

SOIL-CALCIUM DEPLETION LINKED TO ACID RAIN AND FOREST GROWTH IN THE EASTERN UNITED STATES

Since the discovery of acid rain in the 1970's, scientists have been concerned that deposition of acids could cause depletion of calcium in forest soils. Research in the 1980's showed that the amount of calcium in forest soils is controlled by several factors that are difficult to measure. Further research in the 1990's, including several studies by the U.S. Geological Survey, has shown that (1) calcium in forest soils has decreased at locations in the northeastern and southeastern U.S., and (2) acid rain and forest growth (uptake of calcium from the soil by roots) are both factors contributing to calcium depletion.

CALCIUM CYCLING IN FORESTS

Calcium is an essential nutrient for tree growth that is used in the formation of wood and in the maintenance of cell walls, the primary structure of plant tissue. Trees obtain calcium from the soil (fig. 1), but to be taken up by roots, the calcium (a positively charged ion) must be dissolved in soil

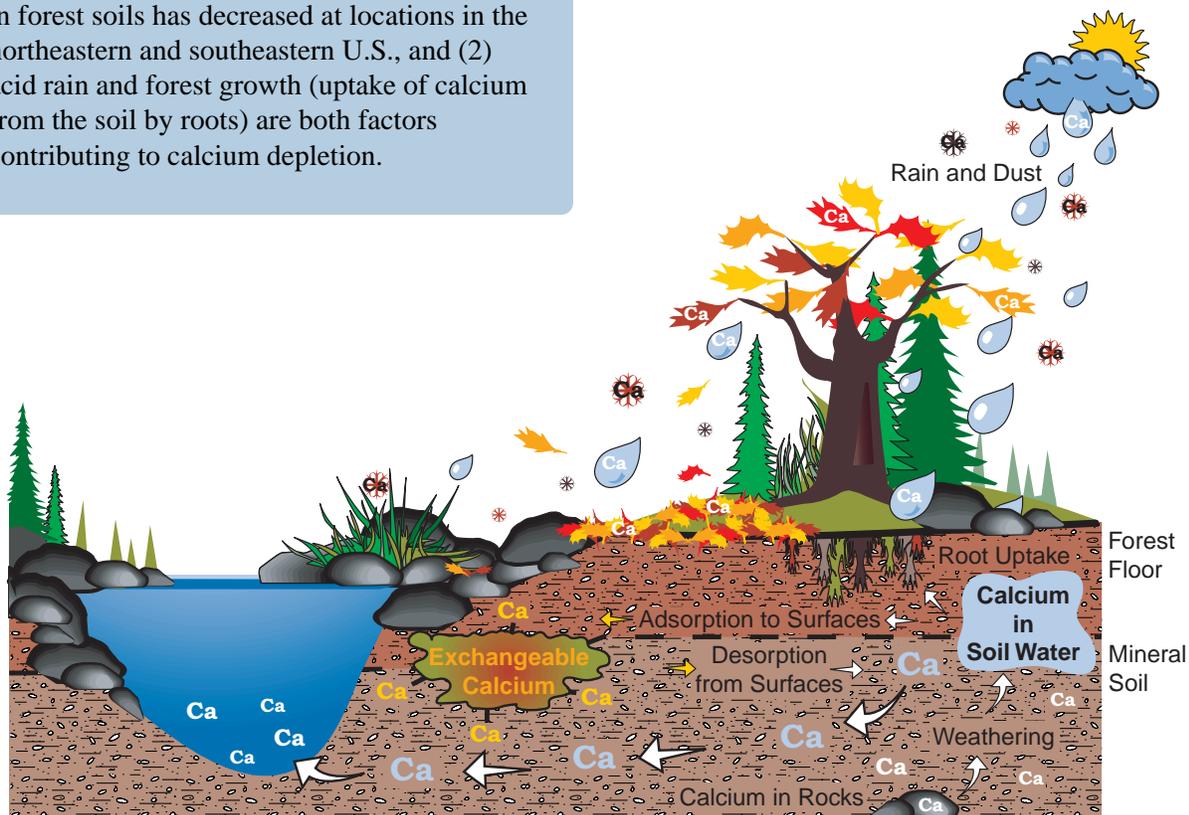


Figure 1. Calcium cycle in forest ecosystems. Inputs to the pool of available calcium in the soil result from weathering of rocks, atmospheric deposition, and litterfall. Outputs from this pool result from root uptake and leaching out of the soil.

water. Calcium adsorbed to negatively charged surfaces of soil particles (termed exchangeable calcium) is also available to roots because both adsorption and desorption of calcium occurs readily through the process of chemical equilibrium. Some calcium is deposited onto forests in an available form in dust and precipitation or is returned to the soil through decomposing leaves and branches that form the forest floor. Most of the calcium in soil, however, is bound within the mineral structure of rocks within the underlying mineral soil, which prevents it from dissolving in water or becoming

adsorbed to particle surfaces. Weathering, the physical and chemical breakdown of rocks, gradually releases calcium to soil water where it can (1) be taken up by roots, (2) adsorb to particle surfaces, or (3) be leached out of the soil by negatively charged ions in percolating water. As calcium is released by weathering, acidity in the form of hydrogen ions is neutralized, which increases the pH of soil water and the surface waters into which it flows. Calcium leached out of the soil into surface waters also serves as an essential nutrient for aquatic plants and animals.

CALCIUM RESEARCH IN THE 1970'S AND 80'S

The discovery of acid rain (acids deposited from the atmosphere in rain, snow, particles and gases, more accurately referred to as acid deposition) in the 1970's prompted concern that deposition of acids could increase leaching of calcium, and other neutralizing cations, such as magnesium, sodium, and potassium (referred to as base cations) from forest soils. Acid deposition provides (1) hydrogen ions, which displace cations adsorbed to soil surfaces, and (2) sulfate and nitrate ions, which tend to keep these cations dissolved in soil water that eventually drains into streams and lakes. Results of preliminary research in the 1970's suggested that elevated leaching might deplete soil calcium, decrease forest growth, and acidify surface-waters (Cowling and Dochinger, 1980). These concerns were somewhat alleviated in the Northeast by the discovery that the soil contained large amounts of calcium. Although most of the soil calcium was known to be in unavailable forms in rocks and minerals, the rate at which calcium was released by weathering was considered to be sufficient to offset

increased leaching caused by acid rain (Johnson and others, 1982).

In the Southeast, the amount of calcium in soils was found to be generally less than in the Northeast, but was thought to be somewhat protected from cation leaching by the high capacity of these soils to adsorb sulfate, a negatively charged ion. The fine texture of soils in the Southeast enhances sulfate adsorption, which removes the negative charge from soil water that is necessary to leach the positively charged cations. Considerable uncertainty as to the status of soil calcium remained, through the 1980's, however, because the processes involved in weathering and leaching were found to be extremely complex. At the close of the research phase of the National Acid Precipitation Assessment Program (NAPAP) in 1990, decreases in the availability of calcium in forest soils from either acid rain or forest growth had not been confirmed, although the possibility of future depletion from acid deposition was acknowledged (NAPAP, 1993).

CALCIUM RESEARCH IN THE 1990'S

Continued research in the 1990's has documented distinct decreases in soil calcium over the past 4 to 5 decades, in both the Northeast (Johnson and others, 1994a) and the Southeast (Richter and others, 1994). These decreases were attributed primarily to the

uptake of calcium by trees in excess of inputs from weathering. Follow-up studies have suggested, however, that both acid deposition (Markewitz and others, 1998) and a decline in deposition of calcium from the atmosphere, a trend that has been underway

since the 1970's, may also have contributed to the decrease in the availability of soil calcium in the East (Johnson and others, 1994b).

Investigations of forest health have identified relations between low calcium availability and a reduction in stress tolerance of red spruce (Shortle and Smith, 1988; DeHayes, 1992; Schlegel and others, 1992), and sugar maple (Wilmot and others,

1995; Long and others, 1997). Related studies have also suggested that forest harvesting could reduce calcium availability through the removal of calcium stored in trees, which could lower the growth rates of the regenerating stand (Federer and others, 1989; Hornbeck and others, 1990). Relationships among acid deposition, calcium availability, and forest productivity remain uncertain, however.

Ongoing research by the U.S. Geological Survey, in collaboration with the U.S. Forest Service, the University of Illinois, the Institute of Ecosystem Studies and Syracuse University, has provided new information on the causes and magnitude of calcium depletion in soils of the eastern United States. Results of this research have been detailed in four articles prepared for scientific journals. A general summary of each of these articles and a description of current USGS calcium research follows.

1. DISCOVERY OF A NEW MECHANISM OF CALCIUM DEPLETION IN FOREST SOILS

Aluminum released to water in the mineral soil by acid rain decreases the availability of calcium in the overlying forest floor, the primary layer for nutrient uptake by roots in forest soils.

Lawrence, G.B., David, M.B., Shortle, W.C., 1995, A new mechanism for calcium loss in forest-floor soils: *Nature*, v. 378, p. 162-164.

Decreases in concentrations of exchangeable calcium are generally attributed to displacement by hydrogen ions, which can originate from either acid deposition or uptake of cations by roots (Johnson and others, 1994a, Richter and others, 1994). A regional survey of soils in northeastern red spruce forests in 1992-93 (fig. 2) has revealed that decreases in exchangeable calcium concentrations in the Oa horizon (a layer within the forest floor, where uptake of nutrients is greatest) can also result from increased concentrations of exchangeable aluminum, which originated in the underlying mineral soil (Lawrence and others, 1995). By lowering the pH of the aluminum-rich mineral soil, acid deposition can increase aluminum concentrations in soil water through dissolution and ion-exchange processes. Once in solution, the aluminum (although not a nutrient) is taken up by roots and transported through the trees to be eventually deposited on the forest floor in leaves and branches. Dissolved aluminum in the mineral soil can also be transported into the forest floor by a rising water table, or during unsaturated conditions,

by capillary movement. Because aluminum has a much higher affinity for negatively charged surfaces than calcium, introduction of aluminum into the forest floor tends to displace adsorbed calcium, which causes it to be more readily leached. A continued buildup of aluminum in the Oa horizon can (1) decrease the availability of calcium for roots (Lawrence and others, 1995), (2) lower the efficiency of calcium uptake because aluminum is more readily taken up than calcium when the ratio of calcium to aluminum in soil water is less than 1 (Cronan and Grigal, 1995), and (3) be toxic to roots at high concentrations (Anderson, 1988).

The Oa horizon has generally been considered immune from acidification by acid deposition because the typical pH of soil water in this horizon is less than 3.8 whereas the pH of rain in the East typically ranges between 4.0 and 4.5 (lower pH indicates greater acidity). The low pH of soil water in the Oa horizon is caused by organic acids that form naturally through the decomposition of plant matter. Organic acids that move downward in percolating water from the Oa horizon into mineral

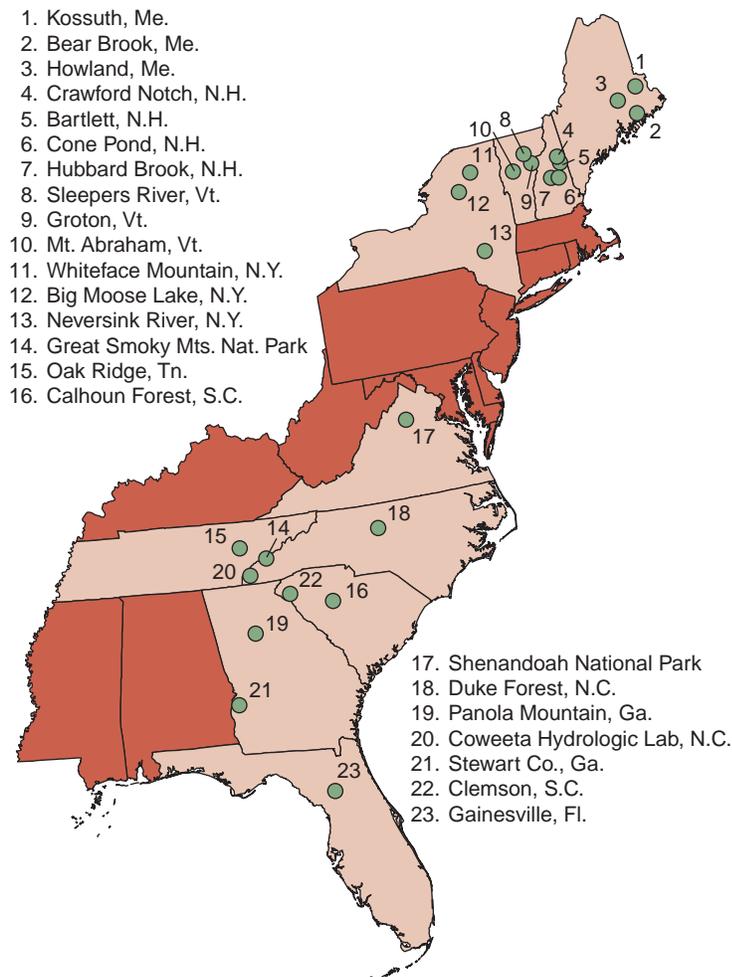


Figure 2. Locations at which soil-calcium assessments have been made in the papers by Lawrence and others, (1995,1997) and Huntington and others (USGS approved).

horizons, which contain little organic matter, tend to be removed from solution through further decomposition or by adsorption to mineral surfaces. Once removed from solution, they are incapable of acidifying the soil, which results in a higher pH in the mineral soil than in the forest floor. Unlike these natural organic acids, sulfuric and nitric acids from acid deposition neither decompose (because they are inorganic) nor adsorb to soil particles readily; rather, they tend to remain in solution within the mineral soil where they lower the pH, thereby releasing aluminum to soil water and causing the leaching of calcium.

The effects of these processes can be seen through a comparison of soils that have been acidified to varying degrees (table 1). The ratio of exchangeable aluminum to exchangeable calcium in the Oa horizon was lowest at Groton, Vt, where the pH of water in the mineral soil was highest, and the pH of soil water in the Oa horizon was lowest. At Big Moose Lake, N.Y. and Mt. Abraham, Vt. the pH of soil water in the B horizon was considerably lower than at the Groton site and the ratios of exchangeable aluminum to exchangeable calcium in the Oa horizons were greater than 1.0, the threshold above which aluminum can interfere with uptake of calcium by roots.

Table 1. pH and ratio of exchangeable aluminum to exchangeable calcium (Al:Ca) in soil water from forest floor (Oa horizon) and mineral soil (upper 10 centimeters of B horizon) in three red spruce stands of the northeastern United States.

Site location	Forest floor		Mineral soil	
	pH	Al:Ca*	pH	Al:Ca*
Groton, Vt.	3.3	0.3	4.8	5
Big Moose Lake, N.Y.	3.5	1.2	4.1	27
Mt. Abraham, Vt.	3.7	5.6	4.1	16

* ratio expressed as centimoles of charge per kilogram Aluminum per centimole of charge per kilogram Calcium

2. STATUS OF SOIL CALCIUM IN THE OA HORIZON OF RED SPRUCE STANDS OF THE NORTHEAST

A regional assessment of forest-soil chemistry supports evidence of soil-calcium depletion in the Northeast; acid rain identified as a probable factor.

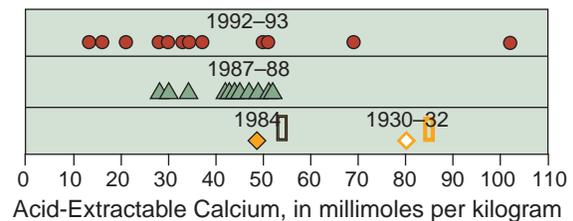
Lawrence, G.,B., David, M.B., Bailey, S.W., Shortle, W.C.,1997, Assessment of calcium status in soils of red spruce forests in the northeastern United States: *Biogeochemistry*, v. 38, p.19-39.

Decreases in available calcium in forest soils of the Northeast have been indicated in several studies in the 1990's (Shortle and Bondietti, 1992; Bailey and others, 1996; Johnson and others, 1994a;b), but the results of these studies could not be directly related to each other because the measurements of soil-calcium concentrations were made with different methods of unknown comparability. To address this problem, soil samples collected by Lawrence and others (1995) in the survey of red spruce forests (fig. 2) were analyzed by the four most common methods currently used for measuring exchangeable calcium (Lawrence and others, 1997). A comparison was also done between the most common current method for determining acid-extractable calcium and the method used by Heimburger (1934), and also by Johnson and others (1994a) in resampling the plots first sampled by Heimburger 50 years earlier (Lawrence and others, 1997). The soil survey of Lawrence and others (1995, 1997) in red spruce forests entailed the selection of 12 sites that together encompassed the range of environmental conditions represented by red spruce stands in the Northeast.

Considerable variability in exchangeable-calcium concentrations was observed among the 12 sites; concentrations ranged from 2.1 to 22.0 centimoles of charge per kilogram in the Oa horizon, and from 0.11 to 0.68 centimoles of charge per kilogram in the upper mineral soil. The primary cause of this variability was mineralogical differences in parent material (rock that weathers to form soil), but results also suggested that acidic deposition had decreased concentrations of exchangeable calcium in the mineral soil at these sites (Lawrence and others, 1997).

Results of the methods-comparison tests were used to relate the long-term decrease documented in the study by Johnson and others (1994a) to the range of calcium variability measured in the study by Lawrence and others (1997). The average value determined by Johnson and others (1994a) for 38 red

spruce stands in the Adirondack Mountains of New York, was near the middle of the range obtained by Lawrence and others (1997), and in the upper range of values obtained in a study by McNulty and others (1991). The average value obtained for Adirondack sites measured by Heimburger (1934) 50 years earlier was in the upper part of the range measured by Lawrence and others (1997). Although considerable variability was caused by local differences in environmental factors such as mineralogy of parent material, and acid deposition rates, the results support the probability indicated by the combined studies of Johnson and others (1994a;b), Shortle and Bondietti (1992), Lawrence and others (1995), and Bailey and others (1996), that concentrations of available calcium in northeastern red spruce forests have decreased in the second half of this century.



EXPLANATION

- Mean concentrations of calcium in soils of individual sites in New York, Vermont, New Hampshire and Maine sampled by Lawrence and others (1997) in 1992-93.
- ▲ Mean concentrations of calcium in soils of individual sites in New York, Vermont, New Hampshire and Maine sampled by McNulty and others (1991) in 1987-88.
- ◇ Mean concentrations of calcium in soil of 38 samples collected by Heimburger (1934) throughout the Adirondack Mountains of New York in 1930-32.
- ◇ Mean concentrations of calcium in soil of 59 samples collected by Johnson and others (1994a) throughout the Adirondack Mountains of New York in 1984.

Figure 3. Acid-extractable calcium in Oa horizons of red spruce stands in the studies of Lawrence and others (1997), McNulty and others (1991), Heimburger (1934), and Johnson and others (1994a).

3. DEPLETION OF SOIL CALCIUM AFFECTS THE RESPONSE OF STREAM CHEMISTRY TO DECLINING RATES OF ACID DEPOSITION IN THE NORTHEAST

Relations among acid deposition rates, base-cation concentrations in soils, and stream-water acidification indicate that changes in soil-calcium status can affect long-term trends in stream chemistry.

Lawrence, G.B., David, M.B., Lovett, G.M., and others, In Press, Soil-calcium status and the response of stream chemistry to changing acidic deposition rates in the Catskill Mountains of New York: Ecological Applications.

Rates of acid deposition have been declining in the Northeast since the 1970's, but many acidified surface waters in the region have unexpectedly shown little or no corresponding increase in acid-neutralizing capacity, an integrated measure of the degree to which a water body is acidified. Long-term records of stream chemistry at the Hubbard Brook Experimental Forest in New Hampshire (fig. 2) showed that the ratio of base cations (calcium, magnesium, sodium, and potassium) to acid anions (sulfate, nitrate and chloride) decreased steadily through the 1970's, then remained fairly stable through the 1980's and early 1990's (Likens and others, 1996). This response was interpreted as an indication that past declines in soil concentrations of calcium and other base cations were impeding recovery of acidified stream-water at this site.

Additional information on the relations between soil-calcium depletion and the status of acidified surface waters was obtained in a recent USGS study by Lawrence and others (in press) in the Neversink River Basin in the Catskill Mountains of New York (fig. 2). Results showed that rates of atmospheric deposition of sulfuric acid increased from the lowest elevations to the highest elevations of a subbasin, whereas the concentrations of exchangeable-base cations in natural soil decreased from lowest to highest elevations (fig. 4 a, b).

Relations between the elevational trends in atmospheric deposition rates and soil chemistry were further investigated through a procedure in which a large quantity of soil was collected at a low elevation in the basin, where exchangeable base-cation concentrations were somewhat higher than in the subbasin being studied. This soil was thoroughly mixed, placed in mesh bags, then buried in the soil in stands of mixed northern hardwoods at varying elevations within the subbasin. Analysis of the samples after 1 year, confirmed a distinct upslope decrease in exchangeable base cation concentrations

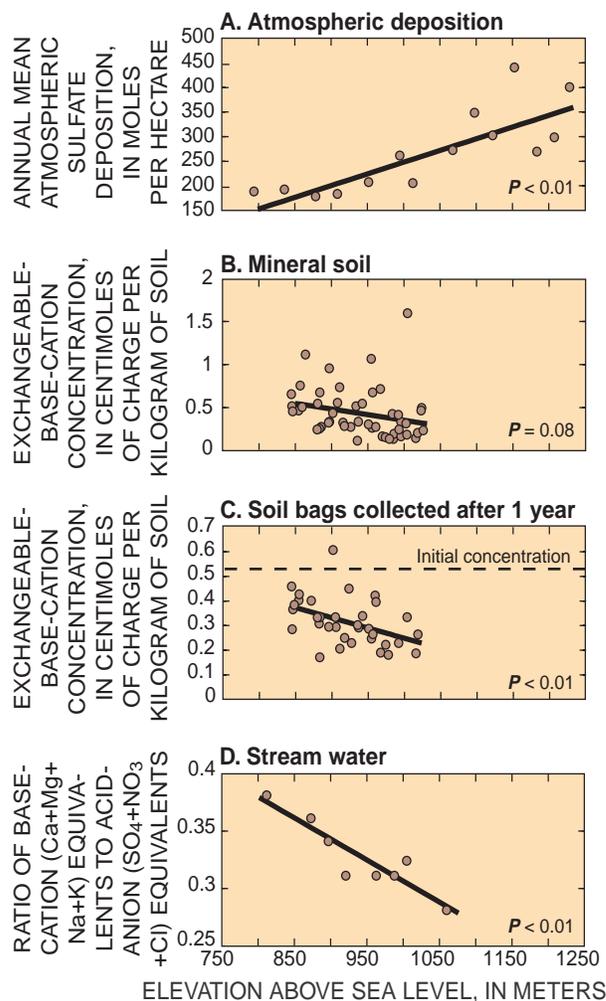


Figure 4. Elevational gradients for selected chemical constituents within a subbasin of the Neversink River, N.Y. A. Annual mean atmospheric sulfate deposition, June 1993 through May 1995. B. Exchangeable-base cation-concentrations in mineral soil samples collected in 1994. C. Exchangeable-base-cation concentrations in initially uniform mineral soil samples that were placed in mesh bags and leached within the mineral-soil profile from June 1994 through May 1995. D. Ratio of base-cation concentrations to acid-anion concentrations from the samples collected on dates when the highest 20% of stream flows occurred.

(fig. 4c), and in base saturation (the base-cation concentration as a percentage of total cation exchange capacity). Detailed analysis of other factors that could cause an elevational gradient in soil acidity and leaching of base cations indicated that the effects of these factors were either minimal or undetectable. These results led to the conclusion that the upslope increase in the rate of atmospheric deposition was the most probable cause of the upslope decrease in base-cation concentrations (and base saturation) in the soil.

The elevational trends in atmospheric deposition and soil chemistry were also reflected in an elevational trend in stream chemistry; the ratio of base cations to acid anions in stream water (an index of acidity) decreased with increasing elevation, which indicates an upslope increase in stream-water acidity (fig. 4d). A followup laboratory soil experiment demonstrated that this ratio in soil water was directly related to soil-base saturation. The upslope increase in atmospheric deposition can therefore be linked to the upslope increase in stream-water acidification through the elevational trend in soil-base saturation.

The effect of the upslope increase in atmospheric deposition on soil chemistry and stream chemistry may be analogous to the effect of past increases in acid deposition rates on temporal trends of soil and stream chemistry, and supports the explanation put forth by Likens and others (1996) that the observed minimal response of stream chemistry to declining acid deposition rates in New Hampshire was due to depletion of base cations in soil. Long-term trends in concentrations of calcium and acid-neutralizing capacity have both shown significant decreases (indicating increases in acidity) for 1984-97 in the Neversink Basin (fig. 5) despite a consistent decreasing trend in rates of atmospheric deposition during this period.

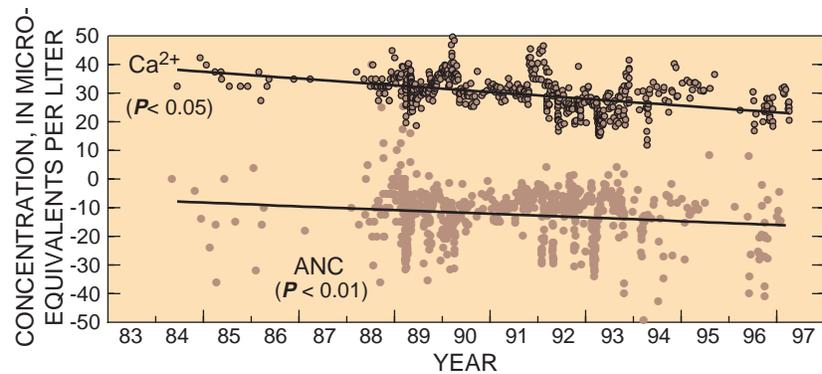


Figure 5. Calcium concentrations and acid-neutralizing capacity (ANC) of stream water in a subbasin of the Neversink Basin, 1984-1997.

4. CALCIUM DEPLETION IN FOREST ECOSYSTEMS OF THE SOUTHEAST

Data from detailed site studies and regional surveys suggest that soil-calcium depletion is common in forests of the Southeast and could diminish long-term forest productivity.

Huntington, T.G., Hooper, R.P., Johnson, C.E., Aulenbach, B.T., and Cappellato, A., in review, Calcium depletion in forest ecosystems of the southeastern United States: Submitted for publication as an article in a technical journal (USGS Approved).

Accumulating evidence indicates possible depletion of soil calcium in forests of the Southeast, as well as the Northeast. Long-term studies at several southeastern forest sites have documented declines in the exchangeable-calcium concentration of soils. In these studies, calcium

inputs from weathering and atmospheric deposition were found to be insufficient to replenish the losses that occur through uptake by vegetation and leaching (Johnson and others, 1988; Johnson and others, 1991; Knoepp and Swank, 1994; Richter and others, 1994).

Several factors suggest that the available calcium in southeastern soils is prone to depletion. These soils have weathered in place for a few hundred thousand to 2 million years and many of them have little weatherable calcium left in soil particles and rocks. Also, poor farming practices caused extensive loss of soil and nutrients on lands that are now used for commercial forestry (Nelson, 1957; Brender, 1974; Trimble, 1974). Forest growth places a continued demand on the remaining calcium in these soils, and when the stands are harvested, the calcium in the trees is removed from the ecosystem. Acidic deposition during the 20th century has placed further strain on soil calcium availability by enhancing calcium leaching rates at a time when the rates of atmospheric deposition of calcium have declined (Lynch and others, 1996).

The potential for calcium depletion in southern forest soils, was evaluated in detail through the development of a calcium budget for Panola Mountain watershed, in the Piedmont region near Atlanta, Ga. (Huntington and others, USGS approved); this budget was then compared with data from other watershed studies and soil surveys to assess the extent of calcium depletion within the Southeast. Calcium-budget calculations for Panola Mountain watershed (averaged over the roughly 90 year life of the current forest stand), indicate that the rate of calcium leaching from the soil approximates the rate of calcium input from atmospheric deposition. Also, chemical and mineralogical analyses of soil and saprolite (the highly weathered layer of residual rock beneath the soil) indicated that only trace amounts of weatherable mineral calcium remain, which suggests that inputs from weathering are negligible. The annual rate of calcium depletion in this watershed is, therefore, similar to the annual rate of uptake by trees of 10.7 kilograms per hectare. Continuous depletion at this rate for 150 years would reduce the total reserves of calcium in the soil to the approximate amount required by a hardwood stand to reach a marketable size.

Budget calculations for other forested study sites in the Southeast showed a wide variation in sensitivity to soil-calcium depletion (table 2). The most sensitive forests are dominated by hardwood species, which have a higher calcium demand than softwoods; at some sites more calcium is contained by the trees than by the soil. Stands that are the least sensitive tend to be dominated by softwood and are in areas that receive the highest amounts of calcium from atmospheric deposition. The rate of calcium depletion estimated for Panola Mountain

watershed was in the middle of the range of values reported for other forested sites in the Southeast.

Lower availability of calcium in soils of the Southeast than the Northeast is suggested by surveys of exchangeable-calcium concentrations in soils. About 70 percent of the sites sampled in the Southern Blue Ridge region through the U.S. EPA Direct-Delayed Response Program (Church and others, 1989) had concentrations of exchangeable calcium less than 1000 kilograms per hectare, whereas in the Northeast, about 50 percent of the

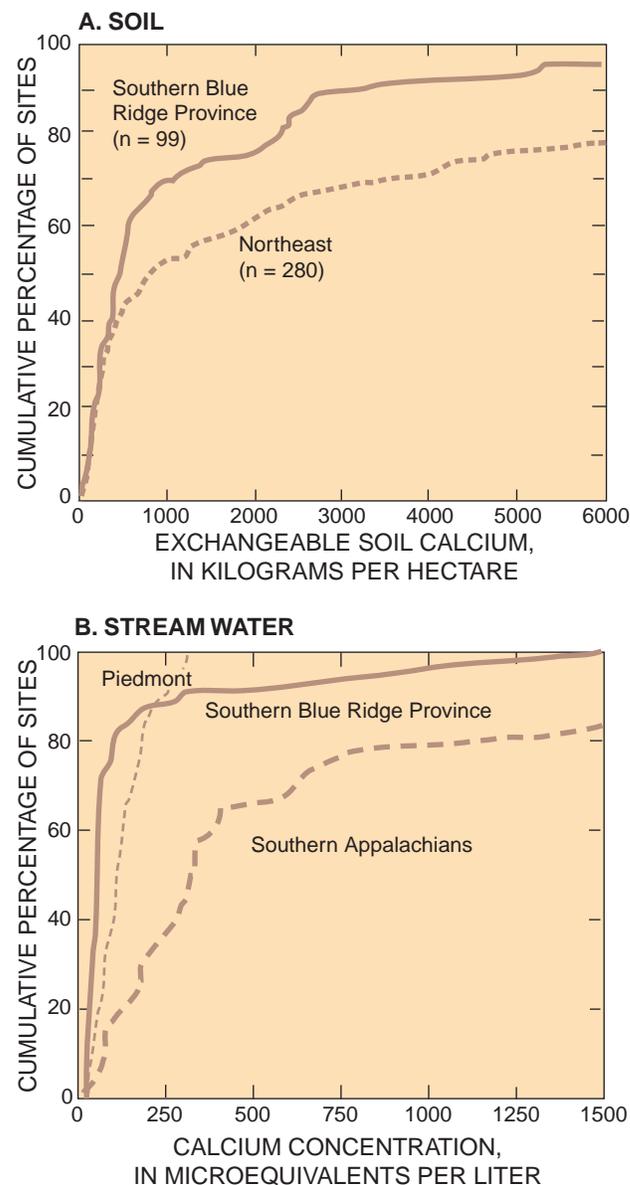


Figure 6. Cumulative percentage of sites as a function of (A) exchangeable calcium concentrations in soil and (B) calcium concentrations in stream water in selected regions of the eastern United States. Figure A adapted from Turner and others (1993); Figure B adapted from Sale and others (1988).

sites sampled had calcium concentrations less than 1000 kilograms per hectare (fig. 6a). Calcium concentrations in southeastern streams also tended to be distributed toward low values, as indicated by the steeply ascending lines in fig. 6b.

The assessments of the calcium budgets at Panola Mountain watershed and other forested sites in the

Southeast, in conjunction with the surveys of soil and stream chemistry, suggest that (1) depletion of calcium in soils is common, (2) the growth of some forests may be limited by insufficient amounts of calcium in soils, and (3) calcium availability will be lowered by forest harvesting of sites currently low in calcium.

Table 2. Calcium (Ca) contents of soil, calcium fluxes, net calcium depletion, and sensitivity to calcium depletion at selected forest sites in the eastern United States.

[kg/ha, kilograms per hectare; (kg/ha)/yr, kilograms per hectare per year; ND, no data]

Site location	Type of forest	Calcium content of soil (kg/ha)		Calcium flux [(kg/ha)/yr]			Net Calcium depletion	Ecosystem sensitivity to Calcium depletion ^a	Source of data ^b
		Exchange-able	Total	Net uptake by trees	Total deposition	Leaching from soil			
A. Sites that are highly sensitive to calcium depletion									
Great Smoky Mountains Nat. Park	Beech	57	2,500	15.9	7.5	6.3	14.7	high ^c	1
Oak Ridge, Tenn.	Oak	140	1,800	8	5.4	1	3.6	high ^c	2
Oak Ridge, Tenn.	Oak	110	1,180	17	5.4	12	23.6	high ^c	2
Calhoun Forest, S.C.	Pine	245	ND	7.5	2.8	10.2	14.9	high ^c	3
Shenandoah Nat. Park, Va.	Mixed pine, hardwood	380	ND	10 ^d	3.9	2.7	8.8	high ^c	4
Oak Ridge, Tenn.	Pine	820	2,500	16	5.4	15	25.6	high ^c	2
Coweeta Hydrologic Laboratory, N.C.	Mixed hardwood	1,370	11,500	12.2	7.1	1.5	6.6	high	97
B. Sites that are moderately sensitive to calcium depletion									
Stewart Co., Ga.	Pine	840	840	6	3.2	1.1	3.9	med.	123
Duke Forest, N.C.	Pine	2,130	4,900	13.6	8.1	8.1	13.6	med.	130
Panola Mountain, Ga.	Mixed pine, hard wood	2,200	2,200	10	2.25	2.9	10.7	med.	150
C. Sites that are insensitive to calcium depletion									
Clemson, S.C.	Pine	1,450	ND	3.4	2.9	3.9	4.4	low	310
Oak Ridge, Tenn., plot 1	Pine	6,900	8,600	5.5	5.4	19.2	19.3	low	350
Gainesville, Fla.	Pine	240	758	5.9	8	2.1	0	low ^e	1
Coweeta Hydrologic Laboratory, N.C.	Pine	667	3,770	3.9	7.1	2.2	-1	low ^e	1
Great Smoky Mountains Nat. Park	Spruce	230	1,800	1.2	19	10	-7.8	low ^e	1

^a Value indicates number of years until current rates of depletion reduce exchangeable stores to twice the expected requirement for a marketable forest stand

^b References:

1. Johnson and Lindberg, 1992; 2. Johnson and Todd, 1990; 3. Richter and others, 1994.
4. Written commun. from J.R. Webb (University of Virginia), June 1995.
5. Huntington and others (USGS approved); 6. Huntington, 1996b; 7. Johnson and others, 1988.

^c Soils already depleted to less than twice the calcium requirement for marketable timber

^d Estimated from typical forest growth rates in this area, on basis of USDA Forest Service—Forest Inventory Analysis data and calcium concentration for oak (*Quercus* spp.)

^e Either soils are accumulating calcium, or output equals input

UNANSWERED QUESTIONS

Much information has been obtained in the 1990's on the calcium status of forest soils in the East, but additional work is needed to define the current trends in soil calcium availability and to determine if these trends will continue into the future. Some specific questions that need to be addressed are:

1. Is the available calcium content of soils currently increasing, decreasing, or remaining stable?
2. How do rates of soil-calcium weathering and leaching vary throughout the East?
3. How is forest growth affected by low levels of available calcium?
4. How does forest harvesting affect the availability of soil calcium and long-term trends in stream chemistry?

ONGOING USGS RESEARCH

Unanswered questions regarding the current and future status of calcium in the East are being addressed through the USGS Hydrologic Benchmark Network (HBN) and the National Trends Network (NTN). The HBN sponsors monitoring of stream flow and chemistry, in undeveloped, medium-sized basins (100 to 200 km² drainage areas). The NTN, which is closely affiliated with the National Atmospheric Deposition Program (NADP), supports the monitoring of chemical deposition in rain and snow (wet-only deposition) at about 100 locations nationwide. The HBN and NTN programs are currently supporting investigations in three HBN watersheds in the Northeast (the Wild River, in New Hampshire and Maine, the Neversink River, in N.Y.,

and Young Womens Creek, in Pennsylvania.) and two in the Southeast (Little River, in Tennessee, and Cataloochee Creek, in North Carolina). These investigations will (1) measure atmospheric deposition rates, stream chemistry, and soil chemistry, (2) determine soil-weathering rates, forest-growth history and past harvesting in these watersheds, and (3) assess the effects of future tree harvesting. A primary objective of this work is to gather detailed information on calcium cycling that can be used to assess current conditions for each of the five basins. This information will be integrated with the long-term monitoring data to better understand past and future changes in soil-calcium status in the eastern United States.

REFERENCES CITED

- Anderson, M., 1988, Toxicity and tolerance of aluminum in vascular plants: *Water, Air and Soil Pollution*, v. 39, p. 439-462.
- Bailey, S.W., Hornbeck, J.W., Driscoll, C.T., and Gaudette, H.E., 1996, Calcium inputs and transport in a base-poor forest ecosystem as interpreted by Sr isotopes: *Water Resources Research*, v. 32, p. 707-719.
- Brender, E.V., 1974, Impact of past land use on the lower Piedmont forest: *Journal of Forestry*, v. 72, p. 34-36.
- Church, M.R., Thornton, K.W., Shaffer, and others, 1989, Direct/delayed response project: future effects of long-term sulfur deposition on surface water chemistry in the Northeast and southern Blue Ridge Province, level I and level II analysis: National Acid Precipitation Program, Washington, D.C., EPA/600/3-89/061b.
- Cronan, C.S., and Grigal, D.F., 1995, Use of calcium/aluminum ratios as indicators of stress in forest ecosystems: *Journal of Environmental Quality*, v. 24, p. 209-226.

- Cowling, E.B., and Dochinger, L.S., 1980, Effects of acidic precipitation on health and productivity of forests: USDA Forest Service Technical Report, PSW-43, 165-173.
- DeHayes, D.H., 1992, Winter injury and developmental cold tolerance of red spruce: in Eager, C. and Adams, M.B., (eds.), Ecology and decline of red spruce in the eastern United States, New York, Springer-Verlag, p. 295-337.
- Federer, C.A., Hornbeck, J.W., Tritton, and others, 1989, Long-term depletion of calcium and other nutrients in eastern U.S. forests: Environmental Management, v. 13, p. 593-601.
- Heimbürger, C.C., 1934, Forest-type studies in the Adirondack Region: Ithaca, N.Y., Cornell University Agriculture Experiment Station Memoir 165.
- Hornbeck, J.W., Smith, C.T., Martin, and others, 1990, Effects of intensive harvesting on nutrient capitals of three forest types in New England: Forest Ecology and Management, v. 30, p. 55-64.
- Huntington, T.G., 1996, Assessment of the potential role of atmospheric deposition in the pattern of southern pine beetle infestation in the northwest Coastal Plain Province of Georgia, 1992-95: U.S. Geological Survey Water-Resources Investigations Report 96-4131, 75 p.
- Johnson, A.H., Anderson, S.B., and Siccama, T.G., 1994a, Acid rain and soils of the Adirondacks. I. Changes in pH and available calcium: Canadian Journal of Forest Research, v. 24 p. 193-198.
- Johnson, A.H., Friedland, A.J., Miller, E.K., and Siccama, T.G., 1994b, Acid rain and soils of the Adirondacks. III. Rates of soil acidification in a montane spruce-fir forest at Whiteface Mountain, New York: Canadian Journal of Forest Research, v. 24, p. 663-669.
- Johnson, D.W., Cresser, M.S., Nilsson, S.I., and others, 1991, Soil changes in forest ecosystems: evidence for and probable causes: Proceedings of the Royal Society of Edinburgh, v. 97B, p. 81-116.
- Johnson, D.W., Henderson, G., and Todd, D., 1988, Changes in nutrient distribution in forests and soils of Walker Branch Watershed, Tennessee, over an eleven year period: Biogeochemistry, v. 5, p. 275-293.
- Johnson, D.W., and Lindberg, S.E., 1992, Atmospheric deposition and forest nutrient cycling, New York, Springer-Verlag.
- Johnson, D.W., and Todd, D.E., 1990, Nutrient cycling in forests of Walker Branch watershed, Tennessee—roles of uptake and leaching in causing soil changes: Journal of Environmental Quality, v. 19, p. 97-104.
- Johnson, D.W., Turner, J., and Kelly, J.M., 1982, The effects of acid rain on forest nutrient status: Water Resources Research, v. 18, p. 449-461.
- Knoepp, J.D., and Swank, W.T., 1994, Long-term soil chemistry changes in aggrading forest ecosystems: Soil Science Society of America, v. 58, p. 325-331.
- Lawrence, G.B., David, M.B., Bailey, S.W., and Shortle, W.C., 1997, Assessment of calcium status in soils of red spruce forests in the northeastern United States: Biogeochemistry, v. 38, p. 19-39.
- Lawrence, G.B., David, M.B., Lovett, G.M., and others, in press, Soil-calcium status and the response of stream chemistry to changing acidic deposition rates in the Catskill Mountains of New York: Ecological Applications.
- Lawrence, G.B., David, M.B., and Shortle, W.C., 1995, A new mechanism for calcium loss in forest-floor soils: Nature, v. 378, p. 162-164.
- Likens, G.E., Driscoll C.T., and Buso, D.C., 1996, Long-term effects of acid rain: response and recovery of a forest ecosystem: Science, v. 272, p. 244-246.
- Long, R.P., Horsley, S.B., and Lilja, P.R., 1997, Impact of forest liming on growth and crown vigor of sugar maple and associated hardwoods: Canadian Journal of Forest Research, v. 27, p. 1560-1573.
- Lynch, J.A., Bowersox, V.C., and Grimm, J.W., 1996, Trends in precipitation chemistry in the United States: 1983-1994, and analysis of the effects in 1995 of Phase I of the Clean Air Act Amendments of 1990, Title IV: U.S. Geological Survey Open File Report 96-0346.
- Markewitz, D., Richter, D.D., Allen, H.L. and Urrego, J.B., 1998, Three decades of observed soil acidification in the Calhoun Experimental Forest: Has acid rain made a difference?: Soil Science Society of America Journal, v. 62, p. 1428-1439.
- McNulty, S.G., Aber, J.D. and Boone, R.D., 1991, Spatial changes in forest floor and foliar chemistry of spruce-fir forests across New England: Biogeochemistry, v. 14, p. 13-29.
- NAPAP (National Atmospheric Precipitation Assessment Program), 1993: 1992 Report to Congress. Washington, D.C.
- Nelson, T.C., 1957, The original forests of the Georgia Piedmont: Ecology, v. 38 p.390-397.

- Richter, D.D., Markewitz, D., Wells, and others, 1994, Soil chemical change in an old-field loblolly pine ecosystem: *Ecology*, v. 75, p. 1463-1473.
- Sale, M.J., Kaufmann, P.R., Jager, H.I., and others, 1988, Chemical characteristics of streams in the mid-Atlantic and southeastern United States volume 2 (Streams sampled, descriptive statistics and compendium of physical and chemical data): Washington, D.C., U.S. Environmental Protection Agency, EPA/600/3-88/021b, 595 p.
- Schlegel, H., Amundson, R.G., and Hueterman, A., 1992, Element distribution in red spruce (*Picea rubens*) fine roots; evidence for aluminum toxicity at Whiteface Mountain: *Canadian Journal of Forest Research*: v. 22, p. 1132-1138.
- Shortle, W.C., and Bondietti, E.A., 1992, Timing, magnitude, and impact of acidic deposition on sensitive forest sites: *Water, Air and Soil Pollution*, v. 61, p. 253-267.
- Shortle, W.C., and Smith, K.T., 1988, Aluminum-induced calcium deficiency syndrome in declining red spruce trees: *Science*, v. 240, p. 1017-1018.
- Trimble, S.W., 1974, Man-induced soil erosion in the southern Piedmont: Ankeny, Iowa, Soil Conservation Society of America.
- Turner, R.S., Brandt, C.C., Schmoyer, D.D., and others, 1993, Direct/Delayed Response Project Data Base: Oak Ridge National Laboratory, Environmental Sciences Division, ESD Publication No. 2871, 107 p.
- Wilmot, T.R., Ellsworth, D.S., and Tyree, M.T., 1995, Relationships among crown condition, growth, and stand nutrition in seven northern Vermont sugarbushes: *Canadian Journal of Forest Research*, v. 25, p. 386-397.

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