BIOGEOCHEMICAL CYCLING OF CARBON, NITROGEN, AND SULFUR AT THE HOWLAND INTEGRATED FOREST STUDY SITE, HOWLAND, MAINE

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Abstract: The biogeochemistry of C, N, and S was studied for six years at the Howland Integrated Forest Study (HIFS) site by measuring those constituents in major above- and below-ground pools and fluxes. Leaching losses of C from the solum were much less than CO_2 efflux, with a mean annual leaching rate of 31.2 kg ha^{-1} yr^{-1}. Carbon return to the forest floor via litterfall and outputs via CO_2 efflux were relatively equal. Mean annual total (wet+plus) atmospheric deposition inputs were 5.51 kg ha^{-1} yr^{-1} for NO_3^--N, 2.64 kg ha^{-1} yr^{-1} for NH_4^+-N, and 8.09 kg ha^{-1} yr^{-1} for SO_4^{2-}-S; wet deposition inputs for C were 6.67 kg ha^{-1} yr^{-1}. Sulfur-deposition, in the form of SO_2 dry deposition, and SO_4^{2-} in wet deposition showed significant decreasing temporal trends during the six year study period. There were no significant temporal trends for NO_3^- in neither dry nor wet deposition. Wet deposition of NH_4^+, however, showed a significant decreasing pattern through the study period. Decreases in precipitation chemical flux was likely the result of decreases in precipitation volume through the study period because no significant decreases in concentration of SO_4^{2-} or NH_4^+ occurred. There was a net ecosystem retention of NO_3^- and NH_4^+, attributable to the N-deficiency of this forest. Mean annual input-output for SO_4^{2-}, however, was near zero for the study period, indicating the conservative behavior of that ion in this ecosystem. Ongoing research is attempting to further define the temporal trends in C, N, and S cycling, and to determine the mechanisms controlling these characteristics including the effects of temperature and moisture.

INTRODUCTION

We have witnessed at least two areas of concern regarding forest ecosystem structure and function during the past two decades; acidic deposition from the 1970's through the 1980's, and global change from the mid 1980's through the present. While nitrogen (N) and sulfur (S) represent the clearest examples of an altered chemical climate to which forest ecosystems are now exposed, the past decade has also witnessed the emergence of widespread concern for the potential of global climate change to simultaneously alter the physical environment of forest ecosystems. Pastor and Post (1988) discussed various models that predict 2° to 4°C increases in global temperatures, and how this change may shift forest distribution and character depending upon related ecosystem conditions, such as water balance and N availability. In Maine, this could result in a northward migration of the southern extent of the spruce-fir forest type. Numerous key soil processes may be influenced by climate change that include organic matter decomposition, N mineralization, and nitrification that have been discussed in the literature (Anderson 1991; Van Cleve et al. 1990; McGuire et al. 1992; Rastetter et al. 1991, 1992).

The Howland Integrated Forest Study (HIFS) has been developed to examine the influences of N and S deposition, and climatic variations, on biogeochemical cycling in a representative, low elevation, commercial coniferous forest ecosystem of northern New England. The program has focused on the role of soil processes in ecosystem function, but includes a wide range of ecological investigations within the practical limits of time and resources.

The HIFS site originally served as the only low-elevation commercial spruce-fir forest site of the six sites in the Spruce-Fir Research Cooperative (SFRC) that was part of the national Forest Response Program (FRP) in the U.S. during the 1980's (Eager and Adams 1992). The HIFS program was also a non-funded cooperating site in the Electric Power Research Institute/Oak Ridge National Laboratory (EPRI/ORNL) Integrated Forest Study (IFS) during this period (Johnson and Lindberg 1992), and part of the U.S. Environmental Protection Agency's Mountain

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Cloud Chemistry Program (MCCP) for the intensive measurement of the chemical and physical climate exposures to forests. Numerous investigators from various institutions have utilized HIFS as part of their research programs, including the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), the USDA Forest Service (USDA FS), and the US Environmental Protection Agency (US EPA), as well as other universities. The National Aeronautics and Space Administration's (NASA) FIFE, FED, and BOREAS field campaigns have also included the HIFS site. During the 1990's a number of new research initiatives were developed as part of the USDA Forest Service's Northern Global Change Research Program (NGCRP) that were built on the foundation of the HIFS program. The purpose of this paper is to present some of the highlights of the biogeochemistry of C, N, and S cycling at the HIFS site from January, 1988 through December, 1993.

MATERIALS AND METHODS

Study Site: The HIFS site is located in east-central Maine within International Paper's Northern Experimental Forest (Fig. 1). The site includes two, 0.2-ha biogeochemical study plots and a 27 m tower that extends above the canopy equipped with meteorological and air pollution monitoring instrumentation. Selected stand characteristics are given in Table 1.

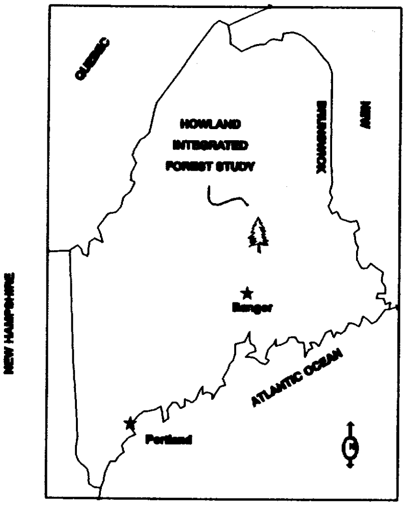

Figure 1.

Sample Collection: Precipitation was sampled weekly from January, 1988 through December, 1993 with a single wet-only Aerochem Metric® collector located in a forest clearing approximately 2 km east of the study site, in accordance with National Atmospheric Deposition Program protocol (Bigelow and Dossett 1988). Throughfall was sampled using two Aerochem Metric® collectors weekly and composited monthly. Chemical fluxes for incident precipitation were estimated as the product of weekly volume-weighted concentrations and hydrologic flux. Chemical fluxes in throughfall were estimated as the product of monthly volume-weighted concentrations and hydrologic flux. Further description of the sampling protocols are given in Lawrence and Fernandez (1991) and McLaughlin et al. (1995).

Air concentrations for vapor-phase SO_2 and HNO_3, and fine-particle SO_4^{2-} and NO_3^-, were measured continuously from January, 1988 through December, 1993 on the meteorological tower 10 m above the forest canopy using filter packs consisting of three sequential filters (Teflon, nylon, and carbonate-treated cellulose) (Meyers et al. 1991). Dry deposition fluxes were estimated as the product of air concentrations and deposition velocities (V_d). Deposition velocities for vapors were estimated using the big-leaf model of Hicks et al. (1987) based on site-specific hourly meteorological measurements and canopy structure and physiological data. Deposition velocities for particles were derived from site specific canopy structure data using the submicron radionuclide tracer methods of Bondietti et al. (1984).

Table 1. Selected stand characteristics for the HIFS site.

Location	45°10'N, 68°40'W
Growing Season (days)	120 to 160
Mean Annual Precipitation (mm)	1063
Mean January Temperature (°C)	-8.9
Mean July Temperature (°C)	20.1
Total Basal Area (m^2)	85
Overstory Vegetation (% basal area)	
Red spruce	50
White pine	22
Hemlock	13
Soils	Aquic Haplorthods Aeric Haplaquods

Soil solution was collected beneath the Oa horizon and from the middle of the Bs horizon using zero-tension lysimetry from six lysimeter stations on each plot. At each sampling station, three lysimeters (23.3 x 12.5 cm-pans) drained into one collection bottle for each horizon. Samples were collected monthly from January, 1988 through December, 1993. Chemical fluxes in the Bs horizon solution were calculated by multiplying monthly solution concentrations by the mean monthly water flux. Monthly water flux was estimated using the Priestly-Taylor equation modified for interception losses (Shuttleworth and Calder 1979; Spittlehouse 1985). Further description of the sample design are given in Fernandez et al. (1995).

Soil CO_2 efflux was measured every three weeks using the soda-lime technique (Edwards and Ross-Todd 1983) at three locations at each plot. Further description is given in Fernandez et al. (1993b). Soil sampling was conducted during 1987 and 1988 using quantitative pits. Twelve 71 cm x 71 cm x 1 m pits were excavated in 1987 (six per plot) and 12 in 1988 (six per plot) for a total of 24 pits (Fernandez et al. 1993a).

Analytical Procedures: Solutions were analyzed for pH, SO_4^{2-}, NO_3^-, NH_4^+, and dissolved organic carbon (DOC). Prior to chemical analyses, solutions were passed through Whatman #42 filter paper. In addition, solutions for DOC analysis were passed through Whatman GF/F glass fiber filters. Sulfate and NO_3^- were measured using a Dionex Model 2000i/SP ion chromatograph. pH was measured potentiometrically using an Orion Model 701A pH meter. NH_4^+ was measured by automated colorimetric phenate (American Public Health association 1981) using a Bran-Lubbe Traacs Model 800 autoanalyzer, and DOC was measured by ultraviolet (UV)/persulfate oxidation with infrared detection of liberated CO_2 (EPA 1992) using an Oceanographic Instrument (OI) Model 700 Total Organic Carbon Analyzer.

Soils were analyzed for total C and N using a Carlo-Erba CHN elemental analyzer, total S on a Leco Sulfur Determinator (SC 132), and phosphate-extractable ("adsorbed") SO_4^{2-} using ion chromatography.

Experimental Design and Statistical Analyses: The intent of this research is to provide an intensive case study of biogeochemical processes at the HIFS site, and to study the interactions of the soil-plant system with its chemical and physical climate. Temporal trends for the chemical constituents of precipitation, dry deposition, and throughfall were analyzed using the Mann-Kendall test for trend analysis (Gilbert 1987).

RESULTS AND DISCUSSION

Total C and N contents were greater in the mineral soil than the forest floor (Table 2), but the reverse was true for total S at the HIFS site. Total C, N, and S generally decreased with depth in the soil profile, with the exception of the albic horizon (E), whereas soil pH increased (Fig. 2). Adsorbed SO_4^{2-}, however, increased from the E to the Bs horizon, but then decreased in the BC and C horizons (Fig. 2). The vertical trends of total C, N, and S, are largely governed by organic matter (Fernandez et al. 1993a). Comparing the quantitative pit method with that of standard morphological sampling suggests that the latter tends to underestimate total C (Fernandez et al. 1993a), which may have important implications in evaluating the sequestering of C in forest soils of the northeastern U.S. Every 1 percent change in the soil coarse fragment estimate at the HIFS site is equivalent to approximately 1 metric ton of C and 31 kg of N per ha. Litterfall C return to the forest floor was 1,300 kg ha^{-1} yr^{-1}, and was about 40-fold higher than C returned via throughfall DOC.

Table 2. Soil carbon, nitrogen, and sulfur contents at the HIFS site.

Constituent	Forest Floor	Mineral Soil
	kg ha^{-1}	
Total carbon	44,000	68,000
Total nitrogen	1,034	2,270
Total sulfur	130	840
Adsorbed sulfate	4	34

Fernandez et al. (1993b) reported that CO_2 efflux from the forest floor at the HIFS was surprisingly similar to that for selected deciduous or harvested forest sites in Maine, being roughly 2000 kg CO_2 ha^{-1} yr^{-1}. Carbon efflux as CO_2 was much greater than that lost through leaching. Carbon output through CO_2 and DOC flux was slightly greater than the amount of C returned to the soil through litterfall and throughfall DOC. These differences, however, are likely not significant.

Dry deposition of SO_4, NO_3, and NH_4 was comparable to wet deposition, suggesting that a simple doubling of wet deposition is a reasonable estimate of total deposition to the forest canopy for these ionic species (Table 3). There was a significant ($p<0.05$) decreasing trend for SO_2-S flux, but no significant ($p>0.05$) pattern occurred for fine-particle SO_4^{2-} (Fig. 3a). Decreasing SO_2 deposition suggests that local S-emissions are probably declining since it is likely that long-range transported SO_2 would be oxidized to SO_4 in transit. Mean annual dry deposition of NO_3^--N was 1.69 ± 0.05 kg ha^{-1} yr^{-1} with HNO_3 vapors accounting for over 99% of the flux. Neither HNO_3 or fine-particle NO_3^- dry deposition showed significant ($p>0.05$) temporal trends for the study period (Fig. 3a).

Table 3. Carbon, nitrogen, and sulfur fluxes for dry deposition, precipitation, throughfall, and soil solution in the Bs horizon at the HIFS site.

Constituent	Dry Deposition	Wet Deposition	Throughfall	Net Canopy Exchange	Bs Horizon Solution
			kg ha^{-1}		
SO_4^{2-}-S	3.45	4.64	8.96	0.87	8.74
NO_3^--N	2.70	2.81	0.52	-4.99	0.04
NH_4^+-N	1.54	1.26	0.26	-2.52	0.41
DOC-C	-	6.67	103	99	31.16

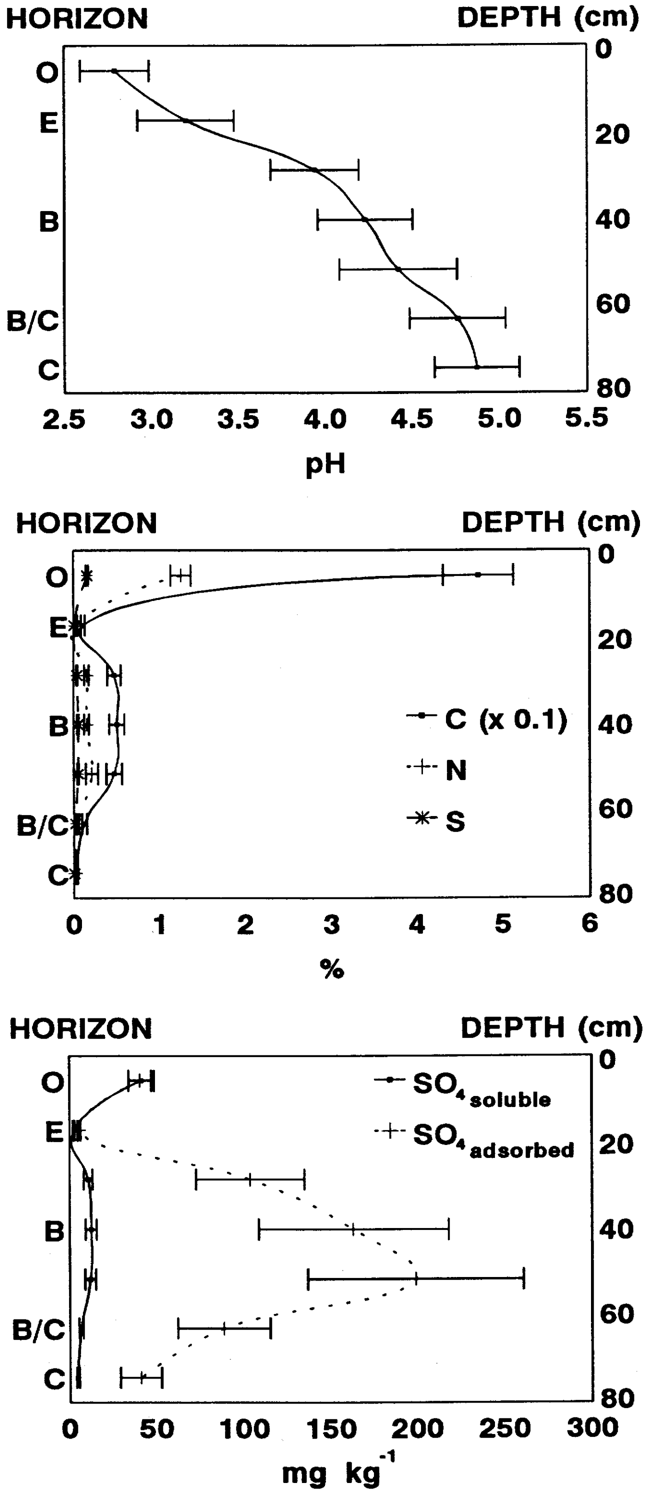

Figure 2. Vertical distribution of soil C, N, S, and pH at the HIFS site.

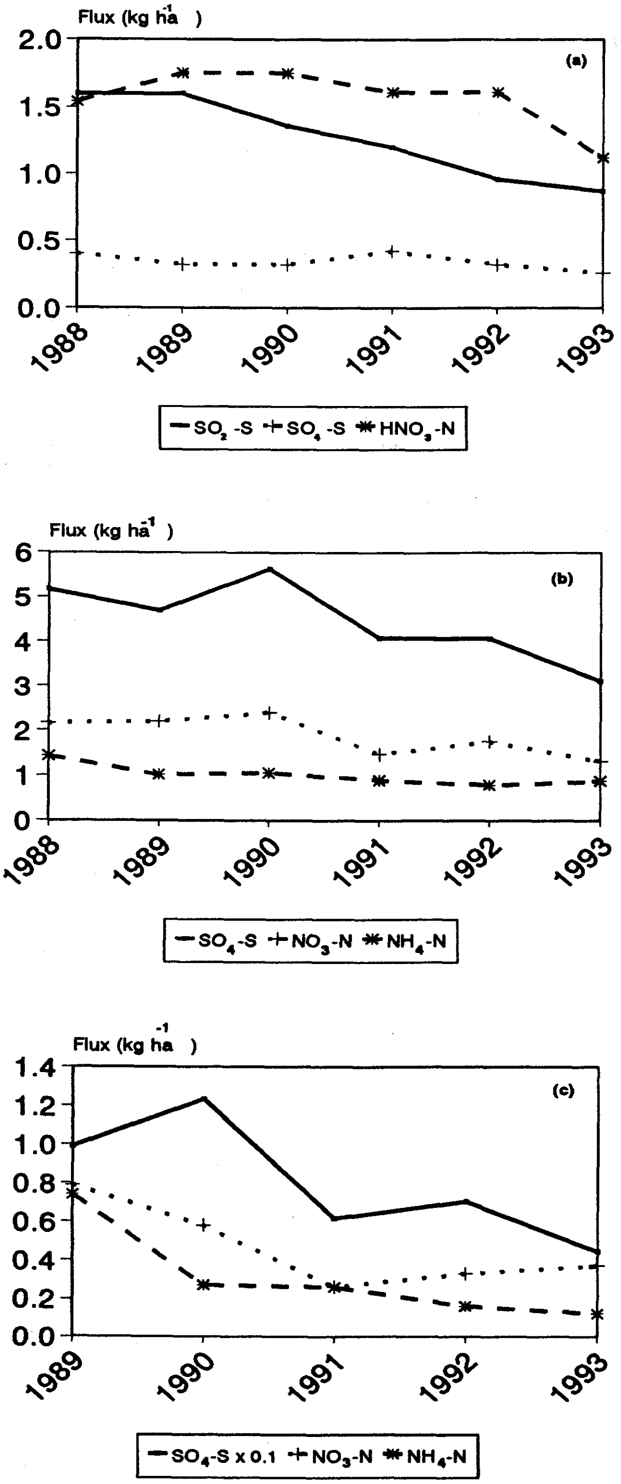

Figure 3. Temporal trends in atmospheric deposition of N and S at HIFS: (a) Dry Deposition, (b) Precipitation, (c) Throughfall. Data adapted from McLaughlin et al. (1995).

Mean annual wet deposition of SO_4^{2-}-S, NO_3^--N, and NH_4^+-N are shown in Table 3. Precipitation flux for SO_4^{2-} and NH_4^+ showed significant ($p<0.05$) decreasing trends, while NO_3^- showed no significant ($p>0.05$) temporal pattern (Fig. 3b). The decrease in flux for precipitation SO_4^{2-}, NH_4^+, and H^+ was likely due to decreases in precipitation amount during the study period (Fig. 3b). McLaughlin et al. (1995) reported that there were no significant temporal patterns for precipitation SO_4^{2-} or NH_4^+ concentrations during the study period.

Sulfate and NH_4^+ throughfall deposition decreased significantly ($p<0.05$) throughout the study period, while no significant trends occurred for NO_3^- (Fig. 3c). McLaughlin et al. (1995) also reported significant decreasing trends for throughfall concentrations of SO_4^{2-}, but not for NO_3^- nor NH_4^+. Therefore, the decreasing NH_4^+ flux probably reflects decreasing throughfall amounts, whereas SO_4^{2-} decreases are likely the result of interactions between concentrations of those ions and throughfall amounts.

Mean annual net canopy exchange (NCE) for the study period indicated canopy uptake of N (Table 3) which is attributable to the N-deficiency of the HIFS site as suggested by Fernandez et al. (1990) based on foliar chemistry. Mean annual NCE of SO_4^{2-}, however, was near zero (Table 3) which is similar to other forest ecosystems in the United States.

Monomeric Al was 0.38 and 0.32 mg L^{-1} in the Oa and Bs horizon solutions, respectively. Organic Al was 0.30 and 0.16 mg L^{-1} in the Oa and Bs horizon solutions, respectively (Fernandez et al. 1995). Aluminum concentrations at the HIFS site are lower than that reported for other sites in the eastern U.S., and Ca/Al ratios do not suggest inhibition of Ca uptake by roots (Fernandez et al. 1995).

There was a net ecosystem retention of N at the HIFS site for the six-year study period (Fig. 4). Mean annual input-output for SO_4^{2-}, however, was near zero for the study period (Fig. 4), indicating the conservative behavior of SO_4^{2-} at HIFS (Lawrence and Fernandez 1991). The relatively high N-retention indicates efficient immobilization by vegetation and soil microflora. However, there were differences between the behavior of NO_3^- and NH_4^+, although both ions showed net retention (Fig. 4). Total output of NO_3^- was only 1 percent of the total atmospheric deposition, with approximately 90 percent retained within the forest canopy. Ninety percent of the NO_3^- that reached the forest floor as throughfall was also retained within the soil. In contrast to NO_3^-, NH_4^+ had approximately a 1.5-fold higher flux from the Bs horizon as opposed to throughfall flux. However, the canopy retained about 90 percent of the total atmospheric NH_4^+ that was deposited to the canopy. The lack of a net retention of SO_4^{2-} at HIFS is also a common occurrence in a number of forest ecosystems in the U.S. Outputs of SO_4^{2-} from the Bs horizon decreased temporally (Fernandez et al. 1995), similarly as dry, wet, and throughfall fluxes reported in this study.

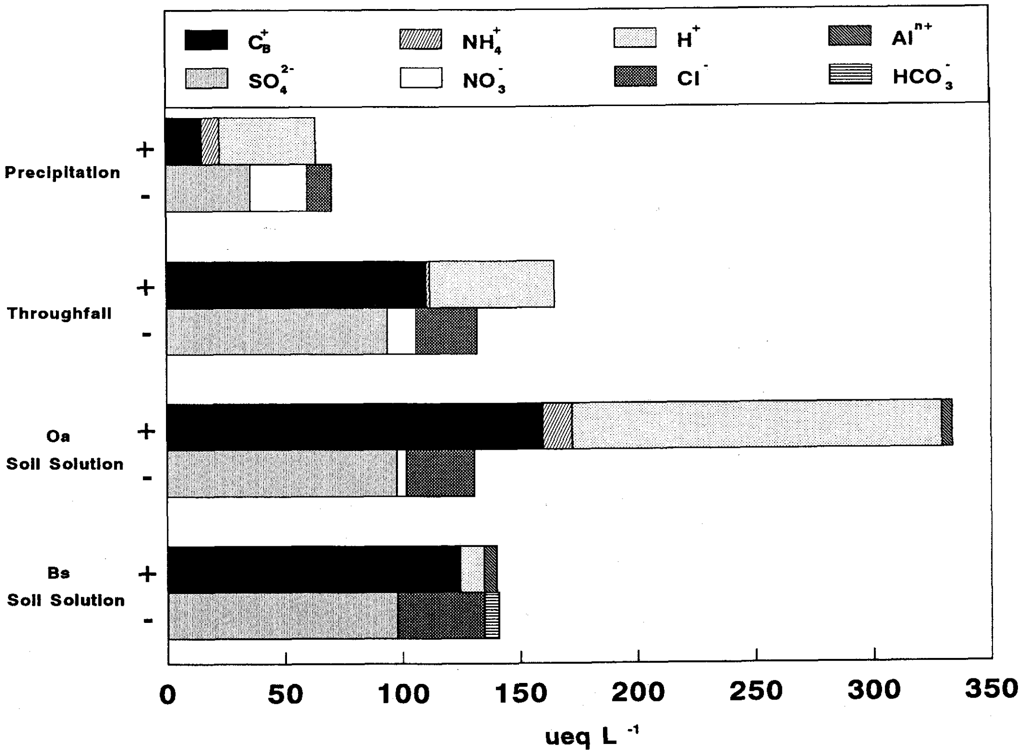

Figure 4. Solution migration through the forest canopy and soil at the HIFS (Lawrence and Fernandez 1991).

SUMMARY

Carbon and N contents were greater in the mineral soil compared to the forest floor. Total C, N, and S decreased with depth, in relation to organic matter, where as adsorbed SO_4^{2-} increased with depth. Carbon return to the forest floor was greater for litterfall than that from throughfall DOC. Carbon dioxide represented the major C flux from the HIFS site.

There was a decline in S-loading, but not N-loading, to the HIFS site between 1988 and 1993. Declining S-loading was due to decreasing SO_2, and may reflect trends in local SO_2 emissions for the state and region. Although little evidence of SO_4^{2-} net ecosystem retention was found, biological immobilization in the canopy and soil removed most atmospherically deposited inorganic N. Only through long-term, intensive investigations of biogeochemical processes at the HIFS site is it possible to define mechanisms controlling temporal trends in atmospheric deposition and their effects on forest biogeochemistry.

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