WATER RESOURCES BULLETIN
VOL. 20, NO. 3 AMERICAN WATER RESOURCES ASSOCIATION JUNE 1984

ATMOSPHERIC CONTRIBUTIONS TO FOREST NUTRIENT CYCLING[1]

Wayne T. Swank[2]

ABSTRACT: The atmosphere is a significant source of plant nutrients that partially replenishes losses due to timber harvesting. The relative importance of wet and dry deposition depends upon the specific nutrient and site. Nitrogen in bulk precipitation (wetfall and dryfall) is equivalent to at least 70 percent of the nitrogen incorporated annually in above-ground woody tissues of some temperate hardwood forests. Atmospheric sources of calcium and potassium supply between 20 and 40 percent of the nutrients sequestered in woody increments. Annual nutrient inputs in bulk precipitation can exceed removals associated with sawlog harvest over a rotation period. Atmospheric inputs of nitrogen are only slightly less than hydrologic losses immediately after timber harvesting. The deposition of nutrients is highly variable in both time and space; interpretations of nutrient inputs and forest management impacts require quantification of inputs for a variety of ecosystems over long periods of time.

(KEY TERMS: forest nutrient cycling; precipitation chemistry; temperate forests; forest management impacts.)

INTRODUCTION

Although the atmosphere has long been recognized as a source of chemicals (Tamm, 1958), only recently have biologists stressed its place in the biogeochemical cycles of plant communities (Bormann and Likens, 1967; Johnson and Swank, 1973). Previous research focused on the litter and soil as the primary sources of elements essential to plant growth. But with the emergence and development of forest ecosystem studies over the past 15 years, the magnitude and role of atmospheric chemical constituents in nutrient replenishment have received increased emphasis (Likens, *et al.*, 1977b; Swank and Henderson, 1976).

Chemicals from the atmosphere can stimulate, inhibit, or have minimal effect on forest productivity. The objective of this paper is to place atmospheric inputs, as a source of plant nutrients, into perspective when considering the impacts of harvesting on forest nutrient cycling. Analyses of the impact on productivity of increased woody biomass utilization are of current concern (Van Hook, *et al.*, 1982). I will describe the atmospheric processes basic to nutrient deposition, characterize the importance of various atmospheric additions to forest ecosystems, identify the temporal and spatial variability of inputs, and conclude with some suggestions for needed research. Published information for a variety of temperate forest ecosystems and data from the Coweeta Hydrologic Laboratory in North Carolina will be used to illustrate principles and major points.

ATMOSPHERIC PROCESSES

The composition of the atmosphere at any place and time is a net result of rates of emission, mixing and transport, chemical conversions, and removal (Hales and Dana, 1979). Natural and anthropogenic emissions and transport have received considerable investigation (Eriksson, 1952; Hidy, 1973; Bolin, *et al.*, 1974; Scriven and Fisher, 1975; Benarie, 1976). Individual cases of regional and continental transport of pollutants have been documented; one of the best known is acid precipitation in Scandinavia, which results from emissions transported up to several thousand kilometers (Nordø, 1976; Ottar, 1976). Excess calcium in rainwater in Japan has been shown to originate from calcite contained in soil dust transported by wind from North China (Ichikuni, 1978). Emissions from the New York metropolitan area have increased ozone concentrations in Connecticut by about 20 percent to the highest concentrations in the Northeast (Cleveland and Graedel, 1979). Sea salt aerosols are a major source of Na and Cl in western North Carolina, even though this mountain region is located more than 450 km from the ocean (Swank and Henderson, 1976).

Thus, forested areas that appear isolated from emission sources and have low baseline values can occasionally receive high inputs of some elements. For example, orthophosphate inputs at Coweeta Hydrologic Laboratory in North Carolina are typically low and relatively uniform throughout the year (Figure 1). However, during the second week of April 1977, a dust storm originating in Texas visibly blanketed much of the southern Appalachian Mountain region. During the next three weeks, with only 13 cm of rainfall, PO_4 input at Coweeta was 30 percent of the amount normally received for the entire year; dryfall accounted for 90 percent of the input. The concentration of other ions was also substantially elevated, and

---

[1] Paper No. 84039 of the *Water Resources Bulletin*.

[2] Plant Ecologist, USDA Forest Service, Southeastern Forest Experiment Station, Coweeta Hydrologic Laboratory, 999 Coweeta Lab Road, Otto, North Carolina 28763.

quantities of NO_3, NH_4, and SO_4 deposited during the event were between 15 and 20 percent of the annual values. Concentrations of metals, organics, and acids in precipitation are increasing along with combustion of fossil fuels and industrial activities (Galloway, *et al.,* 1978); both episodic events and chronic trends of transport and deposition originating from man's activities can be expected in seemingly isolated locations. Models are being developed to account for atmospheric motions on a regional scale. However, as Fox (1977) pointed out, data for tuning and validating models are lacking.

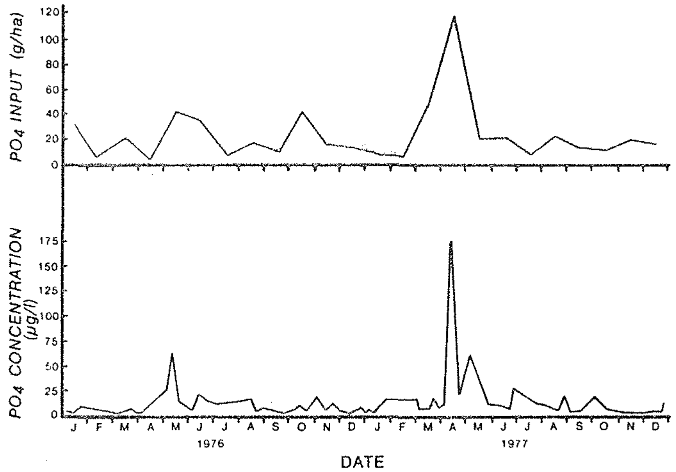

Figure 1. Concentration and Input of Orthophosphate in Bulk Precipitation at Coweeta Hydrologic Laboratory, North Carolina. Atypical deposition is apparent in April 1977 due to dust originating from the Southwestern United States.

Atmospheric deposition occurs through wet and dry processes (Figure 2) which entail complex physical, chemical, and aerodynamic interactions. The wet process, called precipitation scavenging, is a primary mechanism for removing particulates, aerosols, and some gases from the atmosphere. It has two components: rainout, the incorporation of the constituent into cloud droplets within the cloud; and washout, the removal by falling precipitation below the cloud (Rodhe and Grandell, 1972). The efficiency of these processes has been discussed in detail by many investigators, and several symposia have been devoted to precipitation scavenging (U.S. Atomic Energy Commission, 1970; U.S. Energy Research and Development Administration, 1977). Junge (1963) divided rainout into three processes: condensation, attachment, and transfer. He concluded that condensation is most efficient for particles between 0.1-1.0 μm, while for aerosol particles smaller than 0.1 μm, attachment by Brownian motion and transfer by the water vapor gradient are the dominant mechanisms. Impaction scavenging, or washout, is important in removing particles greater than 1 μm, but it is considered to be less effective than rainout under most circumstances. In summarizing field measurements of wet scavenging coefficients, McMahon and Dennison (1979) illustrated the importance of particle size in determining coefficients.

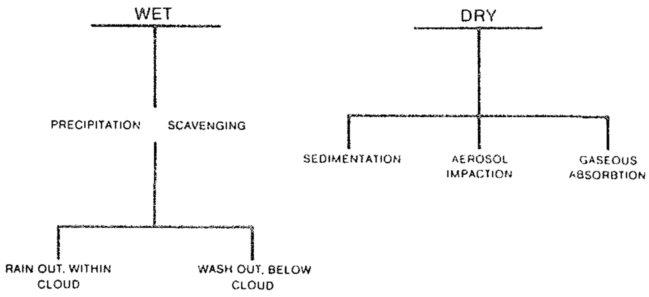

Figure 2. Outline of the Major Atmospheric Deposition Processes.

Dry deposition is also complex and can be separated into three processes: sedimentation, aerosol impaction, and gaseous absorption. A primary distinction between sedimentation and aerosol impaction processes is particle size. McMahon and Dennison (1979) have shown the relationship between deposition velocity and particle size based on laboratory and field measurements, and conclude that the minimum deposition velocity occurs in the 0.1 to 1 μm particle diameter range. They also concluded that deposition velocity is approximately a linear function of wind speed and friction velocity, but cautioned against selecting a "typical" deposition velocity, since it can vary by two orders of magnitude. Forested surfaces furthur complicate the measurements of dry deposition on the landscape, since small particles and gases are transported by turbulence and impacted (i.e., deposited) on a three-dimensional surface containing a variety of configurations and properties. Lindberg and Harriss (1981) summarized the literature dealing with experimental measurements of dry deposition in forests and the relative importance of sedimentation and impaction in deciduous forests. Foliar absorption of atmospheric gases, such as CO_2, SO_2, NH_3, and NO_x, is another major mechanism of elemental addition to forests and will be discussed in a later section of the paper.

Methods and devices for sampling the input of elements from the atmosphere have been discussed in detail by Galloway and Likens (1976, 1978). Bulk samplers which combine precipitation and dry fallout in the same container are most common in forest ecosystem studies. The next most commonly used device is an automated collector which samples dry fallout (primarily sedimentation) separately from precipitation. Vast improvement is needed in methods for measuring aerosol impaction on forest canopies, and little quantitative data exist for this component.

An indication of the relative importance of wet and dry sources of nutrients at two forested sites (Coweeta Hydrologic Laboratory and Walker Branch in eastern Tennessee) is shown in Table 1. Dryfall data represent input primarily from sedimentation and perhaps some aerosols; therefore, total dryfall contributions are underestimated. These data illustrate that wet and dryfall processes are indeed nutrient and site specific. The dryfall component of total input ranges from about 7 percent for NO_3-N at Coweeta to nearly 90 percent for PO_4-P at Walker Branch. Moreover, dryfall only accounts for about 10 percent of the annual PO_4-P input at Coweeta. For K, wetfall comprises about 70 percent of the deposition at Coweeta and only 36 percent at Walker Branch. Although these site differences are partly due to methods of sample collection and analysis, the primary cause is the nature and source of atmospheric constituents associated with land use activities (Swank and Henderson, 1976). Fly ash from local and regional coal fired power plants is a major influence at Walker Branch and results in large dryfall contributions, whereas the main local source of particulates at Coweeta is from agricultural activities such as plowing.

TABLE 1. Mean Annual Wetfall and Dryfall Inputs of Selected Nutrients at Two Sites in the Eastern United States (after Swank and Henderson, 1976).*

	Coweeta		Walker Branch	
Element	Wetfall (kg/ha/year)	Dryfall (kg/ha/year)	Wetfall (kg/ha/year)	Dryfall (kg/ha/year)
Ca	3.92	0.96	9.91	5.82
K	1.11	0.51	1.09	1.90
NO_3-N	2.67	0.21	N/A**	N/A**
NH_4-N	0.41	0.11	N/A**	N/A**
PO_4-P	0.17	0.02	0.06	0.49

*Values for Ca and K based on three years for both sites and values for NO_3-N, NH_4-N, and PO_4-P based on one year, except Walker Branch where PO_4-P data are for three years.

**N/A = not available.

Lindberg and Harriss (1981) studied atmospheric deposition of several trace metals and SO_4 in a deciduous forest on the Walker Branch watershed. Emphasis was on quantifying dry deposition, including aerosol impaction in the forest canopy. Table 2 shows the partitioning of inputs by deposition process for Mn, Pb, Zn, and SO_4-S. Annual dryfall input of Mn is about eightfold greater than wet deposition. For other elements, dry input accounts for 18 to 52 percent of the annual total input. At least 75 percent of the dryfall input occurred when hardwoods were in leaf, which clearly shows the importance of aerosol impaction on foliage.

It is apparent that complex atmospheric processes are involved in the deposition of materials to forest ecosystems, and the relative importance of any one process depends on many variables. Although it is difficult to make generalizations, it appears that dry fallout, and particularly aerosol impaction, is quite important in chemical loading of forest ecosystems and should be considered when evaluating forest nutrient cycling and the effects of management activities.

TABLE 2. The Annual Input of Selected Trace Elements and SO_4-S by Deposition Process to a Deciduous Forest on Walker Branch Watershed (after Lindberg and Harriss, 1981).

Process	Elemental Input (g/ha/year)			
	Mn	Pb	Zn	SO_4-S
Total Wet Deposition	40	73	76	13.0
Total Dry Deposition	310	80	17	6.3
Deposited to Leafy Canopy	240	62	13	4.8
Deposited to Branches (Leafless Period)	31	8	2	0.6
Deposited to Forest Floor (Leafless Period)	39	10	2	0.9

ATMOSPHERIC INPUTS AND RELATIONSHIPS TO MANAGEMENT PRACTICES

Examples of the magnitude of annual nutrient inputs measured in bulk precipitation for heavily forested regions of the United States indicate the large variation to be expected (Table 3). Total N inputs vary from about 1 to 2 kg/ha/year for some of the western ecosystems to 13 kg/ha/year for sites more strongly influences by industrial activities. At locations where organic N has been measured, this form accounts for a significant fraction of the total input. In fact, it is the major form of input at H. J. Andrews Experimental Forest. Phosphorus loading is much smaller and less variable, ranging from a trace to about 0.5 kg/ha/year. Inputs of Ca vary from 2 to 12 kg/ha/year, while K inputs are much lower, with a range of 0.1 to 3.0 kg/ha/year. As with N, the lower inputs of these nutrients are found at the two western locations.

It is useful to compare atmospheric inputs with annual incorporation of some nutrients into woody tissue of hardwood forests (Table 3). At both Walker Branch and Coweeta, N input in bulk precipitation is approximately 70 percent of the quantity annually incorporated in above-ground woody tissue. Atmospheric sources of Ca and K at Walker Branch represent nearly 40 percent of the nutrients contained in woody increments while at Coweeta, values are about 20 percent. Studies in a tropical rain forest have shown even stronger dependence of forest maintenance on nutrients derived from the atmosphere (Jordan, 1982).

Published estimates of atmospheric input are generally conservative because impacted aerosol particles in the forest canopy are excluded. Chemical analysis of throughfall and stemflow show enrichment for most nutrients as water passes through the canopy (Table 4). Quantities of N and Ca delivered to the forest floor are increased between 20 to 100 percent in most of the ecosystems. Enrichment of K and P is usually much larger and more variable. Other investigators have observed similar chemical changes in throughfall compared with precipitation (Rolfe, *et al.*, 1978; Patterson, 1975; Carlisle, *et al.*, 1966). Although some of these chemical fluxes can be attributed to impaction, leaching from plant tissue and

TABLE 3. Comparison of Selected Nutrient Inputs in Bulk Precipitation for Forest Ecosystems in Different Regions of the United States and Annual Woody Increments, Denoted by ( ), for Two Aggrading Eastern Hardwood Forests.

	Nutrient Inputs (kg/ha/year)					
Location	Inorganic N	Organic N	Total N	K	Ca	P
Walker Branch, Eastern Tennessee[1]	9.3	3.7	13.0 (15.0)	3.0 (8.0)	12.0 (31.0)	0.55
Coweeta, Mountains of North Carolina[2]	4.5	4.3	8.8 (13.0)	2.1 (13.0)	4.8 (23.0)	0.11
Hubbard Brook, New Hampshire[3]	6.5			0.9	2.2	0.04
Duke Forest, Piedmont of North Carolina[4]			5.4	1.6	2.8	0.21
H. J. Andrews, Western Cascade Mountains, Oregon[5]	0.7	1.5	2.2	0.1	2.3	0.27
Thompson Research Center, Western Cascade Mountains, Washington[6]			1.1	0.8	2.8	Trace

[1] Henderson and Harris, 1975; Henderson, *et al.*, 1978.
[2] Swank and Waide, 1980.
[3] Likens, *et al.*, 1977a.
[4] Wells and Jorgensen, 1975.
[5] Grier, *et al.*, 1974; Fredriksen, 1975.
[6] Grier, *et al.*, 1974.

microflora also contribute to the enrichment observed in throughfall. Such additions are part of the nutrient recycling process, and should not be considered as an atmospheric input, but few studies have separated impaction quantitatively from leaching contributions.

TABLE 4. Ratios of Throughfall to Bulk Precipitation Inputs Based on Annual Values of Selected Nutrients.

	Throughfall/Precipitation Ratio (based on kg/ha/year)			
Location[1]	N	K	Ca	P
Walker Branch	1.2	7	2.2	N/A
Coweeta	1.4	6[2]	1.9[2]	6.1
Hubbard Brook	1.4	33	3.1	17.5
Duke Forest	1.7	7	1.6	2.2
H. J. Andrews[3]	1.7	15	2.0	4.0
Thompson Research Center	1.5	15	1.6	40.0[4]

[1] Sources of data for each location are the same as cited in bulk precipitation input (Table 3) except as noted.
[2] Best and Monk, 1975.
[3] Sollins, *et al.*, 1980.
[4] Precipitation input of 0.01 kg/ha/year was assumed.

In addition to dissolved and particulate forms, some elements, such as N, enter and leave the ecosystem in gaseous form. Research at Coweeta and H. J. Andrews indicates that N fixation in undisturbed forests substantially exceeds other atmospheric sources (Table 5). The 7.6 kg/ha/year value shown for H. J. Andrews is more than three times the input measured in bulk precipitation.

TABLE 5. Estimated Rates of Nitrogen Fixation for an Oak-Hickory Forest at Coweeta, and for Several Compartments of an Old-Growth Conifer Forest at H. J. Andrews (after Swank and Waide, 1980).

Ecosystem Compartment	Coweeta (kg/ha/year)	H. J. Andrews (kg/ha/year)
Phyllosphere	0.22	5.0
Bole	1.00	
Woody Litter	1.66	2.6
Leaf Litter	0.63	
Soil	8.55	
TOTAL	12.04	

The wide ranges of nutrient inputs to forests take on additional meaning if they are related to specific management practices. A comparison of bulk precipitation inputs with nutrient removals for two forest types, each with two levels of fiber utilization, is shown in Table 6. Over the 90-year rotation of the mixed hardwood stand, atmospheric inputs of K and N appear adequate to replenish nutrients removed in both sawlog and complete-tree (all above-ground woody material) harvests. Inputs of Ca are less than Ca amounts removed in complete-tree harvests. Precipitation additions also equal or exceed sawlog removals over the 50-year rotation for yellow poplar but additions are less than complete-tree removals. The proportionally greater amounts of nutrients removed in complete-tree versus sawlog between the two forest types is due to the greater quantity of small woody material in the 50-year-old stand. Of course, such comparisons of nutrient additions and removals are site-specific and also obscure nutrient dynamics and temporal considerations of supply and demand during the rotation.

TABLE 6. Annual Inputs of Ca, K, and N in Bulk Precipitation and Annual Rates of Removal in Fiber Over Rotations for Two Forest Ecosystems at Coweeta.

Management Alternative	Nutrient and Quantity (kg/ha/year) Ca	K	N
BULK PRECIPITATION INPUT			
	4.8	2.1	8.8
WOODY FIBER REMOVAL			
Yellow Poplar (50-year rotation)			
Merchantable Sawlog	3.8	1.2	2.5
Complete Tree	12.9	4.3	10.0
Mixed Hardwoods (90-year rotation)			
Merchantable Sawlog	4.3	1.3	2.1
Complete Tree	5.6	2.0	3.1

Similarly, atmospheric inputs can be contrasted with hydrologic losses of nutrients that accompany harvesting practices, particularly N (Table 7). A commercial clearcut was recently completed at Coweeta that entailed road construction, clearcutting, and cable logging. Data for the mechanical site preparation treatment were derived from studies in the upper Piedmont of North Carolina (Douglass and Swift, 1977). The treatment consisted of merchantable stem harvest, windrowing with a tractor and burning of windows, followed by disking. In the first two years after the commercial clearcut, atmospheric contributions of NO_3-N and NH_4-N greatly exceeded hydrologic losses. Organic N outputs were 80 percent greater than inputs the first two years after disturbance. However, most of this export came from less than 5 percent of the watershed area and was related to increased discharge of suspended particulates and sediments associated with construction and use of logging roads (Swank and Waide, 1980). Precipitation chemistry data were not available for the mechanically prepared site, but if Coweeta inputs are assumed, inorganic N losses the first year were also less than inputs. Again, organic losses exceeded inputs because of accelerated soil losses. Thus, from the early results of both experiments, it is apparent that inputs from the atmosphere provide an important mechanism for replacing hydrologic losses.

Modeling provides an even broader perspective of the relationship between the atmosphere as a source of N and impacts of harvesting practices. Simulated losses and accretions based on a 15-compartment N cycling model for mixed deciduous forests at Coweeta are given in Table 8. Although removing more fiber increases the loss rate, the magnitude of change is small compared to atmospheric gains and gaseous losses. Such comparative analyses are based on incomplete data and, in a sense, are case histories; a variety of scenarios could be postulated since interpretations are site-specific. Nevertheless, the information is useful in establishing research priorities. In this case, large errors in estimating losses by fiber removal and stream discharge are not serious in comparison to minor inaccuracies in precipitation and gaseous fluxes.

TABLE 8. Simulated Rates of Accretion and Loss for Nitrogen in an Oak-Hickory Forest Ecosystem Subjected to Alternative Management Strategies (after Swank and Waide, 1980).

Component of Loss or Gain	Merchantable Harvest 90-Year Rotation (kg/ha/year)	Whole Tree Harvest 90-Year Rotation (kg/ha/year)
Nitrogen Losses		
Hydrologic	0.5	0.5
Fiber Removal	2.0	5.3
Denitrification	16.1	15.5
Nitrogen Gains		
Fixation	10.9	
Precipitation	8.8	

TABLE 7. Annual Bulk Precipitation Inputs and Hydrologic Outputs for Various Forms of N for Two Different Management Practices in North Carolina Immediately Following Disturbance.

Management Practice and Post-Treatment Year	Hydrologic Fluxes (kg/ha/year) NO_3-N	NH_4-N	Organic N*	Total
BULK PRECIPITATION INPUT				
	2.66	1.87	4.29	8.82
HYDROLOGIC OUTPUT				
Commercial Clearcut				
Year 1	0.04	0.12	9.54	9.70
Year 2	0.63	0.15	6.09	6.87
Harvest and Mechanical Site Preparation (Windrowed and Disked)				
Year 1	1.47	0.48	8.79	10.74

*Organic N = dissolved + particulate + sediment.

TEMPORAL AND SPATIAL VARIABILITY

It is clear that the atmosphere is a significant source of plant nutrients. Based on examination of deposition mechanisms, it is reasonable to expect significant variability in the delivery of nutrients to a given forest site and between sites. Information on the temporal and spatial trends of precipitation chemistry in the United States is fragmented. Collection sites established by a variety of agencies were not located systematically, and many collections were over brief periods. Some of the longest term and most comprehensive data sets on precipitation chemistry for forested regions are those of ecosystem level research programs.

The rate of atmospheric deposition at a given site can be viewed during a single storm (Cooper, *et al.*, 1976), over several storms (Jacobson, *et al.*, 1976), or for extended periods of time. For interpretation of forest management practices, a season is probably the minimum period of importance, and annual values are an essential unit of resolution. For K and NO_3-N, two nutrients important in forest productivity, Figure 3 shows seasonal inputs in bulk precipitation (wetfall plus dryfall) at Coweeta Hydrologic Laboratory over a five-year period. Deposition of K is usually lowest in winter, even though precipitation is usually quite high then. Input is nearly equally distributed among the other seasons, but tends to be slightly higher in spring and fall than in summer. These patterns are partially related to sources and forms of input. As indicated earlier, dryfall is a significant component of K deposition at Coweeta and occurs during peak periods of agricultural activity (Swank and Henderson, 1976). Thus, total K input is poorly correlated with total precipitation ($r = 0.02$). In contrast, dryfall is a small fraction of NO_3-N input, and the largest quantities occur in the spring when precipitation is typically high. Similarly, the smallest inputs occur in the fall when precipitation is usually lowest; therefore, there is a higher correlation ($r = 0.52$) between seasonal input of NO_3-N and precipitation. Other investigators have also shown distinct seasonal trends in deposition of inorganic N (Tabatabai and Laflen, 1976) and other ions (Hornbeck, *et al.*, 1976).

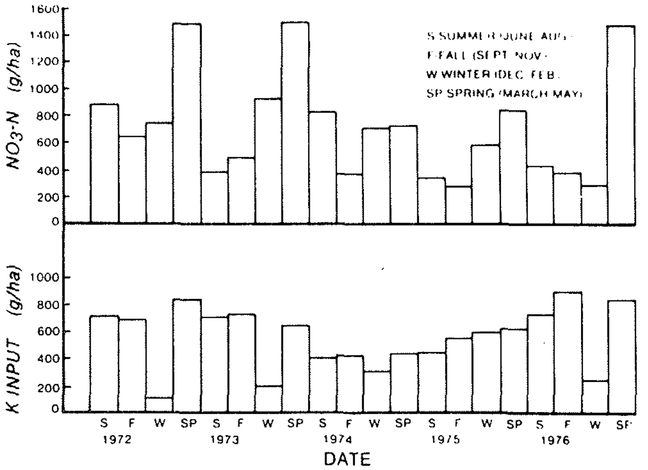

Figure 3. Seasonal Input of Potassium and Nitrate Nitrogen in Bulk Precipitation Over a Five-Year Period at Coweeta Hydrologic Laboratory, North Carolina.

Year-to-year differences in nutrient concentrations are important in evaluating the long-term additions of nutrients to forest ecosystems. Table 9 compares mean annual weighted (by precipitation amounts) concentrations of selected nutrients in bulk precipitation at two sites in the Eastern United States. Values represent an extensive period of record and show several interesting trends. Annual weighted concentrations appear to be slightly less variable at Coweeta, with a range in standard error of estimates of 6 to 16 percent compared with 5 to 29 percent at Hubbard Brook. Although mean concentrations of most ions are substantially different between sites, the ranking of variance is quite similar; i.e., K shows the greatest variation, Ca is intermediate, and NO_3-N is the least variable. From these data, it appears that a long period of continuous precipitation chemistry data is needed to estimate mean annual concentration of some nutrients within ± 10 percent at one standard error.

TABLE 9. Arithmetic Means and Standard Errors of Estimates for Annual Weighted Concentrations of Dissolved Ions in Bulk Precipitation for Hubbard Brook and Coweeta Experimental Watersheds.

	Hubbard Brook*			Coweeta		
Ion	Mean Concentration (mg/l)	SE (percent)	n**	Mean Concentration (mg/l)	SE (percent)	n**
NO_3-N	0.320	7.7	10	0.240	5.8	6
NH_4-N	0.170	4.5	10	0.090	11.5	6
Ca	0.170	11.8	11	0.250	8.8	9
K	0.070	28.6	11	0.110	16.2	9
PO_4	0.008	N/A	2	0.013	7.7	6

*Likens, *et al.*, 1977a.
**Years of record.

Chemical loading estimates based on short periods of record could be quite misleading (Figure 4). For example, if Coweeta data were only available for 1972-76, it would appear that both concentrations and inputs of Ca and K are relatively stable from year to year. But, the inclusion of additional years shows 3 kg/ha/year ranges in K and Ca loading. These data include the highest (223 cm) annual precipitation recorded in 42 years at Coweeta (1972-73) as well as a year (1977-78) with low (164 cm) precipitation. However, these years of extreme precipitation amounts do not coincide with years of maximum or minimum nutrient inputs.

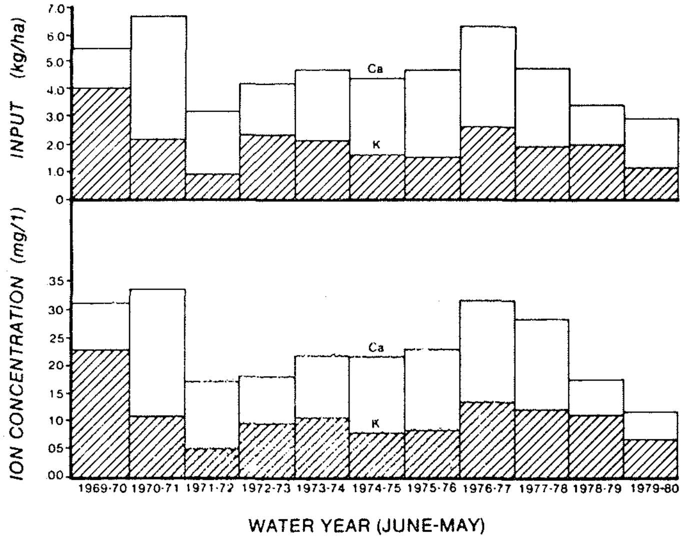

Figure 4. Mean Annual Weighted Concentration and Input of Potassium and Calcium in Bulk Precipitation During an 11-Year Period at Coweeta Hydrologic Laboratory, North Carolina.

The spatial variations in nutrient inputs are of special concern in evaluating the impact of intensive management practices on nutrient cycling. How can one extrapolate from gaged to ungaged forested areas? Several studies have shown that concentrations of many nutrients in precipitation are not significantly different over the elevational gradient of small mountain catchments (Likens, *et al.*, 1967; Swank and Douglass, 1975). Large differences, however, have been observed within a region (Likens, 1972; Boyce and Butcher, 1976; Wolff, *et al.*, 1979). Large errors may occur even over short distances of forested landscape if concentration data are transferred from one site to another (Table 10). Bent Creek Experimental Forest is just 100 km from Coweeta in western North Carolina, but nutrient concentrations are much higher. The extrapolation of Coweeta concentrations to Bent Creek precipitation underestimates measured annual inputs of selected nutrients by 0.7 to 24 kg/ha/year, or about 50 percent for NH_4-N, Ca, and SO_4, and 25 percent for NO_3-N.

CONCLUSIONS

These illustrations of the magnitude and variation in atmospheric deposition and its potential contributions to nutrient replenishment relative to depletions from some forest management practices emphasize the need for coordinated research. Since nutrient inputs and forest management impacts are site-specific, quantification of inputs is needed for a variety of ecosystems concurrent with assessments of nutrient losses. Measurements taken at specific locations should be coupled with mesoscale modeling research to minimize the number of collection stations and improve the accuracy of regional estimates. This approach will require interdisciplinary efforts from an array of investigators in the physical, chemical, and biological sciences. Immediate attention should be given to methods for routinely measuring the magnitude and nature of dry deposition, particularly aerosol impaction and absorption of gases in forest ecosystems. Currently, assessments of total contributions from all atmospheric processes are almost entirely lacking. Additions of N by biological fixation are especially important and should receive high research priority.

ACKNOWLEDGMENTS

This research was supported in part by the Southeastern Forest Experiment Station and in part by grants from the National Science Foundation to the University of Georgia, Athens, Georgia. The author thanks Mr. J. E. Douglass, Dr. W. F. Harris, and Dr. B. Haines for helpful reviews of the manuscript.

TABLE 10. Comparison of Concentrations and Inputs of Selected Nutrients in Bulk Precipitation at Coweeta Hydrologic Laboratory and Bent Creek Experimental Forest, Western North Carolina, for the Period February 9, 1974, Through February 18, 1975.

	Nutrients							
	NO_3-N		NH_4-N		Ca		SO_4	
Location	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)
Coweeta	0.15	3.1	0.12	2.5	0.21	4.5	1.76	37.0
Bent Creek (extrapolated)*		2.1		1.7		2.9		24.7
Bent Creek (measured)	0.21	2.8	0.23	3.1	0.51	7.0	3.49	48.0

*Extrapolated input using Bent Creek precipitation and Coweeta ion concentration.

LITERATURE CITED

Benarie, M., 1976. Transport of Pollutants Considered from the Point of View of a Short and Medium Range-Material Balance. *In:* Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, L. S. Dochinger and T. A. Seliga, Editors. USDA Forest Service General Technical Report NE-23, Northeastern Forest Experiment Station, Upper Darby, Pennsylvania, pp. 251-263.

Best, G. R. and C. D. Monk, 1975. Cation Flux in a Hardwood Forest Watershed and an Eastern White Pine Watershed at Coweeta Hydrologic Laboratory. *In:* Mineral Cycling in Southeastern Ecosystems, F. G. Howell, J. B. Gentry, and M. H. Smith, Editors. ERDA Symposium Series CONF-740513, Technical Information Center, Springfield, Virginia, pp. 847-861.

Bolin, G., G. Aspling, and C. Persson, 1974. Residence Time of Atmospheric Pollutants as Dependent on Source Characteristics, Atmospheric Diffusion Processes and Sink Mechanisms. Tellus 26:185-195.

Bormann, F. H. and G. E. Likens, 1967. Nutrient Cycling. Science 155:424-429.

Boyce, S. D. and S. S. Butcher, 1976. The Effect of a Local Source on the Composition of Precipitation in South-Central Maine. *In:* Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, L. S. Dochinger and T. A. Seliga, Editors. USDA Forest Service General Technical Report NE-23, Northeastern Forest Experiment Station, Upper Darby, Pennsylvania, pp. 309-320.

Carlisle, A., A. H. F. Brown, and E. J. White, 1966. The Organic Matter and Nutrient Elements in the Precipitation Beneath a Sessile Oak (*Quercus petraea*) Canopy. Journal of Ecology 54:87-98.

Cleveland, W. S. and T. E. Graedel, 1979. Photochemical Air Pollution in the Northeast United States. Science 204:1273-1278.

Cooper, H. B. H., Jr., J. M. Demo, and J. A. Lopez, 1976. Chemical Composition of Acid Precipitation in Central Texas. *In:* Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, L. S. Dochinger and T. A. Seliga, Editors. USDA Forest Service General Technical Report NE-23, Northeastern Forest Experiment Station, Upper Darby, Pennsylvania, pp. 281-291.

Douglass, J. E. and L. W. Swift, Jr., 1977. Forest Service Studies of Soil and Nutrient Losses Caused by Roads, Logging, Mechanical Site Preparation, and Prescribed Burning in the Southeast. *In:* Watershed Research in Eastern North America: A Workshop to Compare Results, Vol. II, David L. Correll, Editor. Smithsonian Institution, Edgewater, Maryland, pp. 489-502.

Eriksson, E., 1952. Composition of Atmospheric Precipitation. I. Nitrogen Compounds. Tellus 4:215-232.

Fox, D. G., 1977. Precipitation Quality and Its Effect on Stream Water Quality and the Forest in General. *In:* Proceedings "208" Symposium Non-Point Sources of Pollution from Forested Land, G. M. Aubertin, Editor. Southern Illinois University, Carbondale, Illinois, pp. 103-129.

Fredriksen, R. L., 1975. Nitrogen, Phosphorus, and Particulate Matter Budgets of Five Coniferous Forest Ecosystems in the Western Cascade Range, Oregon. Ph.D. Dissertation, Oregon State University, Corvallis, Oregon, 127 pp.

Galloway, J. N., E. B. Cowling, E. Gorham, and W. W. McFee, 1978. A National Program for Assessing the Problem of Atmospheric Deposition (acid rain). A Report to the Council on Environmental Quality, National Atmospheric Deposition Program. National Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado, 97 pp.

Galloway, J. N. and G. E. Likens, 1976. Calibration of Collection Procedures for the Determination of Precipitation Chemistry. Water, Air, and Soil Pollution 6:241-258.

Galloway, J. N. and G. E. Likens, 1978. The Collection of Precipitation for Chemical Analysis. Tellus 30:71-82.

Grier, C. C., D. W. Cole, C. T. Dyrness, and R. L. Fredriksen, 1974. Nutrient Cycling in 37 and 450 Year Old Douglas-Fir Ecosystems. *In:* Integrated Research in the Coniferous Forest Biome, R. H. Waring and R. L. Edmonds, Editors. College of Forestry Resources CFB Bulletin 5, University of Washington, Seattle, Washington, pp. 21-34.

Hales, J. M. and M. T. Dana, 1979. Precipitation Scavenging of Urban Pollutants by Convective Storm Analysis. Journal of Applied Meteorology 18:294-316.

Henderson, G. S. and W. F. Harris, 1975. An Ecosystem Approach to the Characterization of the Nitrogen Cycle in a Deciduous Forest Watershed. *In:* Forest Soils and Forest Land Management, B. Bernier and C. H. Winget, Editors. Proceedings of the Fourth North American Forest Soils Conference, Les Presses de L'Universite Laval, Quebec, pp. 179-193.

Henderson, G. S., W. T. Swank, J. B. Waide, and C. C. Grier, 1978. Nutrient Budgets of Appalachian and Cascade Region Watersheds: A Comparison. Forest Science 24:385-397.

Hidy, G. M., 1973. Removal Processes of Gaseous and Particulate Pollutants. *In:* Chemistry of the Lower Atmosphere, S. I. Rasol, Editor. Plenum Press, New York, New York, pp. 121-173.

Hornbeck, J. W., G. E. Likens, and J. S. Eaton, 1976. Seasonal Patterns in Acidity of Precipitation and Their Implications for Forest Stream Ecosystems. *In:* Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, L. S. Dochinger and T. A. Seliga, Editors. USDA Forest Service General Technical Report NE-23, Northeastern Forest Experiment Station, Upper Darby, Pennsylvania, pp. 597-609.

Ichikuni, M., 1978. Calcite as a Source of Excess Calcium in Rainwater. Journal of Geophysical Research 83:6249-6252.

Jacobson, J. S., L. I. Heller, and P. Van Leuken, 1976. Acidic Precipitation at a Site Within the Northeastern Conurbation. *In:* Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, L. S. Dochinger and T. A. Seliga, Editors. USDA Forest Service General Technical Report NE-23, Northeastern Forest Experiment Station, Upper Darby, Pennsylvania, pp. 267-279.

Johnson, P. L. and W. T. Swank, 1973. Studies of Cation Budgets in the Southern Appalachians on Four Experimental Watersheds With Contrasting Vegetation. Ecology 54:70-80.

Jordan, C. F., 1982. The Nutrient Balance of an Amazonian Rain Forest. Ecology 63:647-654.

Junge, C. E., 1963. Air Chemistry and Radioactivity. Academic Press, New York, New York, 382 pp.

Likens, G. E., 1972. The Chemistry of Precipitation in the Central Finger Lakes Region. Water Resources and Marine Sciences Center Technical Report 50, Cornell University, Ithaca, New York, 47 pp.

Likens, G. E., F. H. Bormann, N. M. Johnson, and R. S. Pierce, 1967. The Calcium, Magnesium, Potassium and Sodium Budgets for a Small Forested Ecosystem. Ecology 48:772-785.

Likens, G. E., F. H. Bormann, R. S. Pierce, J. S. Eaton, and N. M. Johnson, 1977a. Biogeochemistry of a Forested Ecosystem. Springer Verlag, New York, New York, 146 pp.

Likens, G. E., J. S. Eaton, and J. N. Galloway, 1977b. Precipitation as a Source of Nutrients for Terrestrial and Aquatic Ecosystems. *In:* Precipitation Scavenging (1974). ERDA Symposium Series CONF-741003, Technical Information Center, Springfield, Virginia, pp. 552-570.

Lindberg, S. E. and R. C. Harriss, 1981. The Role of Atmospheric Deposition in an Eastern United States Deciduous Forest. Water, Air, and Soil Pollution 16:13-31.

McMahon, T. A. and P. J. Dennison, 1979. Empirical Atmospheric Deposition Parameters -- A Survey. Atmospheric Environment 13:571-585.

Nordø, J., 1976. Long Range Transport of Air Pollutants in Europe and Acid Precipitation in Norway. *In:* Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, L. S. Dochinger and T. A. Seliga, Editors. USDA Forest Service General Technical Report NE-23, Northeastern Forest Experimental Station, Upper Darby, Pennsylvania, pp. 87-103.

Ottar, B., 1976. Organization of Long Range Transport of Air Pollution Monitoring in Europe. *In:* Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, L. S. Dochinger and T. A. Seliga, Editors. USDA Forest Service General Technical Report NE-23, Northeastern Forest Experiment Station, Upper Darby, Pennsylvania, pp. 105-117.

Patterson, D. T., 1975. Nutrient Return in the Stemflow and Throughfall of Individual Trees in the Piedmont Deciduous Forest. *In:* Mineral Cycling in Southeastern Ecosystems, F. G. Howell, J. B. Gentry, and M. H. Smith, Editors. ERDA Symposium Series CONF-740513, Technical Information Center, Springfield, Virginia, pp. 729-735.

Rodhe, H. and J. Grandell, 1972. On the Removal Time of Aerosol Particles from the Atmosphere by Precipitation Scavening. Tellus 24:442-454.

Rolfe, G. L., M. A. Akhtar, and L. E. Arnold, 1978. Nutrient Fluxes in Precipitation, Throughfall, and Stemflow in an Oak-Hickory Forest of Southern Illinois. Agricultural Experiment Station Forestry Research Report 78-2, University of Illinois, Urbana, Illinois, 3 pp.

Scriven, R. A. and B. E. A. Fisher, 1975. The Long Range Transport of Airborne Material and Its Removal by Deposition and Washout. I. General Considerations. Atmospheric Environment 9:49-58.

Sollins, P., C. C. Grier, F. M. McCorison, K. Cromack, Jr., R. Fogel, and R. L. Fredriksen, 1980. The Internal Element Cycles of an Old-Growth Douglas-Fir Ecosystem in Western Oregon. Ecological Monographs 50:261-285.

Swank, W. T. and J. E. Douglass, 1975. Nutrient Flux in Undisturbed and Manipulated Forest Ecosystems in the Southern Appalachian Mountains. *In:* The Hydrological Characteristics of River Basins and the Effects of These Characteristics of Better Water Management. IASH-AISH Publications No. 117, Proceedings of the Tokyo Symposium, Tokyo, Japan, pp. 445-456.

Swank, W. T. and G. S. Henderson, 1976. Atmospheric Input of Some Cations and Anions to Forest Ecosystems in North Carolina and Tennessee. Water Resources Research 12:541-546.

Swank, W. T. and J. B. Waide, 1980. Interpretation of Nutrient Cycling Research in a Management Context: Evaluating Potential Effects of Alternative Management Strategies on Site Productivity. *In:* Forests: Fresh Perspectives from Ecosystem Analysis, R. H. Waring, Editor. Proceedings of the 40th Annual Biology Colloquium, Oregon State University Press, Corvallis, Oregon, pp. 137-157.

Tabatabai, M. A. and J. M. Laflen, 1976. Nutrient Content of Precipitation Over Iowa. *In:* Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem, L. S. Dochinger and T. A. Seliga, Editors. USDA Forest Service General Technical Report NE-23, Northeastern Forest Experiment Station, Upper Darby, Pennsylvania, pp. 293-308.

Tamm, C. O., 1958. The Atmosphere. Handbuch fur Pflanzenphysiologie 6:233-242.

U.S. Atomic Energy Commission, 1970. Precipitation Scavenging. AEC Symposium Series CONF-700601, National Technical Information Center, Springfield, Virginia.

U.S. Energy Research and Development Administration, 1977. Precipitation Scavenging (1974). ERDA Symposium Series CONF-741003, National Technical Information Center, Springfield, Virginia, 842 pp.

Van Hook, R. I., D. W. Johnson, D. C. West, and L. K. Mann, 1982. Environmental Effects of Harvesting Forests for Energy. Forest Ecology Management 4:79-94.

Wells, C. G. and J. R. Jorgensen, 1975. Nutrient Cycling in Loblolly Pine Plantations. *In:* Forest Soils and Land Management, B. Bernier and C. H. Winget, Editors. Proceedings of the Fourth North American Forest Soils Conference, Les Presses de L'Universite Laval, Laval, Quebec, pp. 137-158.

Wolff, G. T., P. J. Lioy, H. Golub, and J. S. Hawkins, 1979. Acid Precipitation in the New York Metropolitan Area: Its Relationship to Meteorological Factors. Environmental Science Technology 13: 209-212.