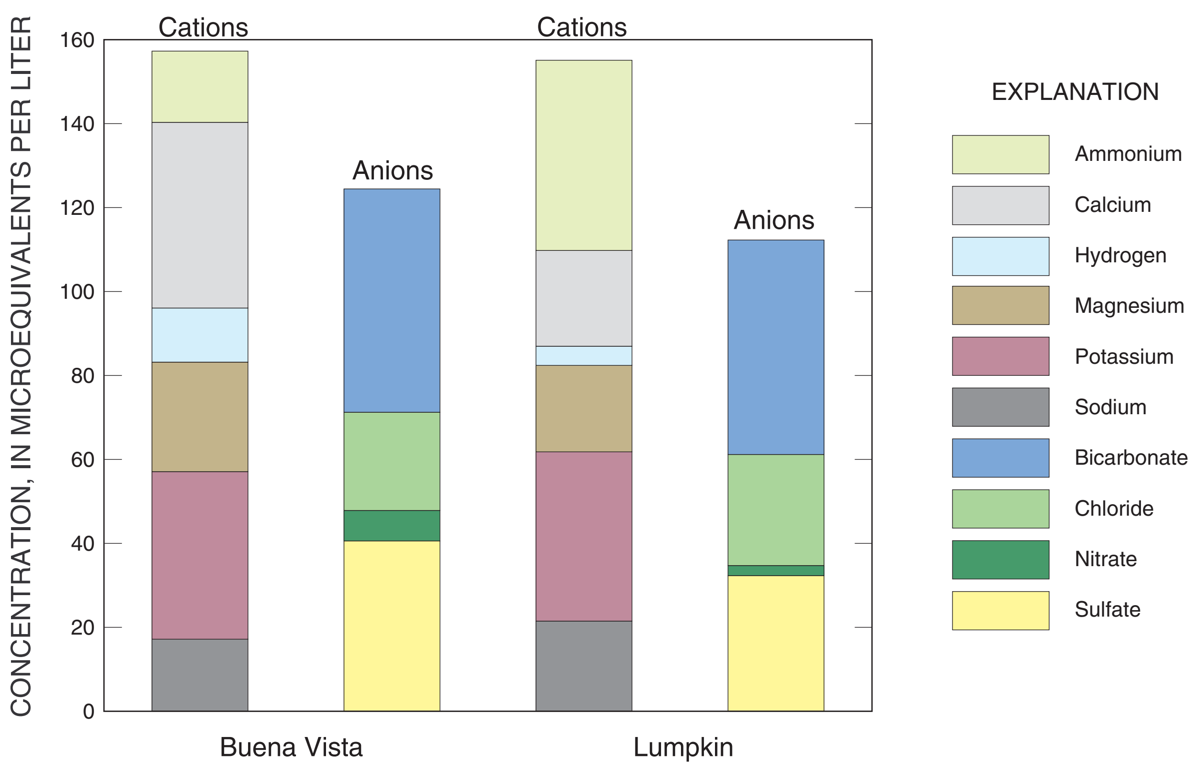

Figure 18. Major solute concentrations in throughfall at Lumpkin (September 1992 through January 1995) and Buena Vista (November 1992 through November 1994), Georgia.

Table 10. Volume-weighted mean concentrations of major inorganic constituents in throughfall from Union and Lumpkin, Georgia, for selected periods in 1994

[μeq L^{-1}, microequivalent per liter]

Location	Period of record	Major inorganic constituents						
		Sodium (μeq L^{-1})	Potassium (μeq L^{-1})	Magnesium (μeq L^{-1})	Calcium (μeq L^{-1})	Ammonium (μeq L^{-1})	Nitrate (μeq L^{-1})	Sulfate (μeq L^{-1})
Union	03/19/94 to 06/16/94	37.7	80.3	33.2	61.9	439.8	6.4	69.2
Lumpkin		33.4	68.5	30.9	37.5	59.3	6.5	47.8
Union	06/17/94 to 07/22/94	12.6	26.0	8.8	18.0	96.0	2.1	23.1
Lumpkin		10.1	19.5	8.3	12.2	10.2	.1	16.4
Union	07/23/94 to 11/30/94	50.5	60.3	13.7	34.5	29.6	.1	42.7
Lumpkin		19.9	50.9	19.4	17.4	41.7	.1	21.1

Ambient Concentrations of Sulfur Dioxide and Ozone

Measurements of ambient concentrations of sulfur dioxide were within normal background levels expected in rural Georgia. The Georgia Department of Natural Resources, Environmental Protection Division, Air Quality Branch, maintains a Air-Quality Surveillance Network that includes ozone sites in Columbus and Leslie, Ga.; and sulfur dioxide sites in Columbus. Concentrations of sulfur dioxide and ozone measured at Union, Ga., as a part of this assessment (fig. 19), are typical of those measured in Columbus and Leslie (Raphael Ballagus, Georgia Department of Natural Resources, Environmental Protection Division, oral commun., 1995); thus, indicating that no local point source of these pollutants elevated ambient concentrations above regional norms. During the approximately 15-month measurement period, sulfur dioxide concentrations generally were under 5 nL L^{-1}. The highest values were recorded during the winter months of November, December, and January when daily highs frequently exceeded 15 nL L^{-1}; and on five days exceeded 30 nL L^{-1} for brief periods. Sulfur dioxide concentrations such as those recorded in Union, Ga. (fig. 19), are not thought to be sufficiently high to have direct adverse affects on trees (Kress and others, 1982; Mohren and others, 1992).

Ozone concentrations measured at Union, Ga., as a part of this assessment, indicate that concentrations frequently exceed 50 to 60 nL L^{-1} for several hours during growing season days (fig. 20). Concentrations tend to be highest during the growing season compared with the dormant season. Concentrations also tend to be higher from midday to late afternoon compared to nighttime and morning. Ozone concentrations typically buildup to their highest levels following a number of days of hot, clear weather with stagnant air masses. Concentrations during the 1993–94 growing seasons in Conyers, Ga., within the Metropolitan Atlanta airshed (fig. 21), are higher than those observed in Union, Stewart County, because of the proximity to pollutant sources. However, it is notable that ozone concentrations in Stewart County are as high as shown in figure 20 because the area is rural and lacks significant sources of sulfur or nitrogen oxides emissions that are common in urban areas.

Evidence from controlled exposure and field studies has shown that loblolly pine is sensitive to ozone at levels that are comparable to those measured in Stewart County during the growing season (McLaughlin and others, 1994; McLaughlin and Downing, 1995). Oxidant damage caused by ambient ozone concentrations probably is an important contributing stress to the overall tree condition, but there are insufficient data to detect any association between the spatial pattern of infestation and ozone concentrations throughout the study area.

There is debate about the most appropriate way to characterize ozone exposures to vegetation (Lefohn, 1990; Taylor and others, 1992); but generally, a 7-hour average or episodic threshold value is reported in characterization data for rural areas. Ozone concentrations measured in Union exceed both the 7-hour average and episodic threshold values typically reported for rural southeastern United States (Lefohn, 1990; Taylor and others, 1992). There are insufficient data to explain why ozone concentrations in Stewart County are elevated above regional norms. These data (fig. 20), together with the conclusions of exposure-response studies, strongly suggest that ambient concentrations of ozone in the study area constitute a substantial chronic stress to loblolly pine. Although it is difficult to quantify the effects of long-term exposure to air pollutants, it is likely that the cumulative effects of chronic exposures can reduce tree growth, particularly under conditions of moisture or nutrient deficit (Jager and Klein, 1976; Mohren and others, 1992).

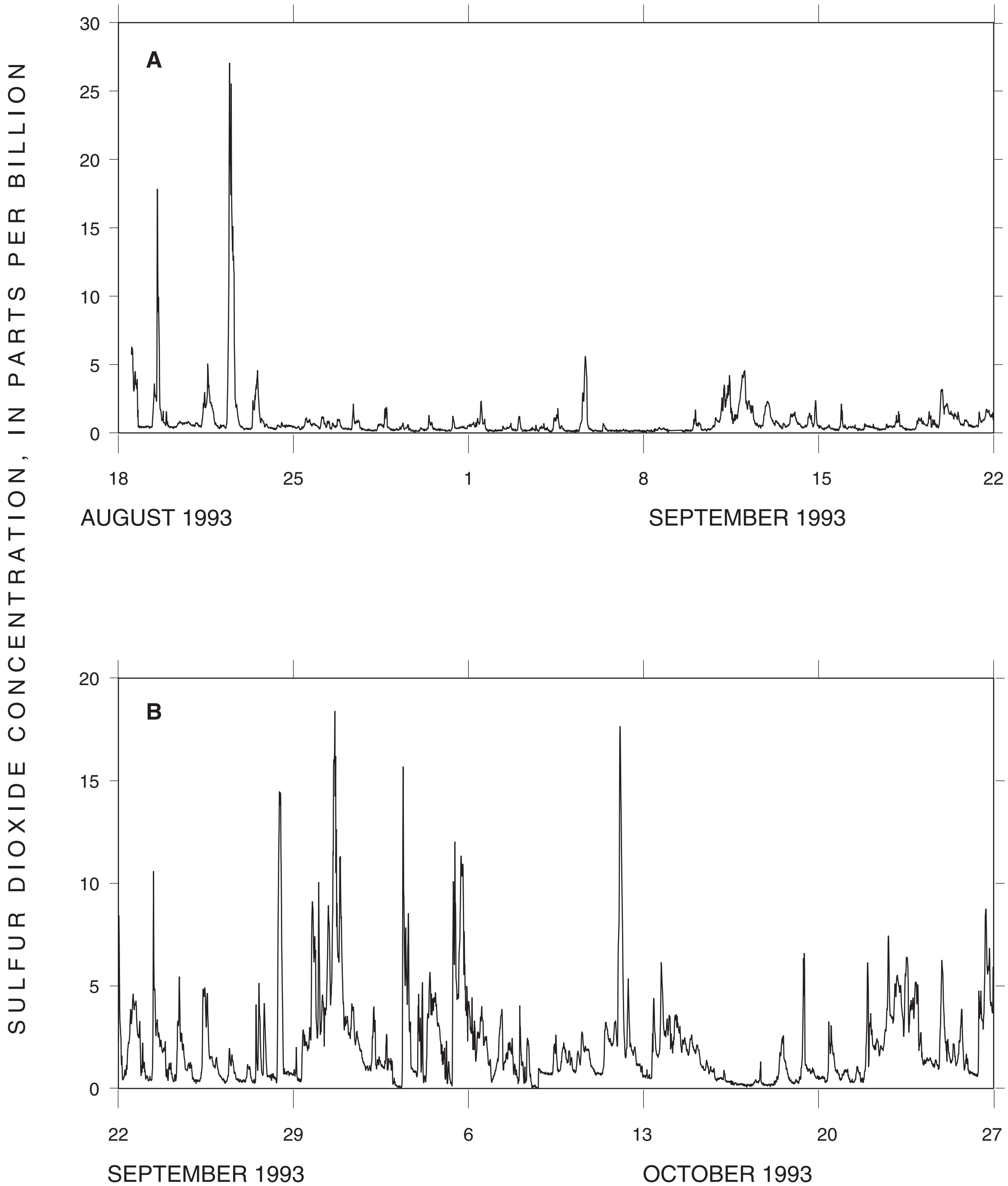

Figure 19. Temporal pattern of ambient concentration of sulfur dioxide at Union, Stewart County, Georgia, August 18, 1993 through November 30, 1994 (blank areas indicate missing data).

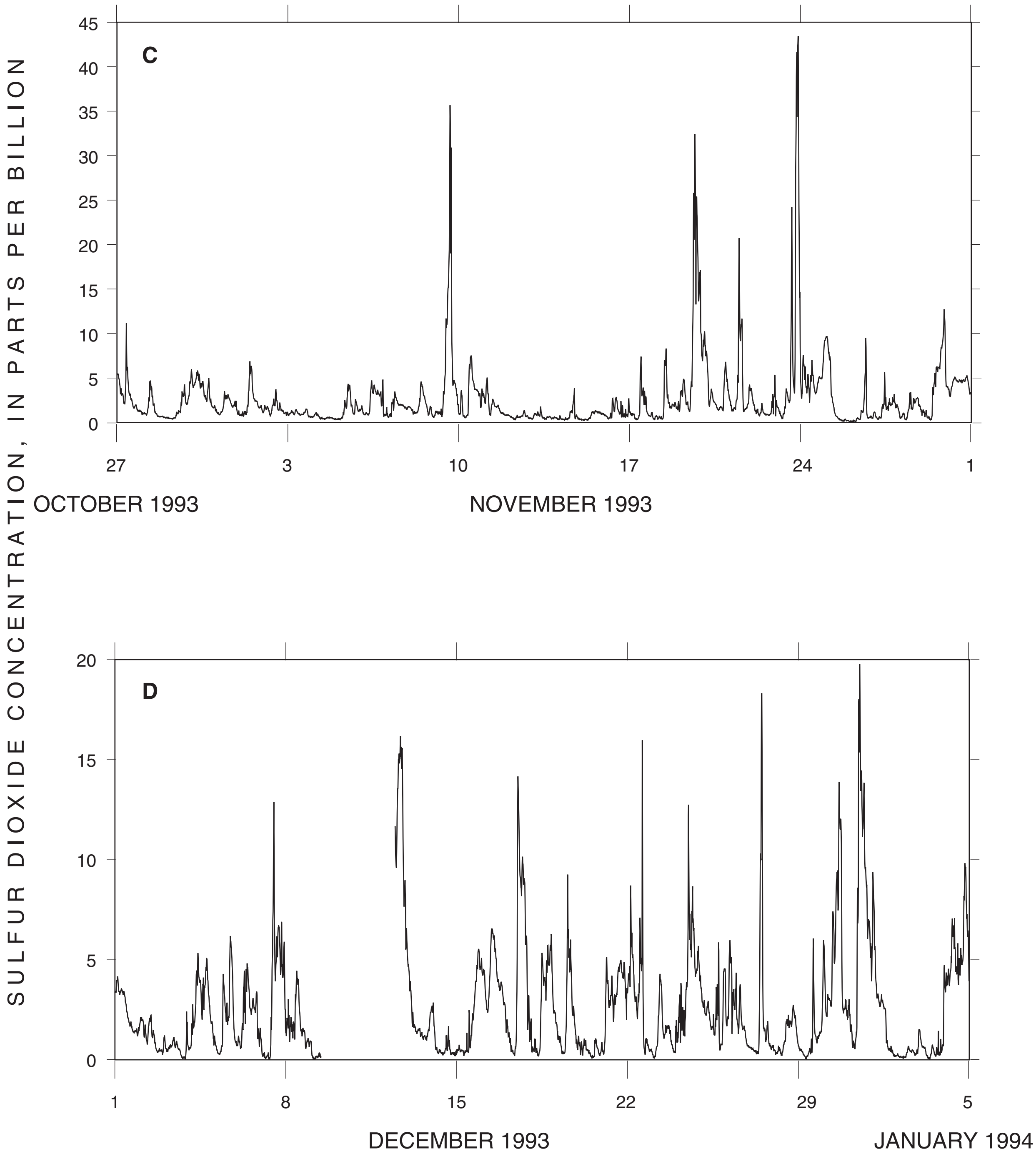

Figure 19. Temporal pattern of ambient concentration of sulfur dioxide at Union, Stewart County, Georgia, August 18, 1993 through November 30, 1994 (blank areas indicate missing data) — continued.

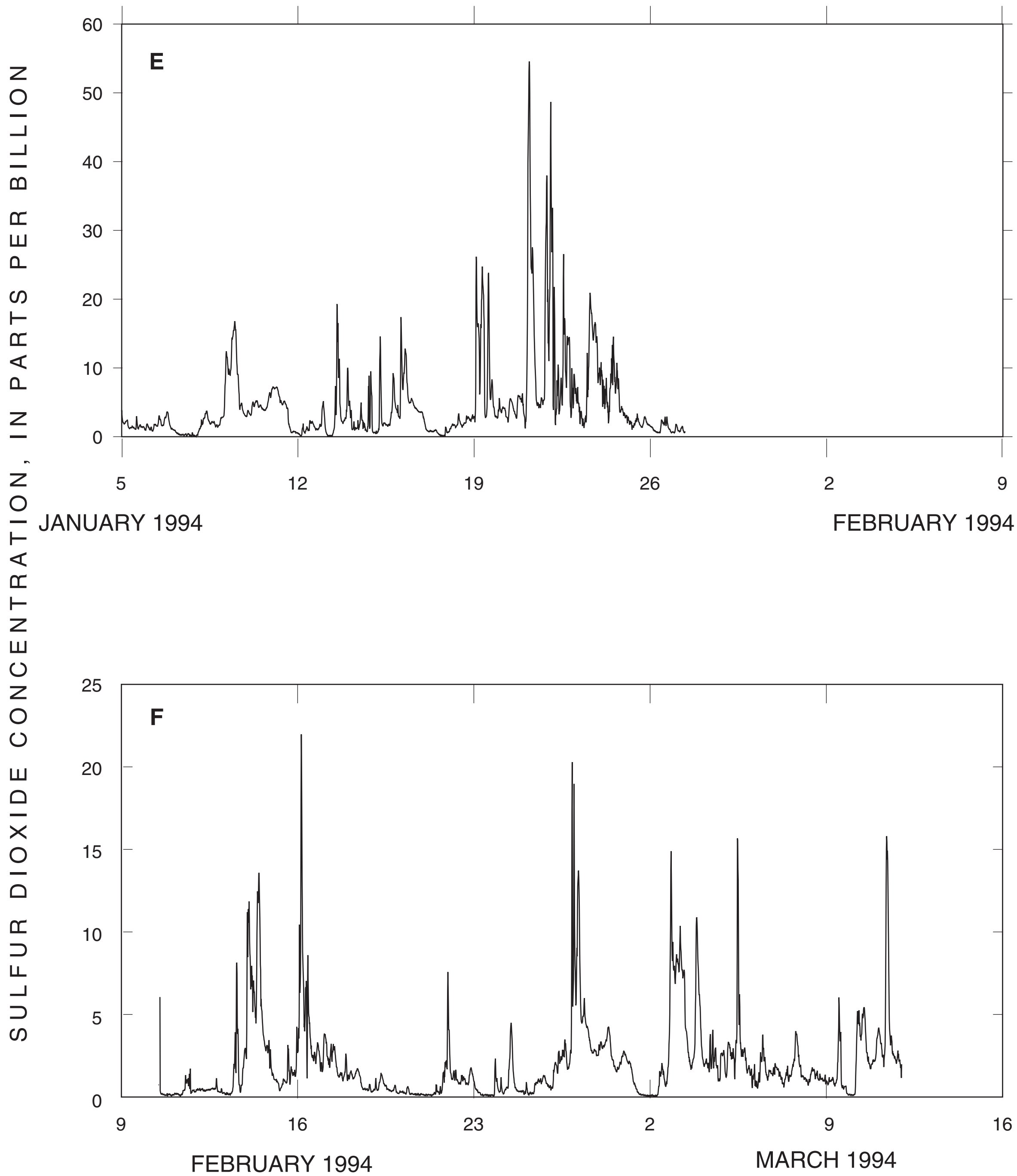

Figure 19. Temporal pattern of ambient concentration of sulfur dioxide at Union, Stewart County, Georgia, August 18, 1993 through November 30, 1994 (blank areas indicate missing data) — continued.

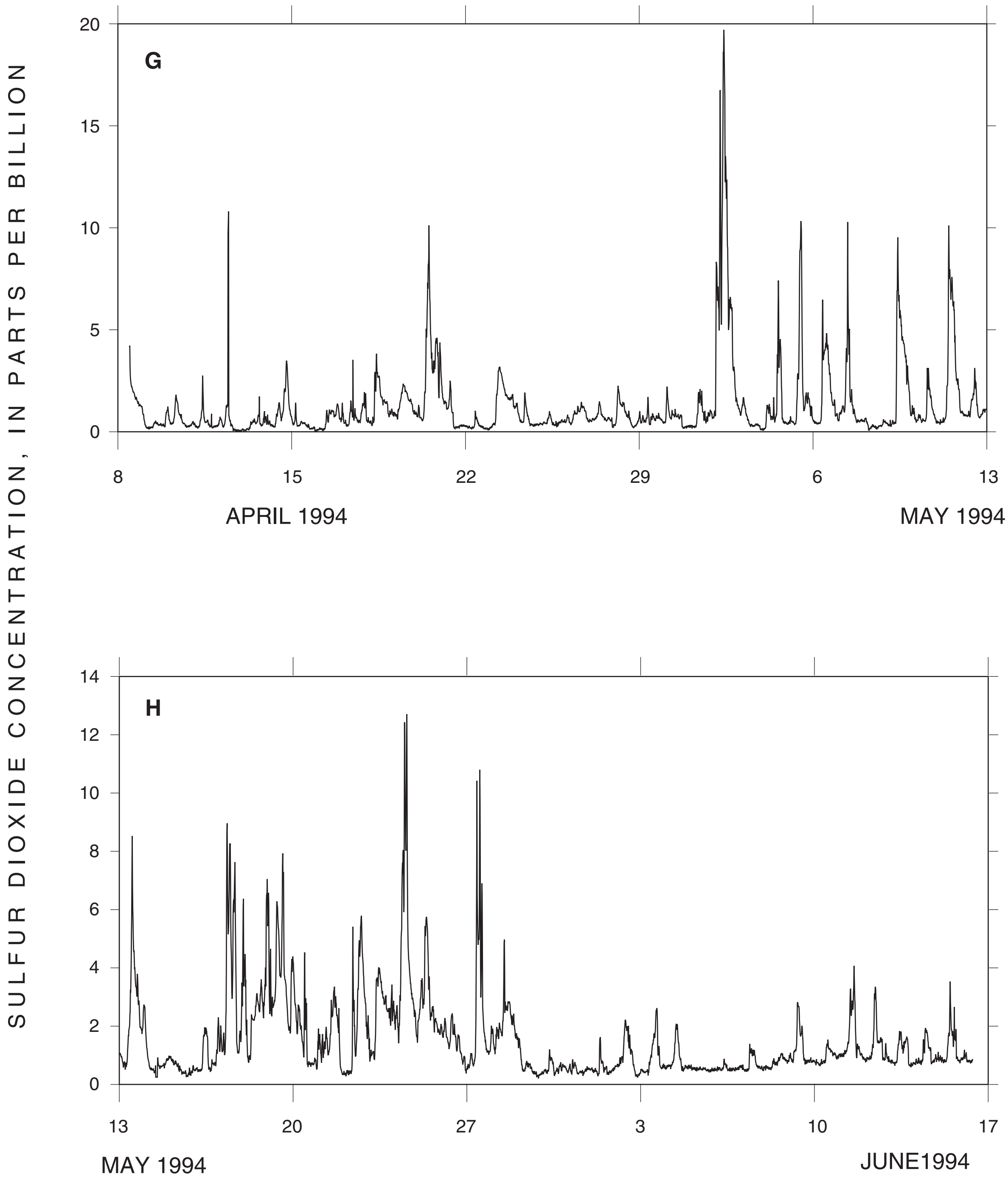

Figure 19. Temporal pattern of ambient concentration of sulfur dioxide at Union, Stewart County, Georgia, August 18, 1993 through November 30, 1994 (blank areas indicate missing data) — continued.

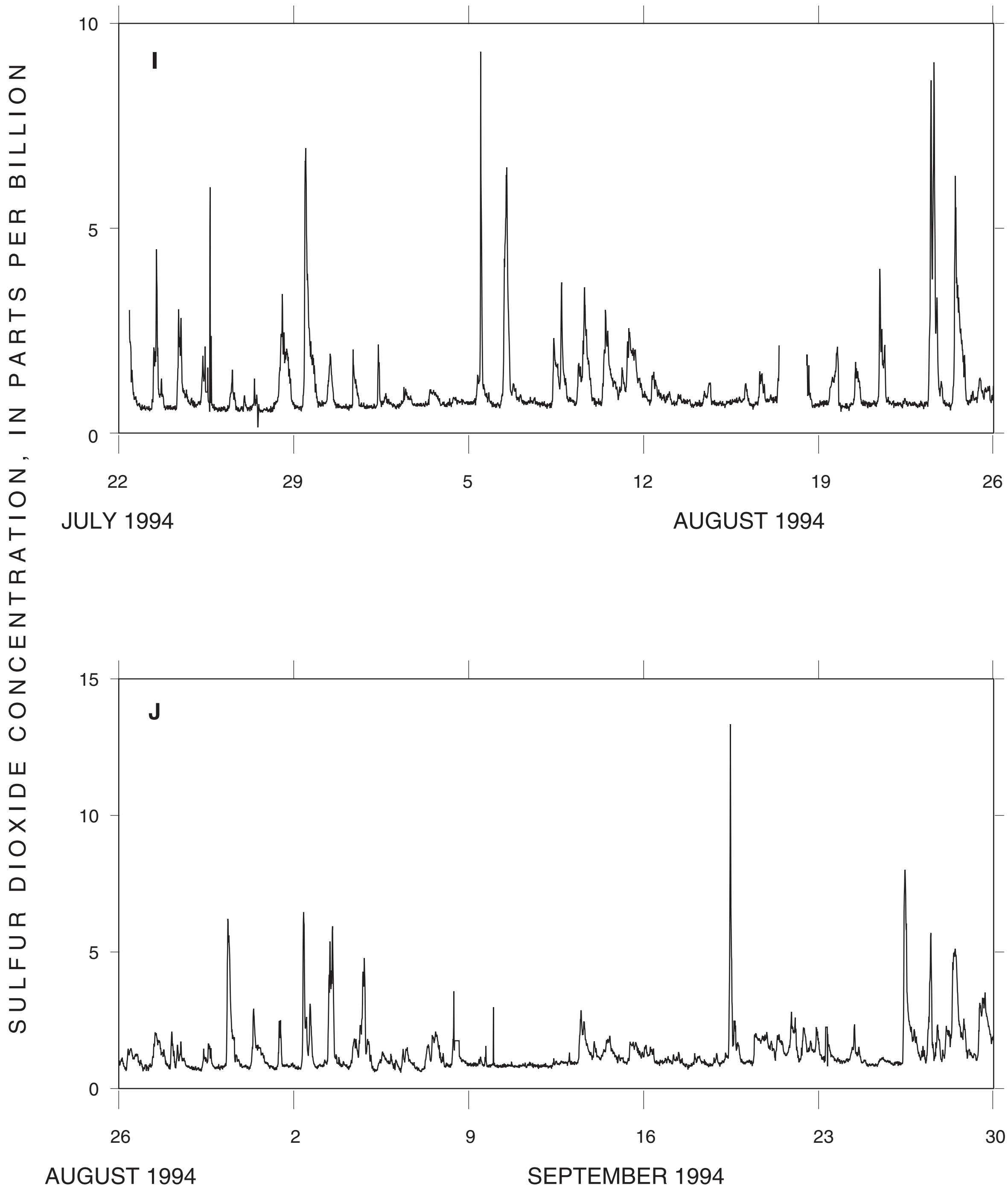

Figure 19. Temporal pattern of ambient concentration of sulfur dioxide at Union, Stewart County, Georgia, August 18, 1993 through November 30, 1994 (blank areas indicate missing data) — continued.

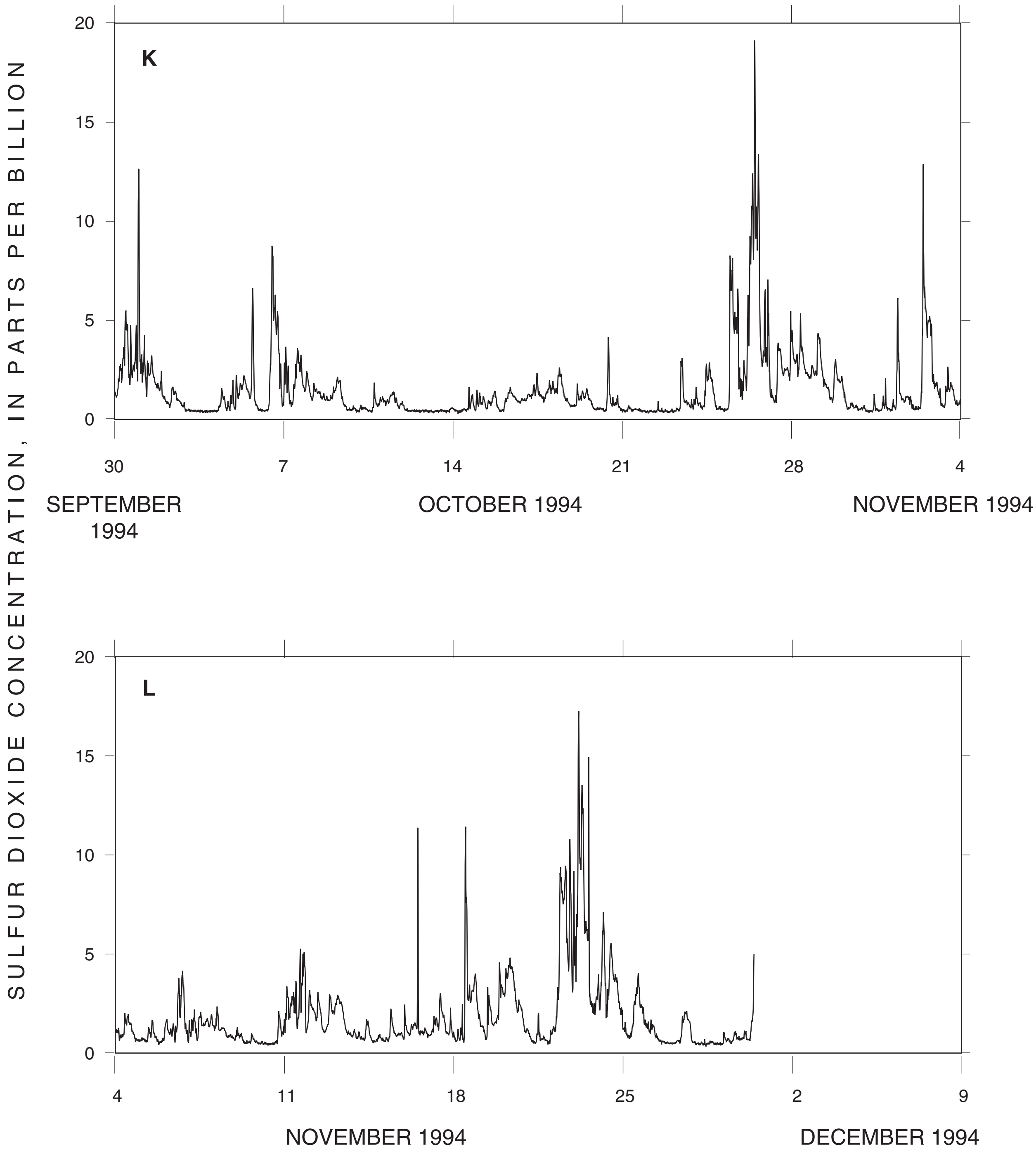

Figure 19. Temporal pattern of ambient concentration of sulfur dioxide at Union, Stewart County, Georgia, August 18, 1993 through November 30, 1994 (blank areas indicate missing data) — continued.

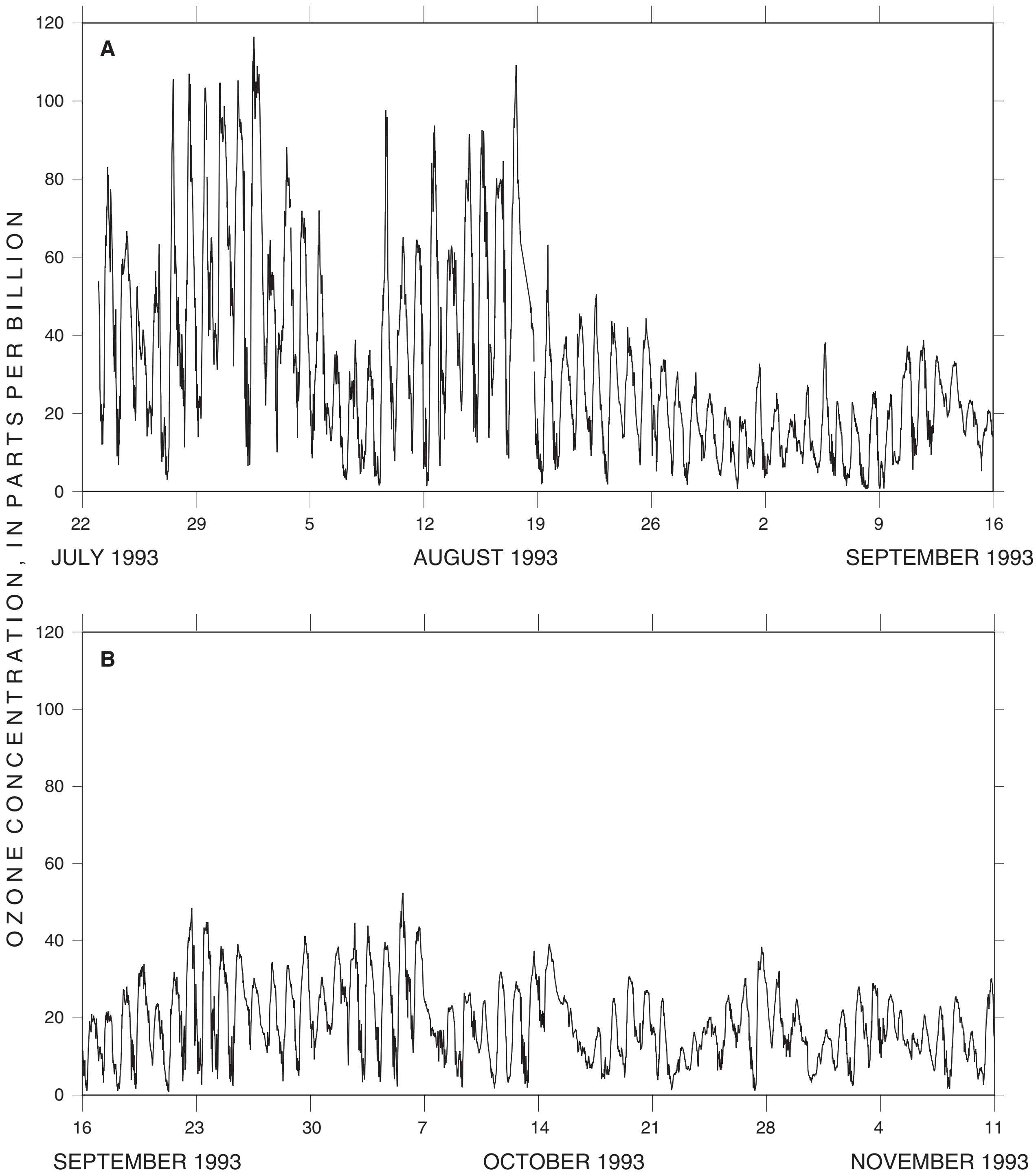

Figure 20. Temporal pattern of ambient concentration of ozone at Union, Stewart County, Georgia, July 22, 1993 through November 30, 1994 (blank areas indicate missing data).

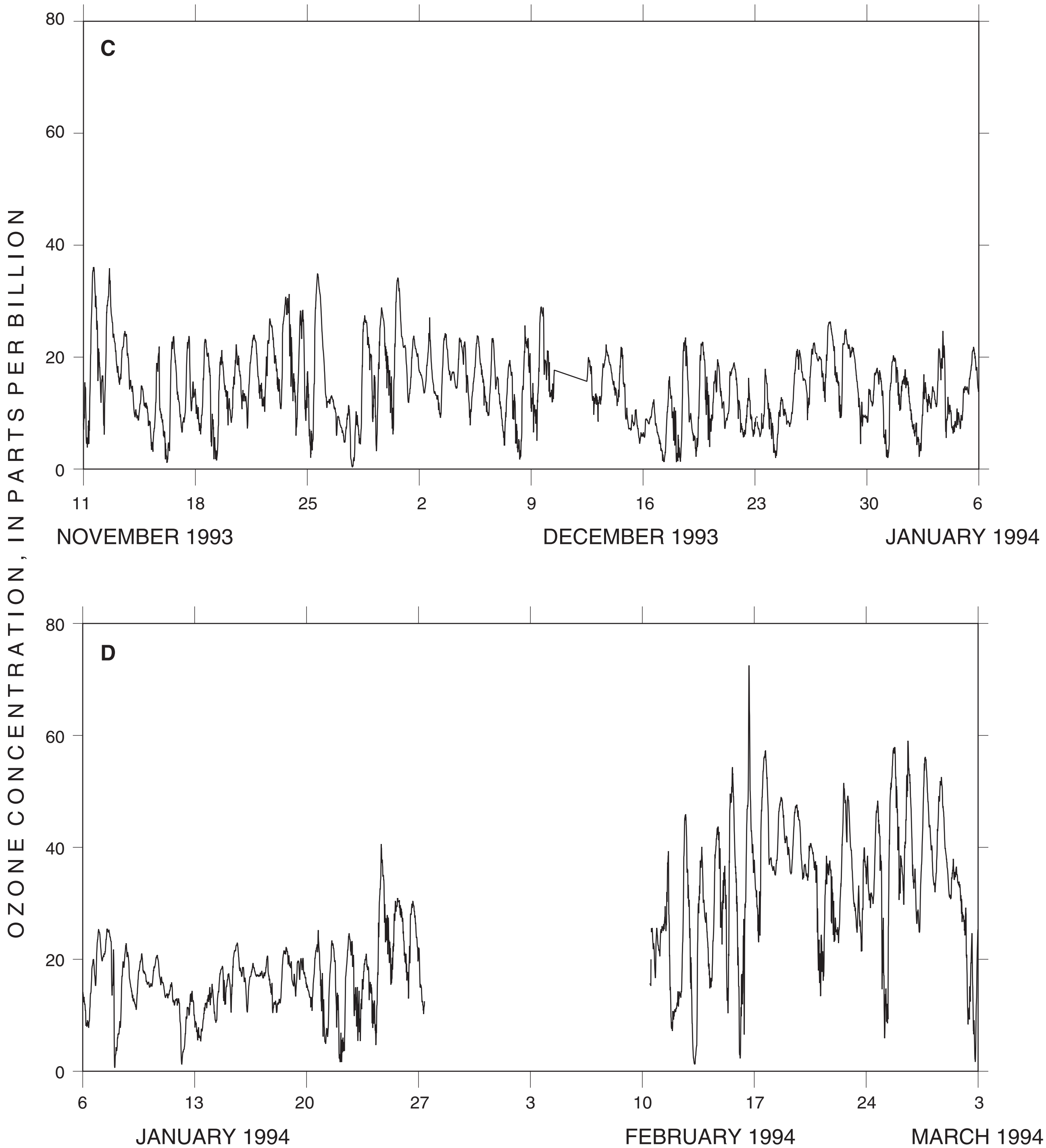

Figure 20. Temporal pattern of ambient concentration of ozone at Union, Stewart County, Georgia, July 22, 1993 through November 30, 1994 (blank areas indicate missing data) — continued.

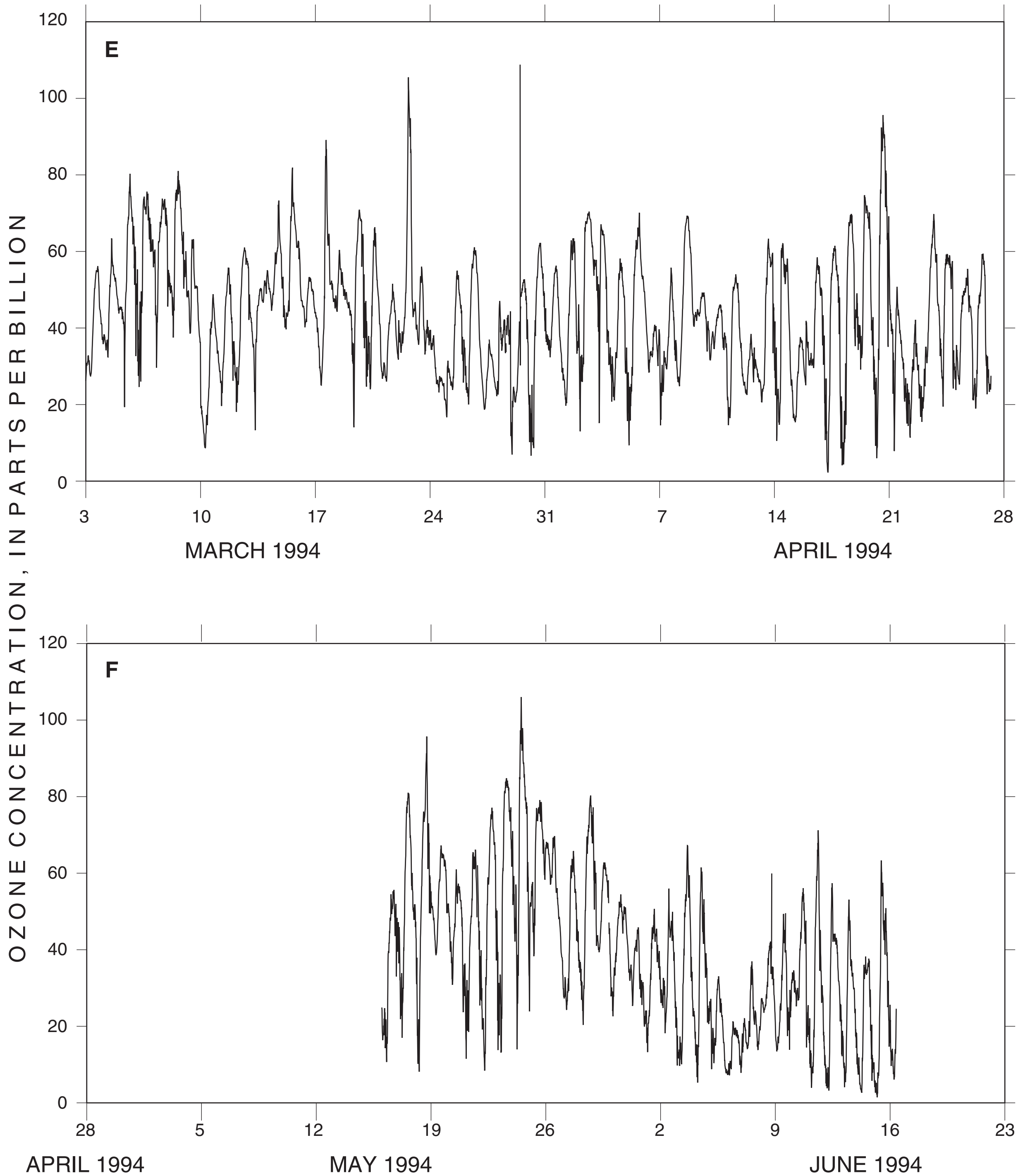

Figure 20. Temporal pattern of ambient concentration of ozone at Union, Stewart County, Georgia, July 22, 1993 through November 30, 1994 (blank areas indicate missing data) — continued.

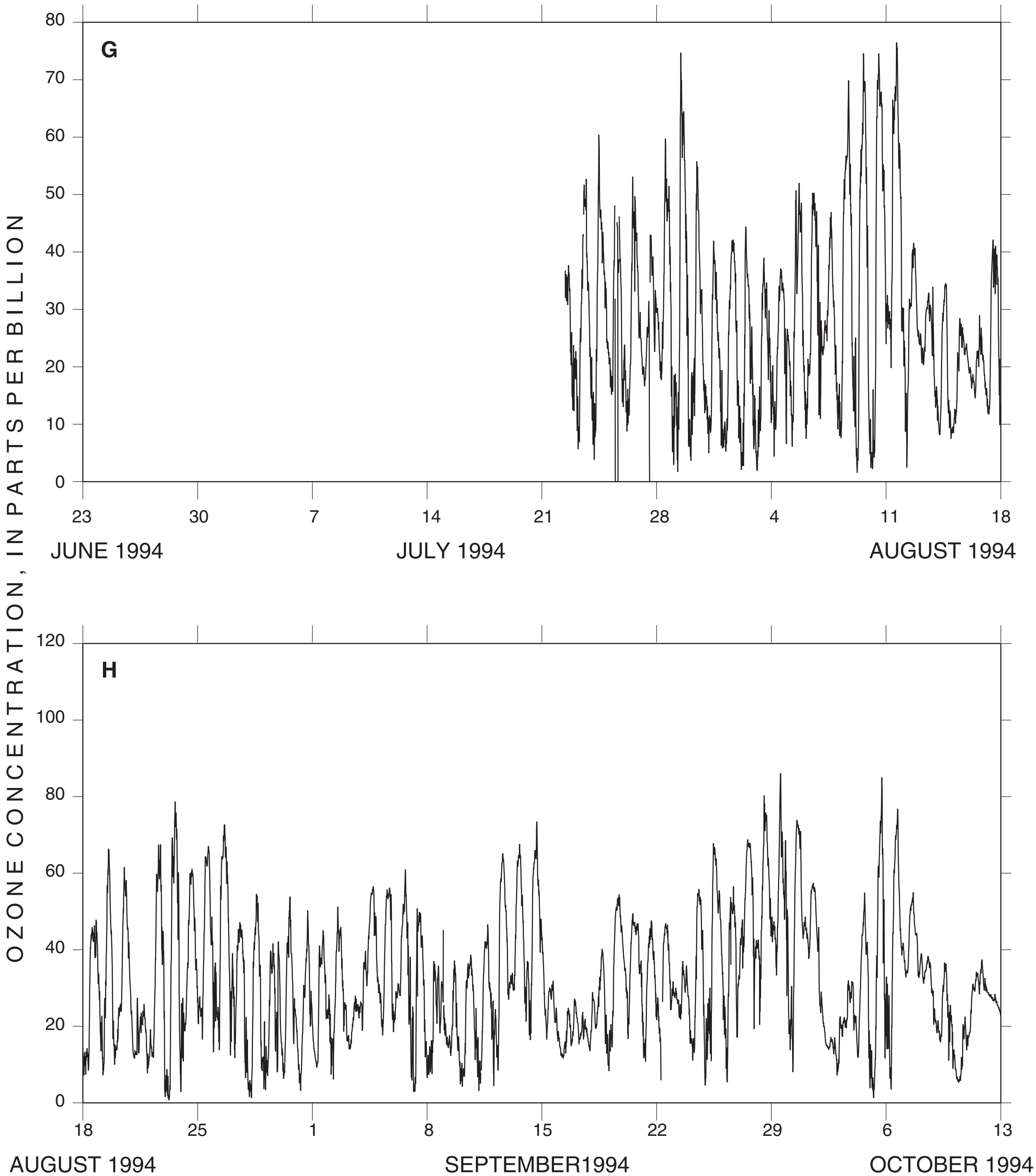

Figure 20. Temporal pattern of ambient concentration of ozone at Union, Stewart County, Georgia, July 22, 1993 through November 30, 1994 (blank areas indicate missing data) — continued.

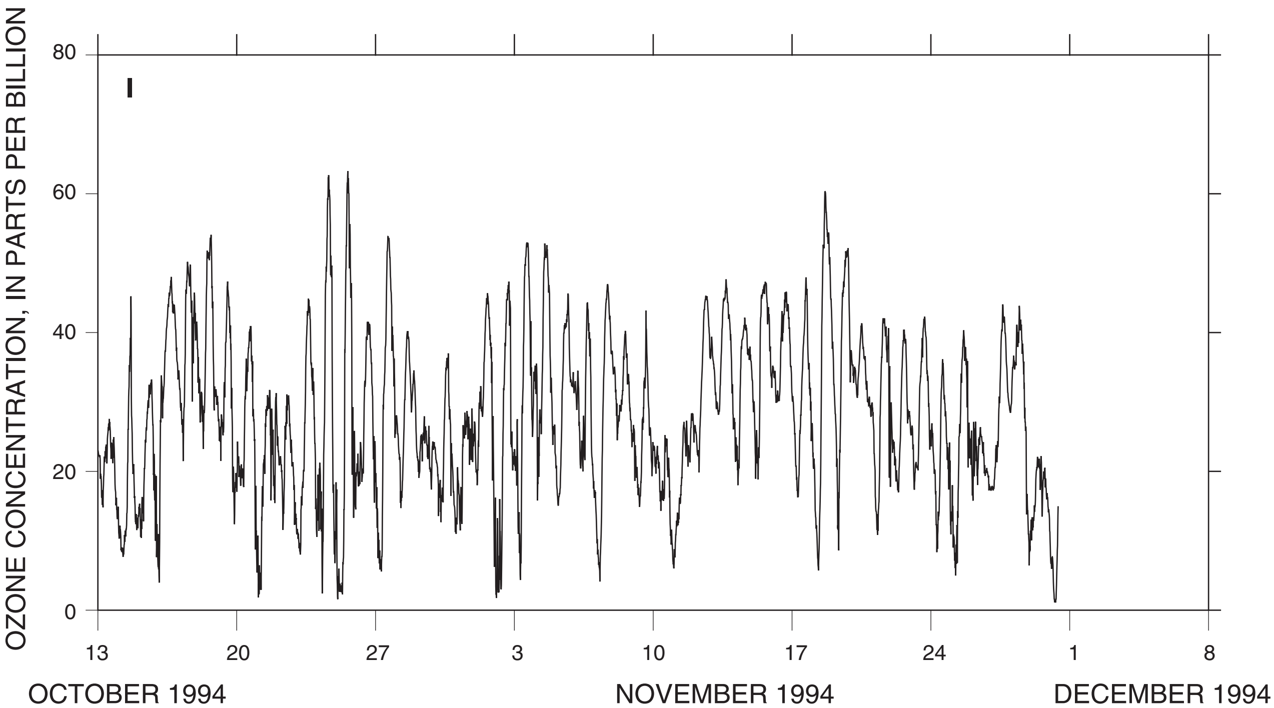

Figure 20. Temporal pattern of ambient concentration of ozone at Union, Stewart County, Georgia, July 22, 1993 through November 30, 1994 (blank areas indicate missing data) — continued.

Soil Properties

Selected soil properties including, exchangeable cations, soil organic matter content, water-extractable sulfate, and phosphate extractable sulfate were examined for soils collected in Stewart and Webster Counties. Samples were collected from adjacent, paired infested and uninfested forest stands to compare soil properties between stands. Multiple, pairwise mean-comparison t-tests were used in the statistical analysis of potential differences between soils of these two categories.

Exchangeable Cations

The most notable conclusion from the comparisons of exchangeable cations in soils is the similarity between infested and uninfested pine stands (table 11). Amounts of individual adsorbed cations, cation ratios, and total cation exchange capacity (CEC) were very similar. There were no significant differences between uninfested and infested plots for any exchangeable cation at any of the three soil depths examined based on paired t-tests (P-Values were greater than 0.05) (table 12). Soils from uninfested and infested plots were low in all exchangeable cations and CEC. These soils are low in native fertility and presumably were degraded by loss of topsoil by erosion during periods of row-crop production during the 1800's. The low availability of exchangeable nutrient cations should be considered a potential stress factor common to the entire study area. These soils also are low in soil-organic matter content (table 11) that contributes to low CEC. Low soil-organic matter also is associated with low available water-holding capacity and low nitrogen and phosphorus availability; however, these properties were not measured during this study.

There was a trend (P=0.15) for more exchangeable aluminum in the 20–60 cm depth interval and a trend (P=0.09) for more magnesium in the 60–100 cm depth interval of infested plots (table 12). There also was a trend (P=0.13) for less exchangeable calcium in the 60–100 cm depth interval of uninfested plots. These differences are small and do not suggest a pattern that links exchangeable cation availability and susceptibility to SPB infestation; this is further emphasized by the lack of any relation between soil base saturation and infestation status. Base saturation is one of the best indicators of soil acidification status, and is positively related to the expected ratio of calcium to aluminum in soil water. Shortle and Smith (1988) suggested that this ratio can be associated with forest health. Trees throughout the study area may be subject to some degree of nutrient stress that is related to calcium supply, that contributes to susceptibility to infestation by pests and pathogens.

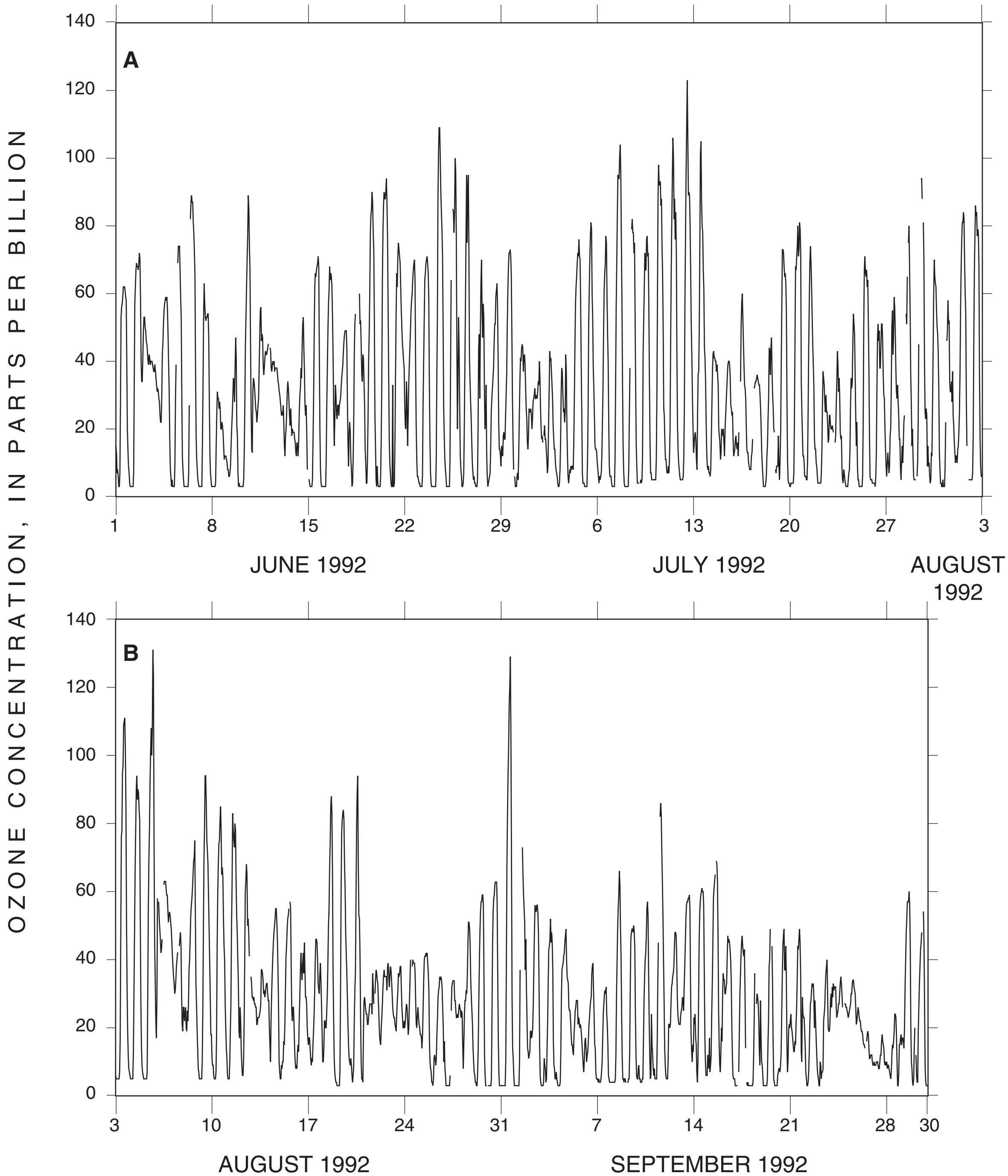

Figure 21. Temporal pattern of ambient concentration of ozone at Conyers, Rockdale County, Georgia, June through September, 1992, 1993, and 1994 (blank areas indicate missing data).

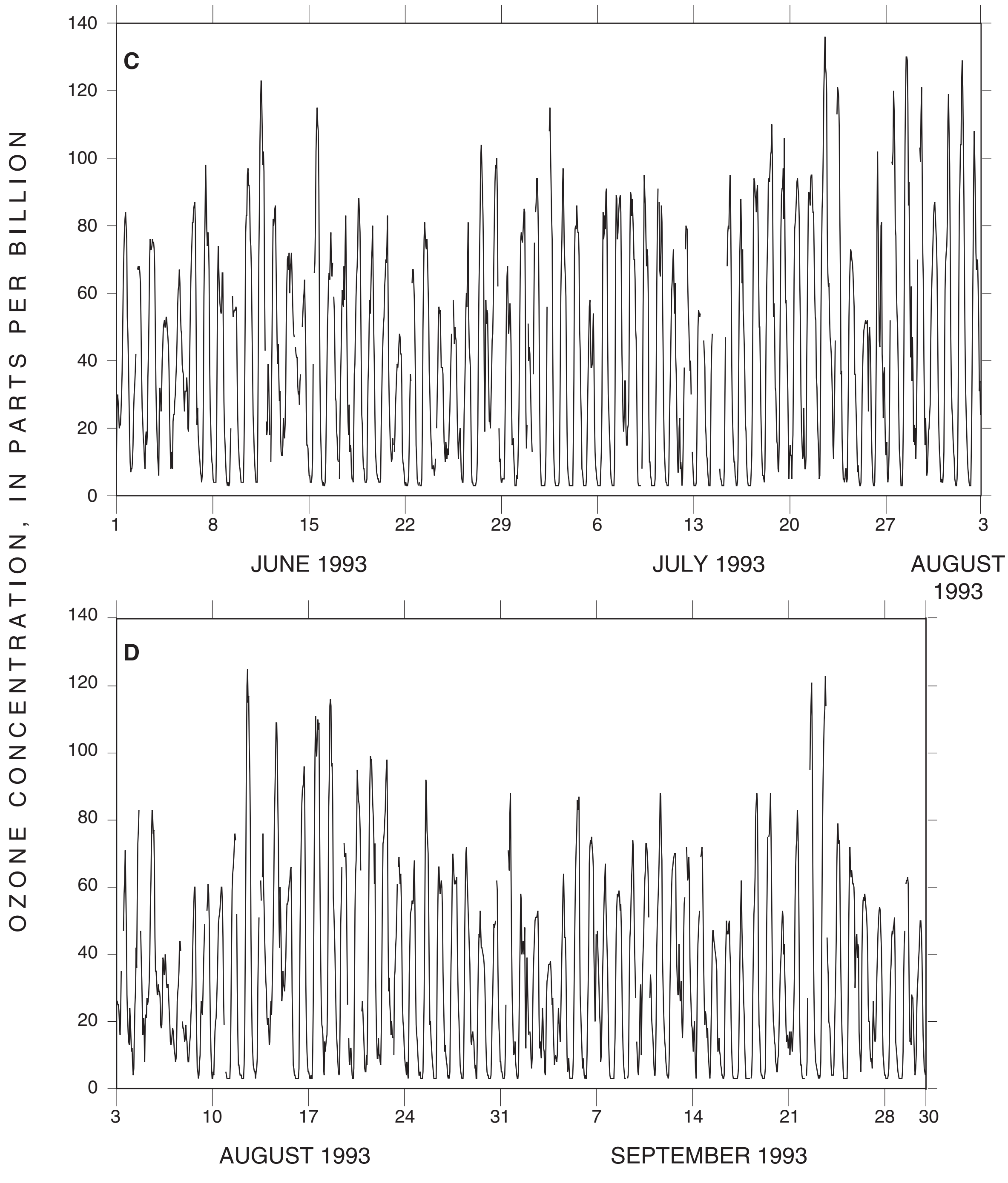

Figure 21. Temporal pattern of ambient concentration of ozone at Conyers, Rockdale County, Georgia, June through September, 1992, 1993, and 1994 (blank areas indicate missing data) — continued.

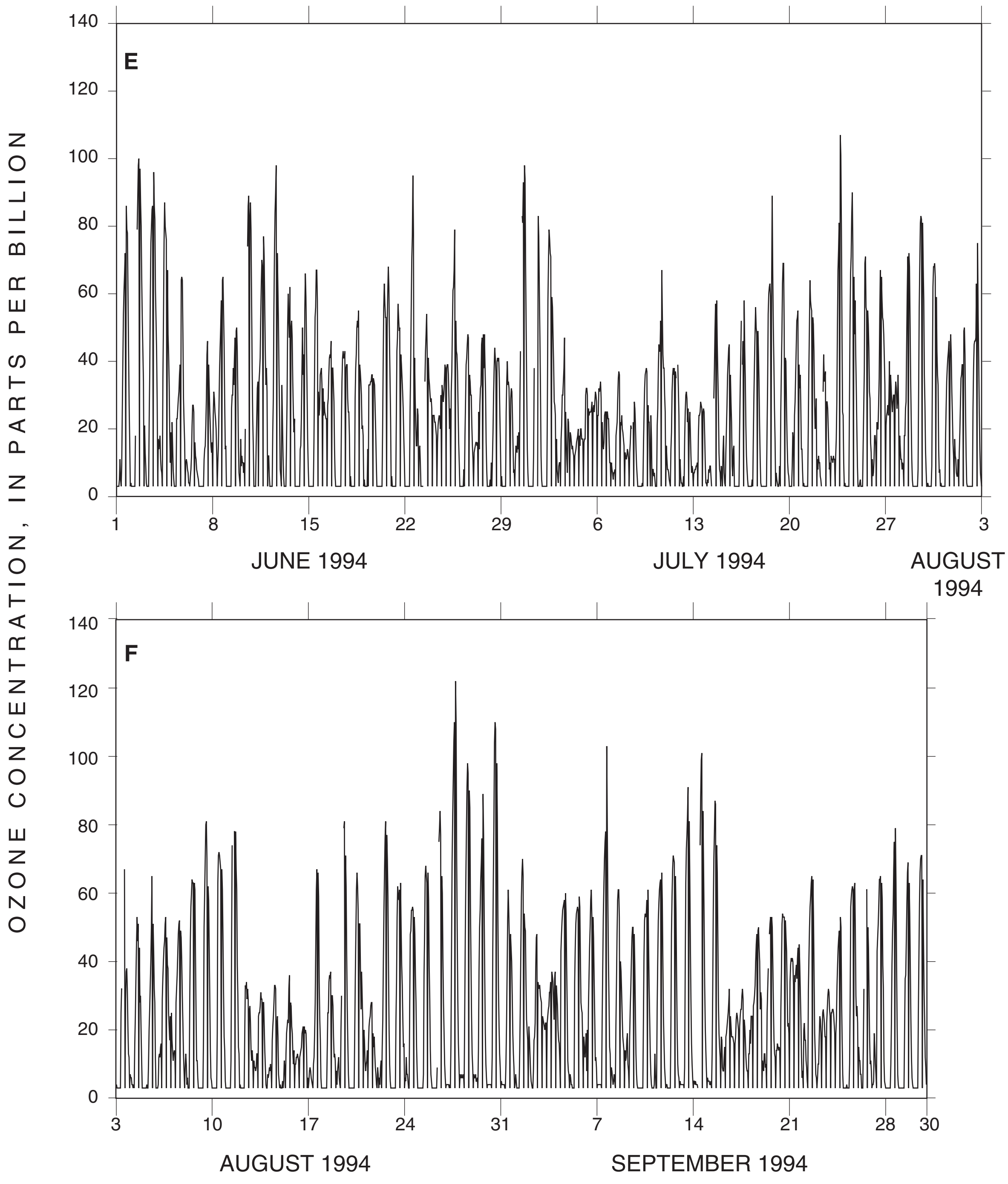

Figure 21. Temporal pattern of ambient concentration of ozone at Conyers, Rockdale County, Georgia, June through September, 1992, 1993, and 1994 (blank areas indicate missing data) — continued.

Table 11. Exchangeable cations, base saturation, and soil organic matter concentration at indicated soil-depth intervals in plots infested and uninfested by the southern pine beetle, Stewart County, Georgia, during 1994
[$cmol_c$ kg^{-1}, centimole positive charge per kilogram; cm, centimeter; nd, not determined].

Type of area	Variable	Soil depth (cm)	Major inorganic constituents: Calcium ($cmol_c$ kg^{-1})	Magnesium ($cmol_c$ kg^{-1})	Potassium ($cmol_c$ kg^{-1})	Sodium ($cmol_c$ kg^{-1})	Aluminium ($cmol_c$ kg^{-1})	Cation exchange capacity[1/]	Base saturation[2/] (percent)	Soil-organic matter[3/] (percent)
Uninfested	mean[4/]	0–20	0.49	0.24	0.066	0.017	0.58	1.4	57	2.47
	standard error		.065	.034	.009	.001	.091	.13	4.8	.26
Infested	mean		.46	.25	.064	.015	.55	1.3	57	2.49
	standard error		.066	.036	.006	.001	.092	.13	4.8	.30
Uninfested	mean	20–60	.54	.35	.077	.018	.60	1.6	62	2.73
	standard error		.11	.059	.019	.002	.17	.32	5.0	.36
Infested	mean		.47	.39	.069	.019	.80	1.8	60	3.26
	standard error		.059	.061	.010	.003	.26	.33	4.9	.37
Uninfested	mean	60–100	.51	.37	.069	.021	.80	1.8	58	nd
	standard error		.085	.051	.015	.003	.25	.33	5.0	nd
Infested	mean		.38	.44	.057	.025	.95	1.9	56	nd
	standard error		.062	.069	.010	.004	.29	.34	5.2	nd

[1/] Sum of cations may be slightly different from reported cations because of rounding.

[2/] Base saturation is percent (calcium plus magnesium plus sodium plus potassium divided by calcium plus magnesium plus sodium plus potassium plus aluminum).

[3/] Using the loss-on-ignition method and reported based on even-dry weight at 105 ° Celsius.

[4/] Standard error was computed as standard deviation divided by the square root of the number of samples.

Table 12. Mean differences (infested minus uninfested) and P-values for selected soil properties based on multiple pairwise mean comparison t-tests for 28 paired plots; where each pair included adjacent infested and uninfested forest stands in Stewart and Webster Counties, Georgia, during 1994
[cm, centimeter; $cmol_c$ kg^{-1}, centimole positive charge per kilogram]

Variable	Soil depth (cm)	Major inorganic constituents: Calcium ($cmol_c$ kg^{-1})	Magnesium ($cmol_c$ kg^{-1})	Potassium ($cmol_c$ kg^{-1})	Sodium ($cmol_c$ kg^{-1})	Aluminum ($cmol_c$ kg^{-1})	Base saturation (percent)
Mean differences	0–20	–0.02	0.003	–0.003	–0.001	–0.031	0.001
P-Value		.47	.92	.75	.24	.74	.96
Mean differences	20–60	–.066	.045	–.008	.002	.20	–.019
P-Value		.47	.17	.69	.13	.15	.53
Mean differences	60–100	–.13	.07	–.012	.004	.15	–.023
P-Value		.13	.09	.41	.09	.26	.58

One potential mechanism by which calcium limitation could be related to overall tree vigor and susceptibility to attack by SPB concerns the relatively high demand for calcium and the potential effect of limited supplies on carbohydrate reserves. Trees have a high apoplastic calcium demand in woody tissues. Metabolic calcium demands are far lower than symplastic demands; therefore, it is unlikely that foliar symptoms of calcium deficiency would be observed. In red spruce (*Picea rubens* Sarg.), limitations in available calcium are thought to cause narrower growth rings and earlier formed, wider rings of sapwood are converted to heartwood, resulting in a decreased volume of sapwood (Shortle and Smith, 1988; Shortle and Bondietti, 1992). Loss of sapwood results in (1) a decreased volume of wood capable of storing starch; (2) less effective wound or oxidant damage response; and (3) lower pest and pathogen resistance. Calcium deficiency, at a level that affects growth and carbohydrate status but does not produce foliar symptoms, could be related to the apparent higher susceptibility of loblolly pine to SPB in Stewart and Chattahoochee Counties compared to Marion County. Calcium deficiency resulting in a decrease in stored carbohydrates could reduce resistance of loblolly pine to SPB by reducing oleoresin synthesis and flow (Waring and Schlesinger, 1985; Lorio, 1993).

Another approach to assessing calcium status of loblolly pine forests in the study area is to construct a simple calcium budget. Quantifying inputs, outputs, and soil reserves provides a better understanding of long-term sustainability of productivity. Acidic deposition directly affects calcium status by accelerating leaching losses. Soil characterizations conducted during this study permit estimation of the magnitude of the soil exchangeable calcium pool in the forested areas of Stewart County. Atmospheric deposition measurements provide an estimate of wet deposition calcium inputs. Net calcium withdrawals in merchantable timber were not measured; however, they can be estimated from timber industry records in the area and from published values for calcium content in loblolly pine wood. Soil leaching losses were not measured; however, these can be estimated using measured soil-exchangeable calcium and published information on calcium leaching rates.

An analysis of calcium pools and fluxes in Stewart County suggests that calcium reserves currently (1994) are being depleted (table 13). This analysis indicates that maintenance of soil fertility and long-term productivity are threatened because net losses exceed net inputs by about 4 kg ha^{-1} yr^{-1}; and soil reserves are small, particularly when compared to other forest ecosystems undergoing calcium depletion (table 13). Current rates of annual calcium leaching losses and vegetation uptake cannot be sustained indefinitely because a typical harvest cycle of 25 years would result in total net loss of 100 kg Ca ha^{-1} or about 10 percent of ecosystem storage. A 10-percent loss of ecosystem storage is a conservative estimate for the following reasons: (1) the region is experiencing declines in atmospheric deposition of calcium; (2) harvesting temporarily disrupts biological cycling that maintains calcium in the system; and (3) harvesting practices frequently result in erosion and loss of calcium-rich topsoil.

Soils were not sampled in the area of low infestation in Marion County in this study; therefore exchangeable cation or other soil properties cannot be compared between areas of higher and lower infestation. Limited soil data are available from other sources for the most common soils series in these areas (U.S. Department of Agriculture, 1994; Perkins, 1987); these data were collected by horizon, instead of by depth increment as was done in this study, and soil-extraction methods differed substantially from the methods used in this report. For example, the U.S. Department of Agriculture (1994) and Perkins (1987) methods used a buffered (pH=7.0), ammonium acetate extractant for cation exchange capacity and exchangeable base cations, and an unbuffered potassium-chloride extractant was used for estimating exchangeable aluminum. Differences in methods of soil characterization preclude comparisons between the data collected in this study and the U.S. Department of Agriculture (1994) and Perkins (1987) data. However, soil properties analyzed by equivalent methods in the previous studies (U.S. Department of Agriculture, 1994; Perkins, 1987) can be compared. Comparisons between exchangeable calcium, magnesium, cation exchange capacity, and percent base saturation suggest that Cowarts and Vaucluse soil series contain at least as much exchangeable nutrient cations as those of Troup and Lakeland soil series (table 14) (U.S. Department of Agriculture, 1994; Perkins, 1987). In general, the Cowarts and Vaucluse soil series are more common in the more highly infested area and Troup and Lakeland soil series are more common in the low infestation area (fig. 7).

Textural analyses of these soils confirm that the Troup and Lakeland soils are sandy throughout; while Cowarts and Vaucluse soils have very sandy surface soil horizons but substantial clay in the B horizon (table 14). For comparable soil thicknesses, drought conditions are more likely to be a problem in the sandier Troup and Lakeland soils than in the Cowarts and Vaucluse soils. All soils contain low organic carbon contents. Data used to contrast these soils represent only four to seven

Table 13. Calcium pools and ecosystem fluxes at selected sites in Connecticut, South Carolina, North Carolina, Georgia, and Tennessee

[kg ha^{-1}, kilogram per hectare; kg ha^{-1} yr^{-1}, kilogram per hectare per year]

Location	Forest type	Calcium soil exchangeable pool (kg ha^{-1})	Calcium total soil pool (kg ha^{-1})	Net-wood increment[1/] (kg ha^{-1})	Atmospheric deposition (kg ha^{-1})	Soil leaching (kg ha^{-1} yr^{-1})
Cockaponse State Forest near East Haddam, Connecticut[2/]	oak, hickory, maple, birch	276	3,410	6.6	2.0	not determined
Calhoun Forest near Whitmire, South Carolina[3/]	loblolly pine	[4/]245	not determined	[5/]7.5	[6/]2.8	10.2
Coweeta Hydrologic Laboratory near Franklin, North Carolina[7/]	white pine	667	3,770	3.9	2.9	2.2
Duke Forest near Mebane, North Carolina[8/]	loblolly pine	2,125	4,940	13.6	8.1	3.3
Panola Mountain State Park near Atlanta, Georgia[9/]	oak, hickory, pine	2,200	2,200	10	1.4	2.7
Stewart County, Georgia[10/]	loblolly pine	840	840	6	3.2	1.1
Walker Branch near Oak Ridge, Tennessee[11/]	loblolly pine	820	2,500	16	5.4	15
	chestnut, oak	110	1,180	17	5.4	12
	oak, hickory	140	1,800	8.0	5.4	1.0

[1/] Based on whole-tree harvesting losses from Johnson and Todd (1990), Johnson and Lindberg (1992), and Mann and others (1988).

[2/] From Hornbeck and others (1990) and Mann and others (1988).

[3/] From Richter and others (1994).

[4/] From Richter and others (1994), measured in 1990 to a depth of 0.6 m, assuming bulk density to be 1.48.

[5/] From Richter and others (1994), estimate of wood increment is total vegetation uptake, including roots, boles, and foliage, divided by stand age.

[6/] From Richter and others (1994), mean of three given values.

[7/] From Johnson and Lindberg (1992).

[8/] Estimated losses at 2-meter soil depth having 33 kg ha^{-1} yr^{-1}.

[9/] From Huntington and others (1994b).

[10/] Total soil pool is assumed to be equivalent to exchangeable soil pool because only trace amounts of weatherable-calcium bearing primary minerals occur in highly weathered Ultisol soils (Perkins and others, 1973; Markewich and others, 1994; Calvert and others, 1980). Exchangeable soil pool was estimated using measured exchangeable calcium concentrations, regression of measured organic matter content, and modeled bulk density to estimate bulk density. Atmospheric deposition is estimated to be 3.17 kg ha^{-1} yr^{-1} based on measured wet deposition of 1.68 kg ha^{-1} yr^{-1} and published estimates of the ratio of wet/dry deposition in southern pine forests of 0.889 (Johnson and Lindberg, 1992). Soil leaching is estimated to be 1.1 assuming that leaching in Stewart County was proportionate to that at Panola Mountain relative to soil pool size.

[11/] From Johnson and Todd (1990), includes wood increment to dead wood components and soil leaching at 60 cm.

Table 14. Selected soil properties from available data on Troup, Lakeland, Cowarts, and Vaucluse soils in Georgia

[$cmol_c\ kg^{-1}$, centimole positive charge per kilogram; data compiled from U.S. Department of Agriculture, Natural Resources Conservation Service (1994) and Perkins (1987); soil-analyses methods are described in U.S. Department of Agriculture, Soil Conservation Service (1992); percents of clay, silt, and sand may not sum to 100 because of rounding]

Soil series (fig. 7)	Type of infestation	Horizon 1/	Physical properties: Clay (percent)	Silt (percent)	Silt (percent)	Carbon (percent)	Major inorganic constituents: Calcium ($cmol_c\ kg^{-1}$)	Magnesium ($cmol_c\ kg^{-1}$)	Aluminum ($cmol_c\ kg^{-1}$)	Cation exchange capacity	Base saturation (percent)
Troup and Lakeland 2/	low	A	3.99	6.65	89.4	0.43	0.37	0.22	0.21	2.00	23.7
	do.	E	2.70	9.20	88.7	.09	.13	.16	.05	.97	34.3
	do.	B	9.71	7.33	82.0	.09	.35	.19	.52	2.40	14.5
Cowarts and Vaucluse 3/	high	A	3.88	8.95	87.2	.62	.48	.10	.55	2.25	22.4
	do.	E	9.15	11.4	79.4	.33	.33	.21	.47	1.93	21.0
	do.	BT1	32.6	9.15	58.3	.19	.70	.38	1.03	3.80	30.7
	do.	BT2&C	40.7	8.94	50.4	.08	.64	.44	1.89	5.04	24.2

1/ Data were averaged for each horizon from four to seven sampled sites.

2/ Generally occur more in Marion County, Ga.

3/ Generally occur more in Stewart and Chattahoochee Counties, Ga.

sampled locations and give a preliminary indication that it is unlikely that soil fertility can explain the pattern of SPB infestation. The thickness of the soil available to plant roots is a crucial variable that can not be determined from the minimal amount of published data. Widespread presence of partially cemented layers within the top meter of the solum reduces the pool of available nutrients and water.

Water- and Phosphate-Extractable Sulfate

Soils from uninfested forest stands contained significantly greater water-extractable sulfate at the 0–20 cm depth interval (p=0.05 in a paired t-test); however, there were no differences at the 20–60 cm interval (tables 15, 16). Higher water-extractable sulfate in the surface soil could indicate a higher sulfate adsorption capacity in soils from uninfested stands; which, in turn, could provide some protection against the leaching of cations. However, the absence of significant differences in exchangeable cations, base saturation, and soil water composition between soils from infested and uninfested stands at the 0–20 cm soil-depth interval is not consistent with the interpretation that soils from uninfested stands are less acidified. Similarities between soils from infested and uninfested stands in water-extractable sulfate in the 20–60 cm depth interval are further evidence that small differences in water-extractable sulfate in the surface horizon probably is not an important factor in overall soil fertility.

Table 15. Water-extractable sulfate in soils collected from areas infested and uninfested by the southern pine beetle in Stewart County, Georgia, during 1994

[cm, centimeter; $mg\ S\ kg^{-1}$, milligrams sulfur per kilogram]

Area type	Variable	Soil depth (cm)	Water-extractable sulfate ($mg\ S\ kg^{-1}$) 1/
Infested	Mean	0–20	2.22
	Standard error	0–20	.22
Uninfested	Mean	0–20	2.56
	Standard error	0–20	.24
Infested	Mean	20–60	2.11
	Standard error	20–60	.27
Uninfested	Mean	20–60	2.36
	Standard	20–60	.23

1/ Based on oven-dry weight at 105 ° Celsius on constant-weight basis.

Table 16. Mean differences (infested minus uninfested) and P-values for water-extractable and phosphate-extractable sulfate in soil samples based on multiple pairwise mean comparison t-tests for the 28 paired plots; where each pair included adjacent infested and uninfested forest stands in Stewart and Webster Counties, Georgia, during 1994

[cm, centimeter; mg S kg^{-1}, milligram sulfur per kilogram]

Variable	Soil depth (cm)	Water-extractable sulfate (mg S kg^{-1})	Phosphate-extractable sulfate (mg S kg^{-1})
Mean difference	0–20	−0.33	−0.90
P-value	0–20	.045	.63
Mean difference	20–60	−.25	2.9
P-value	20–60	.34	.47

There were no differences in phosphate-extractable sulfate at both soil depths between soils from infested and uninfested stands (tables 16, 17). Substantially higher phosphate-extractable sulfate in the 20–60 cm soil-depth interval compared with the 0–20 cm soil-depth interval, indicates the likelihood of higher clay contents and greater potential for sulfate adsorption in the subsoil. Higher clay contents and higher phosphate-extractable sulfate would be expected for Ultisol soils, such as those in the study area, because these soils typically contain a clay-rich subsoil horizon. Surface and subsurface horizons contained substantially more phosphate-extractable sulfate than water-extractable sulfate; this also is typical of Ultisol soils that contain low organic matter concentrations.

Table 17. Phosphate-extractable sulfate in soil sampled from areas infested and uninfested by the southern pine beetle in Stewart County, Georgia, during 1994

[cm, centimeter; mg S kg^{-1}, milligram sulfur per kilogram]

Area type	Variable	Soil depth (cm)	Phosphate-extractable sulfate 1/ (mg S kg^{-1})
Infested	mean	0–20	7.94
	standard error	0–20	1.8
Uninfested	mean	0–20	8.84
	standard error	0–20	2.1
Infested	mean	20–60	28.4
	standard error	20–60	3.9
Uninfested	mean	20–60	26.1
	standard error	20–60	4.1

1/ Based on oven-dry weight at 105 ° Celsius on constant-weight basis using loss-on-ignition method.

Soil-Water Chemistry

Comparison of soil-water chemistry between soils collected in SPB infested and uninfested forest plots indicated that there were no significant differences in mean concentrations for most solutes (table 18). Concentrations of base cations and nitrate were enriched in soil water relative to input simulated throughfall, indicating that the input solution extracted some proportion of solutes in entrained soil water or adsorbed to the soil matrix.

The fact that base cation concentrations in soil water were not significantly different between soils from infested and uninfested stands is consistent with observed similarities in exchangeable soil cations (table 11). These similarities provide further evidence that there are no significant differences in the availability of base cations to loblolly pine between infested and uninfested soils. Aluminum concentrations were higher in soil water from infested plots. The difference in the 20–60 cm soil-depth interval is consistent with the trend in exchangeable aluminum observed for these soils, and indicates higher total aluminum in soil water in infested stands. The relative enrichment in nitrate in soil water compared to the input solution reflects both existing nitrate and nitrate resulting from mineralization between sample collection and extraction. Higher nitrate concentration in soils from infested soils stands reflect higher labile nitrogen pools in these soils (not measured) that could be a result of tree mortality. Tree mortality would result in higher labile nitrogen because of a reduction in normal plant uptake and increased decomposition of dead roots and forest litter.

In general, sulfate was retained in the 0–20 cm and 20–60 cm soil-depth intervals in soils from infested and uninfested stands. Sulfate concentrations in simulated throughfall were 195 μeq L^{-1}. Soil-water concentrations were about 150 μeq L^{-1} in the 0–20 cm soil-depth interval in infested and uninfested stands and about 75 μeq L^{-1} in the 20–60 cm soil-depth interval in both infested and uninfested stands (table 18). These data indicate that sulfate was retained in about the same proportions in soils of infested and uninfested areas after leaching with simulated throughfall. Analysis using on paired comparison t-tests confirmed the absence of significant differences in sulfate retained in the comparison by infestation status (table 19).

Table 18. Means and standard errors for selected major inorganic constituents in soil water collected by leaching field-moist soil with simulated throughfall in a mechanical vacuum extractor in areas infested and uninfested by the southern pine beetle, Stewart County, Georgia

[μeq L^{-1}, microequivalent per liter; μm L^{-1}, micromole per liter]

Area type	Variable	Soil depth (cm)	Major inorganic constituents						
			Nitrate (μeq L^{-1})	Sulfate (μeq L^{-1})	Calcium (μeq L^{-1})	Magnesium (μeq L^{-1})	Potassium (μeq L^{-1})	Sodium (μeq L^{-1})	Aluminum (μmL^{-1})
Infested	mean	0–20	[1/]64.0	149	83.6	68.1	85.2	61.4	[1/]2.62
	standard error	0–20	21.4	11.8	13.9	8.9	8.4	2.0	1.62
Uninfested	mean	0–20	27.3	157	82.7	64.9	81.5	68.8	[1/]1.20
	standard error	0–20	10.9	12.4	12.7	7.6	7.9	2.9	.56
Infested	mean	20–60	[1/]21.2	74.1	25.6	20.7	39.8	68.5	[1/].068
	standard error	20–60	5.4	10.5	5.1	4.4	5.0	5.2	.053
Uninfested	mean	20–60	12.2	78.3	29.1	22.0	42.0	62.8	[1/].026
	standard error	20–60	2.0	10.0	6.1	4.2	4.8	3.2	.013

[1/] Means for infested and uninfested forest plots within a given soil depth were significantly different (alpha=0.05).

Table 19. Sulfate concentrations retained in field-moist soils from 28 pairs of infested and uninfested forest stands during extraction with simulated throughfall

[cm, centimeter; μeq L^{-1}, microequivalent per liter]

Area type	Variable	Soil depth (cm)	Sulfate concentrations retained in field-moist soils during extraction [1/] (μeq L^{-1})
Infested	mean	0–20	7.58
	standard error	0–20	2.02
Uninfested	mean	0–20	6.47
	standard error	0–20	2.13
Infested	mean	20–60	18.8
	standard error	20–60	1.71
Uninfested	mean	20–60	17.7
	standard error	20–60	1.55

[1/] Based on oven-dry weight at 105 ° Celsius on constant-weight basis using loss-on-ignition method.

In contrast, base cations were released from surface soils (0–20 cm soil-depth interval) when fresh soils were leached with simulated throughfall. Releases of base cations were comparable between soils from infested and uninfested forest stands. Base cations were retained in soils from the 20–60 cm depth intervals.

Stream-Water Chemistry

There were major variations in stream-water chemistry between selected streams sampled in the study area (table 20); however, the variations did not support the hypothesis that soils in more heavily infested areas were more acidic than soils in less infested areas. pH varied from 4.7 to 7.5; sulfate concentrations varied from 2.9 to 400 μeq L^{-1}; and measured alkalinity varied from –19 to 1,300 μeq L^{-1}. Streams in more highly infested areas of Stewart and Chattahoochee Counties had the highest sulfate concentrations and the highest alkalinities (table 20, fig. 22). The majority of streams in the less infested area of Marion County had relatively low sulfate concentrations, and also tended to have lower alkalinity. Sulfate and alkalinity were not inversely correlated as would be expected if water quality were controlled by soil chemical composition and had been affected by acidic deposition. The data suggest that stream-water chemistry during baseflow conditions is predominantly controlled by geology rather than soil acidification. Variability in the composition of Cretaceous marine-sand parent material in Chattahoochee, Marion, and Stewart Counties (Reinhardt and Gibson, 1980; Reinhardt and others, 1994) is such that locally, soils might have quite different chemical composition and reactivity. Parent materials could be calcareous, resulting in high soil alkalinity. The parent materials also could contain pyrite and other constituents rich in sulfate, which would explain the relatively high sulfate concentrations in some streams.

Table 20. Water-quality data from selected streams sampled during baseflow conditions in areas infested and less infested by the southern pine beetle in Chattahoochee, Marion, Muscogee, Stewart, and Talbot Counties, Georgia, 1992–94

[μeq L^{-1}, microequivalent per liter; μS cm^{-1}, microSiemen per centimeter at 25 ° C; μm L^{-1}, micromole per liter; ND, may be present but not detected; minus sign (–), constituent was detected but concentration was below minimum detection limit (absolute value listed)]

				Properties			Major inorganic constituents											Trace elements		
Name of stream	Latitude	Longitude	Sampling date(s)	pH (standard units)	Alkalinity (μeq L^{-1})	Specific conductance (μS cm^{-1})	Fluoride (μeq L^{-1}) (μg/L)	Chloride (μeq L^{-1})	Bromide (μeq L^{-1})	Nitrate as N (μeq L^{-1})	Sulfate (μeq L^{-1})	Ammonium (μeq L^{-1})	Sodium (μeq L^{-1})	Potassium (μeq L^{-1})	Magnesium (μeq L^{-1})	Calcium (μeq L^{-1})	Silicate (μm L^{-1})	Aluminum (μm L^{-1})	Iron (μm L^{-1})	Manganese (μm L^{-1})
Sites sampled during baseflow conditions within areas infested by the southern pine beetle																				
Tributary to Turner Creek	32°02'29"	84°56'55"	01/29/93	7.0	340	54	4.2	81	0.3	5.0	75	11	75	18	64	360	110	0.5	14	ND
Tributary to Turner Creek	32°04'13"	84°56'26"	06/18/92	7.0	530	77	9.0	110	.4	3.0	70	12	88	27	104	530	50	.6	4.1	.1
Tributary to Hightower Branch	32°05'09"	84°49'30"	06/12/92	6.6	140	33	1.1	87	.1	1.4	32	5.8	73	16	44	140	50	.4	6.2	.04
Frog Bottom Creek	32°06'09"	84°49'14"	11/10/92	6.8	190	85	ND	82	.3	5.7	18	6.9	75	15	52	180	120	ND	4.9	4.6
Tributary to Grass Creek	32°06'17"	84°55'38"	01/29/93	6.3	110	40	2.6	120	.3	2.1	89	2.	96	14	54	180	180	15	9.6	ND
Tributary to Colochee Creek	32°06'32"	84°50'45"	01/28/93	7.1	560	80	5.3	110	.4	5.7	85	–.2	91	19	74	660	100	.6	9.8	ND
Tributary to Hannahatchee Creek	32°07'51"	84°53'03"	02/05/93	5.6	5.4	44	4.2	87	.3	1.4	230	1.6	81	29	75	130	240	1.5	ND	0.8
Tributary to Hannahatchee Creek	32°08'15"	84°57'05"	11/10/92	6.6	120	51	10.5	76	ND	1.4	190	.6	76	38	66	250	330	.5	2.1	ND
Tributary to Hannahatchee Creek	32°08'18"	84°57'36"	11/10/92	6.1	15	27	ND	72	.3	69	23	.6	81	15	50	58	170	1.3	.5	ND
Tributary to Hannahatchee Creek	32°08'25"	84°56'09"	11/10/92	6.3	110	27	ND	72	ND	ND	13	.8	50	29	71	76	130	.8	3.2	ND
Tributary to Hannahatchee Creek	32°08'35"	84°52'50"	11/10/92	7.0	440	105	13	85	.1	ND	400	.8	165	65	137	630	410	.7	4.0	**ND**
Tributary to Hannahatchee Creek	32°08'39"	84°55'47"	11/10/92	6.9	290	69	6.3	87	.3	ND	210	.6	120	45	82	380	380	.4	2.4	ND
Tributary to Hannahatchee Creek	32°08'58"	84°54'49"	11/10/92	6.1	41	34	3.7	78	.3	ND	120	1.2	74	39	57	87	280	.6	1.0	ND
Hannahatchee Creek	32°09'09"	84°54'23"	11/10/92	6.7	170	48	5.8	90	.3	4.3	130	1.6	79	36	76	230	210	1.0	5.4	ND
Tributary to Hannahatchee Creek	32°09'14"	84°55'45"	11/10/92	6.2	69	24	2.1	74	.3	3.6	22	1.6	58	10	43	79	160	.6	1.3	1.1
			09/20/93	6.4	100	24	3.2	74	.4	11	10	2.7	66	17	53	95	150	1.6	10	–.3
			06/16/94	6.2	69	20	.5	61	.3	5.0	10	2.9	58	9.0	36	65	150	1.5	13	–.4
Tributary to Hannahatchee Creek	32°09'15"	84°55'17"	11/10/92	6.4	55	25	ND	76	.3	1.4	24	2.0	63	21	50	73	170	.9	11	.9
			09/20/93	6.5	93	25	3.7	67	.3	2.9	39	1.4	60	25	56	78	180	.4	11	–.3

Table 20. Water-quality data from selected streams sampled during baseflow conditions in areas infested and less infested by the southern pine beetle in Chattahoochee, Marion, Muscogee, Stewart, and Talbot Counties, Georgia, 1992–94 (Continued)

[μeq L^{-1}, microequivalent per liter; μS cm^{-1}, microSiemen per centimeter at 25 ° C; μm L^{-1}, micromole per liter; ND, may be present but not detected; minus sign (–), constituent was detected but concentration was below minimum detection limit (absolute value listed)]

				Properties			Major inorganic constituents											Trace elements		
Name of stream	Latitude	Longitude	Sampling date(s)	pH (standard units)	Alkalinity (μeq L^{-1})	Specific conductance (μS cm^{-1})	Fluoride (μeq L^{-1}) (μg/L)	Chloride (μeq L^{-1})	Bromide ($\mu\epsilon$q L^{-1})	Nitrate as N (μeq L^{-1})	Sulfate (μeq L^{-1})	Ammonium (μeq L^{-1})	Sodium (μeq L^{-1})	Potassium (μeq L^{-1})	Magnesium (μeq L^{-1})	Calcium (μeq L^{-1})	Silicate (μm L^{-1})	Aluminum (μm L^{-1})	Iron (μm L^{-1})	Manganese (μm L^{-1})
Sally Branch at Fort Benning	32°23'25″	84°42'14″	04/02/93	5.7	21	27	1.6	61	.3	1.4	100	1.2	51	17	54	70	150	.9	1.5	2.1
Little Pine Knot Creek	32°25'15"	84°41'46"	04/02/93	4.7	–19	30	1.1	46	0.1	ND	120	0.9	47	13	41	35	140	6.7	1.6	2.2
Sites sampled during baseflow conditions within areas less infested by the southern pine beetle																				
Muckalee Creek	32°17'45"	84°29'07"	10/15/92	6.2	89	30	ND	ND	.1	54	2.9	.7	78	9.9	92	68	110	ND	0.9	ND
Tributary to Kinchafoonee Creek	32°19'59"	84°33'27"	03/30/93	6.9	97	25	2.1	91	.3	1.4	34	.5	72	19	51	98	92	2.2	3.1	ND
Oochee Creek	32°20'17"	84°29'49"	03/30/93	6.9	320	57	12	120	.4	43	70	4.0	160	41	90	290	87	1.8	6.3	ND
Kinchafoonee, East Branch	32°20'34"	84°35'31"	03/30/93	5.9	47	13	1.1	49	.1	.7	6.9	.5	57	8.6	24	25	67	ND	ND	0.6
Kinchafoonee, West Branch	32°20'49"	84°35'43"	03/30/93	5.7	49	13	1.1	45	.4	2.1	8.1	1.4	42	5.4	28	31	65	ND	1.4	1.7
			09/20/93	5.7	110	26	ND	63	.4	2.1	3.3	11	54	7.0	45	56	120	–.1	–.3	5.7
Pine Knot Creek	32°25'20"	84°35'21"	03/30/93	5.0	–4.5	15	.5	39	.4	.7	54	.5	38	6.3	21	21	90	1.6	1.4	.7
			09/20/93	5.2	–7.1	15	.5	42	.3	.7	37	1.5	40	5.7	18	19	120	–.1	1.8	–.3
Cedar Creek	32°26'09"	84°23'37"	03/30/93	5.7	11	11	ND	39	.1	16	6.7	.9	40	4.9	20	17	76	1.6	1.7	ND
			09/20/93	5.8	17	11	.5	38	.3	16	3.8	1.2	44	4.5	19	16	89	–.1	.5	–.3
Shoal Creek	32°26'26"	84°29'20"	03/30/93	5.4	–1.6	12	1.1	38	.1	ND	27	.8	38	5.0	18	19	47	2.5	2.4	.9
Fort Perry Creek	32°30'25"	84°32'23"	03/30/93	5.3	–0.9	13	ND	37	.1	10	34	1.3	35	6.1	26	23	74	3.0	2.2	ND
Little Juniper Creek	32°30'53"	84°36'26"	03‘/30/93	5.2	–10	12	1.1	37	.1	2.1	27	–.18	33	4.1	18	14	63	4.3	3.3	ND
Kendall Creek	32°32'45"	84°42'52"	03/30/93	7.1	320	48	3.2	59	.3	2.1	94	2.1	200	28	130	150	320	21	6.7	.5
Black Creek	32°32'58"	84°32'00"	03/30/93	5.2	–5.7	14	1.1	39	.1	2.1	39	.4	50	6.1	19	18	94	3.2	2.3	ND
Baker Creek	32°33'07"	84°40'30"	03/30/93	7.1	380	55	5.3	53	.3	4.3	110	1.9	200	30	170	190	350	32	9.0	.6
Upatoi Creek	32°33'43"	84°36'35"	03/30/93	7.0	280	43	3.2	59	.3	5.0	84	1.1	150	22	120	170	260	10	4.9	ND

Table 20. Water-quality data from selected streams sampled during baseflow conditions in areas infested and less infested by the southern pine beetle in Chattahoochee, Marion, Muscogee, Stewart, and Talbot Counties, Georgia, 1992–94 (Continued)

[μeq L^{-1}, microequivalent per liter; μS cm^{-1}, microSiemen per centimeter at 25 ° C; μm L^{-1}, micromole per liter; ND, may be present but not detected; minus sign (–), constituent was detected but concentration was below minimum detection limit (absolute value listed)]

Name of stream	Latitude	Longitude	Sampling date(s)	Properties			Major inorganic constituents											Trace elements		
				pH (standard units)	Alkalinity (μeq L^{-1})	Specific conductance (μS cm^{-1})	Fluoride (μeq L^{-1}) (μg/L)	Chloride (μeq L^{-1})	Bromide (μeq L^{-1})	Nitrate as N (μeq L^{-1})	Sulfate (μeq L^{-1})	Ammonium (μeq L^{-1})	Sodium (μeq L^{-1})	Potassium (μeq L^{-1})	Magnesium (μeq L^{-1})	Calcium (μeq L^{-1})	Silicate (μm L^{-1})	Aluminum (μm L^{-1})	Iron (μm L^{-1})	Manganese (μm L^{-1})
Tributary to Hannahatchee Creek	32° 09'23"	84° 54'51"	11/10/92	6.6	57	25	2.6	7.9	.3	ND	33	1.0	66	27	52	61	180	.5	7.1	.4
Tributary to Hannahatchee Creek	32°09'28"	84°53'44"	11/10/92	6.2	72	27	2.6	85	.3	ND	31	1.4	67	29	63	56	210	.4	8.5	.4
Tributary to Hannahatchee Creek	32°09'28"	84°53'42"	11/10/92	5.9	3.8	26	ND	82	.3	ND	78	.9	60	25	52	48	290	1.2	1.2	2.3
Tributary to Hannahatchee Creek	32°09'30"	84°58'11"	01/29/93	6.1	32	19	2.6	54	.4	1.4	38	.5	65	6.0	31	50	130	.4	.9	ND
Tributary to Hannahatchee Creek	32°09'35"	84°51'28"	02/01/93	5.6	45	26	ND	78	.3	ND	70	.4	67	11	56	59	200	.4	1.2	1.2
Tributary to Hannahatchee Creek	32°10'24"	84°53'53"	01/29/93	5.9	15	23	2.6	54	.1	1.4	81	.9	63	20	44	49	220	.6	1.2	ND
Tributary to Hannahatchee Creek	32°11'23"	84°52'10"	06/18/92	5.3	35	21	1.1	44	0.1	ND	30	5.2	63	22	37	48	210	2.0	25	2.2
Tributary to Chattahoochee River	32°12'05"	84°56'42"	06/18/92	7.0	240	45	6.8	77	.1	4.0	70	2.1	71	35	60	250	220	1.0	2.5	.01
			02/05/93	7.0	210	45	3.2	78	.3	ND	100	.4	75	24	58	250	210	.4	2.5	ND
Tributary to Chattahoochee River	32°12'14"	84°56'45"	02/05/93	6.9	210	43	2.6	83	.4	4.3	84	0.5	74	30	58	230	180	.5	3.9	ND
			06/18/92	6.9	260	44	1.1	67	.3	11	42	4.8	65	35	70	260	150	5.1	18	0.1
Ttributary to Broach Creek	32°13'00"	84°45'01"	060/4/92	6.4	210	43	9.0	86	.1	5.7	65	1.4	86	33	96	170	110	.7	13	0.1
			02/06/93	6.1	95	42	3.7	110	.3	2.1	130	4.4	96	29	78	150	160	1.0	6.6	ND
Sand Branch	32°14'27"	84°52'28"	01/26/93	7.2	330	84	3.2	110	.3	.7	300	1.1	94	26	100	590	240	2.5	2.7	.9
			09/20/93	7.5	1,300	160	15	79	.5	10	260	34	92	96	210	1,600	67	2.2	1.6	–.3
			06/16/94	7.3	630	100	9.0	96	.4	5.0	230	2.4	85	35	118	810	250	1.8	12	–.4
Cany Creek	32°14'42"	84°49'47"	01/26/93	6.9	310	77	ND	110	.1	.7	240	2.0	94	23	92	550	210	1.4	2.9	2.9
			09/20/93	6.4	300	46	5.8	60	.1	2.1	48	43	47	31	62	280	140	2.0	8.9	–0.3
			06/16/94	6.8	600	88	6.3	99	.5	2.1	130	8.0	85	25	100	630	220	.9	11	3.9
Hewell Creek	32°15'28"	84°48'19"	01/26/93	6.8	240	71	1.6	98	.1	.7	260	1.0	90	19	88	500	190	1.7	4.2	1.6
			06/16/94	7.0	380	62	4.2	77	.3	2.1	100	4.0	71	22	67	420	190	.9	11	2.3
Hitchitee Creek	32°16'05"	84°47'10"	01/26/93	6.3	71	41	2.1	89	.3	5.0	140	5.9	84	22	78	160	150	1.0	4.0	2.1
			09/20/93	6.4	99	39	5.8	82	.3	6.4	98	2.6	77	32	67	140	220	.8	11	–.3
			06/16/94	6.6	100	37	4.7	81	.3	5.0	83	6.4	82	25	70	150	180	1.0	31	1.0
Ochillee Creek	32°20'52"	84°41'42"	09/20/93	5.8	58	20	2.6	73	.3	1.4	17	2.9	68	13	34	41	160	–.1	3.9	1.4

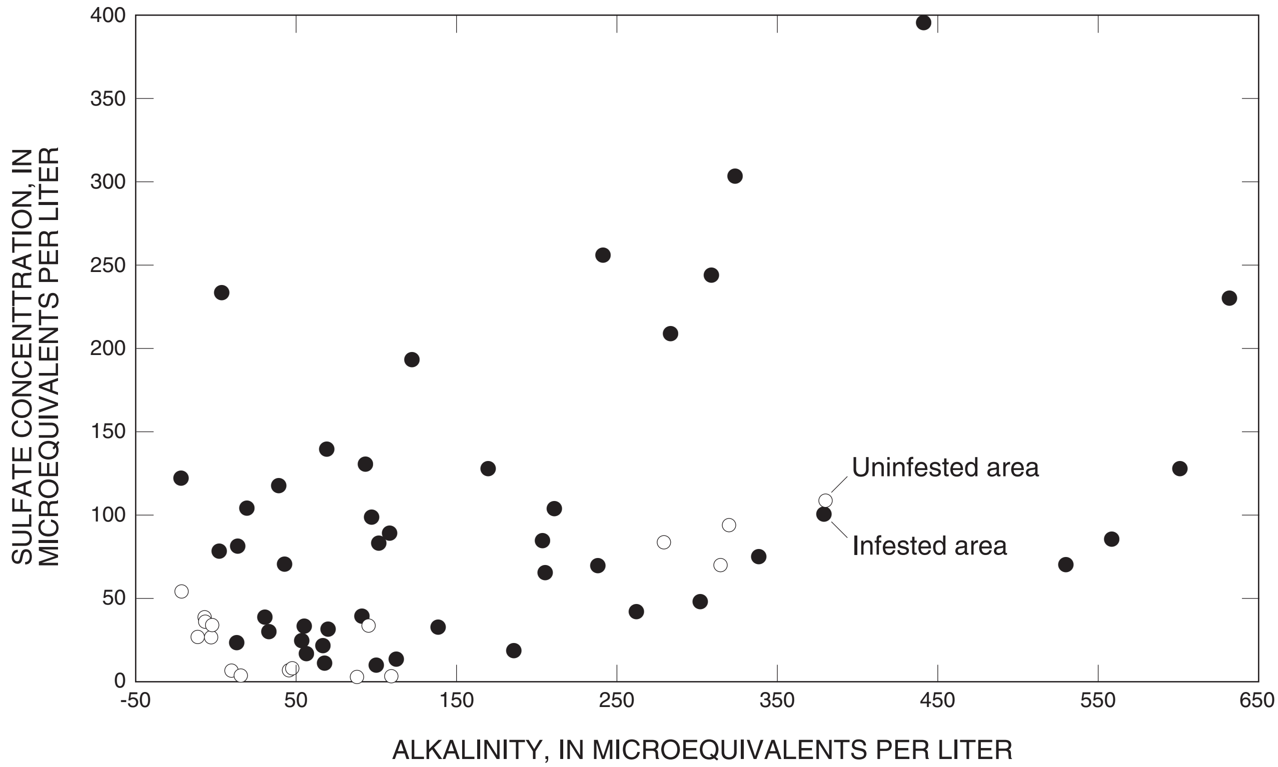

Figure 22. Relation of sulfate concentration and alkalinity in stream water for samples collected in the study area, 1992–94. One sample having a measured alkalinity of 1,300 microequivalents per liter and sulfate of 262 microequivalents per liter was not plotted.

Stream-water samples were analyzed for inorganic phosphate, but generally it was not detected (detection limit = 0.3 µeq L^{-1}). Stream-water samples also were analyzed for lead, strontium, and barium, and in almost all cases, concentrations were either below detection limits or ranged from 0.05 to 1.0 µeq L^{-1} (Appendix 3). Discharge measurements were recorded on five streams under summer baseflow conditions in Stewart County and varied between 46 and 1,350 m^3 hr^{-1} (table 21).

A comparison of major ion chemistry in water sampled at these five sites on June 16, 1994 (summer baseflow conditions) and on January 26, 1993 (winter baseflow conditions) (table 20) showed sulfate concentrations were higher and alkalinity was lower during winter baseflow conditions. This limited data set is consistent with the hypothesis that during higher flow conditions, proportionately more water traverses surficial flowpaths through more sulfate-rich soil horizons as has been reported in a review of numerous previous studies (Wiggington and others, 1992). However, it is uncertain whether such surficial flowpaths are more sulfate rich because of acidic deposition or because they were derived from sediments naturally rich in sulfate. Substantially more intensive sampling would be required to understand concentration and discharge relations for streams in the study area. A better understanding of concentration and discharge relations, as well as ground water and soil-water chemistry, is essential to determine if stream-water quality is influenced by acidic deposition in the study area.

Table 21. Discharge during baseflow conditions at five stream sites in Stewart County, Georgia, June 16, 1994

[m^3 h^{-1}, cubic meter per hour]

Stream name	Latitude	Longitude	Collection time	Discharge (m^3 h^{-1})
Tributary to Hannahatchee Creek	32°0914"	84°55'45"	1225	100
Sand Branch	32°14'27"	84°52'28"	1543	53
Cany Creek	32°14'42"	84°49'47"	1621	46
Hewell Creek	32°15'28"	84°48'19"	1650	74
Hitchitee Creek	32°16'05"	84°47'10"	1720	1,350

Spatial Relations

Geographic Information System (GIS) digital coverages compiled for this study include topographic relief, slope, land use, geology, general soils maps, and hydrography. The spatial patterns of these geographic coverages were compared to the spatial patterns of SPB infestation to determine whether there were any obvious relations that might help to explain the observed pattern of infestation shown in figure 1. This analysis could indicate associations between SPB infestation and environmental data in a general way, but could not be used for interpretation of cause and effect. Both the geographic coverages and the pattern of SPB infestation are very broad generalizations rather than the site-specific detailed information that would be required for a more intensive spatial correlation analysis.

Topographic Relief and Land Use

The shaded relief and slope maps of the study area (figs. 2, 3) indicate that, in general, the topography is similar across the study area with two exceptions. First, there are somewhat more areas having lower slope associated with the Chattahoochee River, Hannahatchee Creek, and Kinchafoonee Creek in Stewart and Webster Counties. Second, there are slightly more extensive areas having higher slopes in Stewart and Chattahoochee Counties than in Webster and Marion Counties. Slope was not a major focus of this study but the potential association between SPB infestation (fig. 1) and steepness of slope (fig. 3) could be evaluated on a broader regional basis. There were also minor differences in land use between the areas of higher and lower beetle infestation (figs. 1, 4); but the overall similarity across the study area suggests that the spatial pattern of land use cannot explain the pattern of SPB infestation.

Geology

Comparison of the surficial geology between the areas of higher and lower SPB infestation in Stewart, Chattahoochee, and Marion Counties indicates that there is no spatial association between surficial geology (figs. 5, 6) and the incidence of SPB infestation (fig. 1) in these counties. The areal abundance as well as the spatial relations between geologic formations are similar in Stewart, Chattahoochee, and Marion Counties.

Soil Physical Properties

One potentially significant difference between the more infested areas of southern Chattahoochee and Stewart Counties (fig. 1) and the less infested areas in Marion County concerns soil physical properties. Soils containing a partially cemented layer that restricts rooting are more abundant in the area of greatest beetle infestation (fig. 7, table 2; and Gerald Pilkerton, U.S. Department of Agriculture, Natural Resource Conservation Service, oral commun., 1994). Cowarts and Vaucluse soil series are very similar (Vaucluse is about 30 cm deeper) and both contain a cemented or partially cemented layer that restricts rooting. In more recent revisions to soil maps within the study area, some areas previously mapped as Vaucluse have been renamed Cowarts soil series.

Vaucluse and Cowarts soils are Typic Hapludults, shallow (56–90 cm depth) and contain a dense, brittle, cemented layer that restricts rooting. The predominant soil associations in the uninfested areas of Marion County contain substantially more Troup, Lakeland, and Orangeburg soils. Troup soils are Grossarenic Paleudults; these are deeper (greater than 200 cm), very sandy soils that do not contain layers restrictive to rooting. Lakeland soils are Typic Quartzisamments, deep sands without argillic horizons and restrictive layers. Orangeburg soils are Typic Paleudults that have a sandy loam subsoil and no restrictive layers. The common occurrence of soils containing a layer which is restrictive to rooting may represent a significant difference between infested and uninfested sites. Soils with restrictive rooting layers are common in the northwestern Coastal Plain Province of Georgia and their occurrence could represent an additional risk factor for SPB infestation.

SUMMARY OF CONCLUSIONS

A comparison of measured rates of atmospheric acidic deposition between the infested and uninfested areas during 1992–95 in the northwestern Coastal Plain of Georgia indicates that there is no spatial relation between acidic deposition and southern pine beetle infestation in loblolly pine. Rates of deposition were comparable to or lower than other published estimates for the Coastal Plain and southern Piedmont physiographic provinces. There is no evidence of regionally significant local point sources of sulfur dioxide. The data suggest chronic sulfate loading, which is of concern because of low soil fertility and the risk of increased leaching of soil nutrient cations. Nitrogen deposition was comparable to other published estimates, indicating no local point sources. Furthermore, nitrogen is likely to have a net positive fertilization effect and does not contribute to the leaching of soil nutrient cations.

Measurements of ambient air quality indicated that sulfur dioxide and ozone were comparable to published norms for the southeastern United States. However, ozone concentrations were high enough to constitute a chronic stress on sensitive loblolly genotypes. Ambient ozone concentration data are expensive to acquire, and thus few records are available. These limited data are not sufficient to evaluate the spatial relation between ozone concentration and southern pine beetle infestation.

Comparisons of soil chemical properties that could be influenced by chronic atmospheric acidic deposition between paired, infested and uninfested plots in Stewart County indicated that there were no significant differences that could explain susceptibility to southern pine beetle infestation. Site conditions throughout the study area are marginal for economic production of loblolly pine because of low soil fertility and a high susceptibility to drought conditions because of the common occurrence of sandy surface soils and high evapotranspiration. Although not a major focus of this study, the U.S. Department of Agriculture, Natural Resources Conservation Service, county-general soil maps indicate that the area of highest infestation contains a greater abundance of soils containing a subsurface horizon that is partially cemented and restrictive to rooting.

Loblolly pine trees in the study area are subject to several different stresses including ozone, low soil fertility, low soil organic matter, and the chronic effects of acidic deposition-induced soil cation leaching. Other stresses that probably affect the health of these trees, but were not investigated in this study, include ultraviolet-B radiation, soils prone to drought conditions, soils with shallow effective rooting volumes, acidic deposition-induced foliar cation leaching, dense stocking levels, and hardwood competition. It is hypothesized that cumulative effects of these interacting stresses are greater in the more highly infested areas, with the result that tree vigor and resistance to infestation by southern pine beetle is effectively reduced. The data collected during this study were insufficient to evaluate most of these stresses individually, or as they interact with one another.

Several areas of investigation could be undertaken to evaluate some of the above-noted stresses and their potential roles in affecting forest health and resistance to the southern pine beetle. Characterization of soil-chemical and physical properties in the less infested area, Marion County, would provide a useful direct comparison between Stewart and Marion Counties. The occurrence of partially cemented subsurface soil horizons that effectively restrict rooting could be documented in the infested and uninfested areas. Characterization of soil-physical properties at points co-located with the soil sampling sites would improve the understanding of this class of potential stresses. In addition to identifying horizons that are restrictive to rooting, physical characterization could include delineating the thickness of sandy surface soils.

Routine aerial surveys to document and map the occurrence of southern pine beetle outbreaks within the study area would be very useful. The aerial surveys conducted to date have been used to alert the Georgia Forestry Commission to problems and to notify affected landowners; however, the data have not been archived to permit an historical reconstruction of past infestations. Future aerial surveys could be used in conjunction with county soil maps which currently (1996) are not published, but which are largely completed for the counties of the study area. Although digitizing county soil maps is very time consuming, incorporation of this information into a Geographic Information System data base would support a powerful spatial correlation analysis between soil properties and southern pine beetle infestation data. Important attributes to include in the soils Geographic Information System data base coverages would be the occurrence of cemented subsurface horizons, the effective rooting volume, and the degree of erosion.

Information on foliar chemistry and sapwood area for loblolly pine in the study area could be used to determine whether there is any evidence for nutrient limitations, and to provide a better understanding of overall forest condition. Systematic data on forest health, including productivity, would be a major enhancement to the existing data base because productivity integrates all factors affecting plant growth.

Integration of spatial information about soil properties, air quality, forest health and productivity, and the pattern of southern pine beetle infestation would provide the foundation for a more comprehensive regional understanding of the association of southern pine beetle and potentially related environmental factors. Spatial analysis of the relation between forest productivity and the incidence of southern pine beetle infestation would provide a tool to evaluate hypotheses concerning productivity and tree susceptibility to attack by southern pine beetle. Establishing such spatial relations would be an initial step in the development of ecosystem management strategies to minimize losses from southern pine beetle.

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APPENDIX 1

Precipitation and concentrations of calcium and sulfur in precipitation and wet deposItion at Panola Mountain Research Watershed, near Atlanta, Georgia

[cm, centimeter; µeq L^{-1}, microequivalent per liter; kg ha^{-1} yr^{-1}, kilogram per hectare per year]

Water year[1/]	Precipitation (cm)	Calcium concentration		Sulfur concentration	
		Precipitation (µeq L^{-1})	Wet deposition (kg ha^{-1} yr^{-1})	Precipitation (µeq L^{-1})	Wet deposition (kg ha^{-1} yr^{-1})
1986	75.8	4.59	0.70	47.25	5.72
1987	113.1	3.69	.83	46.31	8.38
1988	99.6	5.38	1.07	47.92	7.64
1989	130.8	4.48	1.17	36.62	7.63
1990	133.2	2.36	.63	39.07	8.32
1991	137.1	2.96	.81	44.67	9.79
1992	119.4	2.88	.69	33.73	6.44
1993	111.6	2.92	.65	30.89	5.52
1994	158.1	2.32	.73	29.40	7.43
1995	98.8	3.52	.70	24.51	3.87

[1/] Water year is October 1 through September 30.

APPENDIX 2

Annual sulfur wet deposition near the cities of Buena Vista, Lumpkin, Griffin, Bellville, Tifton, and Atlanta, Georgia, 1979–94

Calendar year	Annual sulfur-wet deposition, in kilogram per hectare per year					
	Buena Vista	Lumpkin	Griffin[1/]	Bellville[1/]	Tifton[1/]	Atlanta[2/]
1979	not determined	not determined	7.44	not determined	not determined	not determined
1980	do.	do.	7.09	do.	do.	do.
1981	do.	do.	6.81	do.	do.	do.
1982	do.	do.	7.95	do.	do.	do.
1983	do.	do.	4.96	do.	do.	do.
1984	do.	do.	5.92	5.31	5.53	do.
1985	do.	do.	6.08	4.79	3.64	do.
1986	do.	do.	6.42	3.65	3.77	5.72
1987	do.	do.	4.82	5.49	3.90	8.38
1988	do.	do.	5.80	5.14	3.98	7.64
1989	do.	do.	4.46	4.56	3.35	7.62
1990	do.	do.	5.28	4.09	2.84	8.32
1991	do.	do.	6.31	4.86	5.20	9.78
1992	do.	4.26	4.77	4.13	3.75	6.00
1993	4.72	4.4	5.52	5.34	5.13	5.52
1994	not determined	not determined	5.43	4.78	4.22	7.43

[1/] Data for Griffin, Bellville, and Tifton, Ga., were compiled from the National Acid Precipitation Deposition Program world-wide web (WWW) data at (http://nadp.nrel.colostate.edu/nadp/).
[2/] Data for Atlanta 1986-92 from Huntington and others (1994); data from 1993–94, previously unpublished.

APPENDIX 3

Water-quality data from selected sites sampled during baseflow conditions in Chattahoochee, Marion, Muscogee, Stewart and Talbot Counties, Georgia, 1992–94

[minus sign (–), indicates that the constituent was detected; however, the concentration was below the reporting limit and the absolute value of the number listed is equal to one half of the reporting limit for that analysis

Stream name	Latitude	Longitude	Sampling date	Lead (µeq/L)	Barium (µeq/L)	Strontium (µeq/L)
			More Highly Infested Area			
Tributary to Hannahatchee Creek	32°09'30"	84°58'11"	01/29/93	–0.024	0.275	0.166
Tributary to Hannahatchee Creek	32°08'18"	84°57'36"	11/10/92	–.483	–.007	–.011
Tributary to Hannahatchee Creek	32°08'15"	84°57'05"	11/10/92	–.483	–.007	–.011
Tributary to Turner Creek	32°02'29"	84°56'55"	01/29/93	–.024	.243	.615
Tributary to Chattahoochee	32°12'14"	84°56'45"	02/05/93	–.024	.299	.601
			06/18/92	.049	.355	.681
Tributary to Chattahoochee	32°12'05"	84°56'42"	06/18/92	.033	.258	.647
			02/05/93	–.024	.315	.640
Tributary to Turner Creek	32°04'13"	84°56'26"	06/18/92	.206	.399	1.079
Tributary to Hannahatchee Creek	32°08'25"	84°56'09"	11/10/92	–.483	–.007	–.011
Tributary to Hannahatchee Creek	32°08'39"	84°55'47"	11/10/92	–.483	–.007	–.011
Tributary to Hannahatchee Creek	32°09'14"	84°55'45"	09/20/93	–.039	.185	.251
			11/10/92	–.483	–.007	–.011
			06/16/94	–.048	.228	.199
Tributary to Grass Creek	32°06'17"	84°55'38"	01/29/93	–.024	.421	.357
Tributary to Hannahatchee Creek	32°09'15"	84°55'17"	11/10/92	–.483	–.007	–.011
			09/20/93	–.039	.250	.285
Tributary to Hannahatchee Creek	32°09'23"	84°54'51"	11/10/92	–.483	–.007	–.011
Tributary to Hannahatchee Creek	32°08'58"	84°54'49"	11/10/92	–.483	–.007	–.011
Hannahatchee Creek	32°09'09"	84°54'23"	11/10/92	–.483	–.007	–.011
Tributary to Hannahatchee Creek	32°10'24"	84°53'53"	01/29/93	–.024	.414	.217
Tributary to Hannahatchee Creek	32°09'28"	84°53'44"	11/10/92	–.483	–.007	–.011
Tributary to Hannahatchee Creek	32°09'28"	84°53'42"	11/10/92	–.483	–.007	–.011
Tributary to Hannahatchee Creek	32°07'51"	84°53'03"	02/15/93	–.024	.327	.342
Tributary to Hannahatchee Creek	32°08'35"	84°52'50"	11/10/92	–.483	–.007	–.011
Sand Branch	32°14'27"	84°52'28"	01/26/93	–.193	–.004	–.006
			09/20/93	–.039	.862	3.899
			06/16/94	.626	.510	1.906
Tributary to Hannahatchee Creek	32°11'23"	84°52'10"	06/18/92	.140	.555	.236
Tributary to Hannahatchee Creek	32°09'35"	84°51'28"	02/01/93	–.024	.278	.302
Tributary to Colochee Creek	32°06'32"	84°50'45"	01/28/93	–.024	.238	.977

APPENDIX 3—Continued

Water-quality data from selected sites sampled during baseflow conditions in Chattahoochee, Marion, Muscogee, Stewart and Talbot Counties, Georgia, 1992–94—Continued

[minus sign (–), indicates that the constituent was detected; however, the concentration was below the reporting limit and the absolute value of the number listed is equal to one half of the reporting limit for that analysis

Stream name	Latitude	Longitude	Sampling date	Lead (µeq/L)	Barium (µeq/L)	Strontium (µeq/L)
Cany Creek	32°14'42"	84°49'47"	01/26/93	–.193	–.004	–.006
			09/20/93	–.039	.332	.747
			06/16/94	–.048	.582	.1.583
Tributary to Hightower Branch	32°05'09"	84°49'30"	06/12/92	0.271	0.217	0.291
Frog Bottom Creek	32°06'09"	84°49'14"	11/10/92	–.483	–.007	–.011
Hewell Creek	32°15'28"	84°48'19"	01/26/93	–.193	–.004	–.006
			06/16/94	–.048	.311	.871
Hitchitee Creek	32°16'05"	84°47'10"	01/26/93	–.193	–.004	–.006
			09/20/93	–.039	.289	.330
			06/16/94	–.048	.236	.344
Tributary to Broach Creek	32°13'00"	84°45'00"	02/06/93	.024	.148	.201
			06/04/92	.244	.147	.261
Sally Branch	32°23'25"	84°42'14"	04/02/93	–.024	.603	.209
Little Pine Knot Creek	32°25'15"	84°41'46"	04/02/93	–.024	.617	.146
Ochilee Creek	32°20'52"	84°41'42"	09/20/93	–.039	.217	.131
Less Infected Area						
Kendall Creek	32°32'45"	84°42'52"	03/30/93	–.024	.406	.587
Baker Creek	32°33'07"	84°40'30"	03/30/93	–.024	.425	.819
Upatoi Creek	32°33'43"	84°36'35"	03/30/93	–.024	.461	.605
Little Juniper Creek	32°30'53"	84°36'26"	03/30/93	–.024	.236	.065
Kinchafoone, West Branch	32°20'49"	84°35'43"	03/30/93	–.024	.261	.119
			09/20/93	–.039	.650	.253
Kinchafoone, East Branch	32°20'34"	84°35'31"	03/30/93	–.024	.114	.077
Pine Knot Creek	32°25'20"	84°35'21"	03/30/93	–.024	.194	.076
			09/20/93	–.039	.154	.062
Tributary to Kinchafoone Creek	32°19'59"	84°33'27"	03/30/93	–.024	.219	.173
Fort Perry Creek	32°30'25"	84°32'23"	03/30/93	–.024	.168	.069
Black Creek	32°32'58"	84°32'00"	03/30/93	–.024	.262	.072
Oochee Creek	32°20'17"	84°29'49"	03/30/93	–.024	.241	.467
Shoal Creek	32°26'26"	84°29'20"	03/30/93	–.024	.133	.057
Muckalee Creek	32°17'45"	84°29'07"	10/15/92	–.241	–.073	–.114
Cedar Creek	32°26'09"	84°23'37"	03/30/93	–.024	.132	.062
			09/20/93	–.039	.131	.048

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