EFFECTS OF ACIDIC DEPOSITION ON WATER QUALITY AND FOREST HEALTH IN GEORGIA

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Abstract. Biogeochemical studies at the Panola Mountain Research Watershed near Atlanta, Ga., and in the Coastal Plain Province of Georgia have provided an assessment of some of the potential effects of acid deposition on streamwater quality and forest health in Georgia. Historically, "acid rain" has not been considered a potentially serious problem in the southeastern United States; however, recent studies have raised questions about the sensitivity of forest and aquatic resources to chronic pollutant loading. Intensive streamwater-quality monitoring during storms has shown that episodic acidification presently is occurring and likely will become substantially more severe in future decades. Acidic deposition at current rates does not appear to have direct adverse effects on forest health, but does contribute to the chronic loss of nutrient cations.

INTRODUCTION

This paper briefly reviews several recent studies related to the effects of acidic deposition on water quality and forest health in Georgia. Acidic deposition refers to both wet deposition of sulfuric and nitric acids in precipitation and dry deposition of oxides of sulfur and nitrogen. Oxides of sulfur and nitrogen generally are derived from the products of fossil fuel combustion and they are the precursors of sulfuric and nitric acids in precipitation. Most of the studies were conducted at the Panola Mountain Research Watershed (PMRW), near Atlanta, where the U.S. Geological Survey (USGS) has been investigating biogeochemical processes related to the influences of the atmospheric deposition of sulfur, a non-point source pollutant, on terrestrial ecosystems and aquatic resources since 1985. One study was conducted in the Coastal Plain of Georgia. One common element in many of these studies involves the depletion of soil calcium which is accelerated by acidic deposition. This process and the potential consequences of long-term calcium depletion will be discussed in a later section.

Historically, "acid rain" has not been considered a potentially serious problem in the southeastern United States because pollutant loadings were relatively low and forest soils, although naturally acidic and generally low in fertility, were thought to have a large potential for sulfate adsorption. Southeastern forest ecosystems also are typically nitrogen limited, so nitrate saturation and subsequent leaching has not been an important issue. Therefore, the potential to protect against the accelerated leaching of base cations caused by mobile anions (sulfate and nitrate) was thought to be sufficient to ensure long-term protection against acidification. Research over the last decade has begun to question many of these assumptions, because the capacity of the system to buffer against chronic sulfur loading along critical flow paths is small enough that adverse forest and aquatic effects likely are to emerge sooner than previously thought.

The southern hardwood and loblolly pine mixed forest at PMRW is representative of the dominant forest types of the Southern Plains ecoregion. Tree ring analyses indicate an average tree age for these canopy dominant trees of 60 to 80 years. Soils predominantly are Ultisols developed in residuum and colluvium intergrading to Inceptisols or Entisols developed in colluvium, fluvial sediments, or highly eroded landscape positions.

Investigations of the potential role of acidic deposition in the pattern of southern pine beetle infestation in the northwestern Coastal Plain Province were conducted in collaboration with forest entomologists at the Georgia Forestry Commission (Huntington, 1996). These investigations included measurements of acidic deposition, ambient air quality, soil properties, and surface water quality in areas of high and low beetle infestation. The forest in this study area was predominantly loblolly pine. Soils in this study area are derived from marine sedimentary Cretaceous sand and loamy parent materials. The predominant soil order is Ultisols that are highly weathered, low in cation exchange capacity, organic matter, and base saturation. Ultisols in this study area tend to have a sandy surface horizon of variable thickness overlying a clay-rich horizon.

ATMOSPHERIC ACIDIC DEPOSITION AT THE PANOLA MOUNTAIN RESEARCH WATERSHED AND IN THE NORTHWESTERN COASTAL PLAIN

Dry deposition sulfur fluxes, dominated by sulfur dioxide, are estimated to range from 33 to 50 percent of total atmospheric sulfur deposition at PMRW (Peters, 1989; Meyers *et al.*, 1991; Cappellato and Peters, 1995). Shanley and Peters (1993) have shown that, in spite of high sulfate retention capacity of Ultisol soils at PMRW, during storms streamwater alkalinity approaches zero because of the routing of runoff through acidified surface soil horizons and dilution of more alkaline waters associated with deeper flowpaths. These observations are in accord with a large number of studies of forest ecosystems in the eastern United States that report episodic acidification and sensitivity to chronic sulfur loading because of a reduced soil capacity to retain sulfate (Wiggington *et al.*, 1990; Church *et al.*, 1989). High sulfate concentrations occur in ground water in the headwaters. Also, hydrologic characteristics of the soils and the availability of the sulfate for transport vary seasonally (Shanley and Peters, 1993). Using the model of acidification of ground water in catchments (MAGIC), Hooper and Christophersen (1992) predicted that chronic sulfur loading at current rates would result in substantially more pronounced alkalinity (acid neutralizing capacity) depression during storms occurring during the next 20 to 50 years than occurs presently (Figure 1). Huntington (1994a) showed that future changes in rainfall amounts or seasonal distributions resulting in decreases in runoff would cause greater watershed acidification than if rainfall patterns remained the same for fixed sulfur loading.

Huntington *et al.* (1994a) determined that annual variations in sulfate export at PMRW were related more to annual differences in runoff quantity rather than differences in annual precipitation amount or atmospheric deposition of sulfate. Changes in sulfate export were shown to be associated with changes in soil-water chemistry. Sulfate retention, release, and mobility were strongly influenced by previous hydrologic conditions. The concentration and discharge relation for sulfate was shown to shift between years depending upon the previous years rainfall amount. Water years 1987 and 1989 (water year, October through September), generally had higher streamwater sulfate concentrations at any given discharge, compared with water years 1991 and 1992 (Figure 2). All four water years had average to above average rainfall; however, water years 1987 and 1989 followed years of low rainfall; and water years 1991 and 1992 followed years of average to above average rainfall (Huntington *et al.*, 1994a). These patterns emphasize the importance of hydrologic conditions in the retention and release of sulfate and demonstrate that variations in water quality are strongly influenced by rainfall patterns over relatively short time scales.

Incorporation of annual differences in runoff distributions for the interpretation of sulfate flux is critical for detecting trends in water quality (Aulenbach and Hooper, 1994). Aulenbach and Hooper (1994) showed that typical procedures, involving comparisons of flow-weighted annual average concentrations, induced false positive and false negative trends. Their improved trend-detection techniques incorporating runoff can assist in environmental assessment and design of more cost-effective monitoring studies. A sulfate-concentration trend analysis for 1985 to 1993 indicates no trend in wet deposition, and a decrease in stream-water concentration (Aulenbach *et al.*, 1996). The relative contribution of dry deposition may be important for assessing trends and non-point sources impacts, because it is of comparable magnitude to wet deposition; also the relation between wet and dry deposition is not well known.

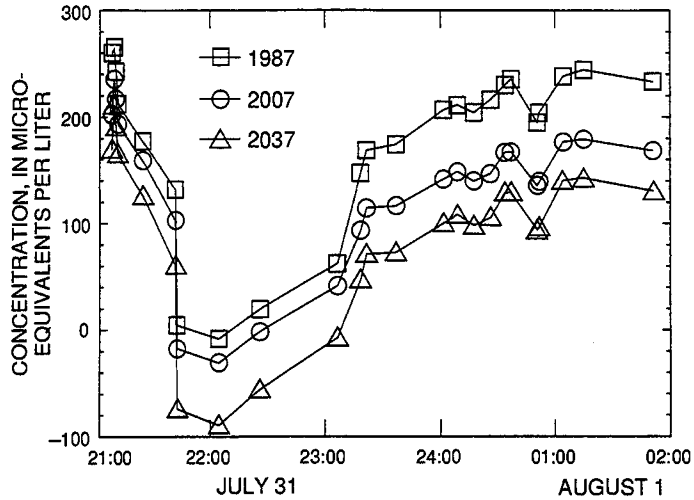

Figure 1. Streamwater acid neutralizing capacity predicted for a summer thunderstorm, hydrologically identical to one observed in 1987, for the years 1987, 2007, and 2037 (based on application of MAGIC; Hooper and Christopherson, 1992).

Investigations at PMRW have not included the effects of acidic precipitation on aquatic biota. However, critical reviews of the relevant literature have demonstrated that almost all stream communities including microbial, macroinvertebrate, and fish are adversely affected by acidification (Elwood and Mulholland, 1989; Baker *et al.*, 1990). The percentage of streams that are acidic in the southern Appalachians and southern Blue Ridge Province is very low. Most of these streams are circumneutral in pH at baseflow conditions, but also are characterized as having relatively low acid neutralizing capacity (ANC) (Baker *et al.*, 1990), suggesting that the streams have not been adversely affected by acidic deposition, but that their capacity to buffer acidic inputs may be limited. Of particular interest in small headwater streams having low ANC and experiencing net ecosystem calcium depletion, is the observation by Baker *et a*l. (1990) that: "In general, aquatic biota tolerate lower pH and higher aluminum in waters with higher calcium concentrations. Small changes in calcium are particularly important at low calcium concentrations (<100 to 150 μeq L-1)."

In response to unexplained chronic outbreaks of southern pine beetle in loblolly pine forests in Stewart and Chattahoochee Counties, Ga., the USGS and the Georgia Forestry Commission conducted a 3-year study to determine whether acidic deposition could explain the pattern of infestation (Huntington, 1996b). There were no significant differences in total acidic deposition between areas of high infestation in Stewart County and low infestation in adjacent Marion County. Annual total atmospheric sulfur deposition was relatively low but still represented substantial pollutant loading. 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, but the limited available data did not indicate a spatial correlation

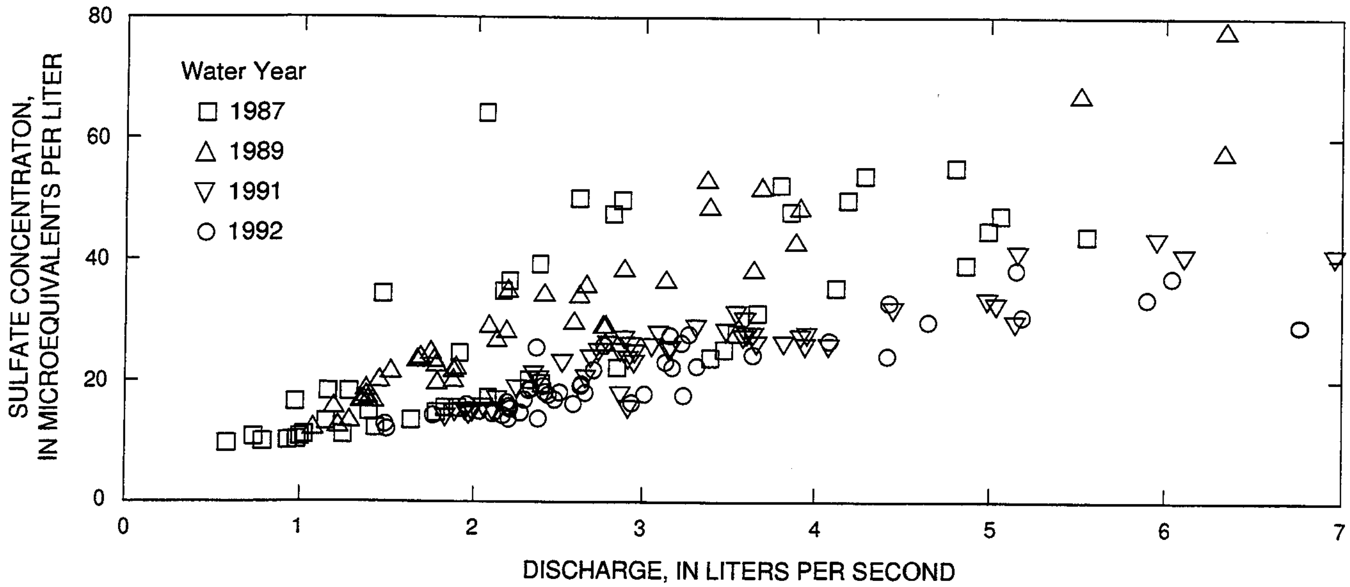

Figure 2. Streamwater sulfate concentrations as a function of discharge at flows less than or equal to 7 liters per second for samples collected weekly at the Panola Mountain Research Watershed.

between ozone concentration and southern pine beetle infestation (Huntington, 1996b).

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 (Huntington, 1996b). Site conditions throughout the study area were 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 indicated that the area of highest infestation contained 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 were growing under multiple, interacting stresses and it was hypothesized that cumulative effects of these stresses were greater in the most highly infested areas.

CALCIUM DEPLETION AND SUSTAINABILITY OF FOREST PRODUCTIVITY

At PMRW, the USGS has been investigating biogeochemical processes related to calcium cycling and the sustainability of forest productivity. The forest and soils at PMRW are representative of the southeastern Piedmont Province. The potential effects of processes occurring at regional scales, such as the recent decline in calcium concentration in precipitation in the eastern United States (Lynch *et al.*, 1995; Hedin *et al.*, 1994), can be evaluated at the scale of the small watershed where many variables can be held constant and changes in other variables are measurable (Likens *et al.*, 1996). Calcium concentration in precipitation at PMRW and at other sites in Georgia also has declined over the last decade (Huntington *et al.*, 1996; Lynch *et al.*, 1995).

At the Fernow Experimental Forest in West Virginia, streamwater calcium concentrations increased in response to increased atmospheric deposition of nitrate and subsequent accelerated soil cation leaching (Edwards and Helvey, 1991). At the Hubbard Brook Experimental Forest in New Hampshire, acidification is thought to have first elevated calcium concentrations in streamwater during a period of soil depletion; and subsequently, concentrations have declined (Likens et al., 1996). Some studies also have reported soil acidification, including declines in calcium contents of the forest floor and surface mineral soil, which are thought to be a result of both vegetation uptake and acid-induced cation leaching (Likens *et al.*, 1996; Richter *et al.*, 1994; Wilson and Grigal, 1995; Ronse *et al.*, 1988; Billet *et al.*, 1990; Bjørnstad, 1991; Johnson *et al.*, 1991; Kuylenstierna and Chadwick, 1991).

Element mass-budget calculations at PMRW and at other intensively studied forest sites in eastern United States (Table 1) indicate that the rate of calcium depletion by vegetation uptake and soil leaching is several times greater than the rate of calcium input in atmospheric wet deposition (Johnson and Todd, 1990; Huntington, 1996b). Weathering of non-exchangeable mineral calcium can be an important process that replenishes calcium lost by leaching and vegetation uptake, but at many sites these pools are relatively small and weathering rates may be too slow to compensate for losses.

Highly weathered Ultisol soils of the southeastern United States frequently are largely depleted of non-exchangeable mineral calcium within the rooting zone (Daniels and Hammer, 1992) so that weathering resupply probably is quite small in these ecosystems. Total elemental analysis of the non-exchangeable fraction of soil, saprolite, and partially weathered rock collected at PMRW indicates that these materials are highly calcium depleted. Soil calcium stores in the soil

Table 1. Calcium soil pools (kilograms per hectare and ecosystem fluxes (kilograms per hectare per year) from selected forest sites in the eastern United States
[Data sources reported in Huntington (1996b); ND= not determined]

	Stewart County, Ga., Loblolly Pine	Coweeta, N.C. White Pine	Duke Forest, N.C. Loblolly Pine	Walker Branch, TN Loblolly Pine	Walker Branch, TN Chesnut-Oak	Walker Branch, TN Oak-Hickory	Calhoun Forest, S.C. Loblolly Pine	Panola Mountain, Ga., Oak-Hickory-Pine	Cockaponset State Forest, CT., Oak, Hickory, Maple, Birch
Soil Exchangeable Pool	840	667	2,125	820	110	140	245	2,200	276
Total Soil Pool	840	3,770	4,940	2,500	1,180	1,800	ND	2,200	3,410
Net Wood Increment	6	3.9	13.6	16	17	8	7.5	10	6.6
Atmospheric Deposition	3.17	2.9	8.1	5.4	5.4	5.4	2.8	1.4	2
Soil Leaching	1.1	2.2	8.1	15	12	1	10.2	2.7	ND

exchangeable pools also are generally small throughout the southeastern Piedmont because soils tend to have low cation exchange capacity (Buol, 1973; Markewich *et al.*, 1990; Huntington *et al.*, 1994a,b) suggesting that calcium supply could limit forest productivity in some forest ecosystems. Budget calculations at PMRW suggest that ecosystem storage could be reduced by about 50 percent in as little as two or three harvest rotations. Current levels of acidic deposition and declining rates of calcium deposition will accelerate calcium depletion.

Limited supplies of calcium could reduce tree vigor and increase susceptibility to attack by insects and diseases because of the potential effects of calcium limitations on carbohydrate reserves. Trees have a high calcium demand in woody tissues. Metabolic calcium demands are far lower, so it is unlikely that foliar symptoms of calcium deficiency would be observed. In red spruce, 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 resulting in a decrease in stored carbohydrates could reduce resistance of loblolly pine to southern pine beetle infestation by reducing oleoresin synthesis and flow (Waring and Schlesinger, 1985; Lorio, 1993). Levels of calcium deficiency that affect growth and carbohydrate status but do not produce foliar symptoms could result in increased susceptibility to insects and diseases.

LITERATURE CITED

Aulenbach, B.T., and R.P. Hooper, 1994. Adjusting solute fluxes for climatic influences. *EOS Trans. Am. Geophys. Union*, 75: 233.

Aulenbach, B.T., R.P. Hooper, and O.P. Bricker, 1996. Trends in precipitation and surface-water chemistry in a national network of small watersheds, *Hydrological Processes*, 10:151-181.

Baker, J.P., D.P. Bernard, S.W. Christensen, and M.J. Sale, 1990. Biological effects of changes in surface water acid-base chemistry: National Acid Precipitation Assessment Program, Washington, D.C. Acid Deposition: State of Science and Technology, Report 13, November 1990, 381 p.

Billet, M.F., F. Parker-Jervis, E.A. Fitzpatrick, and M.S. Cresser, 1990. Forest soil chemical changes between 1949/50 and 1987, *J. Soil Sci.*, 41:133-145.

Bjørnstad, O.N., 1991. Changes in forest soils and vegetation in Sogne, southern Norway, during a 20 year period, *Holarctic Ecol.*, 14:234-244.

Buol, S.W. 1973. Soils of the Southern States and Puerto Rico: North Carolina State University and Soil Conservation Service of the U.S. Department of Agriculture, Southern Cooperative Series Bulletin 174. June 1983, 105 p.

Cappellato, Rosanna, and Peters, N.E., 1995. Dry deposition and canopy leaching rates in deciduous and coniferous forests of the Georgia Piedmont: and assessment of a regression model, *J. Hydrology*, 169: 131-150.

Church, M.R., K.W. Thornton, P.W. Shaffer, D.L. Stevens, B.P. Rochelle, G.R. Holdren, M.G. Johnson, J.J. Lee, R.S. Turner, D.L. Cassell, D.A. Lammers, W.G. Campbell, C.I. Liff, C.C. Brandt, L.H. Liegel, G.D. Bishop, D.C. Mortenson, S.M. Pierson, and D.D. Schmoyer, 1989. Direct/Delayed Response Project: Future Effects of Long-term Sulfur Deposition on Surface Water Chemistry in the Northeast and Southern Blue Ridge Province (Results of the DDRP), Rep. No. EPA/600/3-89/061a-d, + app., U.S. Environ. Prot. Agency, Corvallis, OR. 887 pp.

Daniels, R.B., and R.D. Hammer. 1992. Soil Geomorphology. Wiley, New York, 235 p.

Edwards, P.J., and J.D. Helvey, 1991. Long-term ionic increases from a Central Appalachian forested watershed: J. *Environ. Qual.*, 20:250-255

Elwood, J.W. and P.J. Mullholand, 1989. Effects of acidic precipitation on stream ecosystems: *In* D.C. Adriano and A.H. Johnson, (*eds.*), Acid Precipitation Volume 2: Biological and Ecological Effects, New York, Springer-Verlag, p. 85-135.

Hedin, L.O., L. Granat, G.E. Likens, T.A. Buishand, J.N. Galloway, T.J. Butler, and H. Rodhe, 1994. Steep declines in atmospheric base cations in regions of Europe and North America, *Nature*, 367:351-354.

Hooper, R.P., and N. Christophersen, 1992. Predicting episodic stream acidification in the southeastern United States: combining a long-term acidification model and the end-member mixing concept, *Water Res. Res.*, 28:1983-1990.

Huntington, T.G., 1996a. Predicting watershed acidification under alternate rainfall conditions, *Water, Air, and Soil Pollut.*, 90: 429-450.

___1996b. Assessment of the potential role of atmospheric acidic deposition in the pattern of southern pine beetle infestation in the northwest Coastal Plain Province of Georgia, 1992-1995: U.S. Geological Survey Water-Resources Investigation Report 96-4131, 75 p.

Huntington, T.G., R.P. Hooper, and B.T. Aulenbach. 1994a. Hydrologic processes controlling sulfur mobility: a small watershed approach. *Water Resour. Res.* 30:283-295.

Huntington, T.G., R.P. Hooper, A.E. Blum, C.E. Johnson, B.T. Aulenbach, R. Cappellato, and E.H. Drake, 1994b. Sustainability of Forest Productivity in the Georgia Piedmont, [*abs.*], *Agronomy Abstracts*, p. 385, Annual Meeting of the Soil Science Society of America, Seattle, WA.

Huntington, T.G., Hooper, R.P, Aulenbach, B.T., Cappellato, R., and Drake, E.H. 1996. Temporal trends in calcium concentration of precipitation and calcium deposition in southeastern USA, *EOS, Transactions of the Amer. Geophys. Union* 77:S131.

Johnson, D.W., and D.E. Todd. 1990. Nutrient cycling in forests of Walker Branch Watershed, Tennessee: roles of uptake and leaching in causing soil changes. *J. Environ. Qual.* 19:97-104.

Johnson, D.W., M.S. Cresser, S.I. Nilsson, J. Turner, B. Ulrich, D. Binkley, and D.W. Cole, 1991. Soil changes in forest ecosystems: evidence for and probable causes, *Proceedings of the Royal Soc. of Edinburgh*, 97:81-116.

Kuylenstierna, J.C.I., and M.J. Chadwick, 1991. Increases in soil acidity in North-West Wales between 1957 and 1990, Ambio, 20:118-119.

Likens, G.E., C.T. Driscoll, and D.C. Buso, 1996. Long-term effects of acid rain: Responses and recovery of a forest ecosystem: *Science*, 272:244-246.

Lorio, P.L., Jr., 1993. Environmental stress and whole-tree physiology: *In* T.D. Schowalter and G.M. Filip, (*eds.*), Beetle-Pathogen Interactions in Conifer Forests, Academic Press, San Diego, p. 81-101.

Lynch, J.A., V.C. Bowersox, and C. Simmons, 1995. Precipitation chemistry trends in the United States: 1980-1993, Summary Report, National Atmospheric Deposition Program, Fort Collins, 103 p.

Markewich, H.W., M.J. Pavich, and G.R. Buell, 1990. Contrasting soils and landscapes of the Piedmont and Coastal Plain, eastern United States. *In* P.L.K. Knuepfer and L.D. McFadden (*eds.*), Soils and Landscape Evolution, *Geomorphology*, 3:417-447.

Meyers, T.P., B.B. Hicks, R.P. Jr. Hosker, J.D., Womack, and L.C. Satterfield, 1991. Dry deposition inferential measurement techniques-II. Seasonal and annual deposition rates of sulfur and nitrogen, *Atmos. Environ* 25:2361-2370.

Peters, N.E., 1989. Atmospheric deposition of sulfur to a granite outcrop in the Piedmont of Georgia, U.S.A. *IAHS Publication*, 179:173-181.

Richter, D.D., D. Markewitz, C.G. Wells, H.L. Allen, R. April, P.R. Heine, and B. Urrego, B., 1994. Soil chemical change during three decades in an old-field loblolly pine (*Pinus Taeda L.*) Ecosystem, *Ecology*, 75:1463-1473.

Ronse, A.,L., DeTemmerman, M. Guns, and R. DeBorger, 1988. Evolution of acidity, organic matter content, and CEC in uncultivated soils of North Belgium during the past 25 years, *Soil Sci.*, 146:453-460.

Shanley, J.B., and N.E. Peters, 1993. Variations in aqueous sulfate concentrations at Panola Mountain, GA, *J. Hydrol.*, v. 146:361-382.

Shortle, W.C., and K.T. Smith, 1988. Aluminum-induced calcium deficiency syndrome in declining spruce-fir forests, *Science*, 240:1017-1018.

Shortle, W.C., and E.A. Bondietti, 1992. Timing, magnitude and impact of acidic deposition on sensitive forest sites, *Water, Air, and Soil Pollut.*, 61:253-267.

Waring, R.H., and W.H. Schlesinger, 1985. Forest Ecosystems Concepts and Management, Academic Press, Orlando, 340 p.

Wiggington, P.J., T.D. Davies, M. Tranter, and K.N., Eshleman, 1990. Episodic Acidification of Surface Waters due to Acidic Deposition, Acidic Deposition: State of Science and State of Technology Rep. 12, 200 p., Natl. Acid Precip. Assess. Program, Washington, D.C., 1990.

Wilson, D.M., and D.F., Grigal, 1995. Effects of pine plantations and adjacent deciduous forests on soil calcium, *Soil Sci. Soc. Am. J.*, 59:1755-1761.