## PROJECT SUMMARY

The goal for the project, "Long-term Ecological Research at Hubbard Brook Experimental Forest" is to better understand the ecological patterns and processes that characterize forested landscapes in the Northeast, particularly in response to disturbances. This research is focused at the ecosystem level of organization. Long-term measurements, experiments and process studies are conducted at a variety of scales, ranging from forest plots to small watersheds to the complex landscape of the entire Hubbard Brook Valley to the White Mountain National Forest to the northern forest of the Northeast region. Three types of disturbance that are important to northeastern forests will be examined, including: 1) air pollution, 2) catastrophic events such as clear-cutting and 3) non-catastrophic events such as soil freezing events, ice storms and insect irruptions. Biogeochemical studies focus on the cycles of carbon, nitrogen, phosphorus, calcium and sulfur building on a 40-year record of element fluxes and vegetation dynamics for experimental watersheds. These long-term measurements illustrate striking and surprising trends of element inputs and cycles for the northeastern forest. One important observation is that inputs of strong acids have decreased markedly since the 1970s in response to emission controls of sulfur dioxide associated with the Clean Air Act. Unfortunately decreases in acidic deposition have not resulted in improvements in the acid-base status of soil and stream water at this sensitive site. Coincidently, declines in sugar maple have been observed, particularly at higher elevations. To examine the effects of depletion of soil calcium due to acidic deposition, a whole-watershed experiment is being conducted in which calcium silicate (wollastonite) was added to replace the calcium leached from acidic deposition. This material has a distinctive strontium isotope ratio, which enables tracking of the fate of the added calcium. This past year large increases in sugar maple seedlings and reductions in needle damage of red spruce were observed in the calcium-treated watershed relative to reference sites. Concomitant studies of heterotrophs, including birds, amphibians, mammals, gastropods and insects reveal potential linkages with element fluxes and vegetation dynamics. In this proposal, ongoing experiments and process studies are described as well as new initiatives to examine the effects of compounded disturbances on ecosystem structure and function, elemental stoichiometry and hysteresis phenomena, all in the context of landscape-level variation in ecological state factors. Long-term watershed-scale experiments, including the calcium addition study and clear-cutting studies will be continued. New studies will be initiated of: 1) plot-level fertilization of young and mature forest with nitrogen, phosphorus and calcium, 2) intensive and extensive study of beech bark disease across multiple trophic levels, and 3) detailed study of nitrogen and carbon dynamics in relation to sugar maple decline, forest nutrition and productivity. The acquisition management and dissemination of data and information collected at Hubbard Brook and nearby sites will be accomplished with broader impacts on education and outreach activities. A new management/governance structure has been implemented to provide vision and scientific leadership to the research program, foster integration and synthesis across diverse projects, encourage new scientists and diversity among the research community, and promote communication.

## 1.0 – RESULTS FROM PRIOR NSF SUPPORT

**Timothy J. Fahey, Charles T. Driscoll et al.**

**NSF Award:** 9810221; $4,200,000; 1 December 1998 – 31 November 2004

**Title**: Long-Term Ecological Research (LTER) at the Hubbard Brook Experimental Forest (HBR-LTER)

**Summary:** The overall goal of the HBR-LTER is to improve understanding of the response of northern hardwood ecosystems to natural and anthropogenic disturbances. Toward this end, we have been conducting research on sites within and near the Hubbard Brook Experimental Forest (HBEF) with contrasting histories of disturbance. Our activities include: 1) collection and analysis of long-term data sets (Table 1), 2) studies of ambient disturbance, 3) experimental research to simulate the effects of disturbance at the small watershed or plot-level, and 4) development and application of ecosystem models. Highlights of the past six years include: evaluation of the response of acid-impacted forest and aquatic ecosystems to the 1990 Amendments of the Clean Air Act; initiation of a new watershed-scale experiment to evaluate $Ca^{2+}$ supply as a controller of ecosystem structure and function and recovery from acidic deposition; and development of a new conceptual model that fosters integration of our research program and links to policy and management. A new vehicle for education and outreach, the Hubbard Brook Research Foundation (HBRF), published two "*Science-Links*" reports that had major impacts on policy and legislative debate at the national scale. We also developed and instituted a new project management structure to ensure the sustainability of the long-term research program at the HBEF. Research publications are presented in Table 2 (*listed at end of document*).

**New Conceptual Model**: The Hubbard Brook Ecosystem Study (HBES) has historically focused on a mass balance approach determining inputs, outputs and internal transfers of water and elements in small undisturbed and manipulated forested watersheds (10-80 ha; Bormann and Likens 1979, Likens and Bormann 1995). Based in part on comments received during an external review, we were motivated to develop a new conceptual model (Groffman et al. in press a). We conceive the ecosystem in three components (Fig. 1): 1) ecosystem patterns and processes (i.e., all the organisms that function together in a given area interacting with the physical environment so that flow of energy leads to clearly defined biotic structures and cycling of matter); 2) a suite of "controllers" that drive ecosystem patterns and processes, including state factors and variable or stochastic factors, the latter being both natural and anthropogenic perturbations; and 3) ecosystem functions and services that are valued by humans. We have applied this conceptual model to current research questions at the HBES (Groffman et al. in press a). While the conceptual model is qualitative, we strive to link it to the PnET family of simulation models and other models to provide a quantitative understanding of forest ecosystem response to state factors, variable/stochastic controllers and human management.

**TABLE 1. Current long-term monitoring data sets developed through the HBES and HBR-LTER. The institution responsible for sample collection and funding source are indicated. Data management status includes: a) www.hubbardbrook.org, b) available from PI, and c) hardcopy. *Archived materials are maintained by the USDA FS.**

| Measurement | Institution | Funding Source | Status | Year |
|---|---|---|---|---|
| Physical/Hydrologic Monitoring | | | | |
| Instantaneous streamflow (9 stations) | USFS | USFS | a,b | 1956 |
| Daily streamflow (9 stations) | USFS | USFS | a,b | 1956 |
| Daily precipitation (25 stations) | USFS | USFS | a,b | 1956 |
| Air Temperature: mean, min, max (8 stations) | USFS | USFS | a,b | 1952 |
| Solar radiation | USFS | USFS | a,b | 1958 |
| Wind speed and direction | USFS | USFS | a,b | 1965 |
| Vapor pressure | USFS | USFS | a,b | 1966 |
| Soil frost | USFS | USFS | a,b | 1956 |
| Weekly snow depth and snow water equivalent | USFS | USFS | a,b | 1959 |
| Weekly soil temperature and moisture | USFS | USFS | a,b | 1959 |
| Hourly canopy surface wetness | IES | IES | b | 1989 |
| Air Chemistry ($SO_2$, $HNO_3$, particulates, ozone) | IES | EPA | a,b | 1988 |
| Solution Chemistry | | | | |
| Weekly bulk precipitation (6-10 stations) | IES | LTER/LTREB | a,b | 1963 |
| Event basis throughfall chemistry W5, W6 | IES | NSF-LTER | a,b | 1989 |
| Monthly soil solution chemistry W1, W5, W6, W8, W9 | Syracuse | NSF-LTER | a,b | 1984 |
| Weekly stream chemistry at weirs of W1-9, ML | IES | LTER/LTREB | a,b | 1963 |
| Monthly stream chemistry within W1, W5, W6, W8, W9 | Syracuse | NSF-LTER | a,b | 1982 |
| Organisms | | | | |
| Bird populations | Dartmouth | NSF-LTER | a,b | 1969 |
| Phytophagous insect populations | Dartmouth | NSF-LTER | a,b | 1969 |
| W2 Vegetation, biomass, chemistry | Wyoming | NSF-LTER | a,b | 1970 |
| W4 Vegetation, biomass | USFS | USFS | a,b | 1970 |
| W5 Vegetation, biomass, chemistry | Cornell/ Yale | NSF-LTER | a,b | 1985 |
| W6 Vegetation, biomass, chemistry | Yale | NSF-LTER | a,b | 1965 |
| Valley-wide Vegetation | Cornell | NSF-LTER | b | 1997 |
| Fine-root, biomass, chemistry | Cornell | NSF-LTER | -- | 1992 |
| Microbial biomass and activity | IES | -- | a,b | 1992 |
| Plankton populations - ML | IES | IES | b | 1965 |

| Measurement | Institution | Funding Source | Status | Year |
|---|---|---|---|---|
| Litter-Fall | Cornell | NSF-LTER | a,b | 1988 |
| Soils | | | | |
| Forest floor mass, chemistry (W6, W5; 5-yr intervals) | Yale | NSF-LTER | a,b | 1968 |
| Chemical and physical properties from soil pits (W5, valley-wide) | Syracuse/ Cornell | NSF-LTER | a,b | 1984 |
| Chemical and physical properties from soils bags | Syracuse | NSF-LTER | b | 1992 |
| Archived Materials | | | | |
| Herbarium specimens | USFS | * | c | |
| Archived samples (tree cores and cross sections, forest floor, soils, plant tissues, water samples) | USFS | * | c | |
| Library | USFS/ IES/PVF | * | c | |
| Tree cores and cross sections | Yale/ USFS | * | c | |
| Sediment yield in Weir basin | USFS | USFS | a,b | 1956 |
| Phenology | USFS | USFS | a,b | 1989 |
| Mirror Lake thermal profiles | IES | NSF | a,b | 1981 |

**Quantitative Modeling:** We have used the PnET models to better understand biogeochemical processes in northern forest ecosystems and their response to disturbances, and to extrapolate understanding obtained at the HBEF to other northern forest ecosystems. During this funding cycle, the model was expanded to simulate soil processes and major element biogeochemistry of forest ecosystems (PnET-BGC; Gbondo-Tugbawa et al. 2001). The model has been well validated using intensive data sets collected as part of the LTER and a detailed uncertainty analysis has been conducted (Gbondo-Tugbawa et al. 2001, Aber et al. 2002).

**Ecosystem Response to Air Pollution:** The northeastern U.S. receives elevated inputs of acidic deposition originating from high emissions of $SO_2$ and $NO_x$ (Butler et al. 2001, Likens et al. 2001, Driscoll et al. 2001a). Our measurements of bulk deposition provide the longest continuous record of precipitation chemistry in North America. These together with long-term measurements of vegetation, soil water (Palmer and Driscoll 2002, Palmer et al. in press a) and stream waters (Likens et al. 1996, 2002, Palmer et al. in press a) coupled with model calculations (Gbondo-Tugbawa and Driscoll 2002a, 2003) provide a unique opportunity to track the response of acid-sensitive forest and aquatic ecosystems to decreases in emissions of $SO_2$ and $NO_x$ mandated by the Clean Air Act and project future changes that may occur in response to anticipated additional controls on emissions (Likens et al. 1996, Gbondo-Tugbawa and Driscoll 2002b). One of the most interesting and important effects of elevated inputs of acidic deposition is the marked depletion of available $Ca^{2+}$ that has occurred in forest soils (Likens et al. 1998). The extent to which $Ca^{2+}$ depletion impacts trees is species dependent. Some species appear to have the ability to extract $Ca^{2+}$ directly from soil minerals, while others (e.g., sugar maple) may be susceptible to significant decline due to Ca depletion (Blum et al. 2001).

To assess the effects of $Ca^{2+}$ depletion on the structure and function of the forest ecosystem we added 45 tonnes of wollastonite ($CaSiO_3$) to watershed 1 at the HBEF, essentially restoring the Ca status of soil to values prior to the onset of acidic deposition. The application was funded by a five-year grant from the NSF Ecosystem Studies program, but we view this as a 50-year experiment. Unique Ca/Sr and $^{86}Sr/^{87}Sr$ ratios in the wollastonite have allowed us to trace the movement of the added Ca into specific soil, plant and animal pools and to evaluate its effect on biogeochemical processes (Hall et al. 2001, Fiorentino et al. 2003, Peters et al. in press).

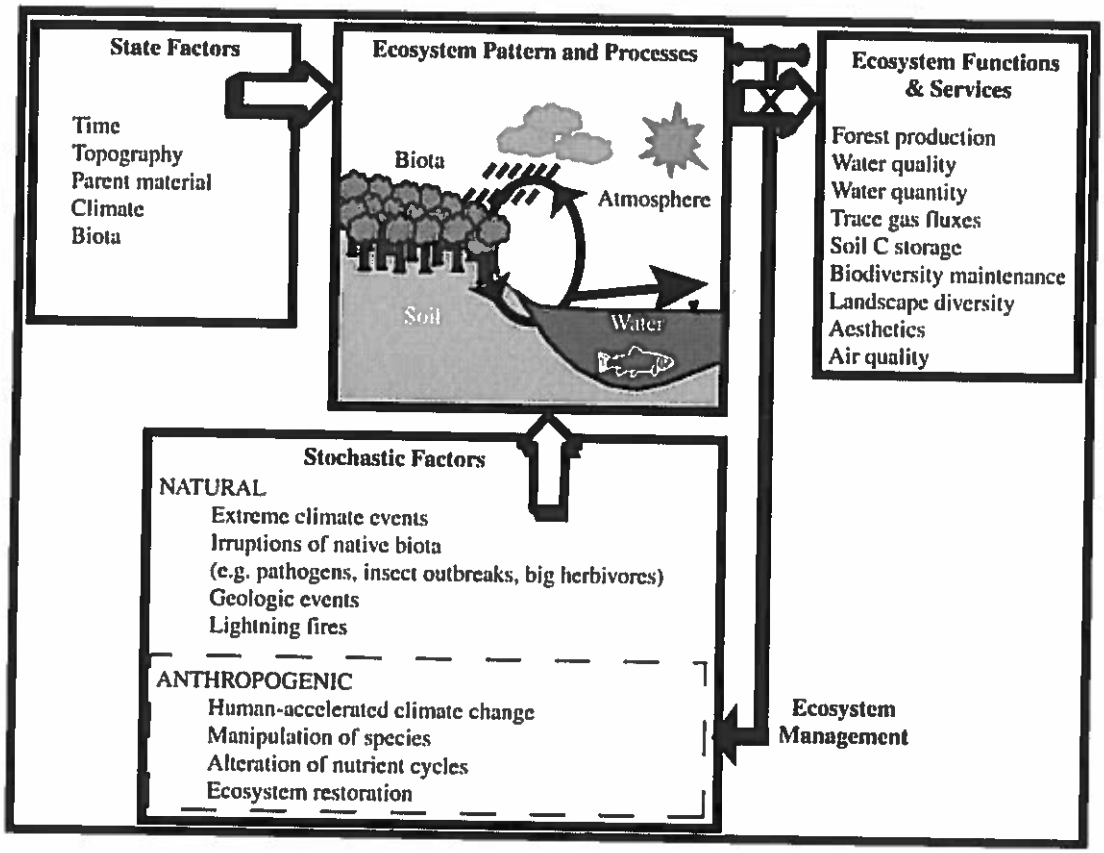


**Figure 1**. A new conceptual diagram for the Hubbard Brook Ecosystem Study, showing how state factors and variable-stochastic factors influence ecosystem pattern and process and, ultimately, ecosystem functions and services. Management actions can be directed to mitigate stochastic factors that are caused by human activities and, therefore, to improve ecosystem functions and services.

**Ecosystem Response to Non-catastrophic Disturbances**: Overwinter and snowmelt processes are critical controllers of biogeochemical cycling and element retention and loss in northern forests. We used funding from the Terrestrial Ecosystems and Global Change (TECO) and NSF Ecosystem Studies programs to manipulate early winter snow cover to induce soil-freezing events in experimental plots at the HBEF. Severe soil freezing events occur periodically (~ 1/10yr) at the HBEF and have been observed to coincide with elevated $NO_3^-$ loss (Mitchell et al. 1996, Likens and Bormann 1995, Fitzhugh et al. 2003a). Snow removal resulted in mild freezing (>-5°C; Hardy et al. 2001) that produced surprisingly dramatic increases in root mortality (Tierney et al. 2001) and elevated leaching of $NO_3^-$ and other solutes during the following

growing season (Fitzhugh et al. 2001, 2003b). Surprisingly, mild freezing events did not increase mineralization or nitrification (Groffman et al. 2001a,b) suggesting that mild freezing (which is likely to increase under a warmer climate) increases nutrient loss by physical disruption of root microbial interactions.

In January 1998 a severe ice storm damaged large areas of the Northeast, including the HBEF. We received SGER funds from the NSF to use the ice storm disturbance as a test of many of the basic concepts about disturbance and recovery developed at HBEF over the past 40 years. The ice storm reduced leaf area by 50% over much of the experimental watersheds of the HBEF (Rhoads et al. 2002) and resulted in elevated losses of $NO_3^-$, cations and acid neutralizing capacity in soil solutions and stream water during the following growing season (Houlton et al. 2003). The extent of $NO_3^-$ loss was reduced by in-stream $NO_3^-$ retention, which increased due to the formation of debris dams in streams in ice-damaged areas (Bernhardt et al. 2003). Because we observed no increases in N mineralization or nitrification in highly damaged areas relative to reference areas, we concluded that the increased $NO_3^-$ losses were due to reductions in plant uptake. This conclusion was confirmed as $NO_3^-$ levels returned to baseline once leaf area recovered from the ice damage. A survey of forest watersheds across the White Mountains revealed similar $NO_3^-$ loss patterns for second-growth forests, but much lower $NO_3^-$ loss for forests that were previously used for agriculture (Houlton et al. 2003).

**Large-scale Disturbance and Recovery:** Following large-scale disturbances (i.e., the clear-cutting of watersheds 2 and 5 at HBEF), $NO_3^-$ leaching from forest soil is greatly increased. This N loss was readily detected as a transient change in the $\delta^{15}N$ of tree foliage in the recovering forest (Pardo et al. 2002). Much of the N loss is from surface soil organic horizons, but the magnitude of change in this large ecosystem pool is smaller than earlier chronosequence studies had indicated (Yanai et al. 2003). Fertilization trials suggested that changes in microbial growth and turnover were responsible for these forest floor responses (Fisk and Fahey 2001). Forest canopy development in the recovering forest also responded to changes in nutrient availability via plasticity in specific leaf area and N concentration in pioneer species (Cramer et al. 2000).

**Forest Dynamics:** We have examined the interacting roles of environment, tree species and neighborhood effects in regulating spatial and temporal patterns of vegetation distribution. The interactions between the two dominant species, sugar maple and beech, are mediated both by relatively frequent diffuse disturbance events (Hane 2003) and by phytotoxic effects (Hane et al. 2003). The key role of neighborhood effects in regulating tree abundance patterns was indicated by a highly significant residual spatial autocorrelation in distribution of six tree species after accounting for environment and disturbance history effects (Schwarz et al. 2003). The probable role of dispersal limitation and vegetative reproduction was suggested by the observation that only the very widely-dispersed species (e.g., yellow birch) did not show such residual auto-correlation and by concordance in the scale of autocorrelation and reproductive traits of the other six species (Schwarz et al. 2003). At the regional scale, presettlement forest patterns reinforced the observation that the HBEF lies at the dynamic interface between the evergreen boreal forest and the deciduous forest biome (Cogbill et al. 2003) where climatic change can be expected to cause compositional shifts in coming decades.

**Heterotroph Populations:** A diverse assemblage of neotropical migrant songbirds forms a key link in the herbivore food chain. New approaches to the study of migrations (Webster et al. 2002), including stable isotopes (Blum et al. 2001, Rubenstein et al. 2002), together with quantitative studies in wintering and breeding grounds, have revealed how events throughout the annual cycle affect population sizes (Sillett and Holmes 2002). For example, ENSO events affect demographic parameters of black-throated blue warblers both in tropical wintering habitats and at HBEF (Sillett et al. 2000). Forest structural changes affect long-term trends in bird population sizes (Holmes and Sherry 2001), and migratory bird populations can be regulated by density-dependent fecundity occurring in breeding areas (Rodenhouse et al. 2003). Less is known about the long-term declines in Lepidoptera larvae (Holmes, unpubl. data), the primary food source for many migratory birds, and salamanders (Likens, unpubl. data).

**Landscape-scale Patterns:** We have initiated a major effort to understand variation in ecosystem structure and function across the entire 3,000 ha HBR valley; expanding the scope of our analysis from the series of small (10 – 30 ha) watersheds that have been the focus of most HBR research. Analyses have focused on the ways in which soil and topographic factors interact with vegetation composition and dynamics to influence base cation weathering (Johnson et al. 2000) dissolved organic carbon mobilization (Palmer et al. in press b, Campbell et al. 2000) and N dynamics (Campbell et al. 2000, Bohlen et al. 2001, Venterea et al. 2003). Soil depth and soil water contact time are also important in regulating these patterns (Johnson et al. 2000). These studies greatly facilitate our efforts to scale up results from HBEF to larger areas within the northeastern U.S.

**Education/Outreach:** During the most recent funding cycle we used LTER funds to reach out to learners at all educational levels. We expanded the HBR web page to include activities and information that K-12 science teachers use in curriculum development. We also improved materials that are used to support tours of the HBEF. Through the New England Science Center Collaborative (25 science centers and research institutes), we have been involved in regional climate change education, with both on and off site educator training.

Our outreach activities largely occur through the *Science-Links* program of the HBRF. This program provides a synthesis of environmental issues that are important to the Northeast region. Each project includes the development of a synthesis article published in a peer-reviewed journal, a general article, and a series of outreach events by a team of researchers who work on the environmental issue at HBR or elsewhere in the region. Projects on acid rain (Driscoll et al. 2001a,b) and nitrogen pollution (Driscoll et al. 2003a,b) were completed during the last funding cycle. Outreach events included press briefings at the National Press Club, briefings to congressional staff, state agencies, NGOs, congressional testimony and numerous interviews with reporters.

**Project Integration:** Integration of the research conducted as part of the HBES has traditionally involved production of synthetic books (Bormann and Likens 1979, Likens and Bormann 1995). More recently, we have focused on a series of synthetic monographs of element biogeochemistry at the HBEF. During this funding cycle detailed articles on the biogeochemistry of $Ca^{2+}$ (Likens et al. 1998), S (Likens et al. 2002), $Cl^-$ (Lovett et al. in revision) and C (Fahey et al. in review) have been developed. We have published an integrated series of articles on our soil freezing

experiments (Groffman et al. 2001a,b, Hardy et al. 2001, Tierney et al. 2001, Fitzhugh et al. 2001) and an integrated analysis of the forest response to the ice storm event (Rhoads et al. 2002, in press, Houlton et al. 2003, Bernhardt et al. 2003). The *Science-Links* synthesis articles are also examples of project integration (Driscoll et al. 2001a, 2003a). The HBES investigators meet quarterly to discuss both scientific and administrative issues, and the Annual Cooperators Meeting provides an opportunity for all HBES researchers to present their latest findings.

**Network Participation and Cross-site Studies:** We continue to participate actively in LTER network and cross-site activities. During the last funding cycle we contributed several chapters to the LTER Soils Methods volume, initiated the development of a primary productivity methods volume and participated in the development of the LTER hydrology database (HYDRO-DB). We co-organized several workshops at the LTER All-Scientist meetings and are presently involved with follow up cross-site proposals. We are coordinating a cross-site study of root uptake from mature trees, conducted at forested sites (Kulpa et al., in review; McFarlane and Yanai, in review). Currently, S. Hamburg, co-chair of the US-LTER International Committee, is coordinating efforts to integrate ILTER into a wider range of LTER research. HBR scientists have also taken the leadership role in developing a network of ecosystem researchers in the Northeast: the Northeastern Ecosystem Research Cooperative (NERC). The NERC, which was begun in 2000, has been highly successful in its goals of promoting the sharing of information, synthesis of results and collaborative regional research among ecosystem scientists in the Northeast (see NERC web site at www.ecostudies.org/nerc/). The NERC currently has over 20 funded projects, many of which involve HBR and other LTER investigators.

**Information Management and Technology**: The HBR-LTER acquires, manages and disseminates data and information collected at the HBEF and nearby sites to facilitate research, education and outreach activities. Our data and information management activities have improved substantially over the last funding cycle. The HBR database includes core data sets that comprise long-term measurements and experiments, as well as data from shorter-term studies. We do not track the use of the web site, but we know it to be widely used, particularly by schools and university classes.

**Site Management:** During the recent funding cycle, we reorganized the management/governance of the HBES (Groffman et al in press b). The new structure includes a "Committee of Scientists" (COS), consisting of principal investigators conducting research at the HBEF. The Scientific Coordinating Committee, (SCC) is elected by the COS and oversees committees, provides vision and scientific leadership to the research program, fosters integration and synthesis across diverse projects, encourages new scientists and diversity among the research community, and promotes communication. Other committees under the SCC include the Research Approval committee, the Information Oversight Committee, the Programs and Meeting Committee, and the Education and Outreach Committee.

## 2.0 – PROPOSAL NARRATIVE

### I. Introduction

A. General

Over the past forty years the research team of the Hubbard Brook Ecosystem Study (HBES) has sought to better comprehend the ecological patterns and processes that characterize northeastern forested landscapes. Our efforts have contributed to the development of general ecological knowledge and more specific qualitative and quantitative understanding of the Hubbard Brook Experimental Forest (HBEF) and the northeastern region. Despite this history of research at the HBEF, our long-term measurements and experiments have recently provided us with many surprises that cannot be explained given our current understanding of ecosystem dynamics. For example:

- Base cation ($C_B$) concentrations in surface waters have declined steadily since 1970, mostly reflecting the depletion of soil available $C_B$ by leaching from acidic deposition. However, despite the large removal of $C_B$ that accompanied the whole-tree harvest of watershed 5 (W5), as well as the high rate of $C_B$ accumulation in the recovering forest vegetation, concentrations of $C_B$ in streamwater draining W5 remain considerably higher than in the undisturbed reference W6 (Fig. 2).

- A severe ice storm in 1998 devastated extensive areas of forest in the HBEF, reducing canopy leaf area index by half and stimulating high $NO_3$ losses. However, plot-level studies revealed no increases in net N mineralization or nitrification in severely disturbed areas, and the intercept of strong relationships between LAI reduction and stream $NO_3^-$ concentration differed markedly between two mature forest watersheds (W1 and W6, Fig. 3). Moreover, a broader survey indicated that the $NO_3^-$ leaching response to ice storm damage differed strikingly among small, forested watersheds in the region.

- During the period 1963-1990, severe soil freezing events resulted in high $NO_3^-$ fluxes from soils with consequent depression of surface water acid neutralizing capacity (ANC). Plot-level studies indicate that disruption of roots and the mycorrhizae-soil complex is the principal cause of this response. However, since 1990 $NO_3^-$ flux from the HBR watersheds has been insensitive to soil freezing events.

- Patterns of forest net primary productivity (NPP) can be predicted with a mechanistic simulation model (PnET) based upon ecological interactions observed at the HBEF and these predictions can be extended to broader spatial scales using remotely-sensed estimates of foliar N concentration (Fig. 4). However, the magnitude of recent declines in NPP at the HBEF is substantially under-predicted in the model, suggesting that some important controls of NPP in forests under multiple stresses are not incorporated into current models.

- The long-term pattern of N loss from the biogeochemical reference W6 can be accurately simulated using PnET for the period 1963-1990 ($r^2 = 0.51$), being explained largely by climatic variations (Fig. 5). However, during the last 14 years the model has consistently

over predicted N loss, suggesting the possibility that fundamental shifts in important N cycling processes have occurred.

- The composition of the mature forest in the gauged watersheds has been shifting gradually away from sugar maple dominance as a result of high mortality and low seedling recruitment (Fig. 6). In 2003, following a "mast" year of sugar maple reproduction, the nutrition, growth, and survival of maple seedlings on W1, which was treated with Ca addition in 1999, were greatly enhanced over adjacent reference stands (Fig. 7). In addition, the severity of winter injury to red spruce populations on W1 was dramatically lower than adjacent reference stands (Fig. 8).

- Striking shifts in the composition of the bird community that have occurred since sampling began in 1969 can be explained in part by changes in forest structure and composition; however, long-term declines in the overall abundance of birds (Fig. 9) as well as other heterotroph groups – Lepidopteran larvae, salamanders and snails – remain largely unexplained and may depend upon shifts at multiple levels as the ecosystem responds to compounded stresses and perturbations.

This selection illustrates the overall framework for discovery on which the HBES is based. We combine a carefully chosen suite of long-term monitoring activities conducted at the scale of the small watershed-ecosystem with experiments, surveys and models to address questions about ecosystem response to perturbations. The small watershed approach allows us to quantify mass-balance budgets and serves as the scale for selected experimental manipulations and for comparative surveys of ecosystem function. Long-term measurements have been essential to the detection of subtle but important trends in ecosystem structure and function as well as serving as a baseline for taking advantage of "natural experiments" presented by climatic and biotic perturbations (e.g., the 1998 ice storm). Our research is applied at the larger scales of the entire Hubbard Brook (HBR) Valley and the Northeast region using both extensive surveys and simulation models. Finally, the results of our research are applied to inform environmental policy and public education by a variety of approaches, including the *Science-Links* Program of the Hubbard Brook Research Foundation (HBRF). The LTER Program is both the intellectual and funding underpinning of the HBES. In addition to facilitating the continuation of our long-term program of research, the LTER has stimulated intensive efforts of integration and synthesis within the HBES (Likens et al. 1994, 1998, 2002) and concerted efforts to improve our data management system (http://www.hubbardbrook.org). Moreover, through the LTER program we have looked outward to an increasing extent in regional, continental and international comparisons and syntheses (Aitkenhead and McDowell 2000, Ohte et al. 2001, Aber et al. 2002, Driscoll et al. 2001a, 2003a).

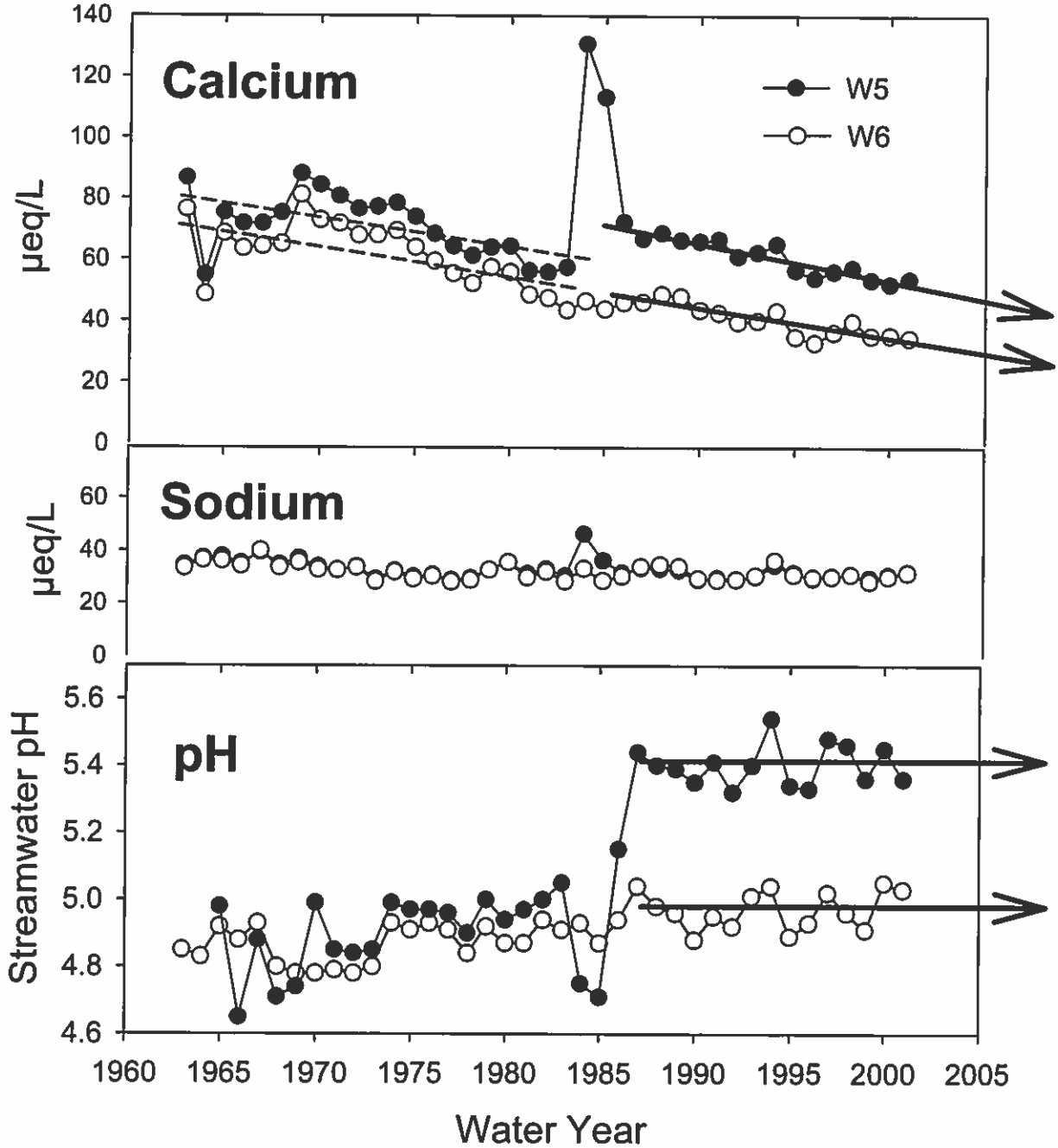


**Figure 2.** Time series of annual volume-weighted concentrations of $Ca^{2+}$, $Na^{+}$ and pH in stream water in W5 (whole-tree harvested) and W6 (reference). Note that following the W5 clear-cut, $Ca^{2+}$ and pH have increased relative to W6 values.

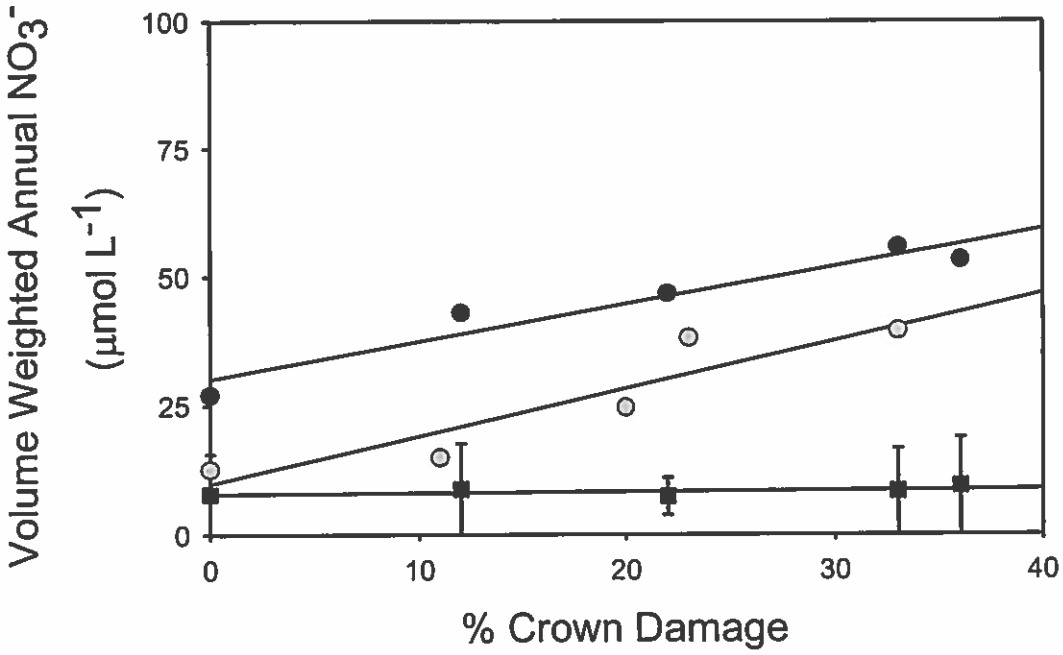


**Figure 3.** Relationship between volume-weighted annual $NO_3^-$ concentrations in stream water and sub-basin crown damage factor before (1991-97: ■; $r^2$ =0.24) and following the ice storm in W1 (1998: •; $r^2$ = 0.90) and in W6 (1998: ○; $r^2$ = 0.85) at the HBEF (after Houlton et al. 2003). Standard deviations were calculated from long-term means.

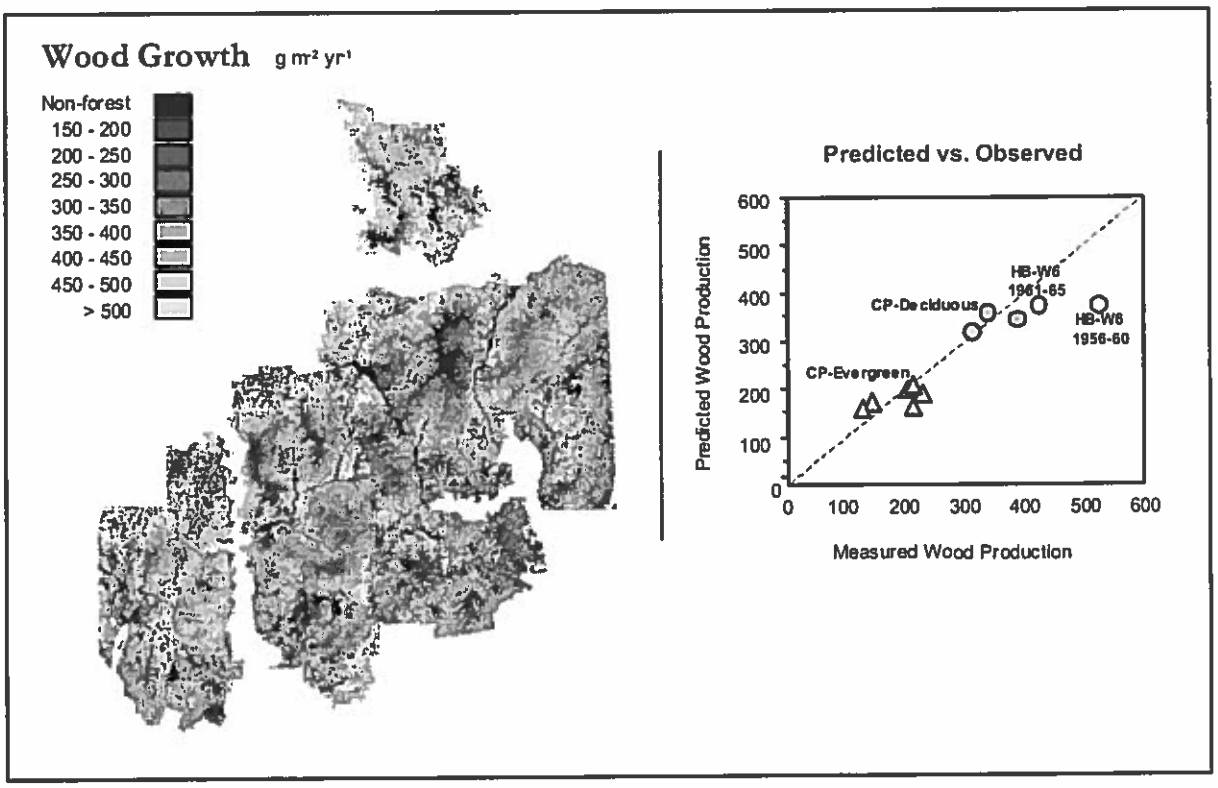


**Figure 4.** Predicted forest productivity based on AVIRIS canopy N and field data (after Smith et al. 2002).

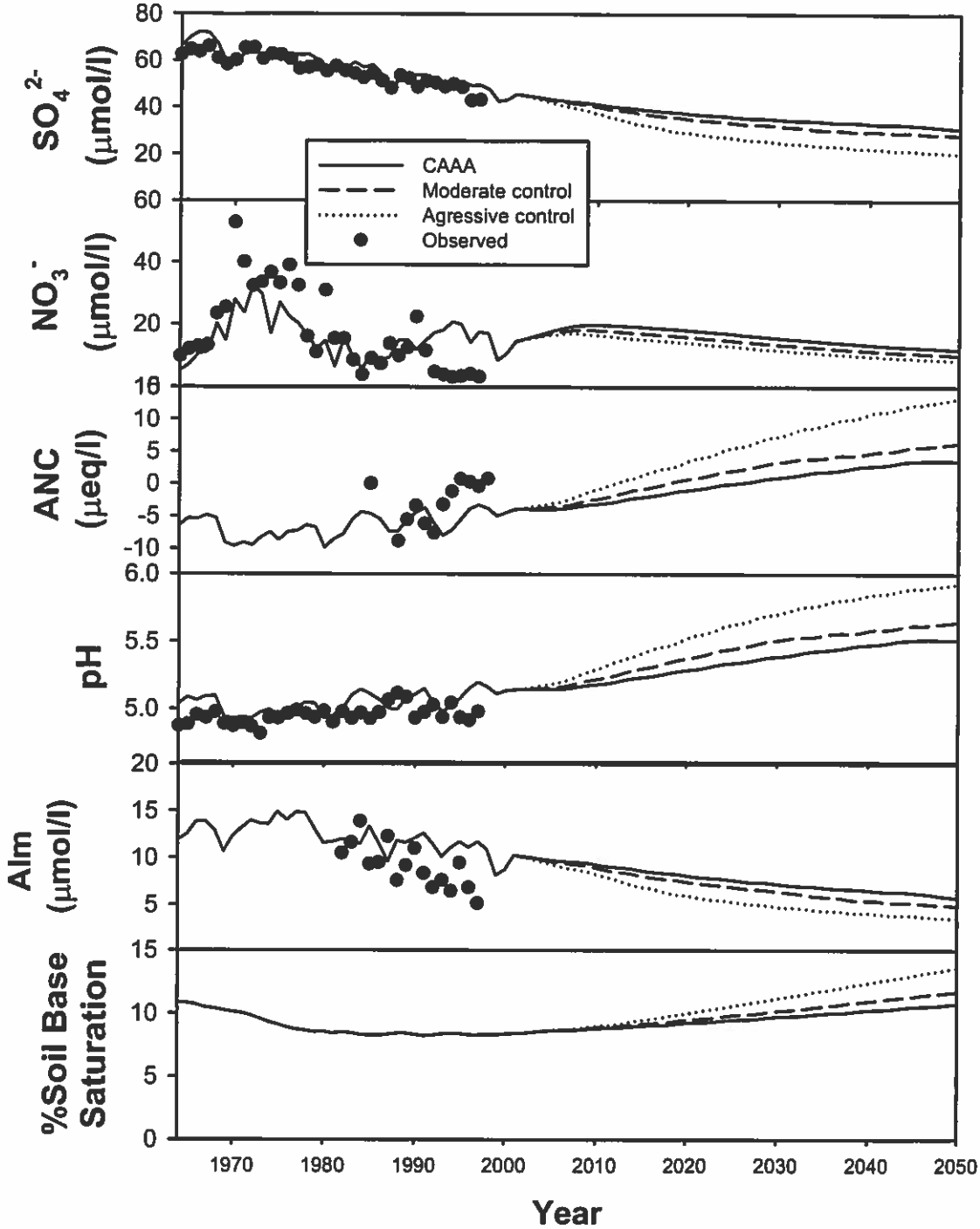


**Figure 5.** Predictions of annual volume-weighted concentrations of $SO_4^{2-}$, $NO_3^-$, ANC, pH, and monomeric Al in stream water and soil % base saturation for W6 of the HBEF for the period 1963-1999 using PnET-BGC in comparison with measured values, and future projections of response to scenarios of changes in atmospheric deposition (2000-2050). Scenarios are based on expected atmospheric deposition under the 1990 Amendments of the Clean Air Act, and moderate and aggressive proposals for additional controls of $SO_2$ and $NO_x$ emissions for electric utilities (updated after Gbondo-Tugbawa and Driscoll 2002). Note the model over-predicts $NO_3^-$ after about 1990 and this causes under-predictions of ANC and over-predictions of Al.

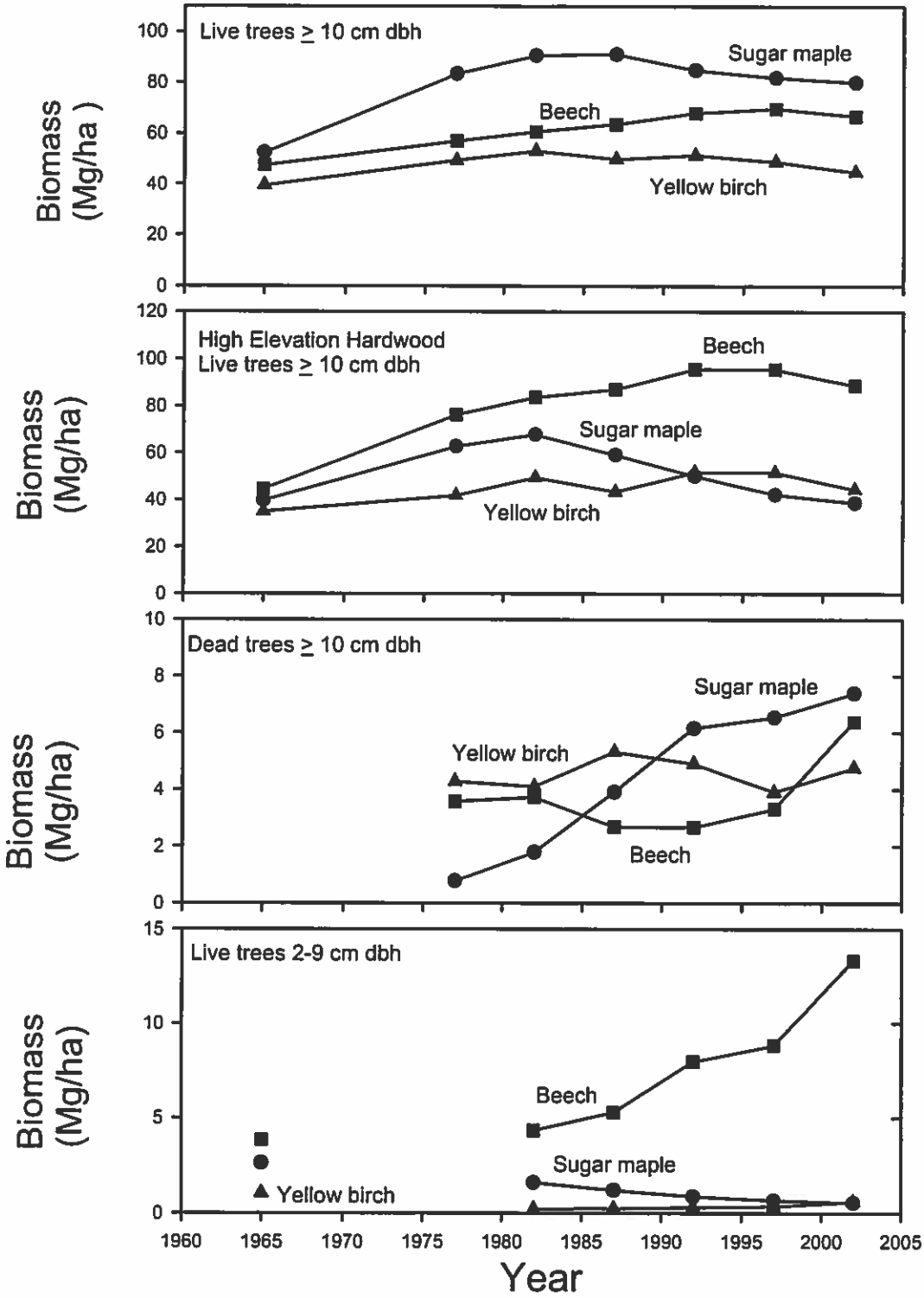


**Figure 6.** Time series of biomass in W6 at the HBEF, including total live trees (≥ 10 cm dbh), live trees (≥ 10 cm dbh) in the high elevation hardwood zone (650-750m), dead trees (≥ 10 cm dbh) and total live trees (2-9 cm dbh). Note the marked decrease in sugar maple biomass, particularly at high elevation, and the decrease in sugar maple seedlings.

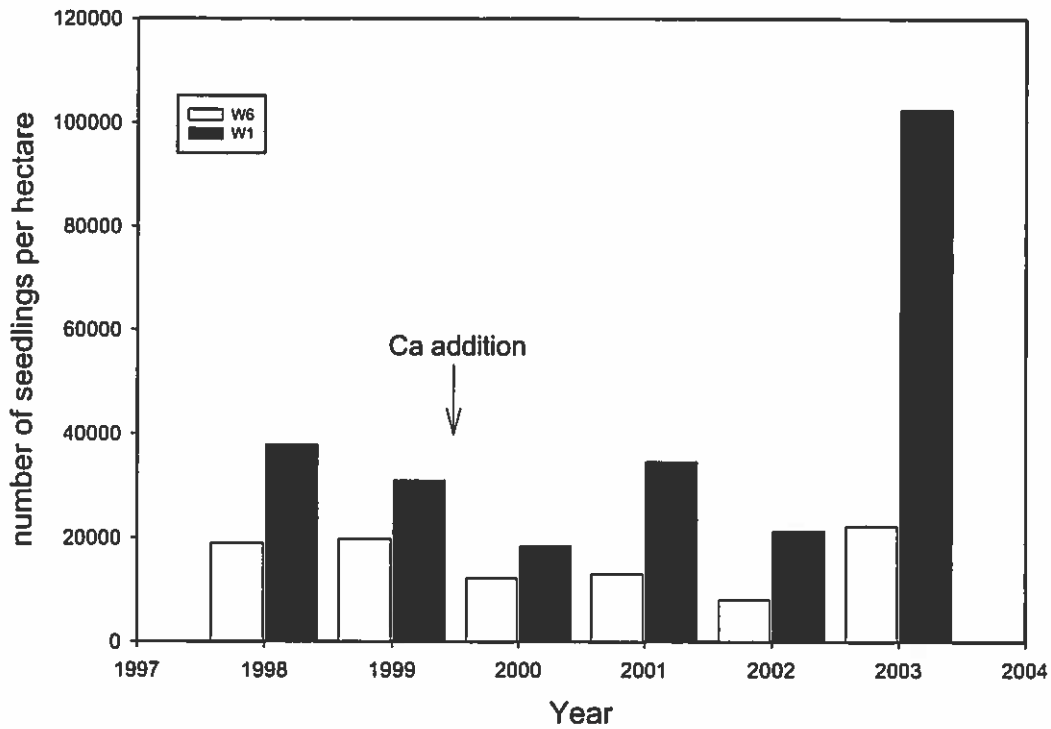


**Figure 7.** Time series of number of seedlings of sugar maple/ha in the hardwood zone of Ca-treated (W1) and reference (W6). Note that $CaSiO_3$ treatment of W1 occurred in 1999 and a large increase in sugar maple seedlings occurred in 2003.

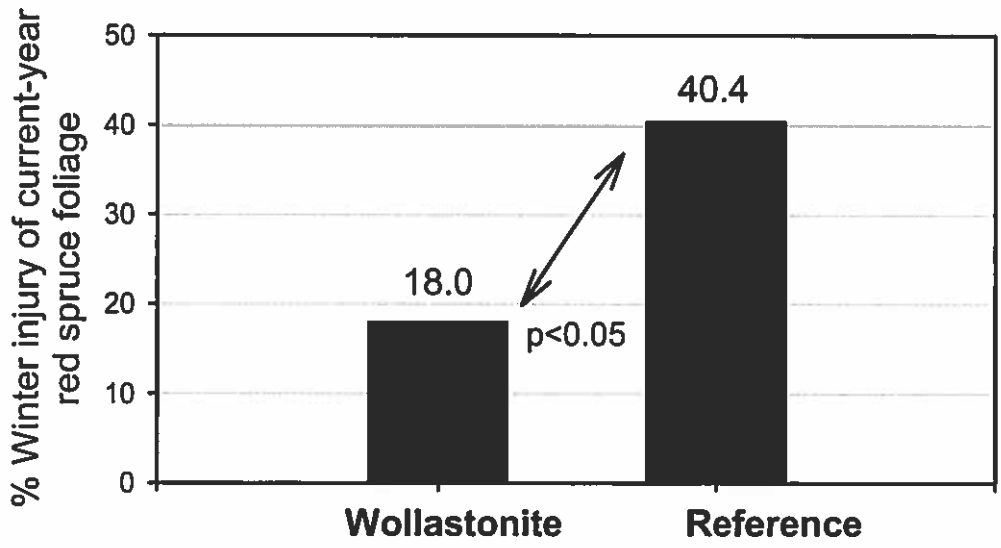


**Figure 8.** Comparison of % winter injury of current-year red spruce foliage in wollastonite treated watershed (W1) with reference site at the HBEF (G. Hawley unpublished data).

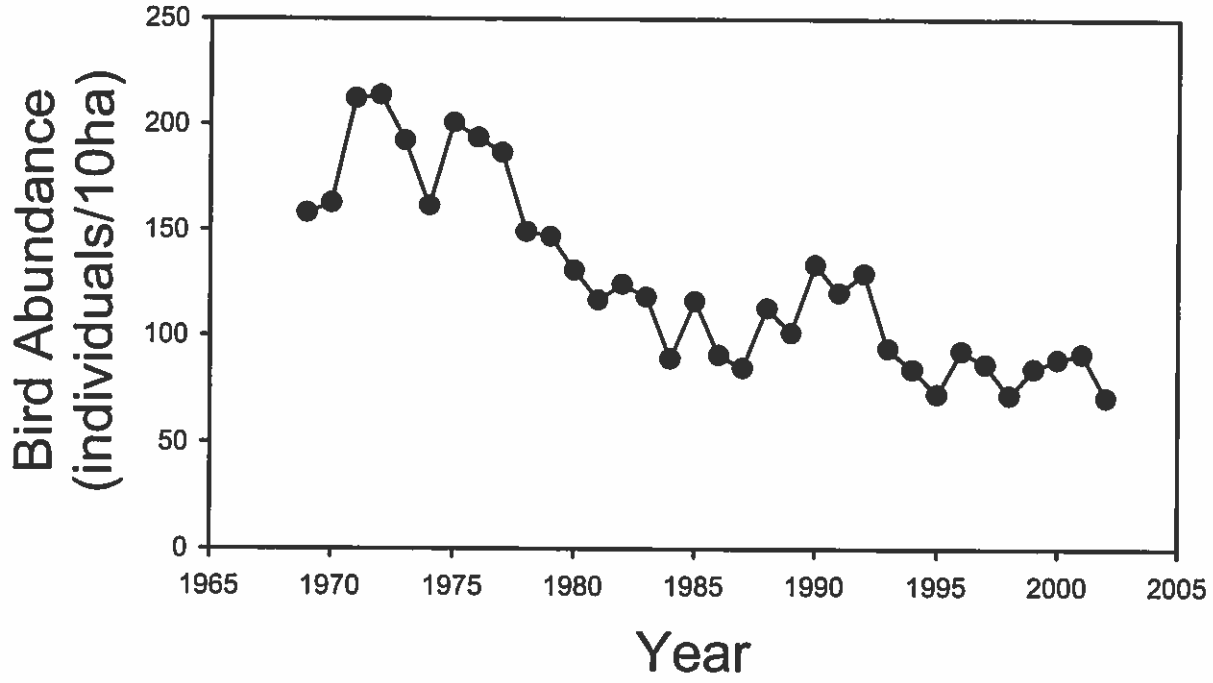


**Figure 9.** Long-term trends in bird abundance at the HBEF. Data show a long-term decline in bird populations.

B. Research Themes and Driving Questions

Our LTER research program is organized around the theme of ecological perturbations, especially those that have been profoundly altered by human activities. Although we recognize that northeastern forests experience compounded perturbations, we have structured this proposal around three principal categories of perturbations: 1) chronic air pollution especially components of acidic deposition; 2) large-scale catastrophic disturbance, such as intense hurricanes and clearcut harvest; and 3) diffuse episodic disturbances, which includes forest-wide phenomena like ice storms and species-specific events like diseases and declines. Our research focus remains at the whole ecosystem level of organization, building an improved understanding of nutrient cycling and energy flow and recognizing the overarching role that biological activity, especially species distribution and abundance, plays in mediating the influence of perturbations on ecosystem structure and function.

Our overall research program continues to seek a better understanding of the complex interconnections governing ecosystem behavior. Ongoing theoretical developments in ecosystem science provide an exciting context for our inquiries. These concepts emerge repeatedly as themes in the research proposed here: 1) compounded ecological perturbations, 2) hysteresis phenomena in ecosystem processes, and 3) stoichiometric coupling among element cycles. Our research explores the connections among these interrelated concepts and how they vary across complex landscapes. While most ecological studies attempt to isolate the effects of single disturbance, natural ecosystems are subject to **compounded perturbations** that are capable of dramatically altering ecosystem structure, function and composition (Paine et al.

1998). For example, the HBEF and surrounding landscapes are still recovering from historical land use and natural catastrophic disturbances, and they are simultaneously responding to air pollution and associated soil chemical changes, irruptions of exotic pests and changes in climate. The complexities of multiple perturbations may lead to a variety of **hysteresis phenomena** that challenge our quantitative understanding of ecosystem dynamics. In general, the term hysteresis refers to dependence in the behavior or states of natural systems on antecedent conditions, and in the ecological realm the connection between hysteresis in environmental drivers and the existence of alternate stable states in ecosystem composition and structure are particularly noteworthy (Carpenter et al. 1999, Frelich and Reich 1999). An intriguing pattern of hysteresis has been observed in the long-term acid-base status of stream water during the period of increasing inputs of acidic deposition (1963-1968) and subsequent decreases in response to $SO_2$ emission controls (Fig. 10). Note that during the recovery phase, stream waters were depleted in $C_B$ for a given concentration of strong acid anions relative to conditions observed during acidification. Long-term observations such as this exemplify the scope for discovery of fundamental mechanisms in biogeochemistry. Investigation of the role of **stoichiometric coupling among element cycles** in explaining complex biogeochemical phenomena (such as hysteresis) was stimulated by the observations of Reiners (1986), building on earlier formulations (Redfield 1958), that ecosystem dynamics are defined by complementary models governing energy flow and material cycling, the latter being dependent upon the ratios of nutrient elements in the environment and biota. In the past decade we focused our synthesis efforts in summaries of the behavior of individual elements in the HBR ecosystem (Likens et al. 1984, 1998, 2002; Lovett et al., in review; Fahey et al., in review), and we now face the challenge of exploring element interactions and advancing theoretical concepts of ecosystem stoichiometry (Vitousek et al. 1987, Elser et al. 2000, Sterner and Elser 2002).

In the broadest sense we seek to uncover the complex causal web governing the range of intriguing observations of long-term ecological patterns and processes in the HBEF outlined at the outset and to interpret this web of interactions in the framework of these theoretical advances in ecosystem science. This goal can be exemplified in the form of overarching questions that emerge from these observations:

- Is there a mechanistic connection among landscape-scale variation in observed depletion of soil base cations, reduction of forest NPP and declining live biomass, and increased retention of atmospheric N deposition in the mature forest at the HBEF? For example, has an efficient system of plant acquisition of limiting nutrients for maintaining stoichiometric requirements been disrupted by compounded perturbations of forest harvest and acidic deposition?

- As inputs of acidic deposition continue to decline and ecosystem solutions become more dilute (Fig. 11, 12), what are the geochemical limits on the acid-base stoichiometry of soil and surface waters that define steady-state pH and ANC, and dissolved Al concentrations and speciation? Do changes in soil chemistry together with other perturbations, cause changes in forest community composition that feed back to create hysteresis in soil and surface water chemical response to changing atmospheric deposition?

- Are the simultaneous declines in a variety of heterotrophic guilds in the HBEF mechanistically connected to changes in forest NPP, soil base status and tree nutrition?

- Do changes in element stoichiometry provide insights into the mechanisms influencing hysteresis in seasonal and long-term surface water chemistry? For example, are recent declines in dissolved organic carbon (DOC) concentrations in ecosystem solutions connected with a long-term hysteresis in patterns of soil C, acid-base balances, or stream $NO_3^-$ or dissolved organic N (DON) concentrations?

In this proposal we describe our ongoing program of long-term measurements and a series of new research initiatives designed to provide answers to these and related intriguing questions about the behavior of the HBR ecosystem. Through this program of continued monitoring, field surveys and experiments and simulation modeling we hope to contribute significant new knowledge to advance theoretical understanding of ecosystem dynamics and the application of that knowledge towards the solution of environmental problems.

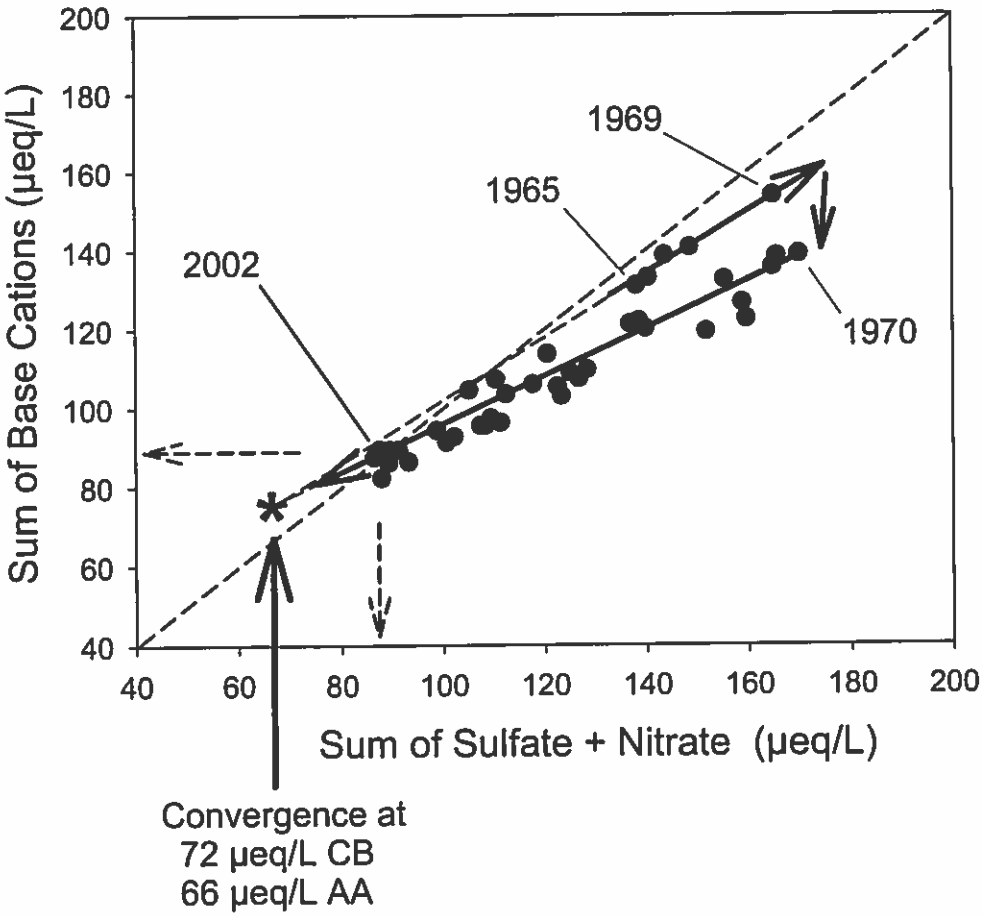


**Figure 10**. Annual volume-weighted concentrations of the sum of basic cations ($C_B$) in comparison to the sum of concentrations of $SO_4^{2-}$ and $NO_3^-$ in stream water of W6 at the HBEF. Note the pattern of hysteresis in acid-base chemistry. During the recovery phase, stream waters were depleted in $C_B$ for a given concentration of strong acid anions relative to conditions observed during acidification. The 1:1 line represents ANC = 0 µeq/L (updated after Likens et al. 1996).

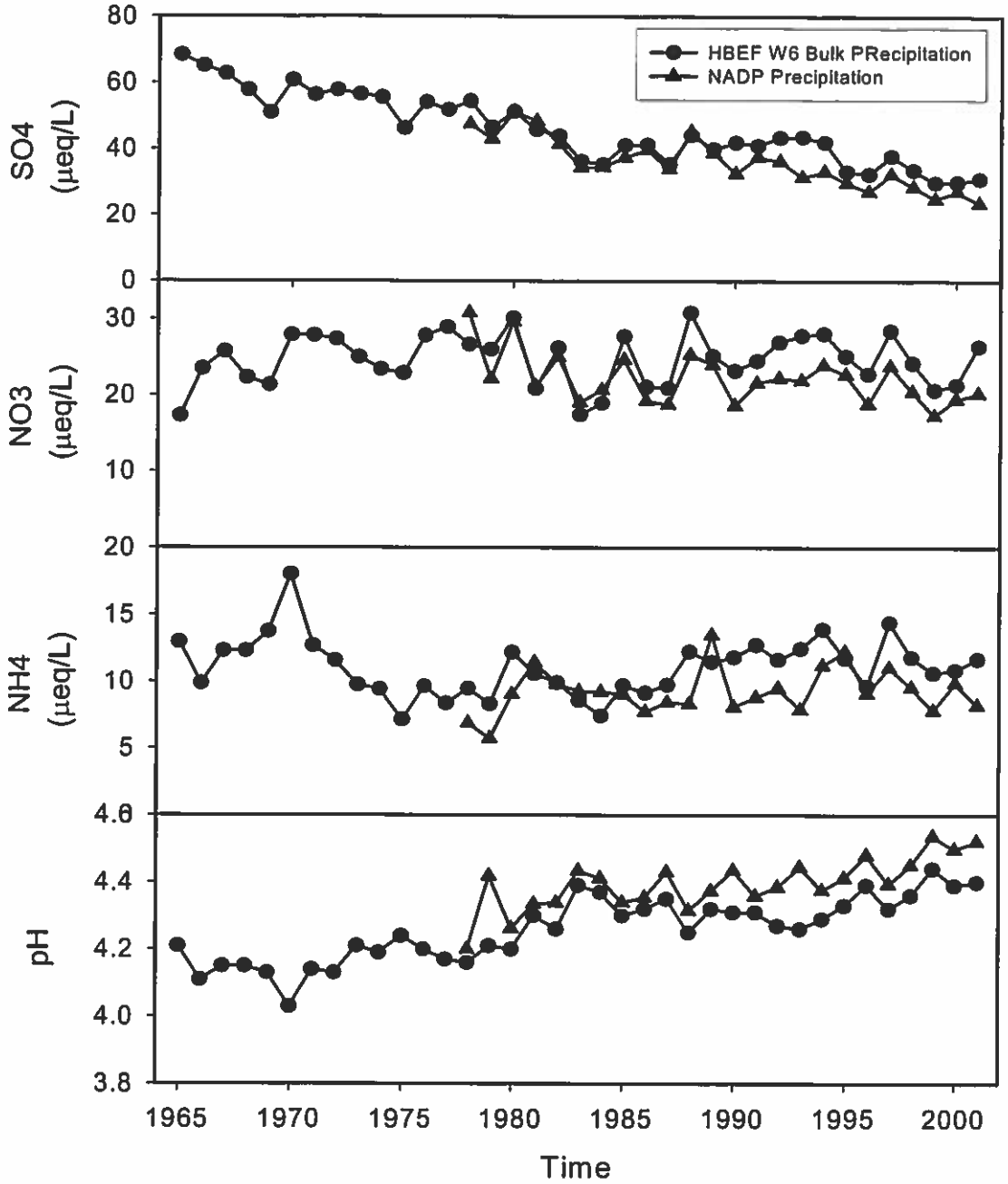


**Figure 11.** Annual volume-weighted concentrations of $SO_4^{2-}$, $NO_3^-$, $NH_4^+$ and pH in bulk and wet-only precipitation in W6 at the HBEF. Note there have been significant decreases in $SO_4^{2-}$ and increases in pH.

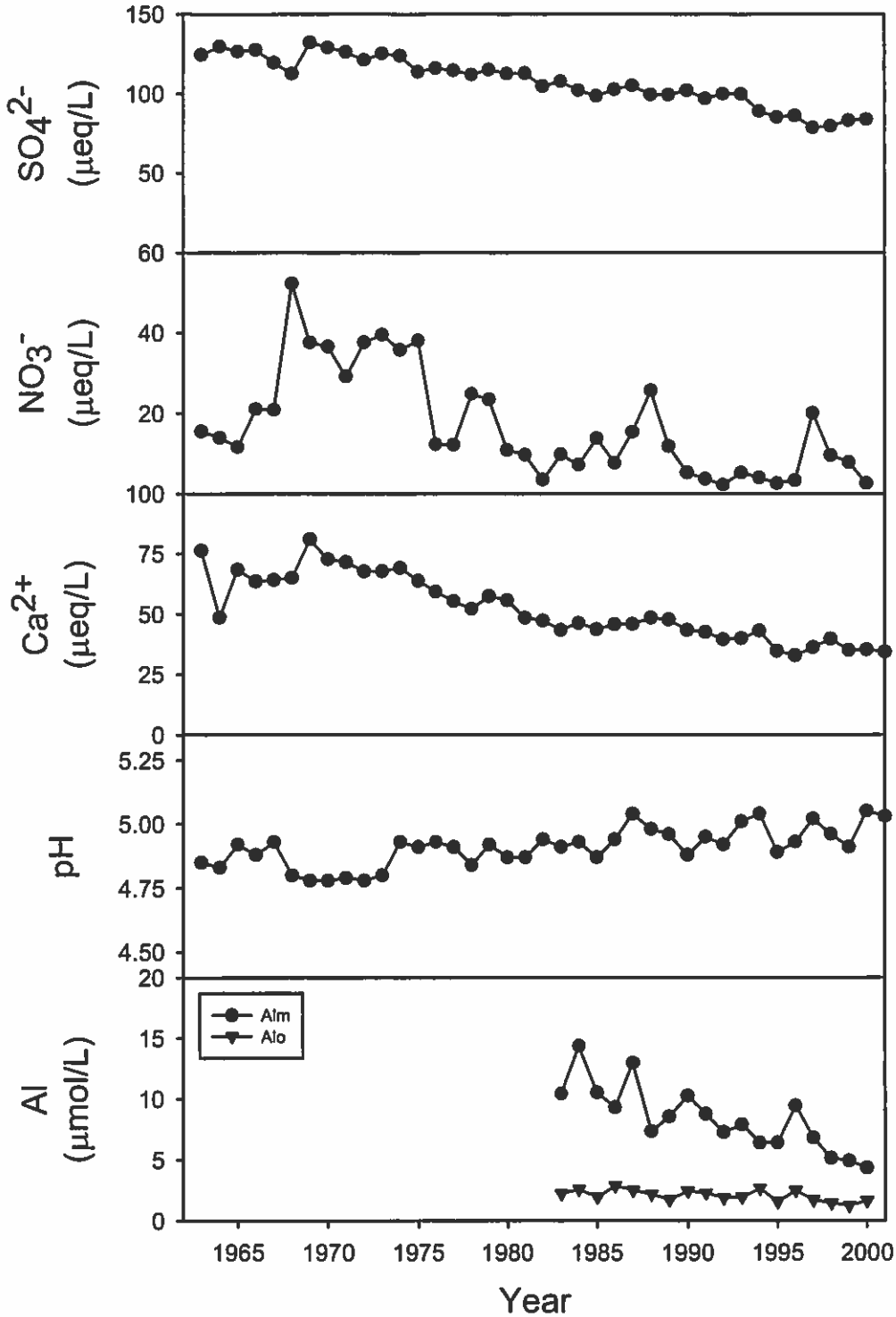


**Figure 12.** Annual volume-weighted concentrations of $SO_4^{2-}$, $NO_3^-$, $Ca^{2+}$, pH and Al species in stream water inW6 at the HBEF. Note that Al measurements include monomeric Al ($Al_m$) and organic monomeric Al ($Al_o$). Inorganic monomeric Al ($Al_i$) is the difference between $Al_m$ and $Al_o$, There have been significant decreases in $SO_4^{2-}$, $NO_3^-$, $Ca^{2+}$ and $Al_i$ and increases in pH.

C. Study Sites

Most of the research in the HBR-LTER project is concentrated at the HBEF in the White Mountains of central NH. Because of space limitations we refer readers to detailed descriptions of the climate, soils, vegetation, and history of the HBEF at our website (http://www.hubbardbrook.org). At the HBEF we have been using the small watershed approach to quantify the response of forest and aquatic ecosystems to disturbance, and several experimental watersheds on the south-facing slope have been manipulated for this purpose (Table 3). Increasingly we have broadened the scope of our studies to encompass the wider HBR Valley including north-facing experimental watersheds and additional landscape elements at HBEF. For example, Mirror Lake is a small (15 ha), clearwater lake near the mouth of Hubbard Brook. Extensive research has been done on the limnology, hydrology and paleoecology of the lake (Likens 1985; Bukaveckas et al. 1998; Rosenberry et al 1999; Winter et al 1989). We have measured precipitation and flow of the inlets and outlet for the lake since 1965, and propose to continue these measurements as part of this LTER. Detailed data on the inlets and outlet streamflow and groundwater flux for the lake are provided from the USGS (www.usgs.gov).

The HBR-LTER also encompasses other regional forested sites that provide further context for studies at the HBEF. In particular, The Bowl Natural Area (BNA) is a nearby large watershed (206 ha) with no history of logging, human settlement or forest fire (Leak 1973), but in other respects closely resembles HBEF. The HBR-LTER has supported periodic surveys of forest vegetation and element cycling at BNA that follow on earlier efforts (Martin 1979) and provide a comparative basis for interpreting temporal patterns at HBEF (Martin et al. 2000, Schwarz et al. 2001). We are also conducting research at the Bartlett Experimental Forest (BEF), located about 30km east of the HBEF, where silvicultural treatment of forests on comparable sites provide a valuable resource for experimental work (Leak and Smith 1996). Finally, Cone Pond Watershed (CPW) is a 53-ha catchment near HBEF that forms a regional end-member in terms of low soil base (fertility) status (Bailey et al. 1995, 1996; Hornbeck et al. 1997). The watershed is gauged and has been monitored for precipitation chemistry, throughfall chemistry, soil and soil solution chemistry, vegetation, hydrology and stream chemistry since 1988. These measurements of CPW will be continued as part of this LTER.

The HBEF is located in the northeastern U.S., a region that is largely forested and contains abundant surface water resources (e.g., 7096 lakes >4 ha) that are characterized by low ionic strength and low ANC. Across the Northeast we have analyzed the effects of atmospheric deposition on soil and surface water chemistry (Ollinger et al. 1993; Aber et al. 1997; Driscoll et al. 2001a). Geographic information system (GIS) data layers for the Northeast region used in our analyses include a digital elevation model (DEM), land-use history, precipitation, atmospheric deposition, vegetation, soil chemistry, and surface water chemistry.

**TABLE 3. Characteristics of monitored watersheds at the HBEF and at adjacent sites.**

| Watershed No. | Size (ha) | Year Started | Treatment/Disturbance |
|---|---|---|---|
| 1 | 11.8 | 1956 | Chemical manipulation, $Ca^{2+}$ (Wollastonite) addition 1999. |
| 2 | 15.6 | 1957 | Clear felled in winter 1965-66; no products removed; sprayed with herbicides summers of 1966, 1967, 1968. Left to regrow from 1969. |
| 3 | 42.4 | 1958 | None; hydrologic reference watershed |
| 4 | 36.1 | 1961 | Clear-cut to a 2 cm minimum diameter, by strips in three phases, 1970, 1972, 1974. Timber products removed. |
| 5 | 21.9 | 1962 | Whole-tree clear-cut to 10 cm diameter, 1983-1984. Timber products removed. |
| 6 | 13.2 | 1963 | None; biogeochemical reference watershed |
| 7 | 76.4 | 1965 | None |
| 8 | 59.4 | 1969 | None |
| 9 | 68.2 | 1986 | None |
| 101 | 12.1 | 1970 | Clear-cut to a 5 cm minimum diameter, as a block in 1970. Timber products removed. Note: streamflow quantity is not monitored, only water quality. |
| Mirror Lake-NE | 20 | 1970 | None/Highway construction 1969-71 |
| Mirror Lake-NW | 34.6 | 1970 | None |
| Mirror Lake-W | 24 | 1970 | None |
| Mirror Lake-Outlet | 103 | 1970 | None |
| Hubbard Brook-1 | 3,037 | 1974 | None |
| Hubbard Brook-2 | 3,289 | 1995 | None |
| Cone Pond | 53 | 1989 | Fire~1820 |
| Bowl Natural Area | 206 | 1973 | None |

D. Description of Long-term Data Sets

A major element of the HBR-LTER is the development of long-term records for reference and experimentally manipulated watershed-ecosystems including: 1) meteorology and hydrology (since 1956); 2) precipitation and streamwater chemistry (1963); 3) forest vegetation (1965); and 4) forest floor mass and chemistry (1965) (Likens et al. 1977, 1984, 1985; Likens and Bormann 1995; Table 1). Annual quantitative surveys of bird and phytophagous insect populations within the forest have been conducted since 1969 (Holmes 1988). Largely through the HBR-LTER, long-term studies of air chemistry, throughfall, litterfall, fine root activity, microbial activity, soil water and soils have been initiated to develop a more comprehensive understanding of the ecology of the northern hardwood forest ecosystem. The great value of these monitoring efforts is emphasized by the background they provided for quantifying responses to disturbance events such as the January 1998 ice storm (Rhoads et al. 2002, Houlton et al. 2003, Bernhardt et al. 2003).

Our long-term measurements have focused on the south-facing experimental watersheds (i.e., W1-6); however, in the previous funding cycle we expanded this effort to include north-facing experimental watersheds (Fig. 13). The north-facing watersheds at the HBEF are characterized by cooler a climate and a greater proportion of coniferous vegetation, which influences biogeochemical behavior (Wellington and Driscoll in press, Palmer et al. b in press).

The routine measurement of precipitation and stream chemistry in these experimental watersheds is the backbone of the biogeochemical monitoring program. All water samples are analyzed for all major solutes following routines that are carefully documented (Buso et al. 2000). The Hubbard Brook LTREB project "Hydrologic-element cycle interactions in small undisturbed and human-manipulated ecosystems" funded by the NSF, provides about 40% of the funding for the routine collection and analysis of precipitation and stream samples described above. We are requesting here funds to support about 60% of this critical monitoring. Thus, both of these funding sources are necessary to sustain the long-term records of biogeochemistry at HBEF.

Other ongoing monitoring programs (Table 1) are conducted at a number of sites within the HBEF. Complete forest surveys (all stems > 10 cm dbh) and forest floor collections are made every five years in W6. Atmospheric chemistry monitoring has continued since 1989 at two sites in the HBEF. Litterfall, microbial activity and soil solution monitoring are conducted immediately west of W6 to minimize disturbance to this reference site (Fig. 13). Fine roots are monitored using fine root coring, and observation of root growth and longevity using minirhizotrons (Tierney and Fahey 2002). Bird and insect population monitoring is conducted in a large area west of W6 (Fig. 13).

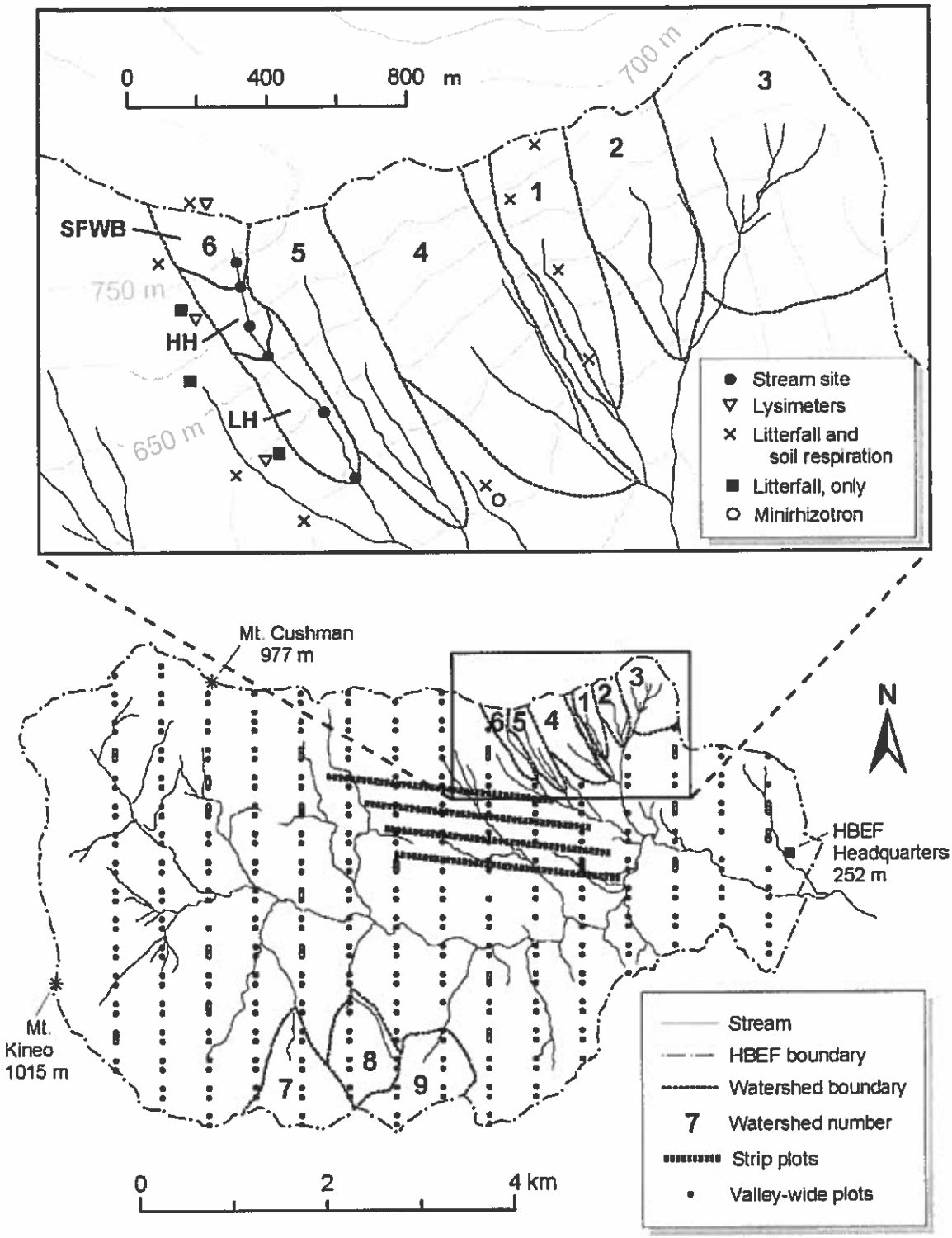


**Figure 13.** Map of the Hubbard Brook Experimental Forest, including experimental watersheds. Shown are valley-wide transects in which vegetation, soil and microbial processes have been characterized in plots, and bird and insect survey lines. A detailed map of the north-facing experimental watersheds is also shown with location of monitoring sites.

E. Description of Models Used

We use models as research tools, to test our current understanding, to integrate ecosystem studies and to develop new hypotheses. The hydrologic model, BROOK, was developed for small forest watersheds, and was based on research at the HBEF (Federer and Lash 1978). BROOK has been expanded to include multiple soil layers (BROOK90; Federer 1995). We have developed and linked two submodels to produce a comprehensive forest-soil-water model to simulate element cycling in forest and interconnected aquatic ecosystems. These submodels include: 1) PnET (Aber and Federer 1992; Aber et al. 1997; Aber and Driscoll 1997), a simple and well validated model of monthly carbon, water and N balances, which provides estimates of forest net primary productivity, nutrient uptake by vegetation and water balances; and 2) BGC (Gbondo-Tugbawa et al. 2001) a soil model which simulates abiotic soil processes, such as cation exchange, weathering, adsorption and solution speciation. Separately or linked (PnET-BGC), these models will be used to assess the effects of air pollution and land disturbance on the biogeochemistry of forest and aquatic ecosystems (e.g. Aber et al. 2002, Gbondo-Tugbawa et al. 2001, 2002, Gbondo-Tugbawa and Driscoll 2002 a,b, 2003, Driscoll et al. 2001a). We are also employing a simple model of N cycling, SINIC (Hong 2004). This model simulates spatial patterns of N loss and has tested well against longitudinal stream $NO_3^-$ data (Fig. 14).

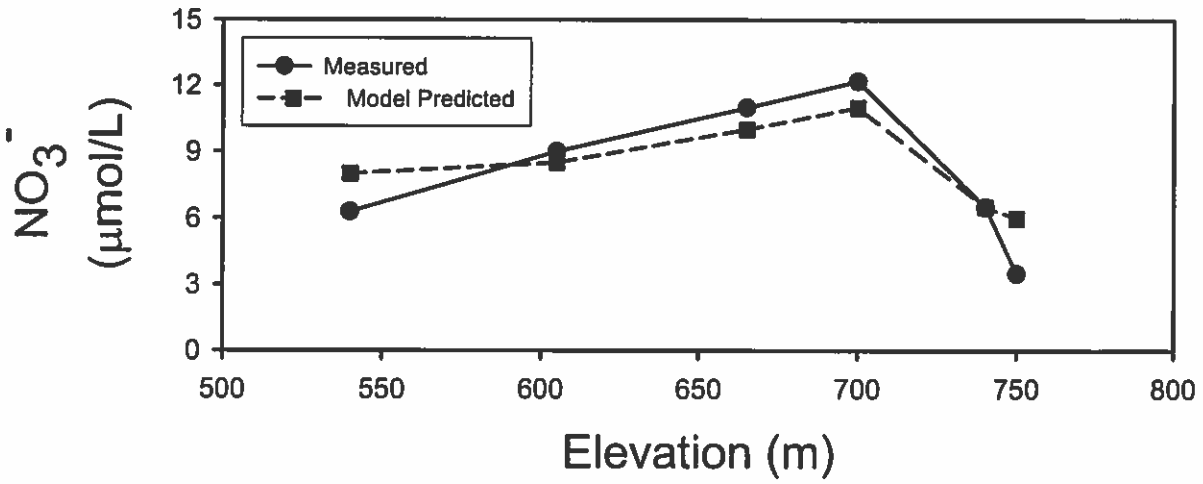


**Figure 14.** Comparison of measured and model-predicted longitudinal concentrations of $NO_3^-$ in the HBEF reference watershed (W6) for the period 1982-1992. Model simulations were made with SINIC (Hong 2004), under alternative combinations of spatially-distributed driving variables, including N mineralization, vegetation uptake, precipitation and elevation.

## II. Perturbation from Air Pollution

### A. <u>Objective 1</u>: To quantify spatial and temporal patterns in the response of pools and fluxes of elements to changes in air pollution.

### B. Introduction

The eastern U.S. has undergone large changes in emissions of air pollutants since the early 1970s (Driscoll et al. 2001a). The 1970 and 1990 Amendments to the Clean Air Act (CAAA) have resulted in decreases in emissions of $SO_2$ (~45%) and associated decreases in atmospheric deposition of $SO_4^{2-}$ at the HBEF (Likens et al. 2002; Fig. 11, 15) and elsewhere in the eastern U.S. (Lynch et al. 2000). In contrast to $SO_4^{2-}$, there have been only minor changes in annual volume-weighted concentrations of $NO_3^-$ or $NH_4^+$ in bulk or wet deposition over the past 40 years. These patterns have resulted in a profound shift in the composition of precipitation (Fig. 16). Early in the study, the anion composition of bulk precipitation was dominated by $SO_4^{2-}$. With decreases in $SO_4^{2-}$ and to a lesser extent $Cl^-$, there has been a relative increase in $NO_3^-$ in precipitation. Over the last few years, we have observed minor decreases in precipitation $NO_3^-$, which appear to be related to decreases in $NO_x$ emissions from electric utilities (Butler et al. 2003; Fig. 15).

Decreases in atmospheric S deposition have coincided with decreases in concentrations of $SO_4^{2-}$ in soil solutions and streamwater in the biogeochemical reference watershed at the HBEF (W6; Palmer and Driscoll 2002; Likens et al. 2002; Palmer et al. in press a) (Fig. 12). Sulfate is the dominant anion in precipitation, throughfall, soil water and streamwater at the HBEF and is critical in regulating the acid-base chemistry of drainage waters. We have also observed intriguing temporal patterns in stream $NO_3^-$ in W6, which do not seem directly related to atmospheric N deposition (Fig. 12). Annual volume-weighted concentrations of $NO_3^-$ in stream water increased early in the record, remained elevated from the late 1960s to the mid-1970s and have generally decreased in recent years (Fig. 17). The recent trend of decreasing $NO_3^-$ in W6 was interrupted by two non-catastrophic disturbance events: a soil freezing event in 1989 (Mitchell et al 1996, Fitzhugh et al. 2003) and an ice storm in 1998 (Houlton et al. 2003, Bernhardt et al. 2003). These disturbances resulted in relatively short (2-3 yr) periods of elevated $NO_3^-$ within the context of the overall decreasing record. The dynamics in N retention in experimentally cut watersheds (e.g., W2, W4) also provided unexpected patterns. During the 10-15 year aggrading phase of experimentally cut watersheds (W2, W4), inputs of N were strongly retained and $NO_3^-$ leaching losses were low. In recent years, this pattern has shifted such that $NO_3^-$ loss in cut watersheds exceeds values observed in the reference watershed (Fig. 17). Changes in watershed N retention strongly influence changes in the acid-base chemistry of drainage waters. In W6 the long-term decrease in stream $NO_3^-$ is contributing to increases in ANC. In contrast, W2 and W4 are showing increasing losses of $NO_3^-$ over the last 15-20 years and this decrease in N retention is responsible for a pattern of recent decreases in ANC (Fig. 17).

Historically, elevated inputs and leaching of $SO_4^{2-}$ and $NO_3^-$ have contributed to the depletion of available $Ca^{2+}$ and $Mg^{2+}$ and the mobilization of Al from forest soils at the HBEF (Likens et al. 1996; 1998, Gbondo-Tugbawa and Driscoll 2003) and elsewhere (Lawrence et al. 1999,

Huntington et al. 2000). This disturbance may have long-term effects on the forest vegetation and aquatic biota (Driscoll et al. 2001a). It is difficult to establish unequivocal evidence for the relationship between acidic deposition and ecosystem damage. However, studies in eastern North America suggest that red spruce (DeHayes et al. 1999, Schaberg et al. 2000) and sugar maple (Horsley et al. 2000, Watmough 2002, Drohan et al. 2002) have been impaired by elevated inputs of acidic deposition. Long-term observations at the HBEF indicate that sugar maple biomass has decreased markedly, particularly at higher elevations (Fig. 6).

A great deal of uncertainty remains regarding the response of northeastern forest ecosystems to past and anticipated future decreases in emissions of $SO_2$ and $NO_x$, and subsequent decreases in atmospheric deposition of $SO_4^{2-}$ and $NO_3^-$. Over the last 20 years significant declines in strong acid anion concentrations in drainage waters have been balanced to some degree by declines in concentrations of base cations (Palmer et al. in press a). The stoichiometry of these changes varies with landscape position (Johnson et al. 2000). Recovery from acidification, as indicated by increasing ANC and decreasing concentration of inorganic monomeric Al ($Al_i$), has so far been confined to soil solutions draining the Bs horizon at mid-to-higher elevations. However, persistently low $Ca^{2+}/Al_i$ ratios (<1) in mineral soil solutions and tree fine roots at these sites may be evidence of continuing Al stress to trees (Cronan and Grigal 1995). Changes in the chemistry of stream water reflect changes in soil solutions, with the greatest increases in ANC occurring at high elevations and the rate of increase decreasing with decreases in elevation. Despite substantial decreases in acidic deposition, the pH of soil solutions and stream solutions has declined or did not change significantly.

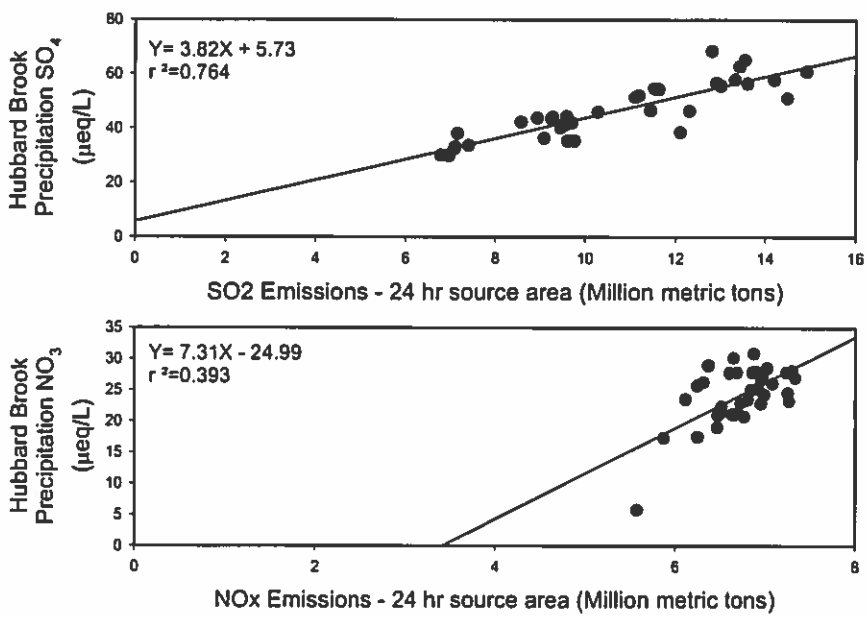


**Figure 15.** Relationship between annual volume-weighted concentrations of $SO_4^{2-}$ and $NO_3^-$ in bulk precipitation at the HBEF and emissions of $SO_2$ and $NO_x$, respectively, from the airshed of the northeastern U.S. defined from 24 hr back-trajectory analysis (Butler et al. 2001).

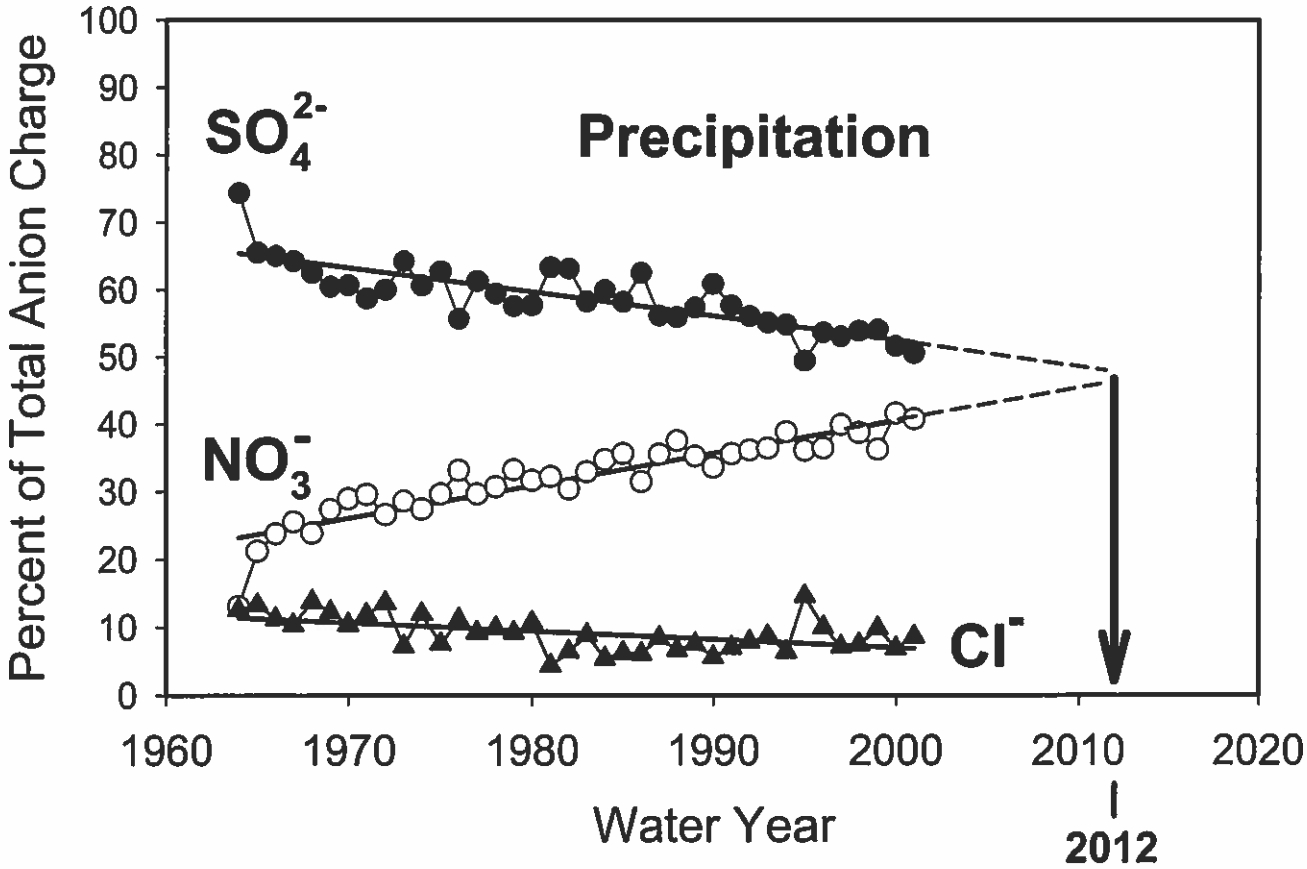


**Figure 16.** Long-term trends in the relative distribution of anions (on an equivalence basis) in bulk precipitation at the HBEF. Note that $SO_4^{2-}$ and $Cl^-$ have decreased in importance while $NO_3^-$ has increased in importance. At current rates of change $SO_4^{2-}$ and $NO_3^-$ concentrations will be equivalent in 2012.

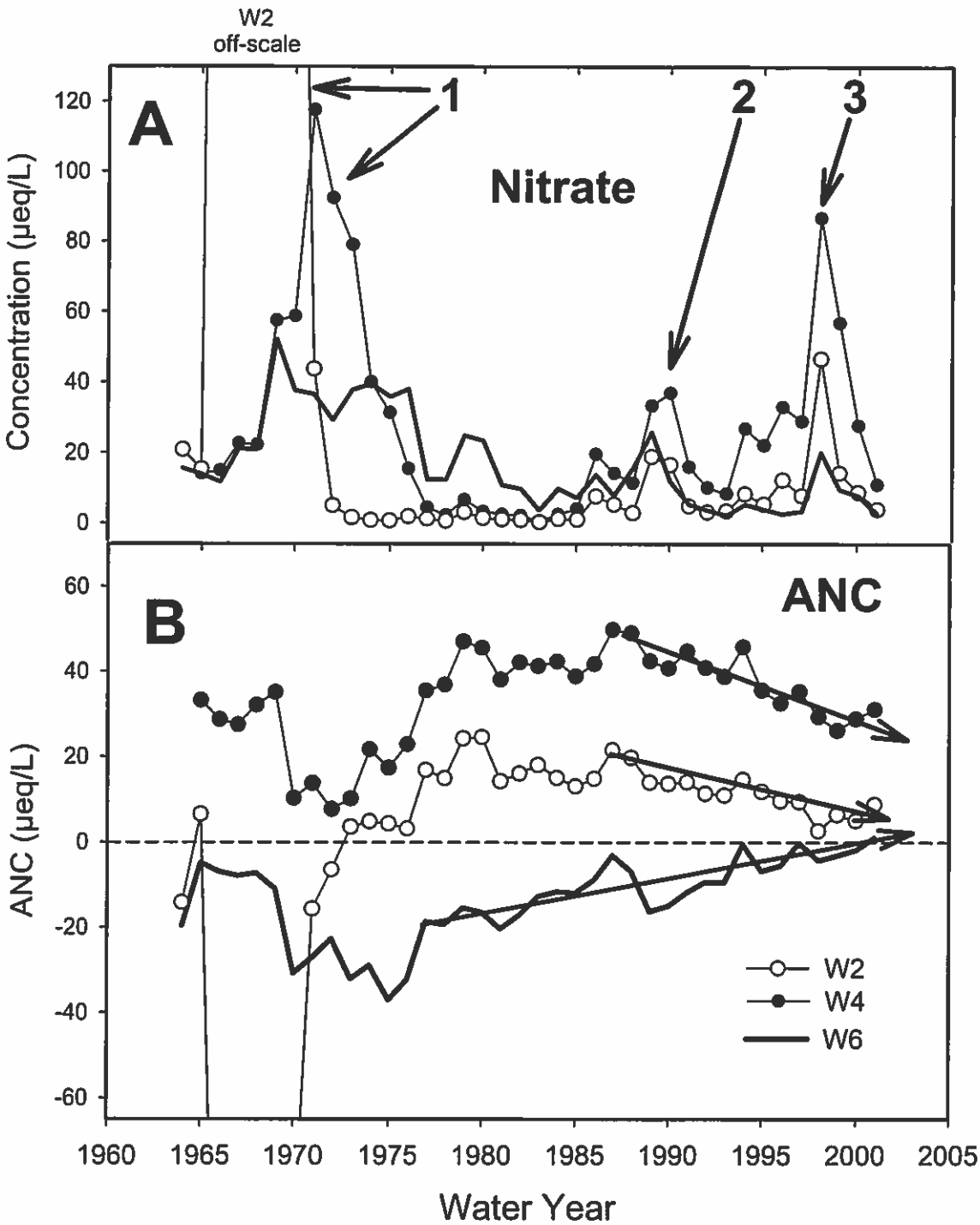


**Figure 17.** Long-term trends in annual volume-weighted concentrations of $NO_3^-$ and ANC in reference (W6), and cut (W2: devegetation and herbicide treatment; W4: strip-cut) watersheds at the HBEF. Note there has been a decrease in concentrations of $NO_3^-$ in W6 in recent years with increasing ANC. In contrast $NO_3^-$ concentrations have increased in cut watersheds (W2, W4) corresponding with decreases in ANC. The large initial increase in $NO_3^-$ in W2 and W4 was the result of the experimental cutting (1). The increase in $NO_3^-$ in the late 1980s was the result of a soil freezing event (2), and the increase in the late 1990s was the result of an ice storm (3).

C. Hypotheses

H.1.1. Concentrations and deposition of S and $NO_3^-$ in bulk and wet deposition will decrease linearly in response to decreases in $SO_2$ and $NO_x$ emissions from electric utilities.

H.1.2. The magnitude of decreases in $SO_4^{2-}$ concentrations in soil water and stream water varies with landscape position due to past and present patterns in atmospheric deposition (i.e., wet vs. dry deposition), mineralization of organic S that has accumulated in soil, and desorption of $SO_4^{2-}$ previously adsorbed in soil.

We anticipate decreases in atmospheric deposition of S and $NO_3^-$ to continue until 2010 when the 1990 Clean Air Act Amendments (CAAA) are fully implemented. In addition there are a number of proposals being debated in Congress to further reduce emissions of $SO_2$ (50-75% reduction) and $NO_x$ (66-70% reduction; Driscoll et al. 2001a). Additional emission controls should continue to decrease inputs of $SO_4^{2-}$ and $NO_3^-$ to the HBEF.

The dynamics of S across forested landscapes at the HBEF remain somewhat mysterious. Rates of long-term decreases in $SO_4^{2-}$ concentrations in forest floor leachate are greater than rates observed in bulk deposition. The mechanism driving this discrepancy is unclear, although it may be due to decreases in the ratio of dry to wet deposition. Unfortunately our record of dry deposition is relatively short (started 1989), but measurements over a longer period may help explain this pattern. Mass balance (Likens et al. 2002) and PnET-BGC calculations (Gbondo-Tugbawa et al. 2002) suggest that inputs of S can be retained in watersheds by vegetation uptake and soil adsorption, and subsequently released under conditions of lower S deposition. We believe that watershed S retention is greatest at the lower elevations of the experimental watersheds due to thicker soils and deeper surficial deposits. Analyses of stable isotopes of $SO_4^{2-}$ ($\delta^{34}S$ and $\delta^{18}O$) at HBEF and elsewhere have strongly suggested that additional internal sources of S have altered $SO_4^{2-}$ loss to surface waters (Alewell et al. 1999, Mitchell et al. 2001, Likens et al. 2002, Bailey et al. in press). Gbondo-Tugbawa et al. (2002) modified the PnET/BGC model to account for different stable S isotopes, confirming that uncertainties in predicting the contributions of dry S deposition, S mineral weathering and mineralization of soil organic S are critical in making long-term predictions of $SO_4^{2-}$ concentrations in surface waters. A key question for ecosystem recovery resulting from decreases in atmospheric S deposition is whether inputs of S will be reversibly released to drainage waters or irreversibly retained.

H.1.3. Depletion of soil exchangeable $Ca^{2+}$ and $Mg^{2+}$ and increases in soil bound Al will continue to delay the recovery of soil and drainage waters from acidic deposition.

H.1.4. The acid-base status of soil and drainage waters, the composition and nutrition of soil microbes, invertebrates and forest vegetation, and the abundance of Lepidoptera larvae and bird reproductive performance are all regulated by the Ca supply and base cation status of watershed ecosystems.

Model calculations using PnET-BGC suggest that recovery of W6 from reductions in acidic deposition will occur slowly over a period of several decades (Fig. 5). Under scenarios of the 1990 CAAA and the 1990 CAAA plus additional controls of $SO_2$ and $NO_x$ emissions, the acid-

base status of soils and surface waters are predicted to improve in W6; the greater the reduction in acidic deposition the greater the rate of recovery (Driscoll et al. 2001a; Gbondo-Tugbawa and Driscoll 2002 b). Model calculations suggest that several watershed processes influence the rate of ANC response to decreases in atmospheric deposition, including depletion of exchangeable basic cations from soil, watershed N retention, desorption of previously adsorbed $SO_4^{2-}$ and net mineralization of soil organic S.

To examine ecosystem response to long-term depletion of $Ca^{2+}$ from acidic deposition, we initiated a $Ca^{2+}$ addition experiment (W1). 45 tons of $CaSiO_3$ (wollastonite) was added to W1 by helicopter in 1999. This amount was designed to replenish the $Ca^{2+}$ depleted from the soil exchange complex since the advent of acidic deposition. The added wollastonite has unique $^{87}Sr/^{86}Sr$ and Ca/Sr ratios, facilitating the tracking of the added $Ca^{2+}$ in soil, soil water, vegetation and stream water. To date, most of the added $Ca^{2+}$ has been retained in the forest floor. However, we have detected significant amounts of the added Ca in vegetation, soil solutions and stream water. The treatment response has been most evident in the upper reaches of the watershed, due to shallow, more acidic soils. This past summer we observed a large increase in sugar maple seedling health and survival (Fig. 7) and reduced damage of red spruce due to winter injury (Fig.8) in W1 compared to the reference watershed. Concomitant changes in both the detrital and the herbivore food web seem likely as a result of driving responses in soil chemistry and forest nutrition; for example, changes in pH should influence the soil microbial community and changes in foliar nutrition (e.g., protein and fiber content) should affect Lepidopteran larvae.

H.1.5. Spatial patterns in watershed loss of N species (e.g., DON, $NO_3^-$) are largely controlled by land disturbance history; temporal patterns in watershed $NO_3^-$ loss are largely regulated by climatic variations. Changes/variations in the composition of forest vegetation and biogeochemical activity within stream channels influence both spatial and temporal patterns in N loss.

Long-term decreases in stream $NO_3^-$ concentrations at the HBEF were unexpected, given a maturing forest and constant atmospheric N deposition (Goodale et al. 2003). Indeed calculations using PnET suggest that early in the record (1965-1990) temporal variations in stream $NO_3^-$ at the HBEF were largely driven by climatic variation and a series of small disturbances (Aber et al. 2002), but the model over-predicts values over the last 10 years (Fig. 5). The pattern of decreasing surface water $NO_3^-$ is not unique to the HBEF; it has been reported across the Northeast (Goodale et al. 2003; Driscoll et al. 2003c) even in old growth forests (Martin et al. 2000). The mechanisms contributing to the pattern of recent decreases in surface water $NO_3^-$ are not evident. It may be due to enhanced leaching of DON. Aber et al. (2002) speculate that it may be due to a fertilization effect associated with elevated $CO_2$. The pattern could also be due to shifts in vegetation composition. The importance of vegetation, especially sugar maple (Lovett and Mitchell, in revision), in affecting $NO_3^-$ concentrations in surface waters has been shown both for the Catskills (Lovett et al.2002, in press) and Adirondack Mountains of New York (Mitchell et al., 2003). An additional mechanism that may contribute to the decline in $NO_3$ flux is a shift in processing of N with the stream (Bernhardt et al. 2003), including possible interaction with changing DOC availability.

D. Approaches to Objective 1

To accomplish this objective and test these hypotheses we propose to continue our long-term measurements of bulk deposition, wet deposition, dry deposition, forest vegetation, microbial biomass and activity, soil, soil solutions and stream water in reference and experimentally manipulated watersheds at the HBEF (Table 1). To test hypothesis H.1.1 we will continue our measurements of bulk and wet-only deposition and of air chemistry and inferred dry deposition through CASTnet. We will continue our analysis of relationships between emissions of $SO_2$ and $NO_x$ from various sources and regions and bulk/wet and dry deposition of $SO_4^{2-}$ and $NO_3^-$ (Butler et al. 2001, 2003, Likens et al. 2001).

To test hypothesis H.1.2, we will rely on our long-term measurements of $SO_4^{2-}$ in lysimeters and along the length of the stream in the biogeochemical reference watershed, in addition to long-term measurements of atmospheric deposition. Our routine measurements will be supplemented by additional measurements using stable isotopes. To better understand S and N dynamics and watershed response to declining atmospheric deposition, we will make additional measurements of the isotopic composition of $SO_4^{2-}$ and $NO_3^-$ including the $\delta^{34}S$, $\delta^{15}N$, and $\delta^{18}O$ values of these solutes. Such isotopic information has been shown to be invaluable in evaluating $SO_4^{2-}$ and $NO_3^-$ sources, particularly the relative role of direct atmospheric inputs versus internal sources. This includes mineralization for both N and S as well as nitrification for mobile N to soil and surface waters (Burns and Kendall 2002, Kendall 1998, Mitchell et al. 1998, Pardo et al. in press). Measurements will be made both spatially and temporally in reference and manipulated watersheds in bulk deposition, soil water and stream water. The interpretation of biogeochemical data will be facilitated by application of PnET-BGC. We propose to enhance the accuracy and extend the applicable of PnET-BGC. We will develop a version of the model that includes multiple soil layers, in order to improve our ability to simulate seasonal patterns in stream chemistry. We plan to use the model to simulate spatial patterns in watershed biogeochemistry by applying the model as a series of linked sub-watershed models.

We will continue our long-term measurements of major solutes and Al species in soil solutions adjacent to and along the length of the stream in the biogeochemical reference watershed (W6) to test hypothesis H.1.3. We will also use PnET-BGC to examine the mechanisms regulating changes in the acid-base status of drainage waters with decreases in atmospheric deposition of strong acids.

To test hypothesis H.1.4, we will continue to make measurements of $^{87}Sr/^{86}Sr$ and Ca/Sr coupled to mixing calculations (Peters et al., in press) to assess the pathways and fluxes of the added $Ca^{2+}$ within W1. These measurements will be supported by data collected on herbaceous and overstory vegetation, fine root dynamics, microbial biomass and activity, foliar chemistry, soil and soil solution chemistry and stream chemistry in W1 and W6. To verify that differences in tree health and injury are associated with $Ca^{2+}$ availability, foliar $Ca^{2+}$ concentrations, especially functionally relevant pools associated with cell membranes, will be measured. We will continue and expand work on detrital foodwebs. We have observed periodic decreases in collembola populations in W1 and will examine in more detail possible changes in species composition associated with higher pH (Chagnon et al 2001, Hagvar et al 1984), and implications for fungal biomass and decomposition processes. This work will be linked with on-going measurements of

microbial biomass and activity, and the soil microbial community also will be examined in more detail. We will examine microbial diversity in W1 and reference soils using molecular techniques, including terminal restriction fragment length polymorphism (TRFLP), RFLP, and sequence analysis of functional and phylogenetic genes. Again these data will be interpreted with results from on-going measurements of microbial biomass and activity in an attempt to relate the composition of microbial communities to microbial function.

We will measure the growth and abundance of Lepidoptera larvae on multiple plant species along an elevational gradient in W1 and W6. Caterpillars are the dominant herbivore in the forest, and observed changes in leaf protein and greenness suggest the quality of the food resource is changing. Monitoring of Lepidoptera larvae will be done by visual surveys of larvae on leaves and twigs (Holmes and Sherry 2001). Bioassays (i.e., larval growth experiments) will be used to quantify the quality of foliage for herbivore growth. Migratory songbirds, such as the Black-throated Blue Warbler (BTBW) are heavily dependent on caterpillars during breeding (Rodenhouse and Holmes 1992). Therefore changes in the growth or distribution of caterpillars associated with the $Ca^{2+}$ addition would likely affect breeding birds. We propose to focus our studies on BTBWs because all aspects of its breeding biology can be readily measured, and because we have extensive data on the relationship between food availability of the reproductive success in this species (Nagy 2002, Sillett and Holmes 2002). Parental activity at the nest and nesting diet will be monitored using video cameras; nesting growth rates will be quantified and all nesting attempts by each breeding pair will be recorded.

Through our coupled measurements of climate, vegetation composition, microbial biomass and activity, and N species in stream chemistry in the reference (W6) and cut watersheds (W2, W4, W5), we will attempt to test hypothesis H.1.5. As discussed above, these measurements will be supported by $\delta^{15}N$ measurements in bulk deposition, foliage, and drainage waters. We intend to use both PnET-BGC and SINIC to interpret patterns of N loss in time and space.

## III. Recovery from Catastrophic Forest Disturbance

### A. <u>Objective 2</u>: To better understand and quantify controls on patterns of ecosystem recovery following large-scale, catastrophic disturbances across the Hubbard Brook and regional landscape.

### B. Introduction

Large-scale catastrophic disturbances did not dominate the natural disturbance regime over most of the northeastern forest because natural fires were rare and severe windstorms probably did not frequently revisit the region (Bormann and Likens 1979, Davis et al. 1985). Following European settlement, however, intensive forest harvest and in some cases agricultural activities disturbed most of the landscape, and forest composition and ecosystem dynamics bear the legacy of these lands-use changes. Moreover, severe wildfires often followed forest harvest activities, though the HBEF was spared this additional disturbance (Likens 1985). While logging continues to be widespread in the region, most agriculture was abandoned during the early 20$^{th}$ century. Major hurricanes have occasionally visited the region, most notably the 1938 hurricane which catastrophically disturbed parts of the HBEF (Cogbill 1983, Merrens and Peart 1992). Most

recently, several small watersheds within the HBEF were experimentally cut to quantify ecosystem responses to catastrophic disturbances (W2-1966, W4-1970 to 1974, W101-1970, W5-1984). Thus, a varied history of large-scale catastrophic disturbance has left its legacy on the HBEF and surrounding forested landscapes, including neighboring research sites at the BEF (variety of silvicultural treatments – Leak and Smith 1996) and CPW (severely burned in 1820; Bailey et al. 1995, Hornbeck and Lawrence 1996). We propose to continue surveys and experiments on these sites, and we plan additional experimental manipulations to address a series of hypotheses about ecosystem recovery from catastrophic disturbances.

Research in the HBEF and other sites has provided a strong theoretical and empirical base upon which to build our understanding of ecosystem recovery from catastrophic disturbances. In the HBES we have conceived of the overall recovery process in four stages: reorganization, aggradation, transition and steady-state (Bormann and Likens 1979). The reorganization phase has been studied in great detail (Likens et al. 1969, Bowden and Bormann 1986, Fahey et al. 1988, Johnson et al. 1991a, b). Also, the dramatic changes in element pools and fluxes that accompany the aggradation phase have been quantified (Reiners 1992, Yanai et al. 1999); however, the mechanisms controlling these patterns are less clear. For example, dissipation and recovery of forest floor organic matter and nutrient pools occurs on decadal time scales (Covington 1981, Federer 1984, Yanai et al. 2000), but the mutual interactions of the soil food web, vegetation and detrital dynamics, and mineral nutrient availability have received only limited study. Similarly, although it is clear that nutrient availability strongly limits NPP in the aggradation phase (Fahey et al. 1998), the interactions among potentially limiting nutrients (N, P, Ca) remain unknown. Moreover, the early and abrupt termination of the transition phase at age 70 yr (Fig. 6) was unexpected, and the causes of the plateau and recent decline in forest biomass are not entirely understood. Finally, regional variations in ecosystem structure, function and composition have accompanied the contrasting large-scale disturbance legacies imprinted on the landscape (Goodale and Aber 2001), but our ability to predict the consequent patterns of forest productivity and nutrient cycling under current and future stresses that accompany human-accelerated environmental changes still remains rudimentary (Aber et al. 2002).

C. Hypotheses

H.2.1. As a result of rapid accumulation of biomass pools, maximum depletion of soil $Ca^{2+}$ pools occurs during the 3rd decade of recovery following large-scale disturbance. The persistence of relatively high leaching losses of $Ca^{2+}$ at this time results from biotically-induced rapid weathering of primary minerals.

The soils of the HBEF have been severely depleted of base cations (Likens et al. 1998). Hence, it is particularly surprising that the additional removal of $Ca^{2+}$ from soil pools that has accompanied the rapid biomass accumulation on W5 – a watershed that was whole-tree harvested so that recycling from mineralization of residual detritus was minimized – has not resulted in reduced $Ca^{2+}$ leaching; quite the contrary, $Ca^{2+}$ leaching is now elevated on W5 relative to the undisturbed reference W6 (Fig. 2). Pool calculations indicate that these patterns can only be explained by mining of deep soil layers or rapid weathering of primary minerals, yet root distributions are not deeper in the W5 soil. Perhaps access to calcium phosphate minerals (apatite) by ectomycorrhizal (ECM) fungal hyphae (van Breemen et al. 2000, Wallander et al. 2002) is maximized in the aggrading forest, which is now dominated ECM tree species (i.e.,

birches, beech, conifers). If so, we would expect higher proportions of apatite-derived Ca in various ecosystem pools and fluxes.

H.2.2. In the high N deposition, low pH environment of the Northeast, limitation of NPP by P becomes increasingly prevalent during the aggradation and transition phases of recovery from catastrophic disturbance. Addition of P to the mature forest will cause renewed growth and ecosystem C accumulation, whereas additional N will exacerbate nutrient imbalances negating any NPP stimulation. The response to P addition will be increased by $Ca^{2+}$ addition and consequent soil pH changes.

The stoichiometric couplings among C, N, P and $Ca^{2+}$ in forest ecosystems may be disrupted by the combined perturbations of forest harvest and air pollution, leading to plant nutrient imbalances and possibly promoting P limitation (Mohren et al. 1986, deVisser and van Breemen 1995, Ljungstrom and Nihlgard 1995, Fluckiger and Braun 1998). In this work we propose to explore the general hypothesis that plants use available C to acquire most efficiently the limiting nutrients needed to maintain their stoichiometry. We expect that the addition and accumulation of N, together with soil depletion of available $Ca^{2+}$ has disrupted this balance. For example, the N:P ratio of tree foliage is unusually high in the mature forest at the HBEF (17 compared with the value of 13 associated with optimal nutrition; Fiorentino et al. 2003, Tessier and Raynal 2003). Most of the P requirement in organic-matter rich soils of the HBEF is supplied by mineralization in forest floor horizons (Yanai 1991); however, the pH in these horizons is exceptionally low, partly as a result of mineralization of organic matter and acidic deposition (see above). Acidification is known to reduce P availability to biota (Schlesinger 1997) in part because the activity of phosphatase enzymes may be suppressed by low pH (Carreira et al. 2000). During the early aggradation phase, the dynamics of changing forest floor organic matter pool size and pH, forest composition and structure, and nutrient demands of accumulating biomass would be expected to influence the balance between N and P limitation of NPP. Addition of $Ca^{2+}$ and the consequent pH increase in the soils of the mature W1 forest resulted in a striking increase in P mineralization and foliar P concentrations (Fiorentino et al. 2003). Although primary mineral weathering represents an abundant pool of P in HBR soils, it is notable that apatite has been depleted by weathering from the upper soil horizons (Blum et al. 2002) so that roots and mycorrhizae must access this P (and $Ca^{2+}$) source from deeper soil layers. Hence, the principal source of N near the soil surface is spatially separated from this key source of P and $Ca^{2+}$ in deeper soil layers, increasing the C cost of balanced tree nutrition. It is worth repeating in this regard that despite the rapid aggradation of biomass in the recently cutover watersheds (W2, W4), N retention is consistently lower than in the mature forests (W1, W6; Fig. 17), indicating that fundamental differences in belowground processing of N (and possibly P) may prevail in younger compared to older forests.

H.2.3. Increased $NO_3^-$ loss during the aggradation phase in three cut watersheds with young forests (W2, W4, W5) in comparison with the reference W6 is related in part to lower in-stream N retention due to decreased abundance of debris dams.

Low-order streams like those in our experimental watersheds are known to be sites of maximal N transformation and N retention (Alexander et al. 2000), so that in-stream processes could buffer stream $NO_3^-$ flux. For example, in-stream processes reduced by 70 to 120% the losses of $NO_3^-$

from W6 following the intense ice storm of 1998 (Bernhardt et al. 2003). Organic matter input to streams strongly influences in-stream nutrient-uptake (Mulholland and Hill 1997), and debris dams serve as hotspots for microbial activity (Bilby 1981, Steinhart et al. 2000). The expected reduction in input of coarse woody debris to streams during the aggradation phase of ecosystem development might reduce in-stream $NO_3^-$ retention in young forest watersheds.

H.2.4. Patterns of forest growth, health and N retention in even-aged 2$^{nd}$-growth forests across the Hubbard Brook Valley and the White Mountain region are correlated with disturbance history, soil base status and forest composition. These patterns can be detected by remote sensing of canopy N status coupled with simulation modeling.

Spatial variation in ANPP across the HBR Valley is related to climatic limitations associated with elevation as well as with variation in soil fertility and species composition. A similar range of variation occurs on a broader scale across the White Mountain National Forest (WMNF) and several recent efforts have investigated the degree to which these patterns can be characterized via remote sensing of canopy N. Canopy N as a scalar for ecosystem processes, stems from well-known relationships between foliar N concentrations and maximum net photosynthesis (Reich et al. 1999). Because photosynthesis is the basis of C acquisition in plants, spatial coverage of canopy N should provide useful information about spatial patterns of ecosystem productivity. Strong relationships between whole canopy N concentration and aboveground productivity have been demonstrated in broad-leaved and conifer forests in the Northeast and have recently been applied over the WMNF using high spectral resolution data from NASA's airborne imaging spectrometer, AVIRIS (Smith et al. 2002; Fig. 4).

The integration of this approach with ecosystem modeling would enhance our ability to examine forest growth patterns in relation to landscape features, such as topography and disturbance and provide an opportunity to extend predictions of ecological function under scenarios of future environmental change. Ollinger and Smith (*in review*), recently applied PnET spatially to the BEF using remotely-sensed canopy N as the primary vegetation input. Results showed strong agreement with plot-level wood production measurements and also revealed contrasting elevational patterns for deciduous and evergreen forests. In deciduous forests, an increase in both foliar N and NPP with increasing elevation was related to increasing moisture availability. In evergreen forests, moisture limitations were less important and were offset to a greater extent by elevational patterns in temperature.

Patterns of foliar N have also been related to variation in soil N status, following the effects of litterfall N on rates of decomposition and the subsequent feedbacks between N mineralization and plant N uptake. In the WMNF, Ollinger et al. (2002) found strong relationships among canopy N, soil C:N ratios and rates of net nitrification, although nitrification rates were also influence by land use history and the abundance of sugar maple.

D. Approaches to Objective 2

During the past four decades we have been measuring ecosystem structure, function and composition on a series of matched small watersheds in the HBEF. This landscape was heavily logged in the early 1900s and consisted of similar, even-aged forests until whole watershed

manipulations were conducted. The disturbance treatments on W2, W4 and W5 initiated "third-growth" forests with differing ecosystem characteristics: 1) the deforestation of W2 left maximum residual organic matter (cut trees left on site) but nutrient pools were greatly depleted and composition altered by preventing regrowth for three years (Reiners 1992); 2) high removal of nutrients, especially $Ca^{2+}$, accompanied the whole-tree harvest on W5; and 3) the lowest nutrient loss was associated with the progress strip-cutting of W4 (where logging debris remained on site; Martin and Pierce 1980, Martin and Hornbeck 1990). The legacy of this differential disturbance is seen in the contrasting composition, productivity, soil nutrient pools and stream chemistry of these 20 to 30-year-old forest watersheds (Fig.2,17).

To test H.2.1, we propose to compare $Ca^{2+}$ sources and pools between the mature forest, minimally depleted W4 and maximally $Ca^{2+}$-depleted W5. Using a combination of Ca/Sr and $^{87}Sr/^{86}Sr$ ratios in vegetation, soil pools and streamwater, we will quantify the proportion of $Ca^{2+}$ derived from three principal sources: atmospheric deposition, weathering of apatite, and weathering of other primary minerals (Blum et al. 2002). We expect highest proportions of apatite-derived $Ca^{2+}$ in W5 as a result of high $Ca^{2+}$ removal from the disturbance, demands of recovering vegetation, and the dominance of ectomycorrhizal tree species. Also, comparative monitoring across these watersheds will be combined with standard surveys of debris dams (Bilby 1981) and in-stream N retention using $^{15}N$ additions to examine H.2.3.

We have initiated planning for a series of plot-level manipulations of nutrient availability to test H.2.2 and related ideas. We propose a fertilization study involving the addition of N, P and $Ca^{2+}$ in all combinations in early successional and mature northern hardwoods in and around the HBEF to examine nutrient limitations and stoichiometric interactions among these three critical macronutrients. The combination of soil acidification and soil $Ca^{2+}$ depletion (Likens et al. 1998), N deposition and saturation (Aber et al. 1989, 2003) and poorly-understood P biogeochemistry leads us to expect this experiment to be a most important and informative endeavor. Surprisingly few factorial fertilization trials have been conducted in our region and none has examined the mechanisms of macronutrient interactions. The larger scope of our proposed experiments exceeds the funding available from the LTER core budget. Pre-treatment measurements and installations would be supported by this proposal, together with the costs of fertilizer applications and some basic measurements of forest response described below. Funds for additional detailed studies will be sought in a separate proposal.

The proposed design of the fertilization study will include treatment of 0.1 ha plots with N, P, Ca, N+P, P + Ca and N+P+Ca. The experiment will be conducted in mature (ca. 100-year-old) forest and 30-year-old forest within the HBEF and replicated at the BEF. By age 30-yr pin cherry dominance in northern hardwoods is so reduced that this species will not play the significant role in the fertilization response that was noted for ages 6-18 yr (Fahey et al. 1998); rather, the mature forest dominants, beech, sugar maple and yellow birch, will determine the response in both age classes. The basic measurements of response will include the following: 1) plant growth and inorganic nutrition, 2) foliar nutrient resorption, 3) microbial biomass and its elemental stoichiometry including fungal/bacterial ratio by PLFA analysis (Waldrop et al. 2000), 4) N and P exoenzyme production (Tabatabai 1994), 5) fertilized root ingrowth cores at soil surface (Raich et al. 1994, Gleeson and Good 2003), and 6) in-growth bags distributed vertically through soils with amendments of apatite (calcium phosphate), wollastonite (calcium silicate) or

high N organic matter. Together these measurements will allow us to address nutrient limitation and mechanisms of its relaxation to examine the efficiency of tree investments to attain stoichiometric requirements in young and mature forests.

To test H.2.4, we propose to expand the regionalization activities at HBR by explicitly coupling hyperspectral remote sensing of forest canopy chemistry with PnET and with spatial data for other important variables such as land use history and species composition. These efforts will include intensive analyses, conducted within the HBEF, and extensive studies that cover the WMNF. At HBEF, we will add remotely-sensed canopy chemistry estimates to the plot-level productivity and N cycling data collected as part of the valley-wide measurement campaigns (Schwarz et al. 2003, Venterea et al. 2003). This will allow us to examine the coupling between C and N cycles at HBEF and may extend our regional-scale predictions by revealing unrecognized relationships between canopy, soil and vegetation processes.

We also plan to improve our modeling capabilities by fully integrating canopy chemistry remote sensing into spatial applications of PnET and by incorporating new data planes for species composition and disturbance history. Given the importance of individual species such as sugar maple as regulators of C-N interactions (Lovett and Reuth 1999, Ollinger et al. 2002), the ability to detect patterns of species-level forest composition (Martin et al. 1998) should greatly enhance our ability to predict patterns of N cycling and N retention.

## IV. Response and Recovery from Non-catastrophic Forest Perturbations

### A. <u>Objective 3</u>: To determine how multiple perturbations interact with ecosystem components to regulate ecosystem function, structure and composition.

### B. Introduction

The predominant natural disturbances in northern hardwood forests consisted of less intense and smaller scale disruptions including the normal senescence of old trees, as well as windstorms, ice storms, and native pathogen irruptions. Because these disturbances act on a local scale, ecosystem structure, function and composition have been conceived as persisting near steady-state when averaged over landscapes much larger than the areas affected by these individual perturbations (Bormann and Likens 1979). Other climatic and biotic perturbations also influenced the pre-settlement forest including severe droughts and soil freezing events, hailstorms and insect defoliation. Currently, a variety of anthropogenic perturbations are afflicting the northern forest, overlying the natural phenomena, and these compounded perturbations may be moving the ecosystem towards increasingly unnatural states (Paine et al. 1998). For example, exotic insects and diseases cause more acute damage to trees and other biotic populations than native pests, and pollution damage has resulted in declines in susceptible forest tree populations, particularly red spruce and sugar maple (Driscoll et al. 2001a). Rapidly changing climatic patterns bring threats of more frequent or extreme climatic stresses and storm events, further accelerating the disturbance regime. The interactions among these perturbations

have received little study and the natural experiment associated with long-term forest change provides an opportunity to provide insight into this difficult problem.

H.3.1. In extreme cases of compounded disturbance – e.g., historical clear-cutting, sugar maple decline and beech bark disease, severe ice storm damage – obligate understory tree species (e.g., *Sorbus americana, Acer pennsylvanicum, A. spicatum*) increase dramatically in abundance and temporarily co-opt these disturbed sites from the overstory trees. This extreme response is most likely in the most disturbance-prone upper landscape positions (e.g., upper slopes), whereas in other positions succession is accelerated or reset.

We propose to examine the combined impacts of these multiple perturbations on vegetation dynamics in the HBR Valley. Current theory suggests three possible outcomes: 1) the accelerated development of the shifting mosaic steady state (Harcombe et al. 2002, Webb and Scagna 2001, Abrams and Nowacki 1992); 2) the resetting of vegetational development to an earlier set successional state (prediction of patch dynamics model, *sensu* Pickett and White 1985); or 3) the deflection of recovery of the mature forest to a retrogressive path (*sensu* Peet 1992, evidence of creeping degradation). In their recent conceptual model, Platt and Connell (2003) describe disturbance scenarios that can lead to two of the three results mentioned above, namely accelerated succession if the disturbance preferentially kills early-successional species and extended succession if late-successional trees are disproportionately impacted. The third potential scenario involves what could be considered an ecological surprise (*sensu* Paine et al. 1998) -- a shift to an alternative vegetational state where the preponderance of disturbances and stressors is such that no canopy species can maintain dominance. Under these conditions, obligate understory tree species proliferate. This situation is observed at the disturbance-prone interface between the broadleaf deciduous and subalpine conifer forests in New England mountains (Siccama 1974). Each scenario has explicit and important implications for community structure and ecosystem function.

Our current monitoring efforts indicate that there is strong landscape-level variation in the intensity of the perturbations and the severity of their impact. For example, ice storm impacts were most severe at upper slope positions in W6 where sugar maple decline is also most evident (Fig. 6), and they interacted directly with damage by beech bark disease (Rhoads et al. 2002). These perturbations and responses occur on a landscape with documented gradients in resource availability and environmental conditions (Schwarz et al. 2003). Thus, we expect that all three scenarios might occur for specific landscape units in HBR Valley. Our goal is to add quantitative detail to the existing conceptual models (Bormann and Likens 1979, Platt and Connell 2003) in order to predict the trajectory for the entire HBEF landscape.

H.3.2. Chronic disturbance in the HBEF by the exotic beech bark disease influences water and nutrient cycling, forest productivity and structure, and patterns of plant and animal communities in heavily infested ecosystems.

Beech bark disease (BBD) is caused by fungi of the genus *Nectria*, whose infection of beech trees is facilitated by an exotic scale insect (*Cryptococcus fagisuga*) (Houston 1994). Beech trees are gradually girdled by cankers and often respond with vigorous root sprouting (Jones and

Raynal 1986, Hane 2003). Tree community responses to the death of beech trees appear to follow two general pathways: 1) in some areas the liberated canopy space is filled by associated species, especially sugar maple (e.g., Catskill Mountains, NY; Lovett, unpublished); 2) in other instances beech can continue to dominate the stand as smaller and younger trees (e.g. Forrester et al 2003). The causes of these distinct pathways are not clear and may depend in part on the vigor of sugar maple populations, as influenced by site quality and especially soil base status. Depending upon the pathway of response, the effects of BBD on ecosystem processes and community structure may be very different (Fig. 18). For example, expansion of sugar maple abundance is expected to favor nitrification and possibly $NO_3^-$ losses (Lovett et al. in press, Lovett and Mitchell, in revision). Changes in productivity, decomposition and organic matter dynamics also would be expected to accompany these different response pathways. Moreover, the ecosystem response to BBD may also feed back to influence community dynamics: Latty et al. (2003) observed that high N concentrations in bark were positively associated with higher BBD loads, so that reductions of N uptake and consequent increases in N availability in infected stands may lead to increased BBD severity. Finally, shifts in forest structure and composition could cause "ripple" effects through the animal community. For instance, reductions in beech abundance and average tree size should reduce the production of beech seeds ("mast"), which are a very important food source for many animals, especially small mammals such as mice and chipmunks. Reductions in small mammal population would have obvious consequences for small-mammal predators such as owls and foxes, and songbird populations could also be affected because small mammals are important nest predators. Songbird populations would also be impacted by changes in forest structure if the forest shifts to smaller size classes of beech or by shifts in food supply if changes in tree species composition engender changes in quantity or quality of Lepidopteran larvae, a major food source for the insectivorous birds.

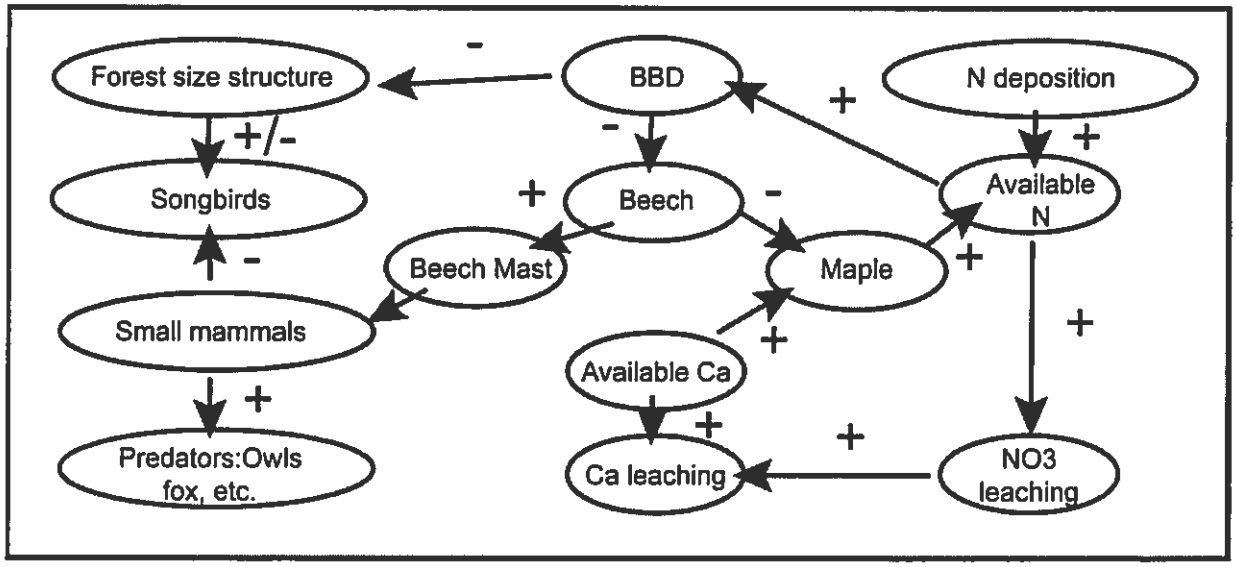


**Figure 18.** Influence diagram depicting hypothetical links between beech bark disease (BBD), N deposition, element cycling and consumers in the forest. Arrows labeled "+" indicate that an increase in one property causes an increase in the other, or a decrease causes a decrease. Arrows labeled "–" indicate that an increase in one property causes a decrease in the other, or a decrease causes an increase. The cascade of interactions illustrates how a disturbance like BBD can ramify throughout many aspects of ecosystem function.

H.3.3. The composition of the mature forest in the Hubbard Brook Valley is undergoing gradual shifts as a result of changing demographics of the dominant species. These shifts are not unidirectional across the entire valley but rather contraction and expansion of population abundances reflect such factors as the legacy of disturbances, site quality differences and the influences of key perturbations.

The exciting observation of exceptionally high abundance and vigor of sugar maple seedlings on $Ca^{2+}$-treated W1 (Fig. 7), together with this species' gradual decline in abundance at selected locations within the HBEF (Fig. 6), stimulates our interest in quantifying the status and causes of trends in tree population abundances across the complex landscape of the HBR Valley. The current forest pattern is partly the product of a series of large-scale disturbances by logging and the 1938 hurricane. Schwarz et al. (2003) demonstrated that most of the dominant trees exhibit strongly clumped spatial patterns that are not entirely accounted for by disturbance or site quality differences but rather reflect neighborhood effects. A crucial question is whether, in the absence of recurring catastrophic disturbances, these neighborhood effects (e.g., seed rain and vegetative expansion of populations) will continue to shape forest pattern under the expanded suite of non-catastrophic disturbances and other perturbations.

H.3.4. The unexpected decline of live biomass on W6 (Fig. 6) reflects a combination of decreased growth rates and increased mortality rates of the dominant tree species; this pattern is repeated in susceptible landscape positions across the Hubbard Brook Valley and is increasing in scale through time.

Although it accurately simulates forest growth in most northern hardwood forests (Aber et al. 2002), the PnET model significantly overpredicts NPP in W6 at the HBEF in the late 1990s (Fahey et al., in review). Smith et al. (2002) ascribed underprediction of NPP on the same watershed for 1955-64 (Fig. 4) in part to the young age of the forest at that time. Certainly part of the continuing NPP decline on W6 probably reflects the well-known (but poorly understood) age-related patterns (Smith and Long 2001). However, unusual growth declines in the dominant species and accelerating mortality of sugar maple and American beech are reflected in the long-term record from W6; Duchesne et al. (2003) recently demonstrated that reduced growth usually preceded crown dieback and other decline symptoms in sugar maple. The decline and mortality of sugar maple in the upper elevation zone of W6 is correlated with exceptionally low soil solution $Ca^{2+}$/Al ratios (Palmer and Driscoll 2002) and foliar $Ca^{2+}$ (Likens et al. 1998), but this syndrome is not widespread across the entire HBR Valley (unpublished data). For example, some of the most productive sites on the S-facing slope are dominated by sugar maple (Fig. 19).

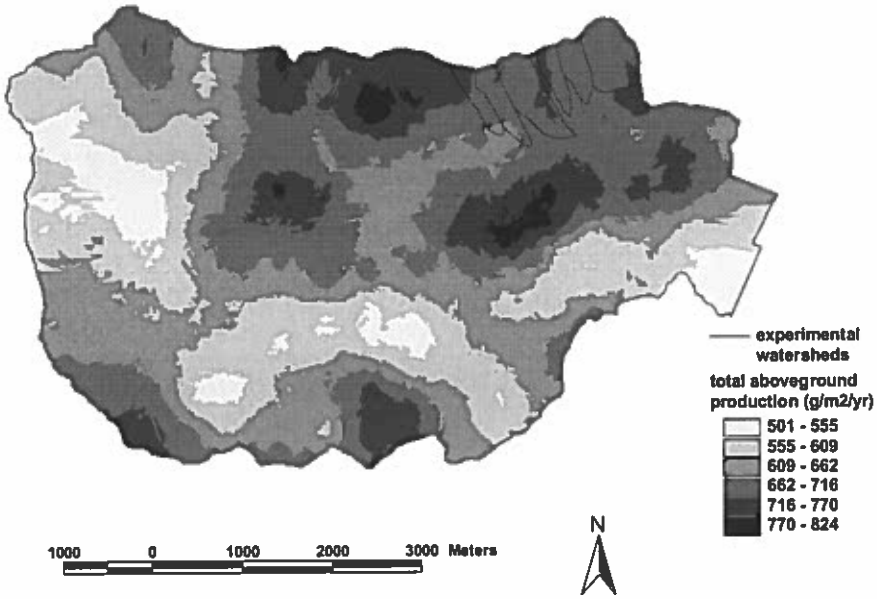


**Figure 19.** Spatial pattern of aboveground wood production across the Hubbard Brook Valley.

C. Approaches for Objective 3

To test H.3.2 and corollary questions, we will conduct extensive surveys of BBD incidence across the HBR Valley. We will take advantage of our valley-wide vegetation surveys (Schwarz et al. 2003) to guide reconnaissance in locating about 200 plots where canopy beech trees are dying or recently dead. In each plot we will measure BBD status, vegetation response, foliage and bark chemistry, and selected soil physical and chemical variables, including soil solution chemistry. We are currently developing a model of C and N dynamics based on these studies at the HBEF and associated work in the Catskills to address questions related to connections between BBD and long-term patterns of stream water N and Ca and forest productivity in experimental watersheds. Furthermore, to connect BBD with the herbivore food web, we propose a valley-wide survey of small mammals, Lepidoptera larvae and their songbird predators. Multivariate and geostatistical analyses will be used (e.g., Doran 2003) to quantify the effects of BBD on these taxa, as we expect that the size of areas severely affected by BBD may act in a threshold manner on food web response.

Our system of permanent vegetation plots in mature forests in the HBEF are essential for testing H.3.1 and H.3.3. These plots encompass three scales: 1) a complete survey of trees in the reference watershed (W6); originally surveyed in 1965 and resurveyed at 5-year intervals since 1977; and in the Ca-treated W1, established in 1996; 2) a series of belt transect plots (total of 10 ha) encompassing the 50 ha bird survey plot, established in 1982 (Fig 13); and 3) about 450 plots distributed on a grid throughout the HBR Valley (valley-wide plots, Fig 13), established in 1995-6 (Schwarz et al. 2001, 2003). All trees >10 cm dbh are permanently tagged in all these plots

(total of about 30,000 stems), providing detailed information on growth, mortality and recruitment. Together with nested measurements of fine and coarse litterfall, ANPP can be estimated accurately using detailed allometric relationships for the site (Siccama et al. 1994). In W6, and the valley-wide plots, saplings, seedling and herbs have been measured in nested plots. Seed deposition has been quantified for 10 years in our intensive plots located along the elevation gradient adjacent to W6 (Fig 13), and more recently seedfall surveys have been conducted in the bird survey area, as well, to explore relationships between mast events and the herbivore food web (Holmes, unpublished). To test H.3.1 and H.3.3 we propose to continue the measurement protocols on these permanent plot networks: valley-wide plots will be resampled in 2005-6, W1 and W6 plots in 2007, and bird survey plots in 2008.

In addition, we propose to establish four mapped vegetation plots in conjunction with each of these plot networks in order to quantify the spatially explicit components of vegetation dynamics. Our primary objectives are to 1) determine the patterns and predictors of tree fecundity; 2) validate previous estimates of seed dispersal (Pacala et al. 1996) for the major tree species; and 3) identify the controls on seedling establishment and canopy recruitment under different disturbance regimes. The location of the plots will be chosen to represent particularly prominent aspects of the observed variation in forest communities (e.g., areas of sugar maple decline in W6, several areas of severe ice storm damage, areas with a high incident of BBD). Given the scale of spatial dependence (Schwarz et al. 2003), all adult trees (> 10 cm dbh) in a 9 ha plot will be mapped to the nearest 0.5 m. Understory trees and saplings will be sampled in smaller nested plots. Seedfall, canopy structure, and understory light availability will be measured annually in a 10 x 10-m grid in the interior of each plot. Field work will begin in 2005. With these data, we will develop site-specific estimates of fecundity and seed dispersal. We will use the inverse method described by Clark et al. (1998, 1999) to fit models to our seedfall data. Moreover, we will examine landscape-scale variation in canopy tree competition and understory-overstory interactions in a spatially explicit context.

## 3.0 – SITE MANAGEMENT

**Site Management and Facilities.** Primary and ultimate responsibility and authority for administering the HBEF is the Chief of the U.S. Forest Service (FS) who in turn delegates authority to the Director of the Northeastern Forest Experiment Station (NFES). The FS has agreed to share the management of the HBES with research institutions, recognizing the need for all parties to commit funds, personnel, and equipment to attain common long-term objectives in research and education. Because of the remote location, general supervision of the HBEF is under the FS principal investigator, the Project Leader (currently Chris Eagar), as delegated by the Director of the NFES. Day-to-day operations of the HBEF are supervised by the resident Research Forester-Manager of the NFES (currently Ian Halm).

The FS operates a year-round field laboratory and office building at HBEF. The Robert S. Pierce Ecosystem Laboratory provides 835 $m^2$ of space, including six offices, four laboratories, one conference room, six dormitory rooms, a kitchen, baths and showers. A sample archive building was constructed in 1990 to house and archive samples of soil, water, plant tissue, and other materials. In addition, there are 280 $m^2$ of maintenance, storage, garage and shop facilities. In 1983, Yale and Cornell Universities purchased Pleasant View Farm (PVF), the 200-yr-old dormitory and laboratory complex, which had been rented for 18 years for use by graduate students and senior researchers, working at the HBEF. In 1993, the Hubbard Brook Research Foundation (HBRF), a non-profit 501(c)(3) charitable organization was established to help assure the long-term integrity and health of the HBES. The HBRF assumed control of PVF and is now supervising extensive renovation of the dormitory and laboratory complex.

**Site Governance.** The original governance structure for the HBES was a Scientific Advisory Committee (SAC) that advised the USFS Project Leader, approved proposed projects and provided some long-term vision. An initial concern of the HBRF was the need for a more inclusive and comprehensive governance structure for the HBES. In response to this concern, a new governance structure was recently developed for the HBES (Figure 20; Groffman et al. in press b).

At the center of the new governance structure is the "Committee of Scientists (COS)," which consists of principal investigators conducting research in the HBEF. The initial COS was assembled by group consensus. The membership of the COS will be reviewed at three-year intervals. There are currently 37 members of the HBES COS. The Scientific Coordinating Committee (SCC) provides leadership for the COS, overseeing a series of committees, providing vision and scientific leadership to the research program, fostering integration and synthesis across diverse projects, encouraging new scientists to work at the sites, enhancing diversity among the scientific community, and promoting interactions and communication among HBES scientists. The "visioning" function of the SCC is considered to be particularly critical as governance activities for large projects can become mired in practical detail. The SCC has 10 members, five of which are elected by the COS (currently Groffman, chair, Driscoll, Fisk, Likens, Pardo). Other members include one of the two HBR LTER principal investigators

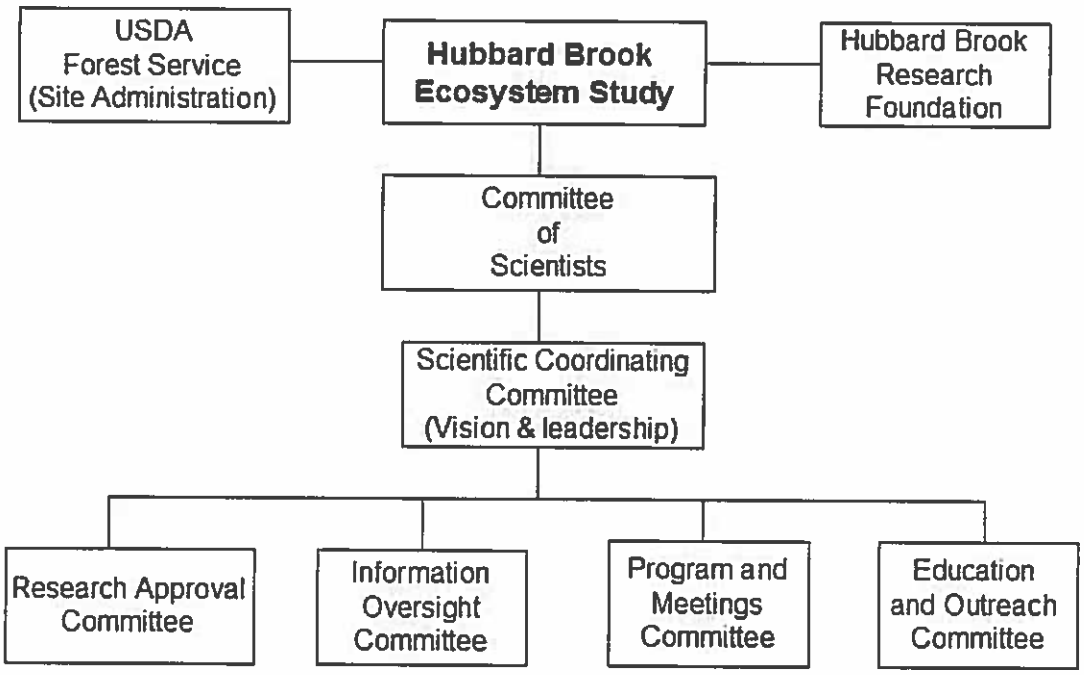


**Figure 20.** Governance structure of the Hubbard Brook Ecosystem Study.

(chosen amongst themselves, currently Fahey), a senior scientist (chosen from amongst a group of the five investigators with the longest experience in the HBES, currently Holmes), a scientist not associated with the HBES (chosen and invited by the other SCC members, currently Diane McKnight from the University of Colorado), a representative from the HBRF Board of Directors (a non-scientist, currently vacant), the USFS Project Leader for the HBEF (ex-officio, currently Chris Eagar), and the Executive Director of the HBRF (ex-officio, currently David Sleeper).

The Research Approval Committee (RAC) is advisory to the USFS Project Leader, who bears ultimate responsibility for research activities at the HBEF. This committee evaluates and approves proposed projects, facilitates coordination and prevents conflicts among different research projects at the site. Anyone wishing to conduct research at HBEF must submit a brief proposal to the RAC (proposals are accepted three times per year). The Information Oversight Committee (IOC) is responsible for the content of the HBR web site (www.hubbardbrook.org), data management and maintenance of the HBES data, sample and document archives. The Program and Meetings Committee (PMC) organizes a series of COS meetings (four per year) as well as the annual HBES cooperator's meeting. The Education and Outreach Committee (EOC)

facilitates links between HBES research and learning groups ranging from K – 12 to local residents to management and policy communities.

The quarterly COS meetings are a key venue for project management; with time allocated for logistical issues (25%) and discussion of overarching scientific topics (75%). All investigators working at HBEF are required to make presentations at the annual Cooperator's Meeting in July which is attended each year by approximately 150 people and includes a group dinner, barn dance and midnight swim that facilitate project morale and cohesion.

We envision that the new governance structure will maintain the vitality of the HBES for decades to come. We hope that the structure will maintain the integrity of the long-term data and experiments, attract new people to the project, encourage and enhance diversity among scientists working at the site, help us to develop new ideas and experiments and increase participation in project leadership. It is our intent that the new structure will allow us to focus more on our vision for the future of the HBES. The SCC and PMC will establish an agenda to foster regular discussion of issues such as "new experiments," "synthesis," "gaps in coverage", "strategies to attract new scientists and enhance diversity" and "improvements in education and outreach."

The new governance structure and our new conceptual model (Groffman et al. in press a; Figure 1) were useful in the preparation of this renewal proposal, allowing researchers to articulate how their ideas fit into the overall ecosystem study and organizational framework of the project in a public and transparent process. This process has helped the principal investigators make decisions about how to allocate LTER funds for in a scientifically sound, semi-democratic way.

The new governance structure also facilitated our ability to increase and maintain the participation of under-represented groups in the project, which has been identified as a priority in previous reviews of the HBR-LTER. It helped us to justify a new hire at Syracuse University that participates in the project (Andria Costello), to provide funds to keep Melany Fisk involved as she started a new job at Appalachian State University in North Carolina, and to add USFS-employee Lindsey Rustad to the project. Rustad is leading an effort to create a partnership between the University of New Hampshire and an HBCU in Ohio, Central State University, the goal of which is to provide a "pipeline" for qualified minority students to train at their home institution and to participate in summer research at the proposed Hubbard Brook Precipitation Manipulation Experiment. Once established, we hope to extend this program to partnerships with additional HBCU's through application for standard REU supplements.

## 4.0 – INFORMATION MANAGEMENT AND TECHNOLOGY

### Governance

The HBR LTER acquires, manages and disseminates data and information to facilitate research, educational and outreach activities. Information management for the HBR-LTER is supervised by the information oversight committee (IOC) comprised of three subcommittees (data, web page editorial, and external activities; see section 3). The IOC reports annually on information management-related issues to the HBES Scientific Coordinating Committee (SCC – see section 3). The information manager has historically been a USDA Forest Service (USDA FS) employee. The primary role of the information manager is to oversee the development and structure of the HBES database management system and to serve as a representative and liaison for HBEF information management. The information manager also provides expertise and support for scientists conducting research projects and data syntheses. Note that responsibility for information management is deeply and widely rooted in the HBES. The IOC is lead by a founding member of the HBES (Likens) and includes a high diversity of participants. Previous reviews have motivated a "recommitment to information management" in our project.

### Data acquisition

Research at the HBEF is conducted by a geographically dispersed group of cooperating scientists from many institutions. The data collected by these scientists include core data sets that comprise the long-term monitoring program (see Table 1), as well as data from shorter-term studies. When a scientist submits a proposal to conduct research at the HBEF they agree to contribute the data obtained in the study and accompanying metadata to the HBR database. In addition all HBR LTER scientists are required to provide their data to the HBR database. HBR scientists may operate independently; however the data they collect are ultimately stored in a centralized database management system at the USDA FS in Durham, NH. Since the data are diverse and often highly specialized, individual researchers are responsible for developing their own database management protocols (database design, QA/QC, and backup) prior to submission to the centralized database. However the information manager provides guidance and assistance at the onset and through all phases of research to ensure the integrity and safety of the data and metadata. The IOC has recently developed data backup guidelines for researchers to ensure that valuable data from HBR are not lost before they are entered into the centralized database.

### Data management

HBR data are typically updated in the centralized database management system on an annual basis. Data are only accepted in American Standard Code for Information Interchange (ASCII) format because this format is likely to always be available across computing hardware platforms and can be imported into nearly all software packages. Data are copied and archived in their original, unmanipulated form (and medium if applicable) in a fire resistant vault at the USDA FS in Durham, NH. A limited amount of hardware is also stored at the USDA FS for reading antiquated storage mediums (e.g. 5.25 and 3.5 inch disk drives, Bernoulli drives, zip drives). Data formatting and comprehensive QA/QC checks are made with a series of manual inspections and computer programs. Corrected data and metadata are posted on the HBES web site and are reviewed by the scientist before they are made available to the public. Data are archived at the

USDA FS and are backed up regularly. Duplicate backups of the entire HBR database are stored at the USDA FS in Durham, NH and at the HBEF.

**Data dissemination**

HBR was the first LTER site to distribute data through a fully functional, networked database retrieval system, beginning in 1988 with a publicly accessible direct-dial computer bulletin board. Since that time, HBES information management has evolved with technological advances, yet the commitment to making HBR data publicly available has remained steadfast. Currently, the HBR World Wide Web site is the primary means by which HBR data and information are disseminated. Data are updated on the web site on an annual basis or in some cases more frequently. The maximum time lag for making data publicly available is two years after collection, except for several biogeochemical datasets which are made public five years after collection. An example of HRB data access guidelines can be viewed at http://www.hubbardbrook.org/research/data/stream/dataform.htm.

The HBR web site resides on an LTER server in New Mexico, taking advantage of the hardware and support provided through the Network Office. Furthermore, having the Network Office host the HBR web site enables us to more easily integrate data and information from HBR with the broader scope and initiatives of the LTER Network. When new data sets are added to the web site or when other significant changes to the web site are proposed, they are first reviewed by the HBR web site editorial subcommittee to ensure the quality of the material posted. Highlights of data and information posted on the HBR web site are below:

**GIS database** – The HBR geographic database consists of Geographic Information System (GIS) coverages and remote sensing images. All GIS data and associated metadata can be viewed and downloaded from the HBR web site. There are currently over 20 vector and raster geographic data sets. Future work will include augmenting and updating the metadata to comply with Federal Geographic Data Committee and Ecological Metadata Language (EML) standards.

**Personnel database** – A personnel database, including curriculum vitas, is maintained on the HBR web site. Vitas are updated via a web form by researchers, students, and employees associated with HBR. Updates can be made anytime and reminders (and subsequent follow-ups) are sent out biannually to ensure that the information is current.

**Current Research** – A description of current research activities is available through the HBR web site to keep the public abreast of research initiatives and preliminary findings. Updates are made frequently to reflect changes in the development and scope of current research. The annual HBES Cooperator's Meeting is an important tool for updating this section. The information manager and chair of the WWW editorial sub-committee of the IOC use this meeting as an opportunity to identify and work with researchers beginning new and exciting research projects and to get these projects represented on the page in a timely manner. These early project descriptions then provide a natural platform for posting of data collected as the projects develop.

**Photo archive** – An archive of digital images (>325 images) is maintained by the USDA FS. These images are available on the WWW site and are frequently used in publications, presentations and textbooks. In addition to obtaining new images, the USDA FS has initiated a

major effort to scan historical HBR photographs and slides at high resolution to ensure that image quality is preserved.

**Bibliographic references** - A document archive including paper copies of HBR publications, theses, correspondence and maps is maintained at the Institute of Ecosystem Studies (IES) in Millbrook, NY. The IES also maintains a digital database of the HBR publication list, which includes both LTER and non-LTER publications dating back to 1955 (> 1850 publications). The database is accessible in a searchable format on the HBR web site.

**Interactive calculators** – An experiment utilizing web technologies has produced a series of interactive web programs that allow a user to calculate and graph forest summary statistics (e.g. species-specific basal area, stem density, biomass) from various HBR vegetation datasets. The options for criteria selection are flexible enough to make this a potentially useful tool for researchers or students to generate summaries for very specific subsets of the data (e.g. a specific set of plots, a specific tree diameter range).

**Education and Outreach**. A major addition to the HBES WWW page was the development of an education page (partially created using Schoolyard LTER supplement funds) for teachers and students and a page for the HBRF that is responsible for major outreach activities for policy makers and managers. The Education page has been widely used by teachers and students.

## Sample Archive

HBR is committed to the permanent storage of physical samples (e.g. streamwater, precipitation, lakewater, vegetation, soil) so that they will be available for future research. After samples are collected and analyzed, they are stored in a physical sample archive building located at HBR. The building was constructed solely for this purpose and now houses approximately 40,000 samples. Samples are preserved, barcoded, and cataloged with accompanying metadata in a database that is accessible on the HBR web site. Requests for reanalysis of these samples (e.g. isotopic analyses, heavy metals, etc.) are received periodically, and have resulted in a number of publications. Limitations on storage space are becoming a concern and it may be necessary to expand the facility or prioritize the samples to store.

## Future direction

The future thrust of information management at HBR will be focused on improving integration of heterogeneous data and information of the HBES. The proposed system will create linkages among current HBR databases (e.g. GIS data, chemical database, physical sample archive database, personnel database, bibliography) so that data and related information can be extracted easily by end-users. We propose to achieve this goal by using Ecological Metadata Language (EML) as the framework for the HBR database management system. Use of this standard will make HBR data more accessible to researchers and will improve integration with the LTER network and other entities that collect ecological data. We are currently in the process of converting existing metadata into EML and will work with HBR researchers to expand existing metadata and create metadata for new data contributions.

## 5.0 -- OUTREACH/EDUCATION

### Outreach

The Hubbard Brook Research Foundation's (HBRF) *Science Links*™ program was initiated to build on the expertise and long-term research of the HBES. In 1996, HBRF conducted a study, which determined that ecosystem science, is under-utilized in conservation and environmental policy. This gap is the result of poor access to research findings, lack of a constructive process of engagement for scientists, and paucity of published research design with management and policy goals in mind. *Science Links* is a series of scientific synthesis projects on issues in ecosystem science designed to facilitate information exchange among scientists, policy makers and the public, and actively disseminating HBES research related to environmental issues in the Northeast.

The program is built on three related premises: 1) environmental policy is more effective when it is grounded in environmental science; 2) ecosystem science can be enriched by an awareness of current public policy issues and social concerns; and 3) science serves the public best when it does not advocate specific policies, but instead provides scientific information about the likely outcomes of policy choices.

To address the need for improving the scientific basis for decision-making, HBRF has launched a series of projects on effects of atmospheric emissions of S, N, Hg and C. Each project results in both a scientific and policy publication. The findings are disseminated through a communication strategy for educators, policy makers, the general public and the media. To reach educators, we will participate in teacher trainings in the region, and collaborate with the National Science Teachers Association. Outreach to policy makers includes mailings, Congressional briefings, and policy workshops across the region. To reach the public and the media, we create press kits, detailed media contact information, and conduct press conferences at the National Press Club and other venues. HBRF also conducts dozens of briefings with policy-makers, and sponsors and presents at conferences and all through the Northeast.

Although *Science Links* projects on acid rain (S; Driscoll et al. 2001) and N pollution (Driscoll et al. 2003a,b) have been completed, they continue to generate attention and ongoing demand for the publications and updated information. We are currently working on projects of Hg, and C.

**Mercury:** Eighty-seven percent of anthropogenic Hg originates from waste and fossil fuel combustion. Due to its tendency to bioconcentrate in the aquatic food chain, 44 states have issued fish consumption advisories for Hg. The HBRF has convened a team of scientists and policy experts to develop a synthesis article on Hg contamination in forest and aquatic ecosystems. This article will be completed in two years.

**Carbon:** There is a critical need to quantify to what extent forests in the Northeast sequester C and thereby offset $CO_2$ emissions. One contentious area is the proper accounting of offsets for $CO_2$ emissions. This contention is fueled by insufficient information regarding the potential of forests to store C and for what period of time. Researchers from the HBEF, Harvard Forest and institutions will draw on the results of a C monograph for the HBEF (Fahey et al. in review) and

other studies. The C project was initiated with a scoping study in the summer of 2003, which will culminate in a full project in late 2004.

## Education

Educational activities at the HBEF have focused on four areas:

**Public tours at the HBEF:** We have continued to improve tours to meet the needs and interests of various constituencies (e.g., students, adults, scientists). We have increased potential tour topics to include research not previously addressed. In 2003, approximately 600 individuals toured the HBEF.

**Outreach to public schools:** We formally introduced ourselves to local school districts, via a letter to principals and science department chairs. Teachers that responded were invited to attend our Annual Cooperator's Meeting (July 2003), which served as a basis for exploring potential areas of cooperation between the schools and the HBES. There are currently two local teachers with plans to visit and use HBES work in the classroom, in addition to the four secondary teachers in the wider region who already do visit and use us in the classroom.

**Articles for regional publications:** The on-site educator wrote six research summary articles, four of which were syndicated in 12 newspapers throughout the region.

**Education and Outreach Committee:** The education and outreach committee is a standing committee of the COS (see Site Management section 3) and consists of PIs, on-site staff, and HBRF board and staff members. Current issues include the needs of staff in leading tours, and future direction and scope of our educational efforts.

**Proposed work**: We will continue our interactions with local schools, with the goal of conducting a secondary education teacher-training event in 2005. We plan to work closely with each teacher, including visits to the classroom, to put secondary school tours in a curriculum-relevant classroom context. During the summer the teachers will be invited to 2-3 days of seminar aimed at planning the teacher-training event for other teachers in the region. This will include a day at the Annual Cooperator's meeting and a day or two of planning activities.

We intend to continue to expand our program of research summary articles. New ideas will be solicited from PIs and new venues for publication will be sought.

We will continue to diversify tour offerings. Active PIs will develop 1-2 page summaries of their research, and these summaries will be compiled for use by staff who conduct tours. We will also organize a one-day session for scientists to "train" tour leaders by providing current research that can be drawn upon during tours.

## LITERATURE CITED


Aber, J.D., K.J. Nadelhoffer, P. Steudler and J.M. Melillo. 1989. Nitrogen saturation in northern forest ecosystems. BioScience 39:378-386.

Aber, J. D. and C. A. Federer. 1992. A generalized, lumped-parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems. Oecologia 92:463-474.

Aber, J. D. and C. T. Driscoll. 1997. Effects of land use, climate variation and N deposition on N cycling and C storage in northern hardwood forests. Global Biogeochem. Cy. 11:639-648.

Aber, J. D., S. V. Ollinger and C. T. Driscoll. 1997. Modeling nitrogen saturation in forest ecosystems in response to land use and atmospheric deposition. Ecol. Model. 101:61-78.

Aber, J.D., S.V. Ollinger, C.T. Driscoll, G.E. Likens, R.T. Holmes, R.J. Freuder and C.L. Goodale. 2002. Inorganic N losses from a forested ecosystem in response to physical, chemical, biotic and climatic perturbances. Ecosystems 5:648-658.

Aber, J.D., C.L. Goodale, S.V. Ollinger, M.-L. Smith, A.H. Magill, M.E. Martin, J.L. Stoddard. 2003. Is nitrogen altering the nitrogen status of northeastern forests? BioScience 53:375-390.

Abrams, M.D. and G.J. Nowacki. 1992. Historical variation in fire, oak recruitment, and post-logging accelerated succession in central Pennsylvania, Bulletin of the Torrey Botanical Club 119: 19-29.

Aitkenhead, J. A. and W. H. McDowell. 2000. Soil C:N ratio as a predictor of annual riverine DOC flux at local and global scales. Global Biogeochemical Cycles 14(1):127-138.

Alexander, R.B., R.A. Smith and G.E. Schwarz. 2000. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. Nature 403:758-761.

Alewell, C., M. Mitchell, G. Likens and R. Krouse. 1999. Sources of stream sulfate at the Hubbard Brook Experimental Forest: long-term analysis using stable isotopes. Biogeochemistry 44:281-299.

Bailey, S.W., C.T. Driscoll and J.W. Hornbeck. 1995. Acid-base chemistry and aluminum transport in an acidic watershed and pond in New Hampshire. Biogeochemistry 28:69-91.

Bailey, S.W., J.W. Hornbeck, C.T. Driscoll and H.E. Gaudette. 1996. Calcium imports and transport in a base-poor forest ecosystem as interpreted by Sr isotopes. Water Resour. Res. 32:707-719.

Bailey, S. W., B. Mayer and M. J. Mitchell. (in press). The influence of mineral weathering on drainage water sulfate in the northeastern United States. Hydrol. Proc.

Bernhardt, E. S., G. E. Likens, D. C. Buso and C. T. Driscoll. 2003. In-stream update dampens effects of major forest disturbance on watershed nitrogen export. P. Natl. Acad. Sci. 100(18):10304-10308.

Bilby, R. E. 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. Ecology 62(5):1234-1243.

Blum, J. D., E. H. Taliaferro, M. T. Weisse and R. T. Holmes. 2000. Changes in Sr/Ca, Ba/Ca and $^{87}Sr/^{86}Sr$ ratios between trophic levels in two forest ecosystems in the northeastern U.S.A. Biogeochemistry 49:87-101.

Blum, J. D., E. H. Taliaferro and R. T. Holmes. 2001. Determining the sources of calcium for migratory songbirds using stable strontium isotopes. Oecologia 126:569-574.

Blum, J. D., A. Klaue, C. A. Nezat, C. T. Driscoll, C. E. Johnson, T. G. Siccama, C. Eagar, T. J. Fahey and G. E. Likens. 2002. Mycorrhizal weathering of apatite as an important calcium source in base-poor forest ecosystems. Nature 417:729-731.

Bohlen, P. J., P. M. Groffman, C. T. Driscoll, T. J. Fahey, and T. G. Siccama. 2001. Plant-soil-microbial interactions in a northern hardwood forest. Ecology 82(4):965-978.

Bormann, F. H. and G. E. Likens. 1979. Catastrophic disturbance and the steady state in northern hardwood forests. Amer. Sci. 67(6):660-669.

Bowden, W. B. and F. H. Bormann. 1986. Transport and loss of nitrous oxide in soil water after forest clear-cutting. Science 233:867-869.

Bukaveckas, P. A., G. E. Likens, T. C. Winter and D. C. Buso. 1998. A comparison of methods for deriving solute flux rates using long-term data from streams in the Mirror Lake watershed. Water, Air, and Soil Pollut. 105:277-293.

Burns, D. A. and Kendall C. 2002. Analysis of $^{15}N$ and $^{18}O$ to differentiate $NO_3^-$ sources in runoff at two watersheds in the Catskill Mountains of New York. Water Res. Res. 38: 9/1-9/11.

Buso, D. C., G. E. Likens and J. S. Eaton. 2000. Chemistry of precipitation, stream water and lake water from the Hubbard Brook Ecosystem Study: A record of sampling protocols and analytical procedures. General Tech. Report NE-275. Newtown Square, PA: USDA Forest Service, Northeastern Research Station. 52 pp.

Butler, T. J., G. E. Likens and B.J.B. Stunder. 2001. Regional-scale impacts of Phase I of the Clean Air Act Amendments: The relation between emissions and concentrations, both wet and dry. Atmos. Environ. 35(6):1015-1028.

Butler, T. J., G. E. Likens, F. M. Vermeylen and B. J. B. Stunder. 2003. The relation between NO emissions and precipitation $NO_3^-$ in the eastern USA. Atmos. Environ. 37(15):2093-2104.

Campbell, J. L., J. W. Hornbeck, W. H. McDowell, D. C. Buso, J. B. Shanley and G. E. Likens. 2000. Dissolved organic nitrogen budgets for upland, forested ecosystems in New England. Biogeochemistry 49:123-142.

Carpenter, S.R., D. Ludwig and W.A. Brock. 1999. Management of eutrophication for lakes subject to potentially irreversible change. Ecol. Appl. 9:751-771.

Carreira, J.A., R. Garcia-Ruiz, J. Lietor and A.F. Harrison. 2000. Changes in soil phosphatase activity and P transformation rates induced by application of N- and S-containing acid mist to a forest canopy. Soil Biol. Biochem. 32:1857-1865.

Chagnon M., D. Pare, C. Hebert, C. Camire. 2001. Effects of experimental liming on collebolan communities and soil microbial biomass in a southern Quebec sugar maple (Acer saccharum Marsh.) stand. Applied Soil Ecology 17:81-90.

Clark, J.S., E. Macklin, and L. Wood. 1998. Stages and spatial scales of recruitment limitation in southern Appalachian Forests. Ecological Monographs 68: 213-235.

Clark, J.S., M. Silman, R. Kern, E. Macklin, and J. HilleRisLambers. 1999. Seed dispersal near and far: Patterns across temperate and tropical forests. Ecology 80:1475-1494.

Cogbill, C.V. 1993. Hubbard Brook Revisited: Land-use History of the Hubbard Brook Valley, NH. Unpublished Ms. (available on request from the author).

Cogbill, C. V., J. Burk and G. Motzkin. 2003. The forests of presettlement New England, USA: spatial and compositional patterns based on town proprietor surveys. J. Biogeography 29:1279-1304.

Covington, W. W. 1981. Changes in forest floor organic matter and nutrient content following clearcutting in northern hardwoods. Ecology 62(1):41-48.

Cramer, J., T. J. Fahey and J. J. Battles. 2000. Patterns of leaf mass, area and nitrogen in young northern hardwood forests. Amer. Midl. Nat. 144:253-264.

Cronan C. S., D. F. Grigal. 1995. Use of calcium/aluminum ratios as indicators of stress in forest ecosystems. J. Environ. Qual. 24:209-226.

Davis, M. B., R. E. Moeller, G. E. Likens, J. Ford, J. Sherman and C. Goulden. 1985. Paleoecology of Mirror Lake and its watershed. pp. 410-429. In: G.E. Likens (ed.). An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment. Springer-Verlag New York Inc.

DeHayes, D. H., P. G. Schaberg, G. J. Hawley, G. R. Strimbeck. 1999. Acid rain impacts calcium nutrition and forest health: alteration of membrane-associated calcium leads to membrane destabilization and foliar injury in red spruce. BioScience 49:789-800.

de Visser, P.H.B. and N. van Breemen. 1995. Effects of water and nutrient applications in a Scots pine stand to tree growth and nutrient cycling. Plant and Soil 173:299-310.

Doran, P.J. 2003. Intraspecific spatial variation in bird abundance: patterns and processes. Ph.D. Thesis, Dartmouth College.

Driscoll, C. T., G. E. Likens and M. R. Church. 1998. Recovery of surface waters in the northeastern U.S. from decreases in atmospheric deposition of sulfur. Water, Air, and Soil Pollut. 105:319-329.

Driscoll, C. T., G. B. Lawrence, A. J. Bulger, T. J. Butler, C. S. Cronan, C. Eagar, K. Fallon Lambert, G. E. Likens, J. L. Stoddard and K. C. Weathers. 2001(a). Acidic deposition in the northeastern United States: sources and inputs, ecosystem effects, and management strategies. BioScience 51(3):180-198.

Driscoll, C.T., G.B. Lawrence, A.J. Bulger, T.J. Butler, C.S. Cronan, C. Eagar, K.F. Lambert, G.E. Likens, J.L. Stoddard, and K.C. Weathers. 2001(b). Acid rain revisited: advances in scientific understanding since the passage of the 1970 and 1990 Clean Air Act Amendments. Hubbard Brook Research Foundation, Science Links™ Publication, Hanover, NH, 20 pp.

Driscoll, C., D. Whitall, J. Aber, E. Boyer, M. Castro, C. Cronan, C. Goodale, P. Groffman, C. Hopkinson, K. Lambert, G. Lawrence and S. Ollinger. 2003(a). Nitrogen pollution in the Northeastern United States: sources, effects and management options. BioScience 53:357-374.

Driscoll, C., D. Whitall, J. Aber, E. Boyer, M. Castro, C. Cronan, C. Goodale, P. Groffman, C. Hopkinson, K. Lambert, G. Lawrence and S. Ollinger. 2003(b). Nitrogen Pollution: Sources and Consequences in the U.S. Northeast. Environment 45: 8-22.

Driscoll, C. T., K. M. Driscoll, K. M. Roy and M. J.. Mitchell. 2003(c). Chemical response of lakes in the Adirondack Region of New York to declines in acidic deposition. Environ. Sci. Technol. 37:2036-2042.

Drohan, P., S. L. Stout, and G. Petersen. 2002. Sugar maple (*Acer saccharum Marsh.*) decline during 1979-1989 in northern Pennsylvania. For. Ecol. Manage. 170:1-17.

Duchesne, L., R. Ouimet and C. Mourneau. 2003. Assessment of sugar maple health based on basal area growth pattern. Can. J. For. Res. 33:2074-2080.

Elser, J.J., R.W. Sterner, E. Govokhova, W.F. Fagan, T.A. Markow, J.B. Cotner, J.F. Harrison, S.E. Hobbie, G.M. Odell and L.J. Weider. 2000. Biological stoichiometry from genes to ecosystems.

Fahey, T. J., J. W. Hughes, Mou Pu and M. A. Arthur. 1988. Root decomposition and nutrient flux following whole-tree harvest of northern hardwood forest. Forest Science 34(3):744-768.

Fahey, T.J., J.J. Battles, G.F. Wilson. 1998. Response of early successional northern hardwood forests to changes in nutrient availability. Ecol. Monogr. 68(2):183-212.

Fahey, T.J., T.G. Siccama, C.T. Driscoll, G.E. Likens, J. Campbell, C.E. Johnson, J.D. Aber, J.J. Cole, M.C. Fisk, P.M. Groffman, S.P. Hamburg, R.T. Holmes, P.A. Schwarz and R.D. Yanai. (in review). The Biogeochemistry of Carbon at Hubbard Brook.

Federer, C. A. 1984. Organic matter and nitrogen content of the forest floor in even-aged northern hardwoods. Can. J. For. Res. 14(6):763-767.
Federer, C.A. 1995. BROOK90: a simulation model for evaporation, soil water and streamflow. USDA Forest Service, PO Box 640, Durham, NH 03824.

Fiorentino, I., T. J. Fahey, P.M. Groffman, C. Eagar, C. T. Driscoll and T. G. Siccama. 2003. Initial responses of phosphorus biogeochemistry to calcium addition in a northern forest ecosystem. Can. J. For. Res. 33:1864-1873.

Fisk, M. C. and T. J. Fahey. 2001. Microbial biomass and nitrogen cycling responses to fertilization and litter removal in young northern hardwood forests. Biogeochemistry 53(2):201-223.

Fitzhugh, R. D., C. T. Driscoll, P. M. Groffman, G. L. Tierney, T. J. Fahey and J. P. Hardy. 2001. Effects of soil freezing disturbance on soil solution nitrogen, phosphorus, and carbon chemistry in a northern hardwood ecosystem. Biogeochemistry 56(2):215-238.

Fitzhugh, R. D., G. E. Likens, C. T. Driscoll, M. J. Mitchell, P. M. Groffman, T. J. Fahey and J. P. Hardy. 2003(a). The role of soil freezing events in interannual patterns of stream chemistry at the Hubbard Brook Experimental Forest, New Hampshire. Environ. Sci. Technol. 37:1575-1580.

Fitzhugh, R. D., C. T. Driscoll, P. M. Groffman, G. L. Tierney, T. J. Fahey and J. P. Hardy. 2003(b). Soil freezing and the acid-base chemistry of soil solutions in a northern hardwood forest. Soil Sci. Soc. Am. J. 67:1897-1908.

Fluckinger, W. and S. Braun. 1998. Nitrogen and its effect on growth, nutrient status and parasite attacks in beech and Norway spruce. Water, Air, Soil Pollut. 116-99-110.

Frelich, L.E. and P.B. Reich. 1999. Neighborhood effects, disturbance severity and community stability in forests. Ecosystems 2:151-166.

Gbondo-Tugbawa, S. S., C. T. Driscoll, J. D. Aber and G. E. Likens. 2001. Evaluation of an integrated biogeochemical model (PnET-BGC) at a northern hardwood forest ecosystem. Water Resour. Res. 37(4):1057-1070.

Gbondo-Tugbawa, S.S. and C.T. Driscoll. 2002(a). A retrospective analysis of the response of soil and stream chemistry of a northern forest ecosystem to atmospheric emission controls from the 1970 and 1990 Amendments of the Clean Air Act. Environ. Sci. Technol. 36:4714-4720.

Gbondo-Tugbawa, S. S. and C. T. Driscoll. 2002(b). Evaluation of the effects of future controls on sulfur dioxide and nitrogen oxide emissions on the acid-base status of a northern forest ecosystem. Atmos. Environ. 36:1631-1643.

Gbondo-Tugbawa, S. S., C. T. Driscoll, M. J. Mitchell, J. D. Aber and G. E. Likens. 2002. A model to simulate the response of a northern hardwood forest ecosystem to changes in S deposition. Ecol. Appl. 12(1):8-23.

Gbondo-Tugbawa, S. S. and C. T. Driscoll. 2003. Factors controlling long-term changes in soil pools of exchangeable basic cations and stream acid neutralizing capacity in a northern hardwood forest ecosystem. Biogeochemistry 63:161-185.

Gleeson, S.K. and R.E. Good. 2003. Root allocation and multiple nutrient limitation in the New Jersey Pinelands. Ecol. Lett 6:220-227.

Goodale, C.L. and J.D. Aber. 2001. The long-term effects of land-use history on nitrogen cycling in northern hardwood forests. Ecol. Appl. 11:253-267.

Goodale C. L., J. D. Aber, P. M. Vitousek. 2003. An unexpected nitrate decline in New Hampshire streams. Ecosystems 6(1): 75-86.

Groffman, P. M., C. T. Driscoll, T. J. Fahey, J. P. Hardy, R. D. Fitzhugh and G. L. Tierney. 2001(a). Colder soils in a warmer world: A snow manipulation study in a northern hardwood forest ecosystem. Biogeochemistry 56(2):135-150.

Groffman, P. M., C. T. Driscoll, T. J. Fahey, J. P. Hardy, R. D. Fitzhugh and G. L. Tierney. 2001(b). Effects of mild winter freezing on soil nitrogen and carbon dynamics in a northern hardwood forest. Biogeochemistry 56(2):191-213.

Groffman, P. M., C. T. Driscoll, G. E. Likens, T. J. Fahey, R. T. Holmes, C. Eagar and J. D. Aber. (in press(a)). Neither snow, nor rain, nor heat, nor gloom of night: a new conceptual model for the Hubbard Brook Ecosystem Study. BioScience.

Groffman, P. M., C. T. Driscoll, C. Eager, M. C. Fisk, T. J. Fahey, R. T. Holmes, G. E. Likens and L. Pardo. (in press (b)). A new governance structure for the Hubbard Brook Ecosystem Study. Bull. Ecol. Soc. Am.

Hagvar, S. 1984. Effects of liming and artificial acid rain on Collembola and Protura in coniferous forest. Pedobiologia 27: 341-354.

Hall, R. O., Jr., K. H. Macneale, E. S. Bernhardt, M. Field and G. E. Likens. 2001. Biogeochemical responses of two forest streams to a two-month calcium addition. Freshwater Biology 46(3):291-302.

Hane, E. N. 2003. Indirect effects of beech bark disease on sugar maple seedling survival. Can. J. For. Res. 33:807-813.

Hane, E. N., S. P. Hamburg, A. L. Barber and J. A. Plaut. 2003. Phytotoxicity of American beech leaf leachate to sugar maple seedlings in a greenhouse experiment. Can. J. For. Res. 33:814-821.

Harcombe, P.A., C.J. Bill, M. Fulton, J.S. Glitzenstein, P.L. Mark, and I.S. Elisk. 2002. Stand dynamics over 18 years in a southern mixed hardwood forest, Texas, USA. Journal of Ecology 90:947-957.

Hardy, J. P., P. M. Groffman, R. D. Fitzhugh, K. S. Henry, T. A Welman, J. D. Demers, T. J. Fahey, C. T. Driscoll, G. L. Tierney and S. Nolan. 2001. Snow depth manipulation and its influence on soil frost and water dynamics in a northern hardwood forest. Biogeochemistry 56(2):151-174.

Holmes, R.T. 1988. Community structure, population fluctations, and resource dynamics of birds in temperate deciduous forests. Proc. XIX Internt. Ornith. Congr. (Ottawa) 10:1318-1327.

Holmes, R. T. and T. W. Sherry. 2001. Thirty-year bird population trends in an unfragmented temperate deciduous forest: importance of habitat change. Auk 118(3):589-609.

Hong, B. 2004. Controls on the temporal and spatial patterns of streamflow and nitrate flux at Hubbard Brook Watershed Six, New Hampshire, USA. Ph.D. Dissertation, Cornell University. 306 p.

Hornbeck, J.W., S.W. Bailey, D.C. Buso and J.B. Shanley. 1997. Streamwater chemistry and nutrient budgets for forested watersheds in New England: Variability and management implications. Forest Ecol. Manage. 93:73-89.

Horsley, S. B., R. P. Long, S. W. Bailey, R. A. Hallett and T. J. Hall. 2000. Factors associated with the decline disease of sugar maple on the Allegheny Plateau. Can. J. For. Res. 30:1365-1378.

Houlton, B. Z., C. T. Driscoll, T. J. Fahey, G. E. Likens, P. M. Groffman, E. S. Bernhardt and D. C. Buso. 2003. Nitrogen dynamics in ice storm damaged forest ecosystems: implications for nitrogen limitation theory. Ecosystems 6:431-443.

Houston, D.R. 1994. Major new tree disease epidemics: beech bark disease. Am. Rev. Phytopath 32:75-87.

Huntington, T. G., R. P. Hooper, C. E. Johnson, B. T. Aulenbach, R. Cappellato and A. E. Blum. 2000. Calcium depletion in a southeastern United States forest ecosystem. Soil Sci. Soc. Am. J. 64:1845-1858.

Johnson, C. E., A. H. Johnson, T. G. Huntington and T. G. Siccama. 1991a. Whole-tree clear-cutting effects on soil horizons and organic-matter pools. Soil Sci. Soc. Am. J. 55:497-502.

Johnson, C. E., A. H. Johnson and T. G. Siccama. 1991b. Whole-tree clear-cutting effects on exchangeable cations and soil acidity. Soil Sci. Soc. Am. J. 55:502-508.

Johnson, C. E., C. T. Driscoll, T. G. Siccama and G. E. Likens. 2000. Element fluxes and landscape position in a northern hardwood forest watershed-ecosystem. Ecosystems 3:159-184.

Jones, R.H. and D.J. Raynal. 1986. Spatial distribution and development of root sprouts in *Fagus grandifolia* (Fagaceae). Amer. J. Bot. 73:1723-1732.

Kendall, C. 1998. Tracing nitrogen sources and cycling in catchments. In: Kendall C & McDonnell JJ (Ed) Isotope Tracers in catchment hydrology (pp 519-576). Elsevier Science, BV.

Kulpa, S.E., R.D. Yanai, and K.J. McFarlane. In review. Calcium efflux and strontium uptake by intact Norway spruce (*Picea abies* (L.) Karst.) roots. J. Plant Nutr.

Latty, E., C.D. Canham and P.L. Marks. 2003. Beech bark disease in northern hardwood forests: The importance of nitrogen dynamics and forest history for disease severity. Can. J. For. Res. 33:257-268.

Lawrence, G. B., M. B. David, G. M. Lovett, P. S. Murdoch, D. A. Burns, J. L. Stoddard, B. P. Baldigo, J. H. Porter and A. W. Thompson. 1999. Soil calcium status and the response of stream chemistry to changing acidic deposition rates in the Catskill Mountains of New York. Ecol. Appl. 9:1059-1072.

Leak, W.B. 1973. Species and structure of a virgin northern hardwood stand in New Hampshire. USDA Forest Service. NEFES. Research Note NE-181. 4 p.

Leak, W.B. and M.L. Smith. 1996. Sixty years of management and natural disturbance in a New England forested landscape. For. Ecol. Manage. 81:63-73.

Likens, G. E., F. H. Bormann and N. M. Johnson. 1969. Nitrification: importance to nutrient losses from a cutover forested ecosystem. Science 163:1205-1206.

Likens, G.E. (ed.). 1985. An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment. Springer-Verlag, New York. 516 pp.

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

Likens, G.E., F.H. Bormann, R.S. Pierce, J.S. Eaton and R.E. Munn. 1984. Long-term trends in precipitation chemistry at Hubbard Brook, New Hampshire. Atmos. Environ. 18:2641-2647.

Likens, G.E., F.H. Bormann, R.S. Pierce and J.S. Eaton. 1985. The Hubbard Brook Valley. In: G.E. Likens (ed.) An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment. Springer-Verlag, New York. pp. 9-39.

Likens, G. E., C. T. Driscoll, D. C. Buso, T. G. Siccama, C. E. Johnson, D. F. Ryan, G. M. Lovett, T. Fahey and W. A. Reiners. 1994. The biogeochemistry of potassium at Hubbard Brook. Biogeochemistry 25:61-125.

Likens, G. E. and F. H. Bormann. 1995. Biogeochemistry of a Forested Ecosystem. Second Edition, Springer-Verlag New York Inc. 159 pp.

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

Likens, G. E., C. T. Driscoll, D. C. Buso, T. G. Siccama, C. E. Johnson, G. M. Lovett, T. J. Fahey, W. A. Reiners, D. F. Ryan, C. W. Martin and S. W. Bailey. 1998. The biogeochemistry of calcium at Hubbard Brook. Biogeochemistry 41(2):89-173.

Likens, G. E., T. J. Butler and D. C. Buso. 2001. Long- and short-term changes in sulfate deposition: Effects of The 1990 Clean Air Act Amendments. Biogeochemistry 52(1):1-11

Likens, G. E., C. T. Driscoll, D. C. Buso, M. J. Mitchell, G. M. Lovett, S. W. Bailey, T. G. Siccama, W. A. Reiners, C. Alewell. 2002. The biogeochemistry of sulfur at Hubbard Brook. Biogeochemistry 60:235-316.

Ljungstrom, M. and B. Nihlgard. 1995. Effects of lime and phosphate additions on nutrient status and growth of beech (*Fagus sylvatica* L.) seedlings. For. Ecol. Manage. 74:133-148.

Lovett G. M., K. C. Weathers and M. A. Arthur. 2002. Control of N loss from forested watersheds by soil C:N ratio and tree species composition. Ecosystems 5: 712-718.

Lovett G. M., K. C. Weathers, M. A. Arthur and J. C. Schultz. (in press). Nitrogen cycling in a northern hardwood forest: Do species matter? Biogeochemistry.

Lovett, G. and M. J. Mitchell. (in revision). The critical role of sugar maple in nitrogen retention by forested watersheds in northeastern North America. Frontiers Ecol. Environ.

Lovett, G.M., G.E. Likens, D.C. Buso, C.T. Driscoll and S.W. Bailey. (in revision). The biogeochemistry of chlorine at Hubbard Brook. Biogeochemistry.

Lynch, J. A., V. C. Bowersox and J. W. Grimm. 2000. Changes in sulfate deposition in eastern USA following implementation of Phase I of Title IV of the Clean Air Act Amendments of 1990. Atmos. Environ. 34:1665-1680.

Martin, C.W. 1979. Precipitation and streamwater chemistry in an undisturbed forested watershed in New Hampshire. Ecology 60:36-42.

Martin, C. W. and R. S. Pierce. 1980. Clearcutting patterns affect nitrate and calcium in New Hampshire streams. J. Forestry 78(6):268-272.

Martin, C.W. and J.W. Hornbeck. 1990. Regeneration after strip-cutting and block clearcutting in northern hardwoods. Northern J. Appl. For. 7:65-88.

Martin, C. W., C. T. Driscoll and T. J. Fahey. 2000. Changes in streamwater chemistry after 20 years from forested watersheds in New Hampshire, USA. Can. J. For. Res. 30(8):1206-1213.

Martin, M.E., S.D. Newman, J.D. Aber and R.G. Congalton. 1998. Determining forest species composition using high spectral resolution remote sensing data. Rem. Sens. Environ. 65:249-254.

McFarlane, K.J. and R.D. Yanai. In review. Comparing methods for measuring nutrient uptake by intact roots of mature trees. Soil Sci. Soc. Am. J.

Merrens, E. J. and D. R. Peart. 1992. Effects of hurricane damage on individual growth and stand structure in a hardwood forest in New Hampshire, USA. J. Ecology 80(4):787-795.

Mitchell, M. J., C. T. Driscoll, J. S. Kahl, G. E. Likens, P. S. Murdoch and L. H. Pardo. 1996. Climatic control of nitrate loss from forested watersheds in the northeastern United States. Environ. Sci. Technol. 30:2609-2612.

Mitchell, M. J., C. R. Krouse, B. Mayer, A. C. Stam and Y. Zhang. 1998. Use of stable isotopes in evaluating sulfur biogeochemistry of forest ecosystems. p. 489-518. In: C. Kendall and J.J. McDonnell (eds.). Isotope Tracers in Catchment Hydrology. Elsevier, Amsterdam.

Mitchell, M. J., B. Mayer, S. W. Bailey, J. W. Hornbeck, C. Alewell, C. T. Driscoll and G. E. Likens. 2001. Use of stable isotope ratios for evaluating sulfur sources and losses at the Hubbard Brook Experimental Forest. Proceedings of Acid Rain 2000, Japan. Water Air Soil Poll. 130: 75-86.

Mitchell, M. J., C. T. Driscoll, S. Inamdar, G. McGee, M. Mbila, and D. Raynal. 2003. Nitrogen biogeochemistry in the Adirondack mountains of New York: hardwood ecosystems and associated surface waters. Environ. Pollut. 123:355-364.

Mohren, G.M.J., J. van den Burg and F.W. Burger. 1986. Phosphorus deficiency induced by nitrogen input in Douglas-fir in the Netherlands. Plant and Soil 95:191-200.

Mulholland, P.J. and W.R. Hill. 1997. Seasonal patterns in streamwater nutrient and dissolved organic carbon concentrations: separating catchment flow path and in-stream effects. Water Resources Res. 33:1297-1306.

Nagy, L. R. 2002. Causes and consequences of individual variation in reproductive output in a forest-dwelling Neotropical migrant songbird. Ph.D. Thesis, Dartmouth College.

Ohte, N., M. J. Mitchell, H. Shibata , N. Tokuchi, H. Toda and G. Iwatsubo. 2001. Comparative evaluation on nitrogen saturation of forest catchments in Japan and North America. Water, Air and Soil Pollution 130:649-654.

Ollinger, S.V., J.D. Aver, G.M. Lovett, S.E. Millham, R.G. Lathrop and J.M. Ellis. 1993 A spatial model of atmospheric deposition for the northeastern U.S. Ecol. Appl. 3:459-472.

Ollinger, S.V., M.L. Smith, M.E. Martin, R.A. Hallett, C.L. Goodale and J.D. Aber. 2002. Regional variation in foliar chemistry and soil nitrogen status among forests of diverse history and composition. Ecology 83:339-355.

Pacala, S.W., C.D. Canham, J. Saponara, J.A. Silander, R.K. Kobe and E. Ribbens. 1996. Forest models defined by field measurements: Estimation, error analysis and dynamics. Ecol. Mongr. 66:1-43.

Paine, R.T., M.J. Tegner and E.A. Johnson. 1998. Compounded perturbations yield ecological surprises. Ecosystems 1:535-545.

Palmer, S. M. and C. T. Driscoll. 2002. Acidic deposition. Decline in mobilization of toxic aluminum. Nature 417:242-243.

Palmer, S. M., C. T. Driscoll and C. E. Johnson. (in press (a)). Long-term trends in soil solution and stream water chemistry at the Hubbard Brook Experimental Forest: relationship with landscape position. Biogeochemistry.

Palmer, S. M., B. I. Wellington, C. E. Johnson and C. T. Driscoll. (in press (b)). Landscape influences on aluminum and dissolved organic carbon in streams draining a northern hardwood forest. Hydrol. Proc.

Pardo, L. H., H. F. Hemond, J. P. Montoya, T. J. Fahey and T. G. Siccama. 2002. Response of the natural abundance of 15N in forest soils and foliage to high nitrate loss following clear-cutting. Can J. For. Res. 32:1126-1136.

Pardo, L. H., C. Kendall, J. Pett-Ridge, and C. C. Y. Chang. (in press). Evaluating the source of streamwater nitrate using $^{15}N$ and $^{18}0$ in nitrate in two watersheds in New Hampshire, USA. Hydrol. Proc.

Peet, R.K. 1992. Community structure and ecosystem function. In: Plant succession: theory and prediction. Edited by D.C. Glenn-Lewin, R.K. Peet, and T.T. Veblen. Chapman and Hall, London, pp. 103-151.

Peters, S., J. Blum, C. T. Driscoll and G. E. Likens. (in press). Dissolution of wollastonite during the experimental manipulation of Hubbard Brook Watershed 1. Biogeochemistry.

Pickett, S.T.A. and P.S. White. 1985. Natural disturbances and patch dynamics: An introduction. In: The ecology of natural disturbances and patch dynamics. Edited by S.T.A. Pickett and P.S. White. Academic Press, New York, pp: 3-13.

Platt, W.J. and J.H. Connell. 2003. Natural disturbances and directional replacement of species. Ecological Monographs 73: 507-522.

Raich, J.W., R.H. Riley and P.M. Vitousek. 1994. Use of rooting growth cores to assess nutrient limitations in forest ecosystems. Can. J. For. Res. 24:2135-2138.

Redfield, A.C. 1958. The biological control of chemical factors in the environment. Amer. Sci. 46:205-221.

Reich, P.B., D.S. Ellsworth, M.B. Walters, J.M. Vose, C. Gresham, J.C. Volin and W.D. Bowman. 1999. Generality of leaf trait relationships: A test across six biomes. Ecol. 80:1955-1969.

Reiners, W.A. 1986. Complementary models for ecosystems. Amer. Nat. 127:59-73.

Reiners, W. A. 1992. Twenty years of ecosystem reorganization following experimental deforestation and regrowth suppression. Ecol. Monogr. 62(4):503-523.

Rhoads, A. G., S. Hamburg, T. J. Fahey, T. G. Siccama, E. N. Hane, J. Battles, C. Cogbill, J. Randall and G. Wilson. 2002. Effects of an intense ice storm on the structure of a northern hardwood forest. Can. J. For. Res. 32:1763-1775.

Rhoads, A.G., S.P. Hamburg, T.J. Fahey, T.G. Siccama and R. Kobe. (in press). Comparing direct and indirect methods of assessing canopy structure in a northern hardwood forest. Can. J. For. Res.

Rodenhouse, N. L. and R. T. Holmes. 1992. Results of natural and experimental food reductions on breeding Black-throated Blue Warblers. Ecology 73: 357-372.

Rodenhouse, N. L., T. S.Sillett, P. J. Doran and R. T. Holmes. 2003. Regulation of a migratory bird population by multiple density-dependence mechanisms. Proceedings of the Royal Society of London, B 270:2105-2110.

Rosenberry, D.O., P. A. Bukaveckas, D. C. Buso, G. E. Likens, A. M. Shapiro and T. C. Winter. 1999. Movement of road salt to a small New Hampshire lake. Water, Air, and Soil Pollution 109:179-206.

Rubenstein, D. R., C. P. Chamberlain, R. T. Holmes, M. P. Ayres, J. R. Waldbauer, G. R. Graves and N. C. Tuross. 2002. Linking breeding and wintering ranges of a migratory songbird using stable isotopes. Science 295:1062-1065.

Schaberg, P. G., D. H. DeHayes, G. J. Hawley, G. R. Strimbeck, J. R. Cumming, P. F. Murakami, C. H. Borer. 2000. Acid mist, soil Ca and Al alter the mineral nutrition and physiology of red spruce. Tree Physiol. 20:73-85.

Schwarz, P. A., T. J. Fahey, C. W. Martin, T. G. Siccama, and A. Bailey. 2001. Structure and composition of three northern hardwood-conifer forests with differing disturbance histories. Forest Ecology and Management 144: 201212.

Schwarz, P. A., T. J. Fahey and C. E. McCulloch. 2003. Factors controlling spatial variation of tree species abundance in a forested landscape. Ecology 84(7):1862-1878.

Schlesinger, W.H. 1997. Biochemistry: An Analysis of Global Change. 2nd ed. Academic Press, San Diego, CA.

Siccama, T.G. 1974. Vegetation, soil, and climate on the Green Mountains of Vermont. Ecol. Monogr. 44:325-349.

Sillett, T. S., R. T. Holmes and T. W. Shery. 2000. Impacts of a global climate cycle on population dynamics of a migratory songbird. Science 288:2040-2042.

Sillett, T.S., and R.T. Holmes. 2002. Variation in survivorship of a migratory songbird throughout its annual cycle. J. Anim. Ecol. 71:296-308.

Smith, F.W. and J.N. Long. 2001. Age-related decline in forest growth: An emergent property. For. Ecol. Manage. 144:175-181.

Smith, M.L., S.V. Ollinger, M.E. Martin, J.D. Aber, R.A. Hallett and C.L. Goodale. 2002. Direct estimation of aboveground forest productivity through hyperspectral remote sensing of canopy nitrogen. Ecol. Appl. 12:1286-1302.

Steinhart, G. S., G. E. Likens and P. M. Groffman. 2000. Denitrification in stream sediments in five northeastern (USA) streams. Verh. Internat. Verein. Limnol. 27(3):1331-1336.

Sterner, R.W. and J.J. Elser. 2002. Ecological Stoichiometry, Princeton Univ. Press, Princeton, NJ.

M.A. Tabatabai. Soil Enzymes. 1994. In: Methods of Soil Analysis Part 2 Microbiological and Biochemical Properties. R.W. Weaver, A. Angle, P. Bottomley, D. Bezdicek, S. Smith, A. Tabatabai, A. Wollum Eds. Soil Science Society of America, Inc. pp 775 - 833.

Tessier, J.T. and D.J. Raynal. 2003. Use of nitrogen to phosphorus ratios in plant tissue as an indicator of nutrient limitation and nitrogen saturation. J. Appl. Ecol. 40:523-534.

Tierney, G. L., T. J. Fahey, P. M. Groffman, J. P. Hardy, R. D. Fitzhugh and C. T. Driscoll. 2001. Soil freezing alters fine root dynamics in a northern hardwood forest. Biogeochemistry 56(2):175-190.

Tierney, G. L. and T. J. Fahey. 2002. Fine root turnover in a northern hardwood forest: a direct comparison of the radiocarbon and minirhizotron methods. *Can.* J. For. Res. Rapid Communication 32:1692-1697.

VanBreemen, N. et al. 2000. Mycorrhizal weathering: a true case of mineral plant nutrition. Biogeochem. 49:53-67.

Venterea, R. T., G. M. Lovett, P. M. Groffman and P. A. Schwarz. 2003. Landscape patterns of net nitrification in a northern hardwood-conifer forest. Soil Sci. Soc. Am. J. 67:527-539.

Vitousek, P.M., T.J. Fahey, D.W. Johnson, and M. Swift. 1987. Interactions of carbon, nitrogen, phosphorus and sulfur in forest ecosystems. Biogeochemistry 3: 465-490.

Waldrop, M.P., T.C. Balser and M.K. Firestone. 2000. Linking microbial community composition to function in a tropical soil. Soil Biol. Biochem. 32:1837-1846.

Wallander, H., L. Johansson and J. Pallon. 2002. PIXE analysis to estimate the elemental composition of ectomycorrhizal rhizomorphs grown in contact with different minerals in forest soil. FEMS Microbiol. Ecol. 1320:1-20.

Watmough, S. A. 2002. A dendrochemical survey of sugar maple (Acer saccharum Marsh) in South-Central Ontario, Canada. Water Air Soil Poll.136:165-187.

Webb, S.L. and S.E. Scanga. 2001. Windstorm disturbance without patch dynamics: Twelve years of change in a Minnesota forest. Ecology 82: 893-897.

Webster, M. S., P. P. Marra, S. M. Haig, S. Bensch and R.T. Holmes. 2002. Links between worlds: unraveling migratory connectivity. Trends Ecol. Evol. 17:76-83.

Wellington, B. I. and C. T. Driscoll. (in press). The episodic acidification of a stream with elevated concentrations of dissolved organic carbon. Hydrol. Proc.

Winter, T.C., J.S. Eaton and G.E. Likens. 1989. Evaluation of inflow to Mirror Lake, New Hampshire. Water Resour. Bull. 25:991-1008.

Yanai, R. D. 1991. Soil solution phosphorus dynamics in a whole-tree-harvested northern hardwood forest. Soil Sci. Am.J. 55(6):1746-1752.

Yanai, R. D., T. G. Siccama, M. A. Arthur, C. A. Federer and A. J. Friedland. 1999. Accumulation and depletion of base cations in forest floors in the northeastern United States. Ecology 80(8):2774-2787.

Yanai, R. D., M. A. Arthur, T. G Siccama and C. A. Federer. 2000. Challenges of measuring forest floor organic matter dynamics: repeated measures from a chronosequence. For. Ecol. Manage. 138:273-283.

Yanai, R. D., S. V. Stehman, M. A. Arthur, C. E. Prescott, A. J. Friedland, T. G. Siccama and D. Binkley. 2003. Detecting change in forest floor carbon. Soil Sci. Soc. Am. J. 67(5):1583-1593.

**Table 2. Publications of the Hubbard Brook Ecosystem Study (1998-2004)**

## 1998

### Journal Articles

**Berner, R. A., J. L. Rao, S. B. Chang, R. OBrien and C. K. Keller. 1998.** Seasonal variability of adsorption and exchange equilibria in soil waters. Aquat. Geochem. 4:273-290.

**Bormann, B. T., D. Wang, F. H. Bormann, G. Benoit, R. April and M. C. Snyder. 1998.** Rapid plant-induced weathering in an aggrading experimental ecosystem. Biogeochemistry 43:129-155.

**Bukaveckas, P. and W. Shaw. 1998.** Phytoplankton responses to nutrient and grazer manipulations among northeastern lakes of varying pH. Can. J. Fish. Aquat. Sci. 55(4):958-966.

**Bukaveckas, P. A., G. E. Likens, T. C. Winter and D. C. Buso. 1998.** A comparison of methods for deriving solute flux rates using long-term data from streams in the Mirror Lake watershed. Water Air Soil Pollut. 105:277-293.

**Christensen, K. K. and C. Wigand. 1998.** Formation of root plaques and their influence on tissue phosphorus content in Lobelia dortmanna. Aquat. Bot. 61:111-122.

**Cole, J. J. and N. F. Caraco. 1998.** Atmospheric exchange of carbon dioxide in a low-wind, oligotrophic lake measured by the addition of SF6. Limnol. Oceanogr. 43(4):647-656.

**Driscoll, C. T., G. E. Likens and M. R. Church. 1998.** Recovery of surface waters in the northeastern U.S. from decreases in atmospheric deposition of sulfur. Water Air Soil Pollut. 105:319-329.

**Fahey, T. J., J. J. Battles and G. F. Wilson. 1998.** Responses of early successional northern hardwood forests to changes in nutrient availability. Ecol. Monogr. 68(2):183-212.

**Gill, D. S., J. S. Amthor and F. H. Bormann. 1998.** Leaf phenology, photosynthesis, and the persistence of saplings and shrubs in a mature northern hardwood forest. Tree Physiol. 18:281-289.

**Hislop, J. E., J. W. Hornbeck, S. W. Bailey and R. A. Hallett. 1998.** Development of internal forest soil reference samples and testing of digestion methods. Commun. Soil Sci. Plant Anal. 29(11-14):1991-1996.

**Hunt, P. D. 1998.** Evidence from a landscape population model of the importance of early successional habitat to the American Redstart. Conserv. Biol. 12:1377-1389.

**Huszar, V. and N. F. Caraco. 1998.** The relationship between phytoplankton composition and physical-chemical variables: a comparison of taxonomic and morphological-functional descriptors in six temperate lakes. Freshwater Biol. 40:679-696.

**Johnson, C. E. and R. J. Petras. 1998.** Distribution of zinc and lead fractions within a forest Spodosol. Soil Sci. Soc. Am. J. 62(3):782-789.

**Leak, W. B. and J. W. Hornbeck. 1998.** The Northeasts forest lab. Forest Notes 219:12-13.

**Likens, G. E. and K. Fallon Lambert. 1998.** The importance of long-term data in addressing regional environmental issues. Northeastern Nat. 5(2):127-136.

**Likens, G. E., C. T. Driscoll, D. C. Buso, T. G. Siccama, C. E. Johnson, G. M. Lovett, T. J. Fahey, W. A. Reiners, D. F. Ryan, C. W. Martin and S. W. Bailey. 1998.** The biogeochemistry of calcium at Hubbard Brook. Biogeochemistry 41(2):89-173.

**Likens, G. E., K. C. Weathers, T. J. Butler and D. C. Buso. 1998.** Solving the acid rain problem. Science. 282(5396):1991-1992.

**Marra, P. P., and R. L. Holberton. 1998.** Corticosterone levels as indicators of habitat quality: effects of habitat segregation in a migratory bird during the non-breeding period. Oecologia 116:284-292.

**Marra, P. P., K. A. Hobson and R. T. Holmes. 1998.** Linking winter and summer events in a migratory bird by using stable-carbon isotopes. Science 282:1884-1886.

**Mitchell, M. J., R. C. Santore, C. T. Driscoll and B. R. Dhamala. 1998.** Forest soil sulfur in the Adirondack Mountains: Response to chemical manipulations. Soil Sci. Soc. Am. J. 62:272-280.

**Paillet, F. L. 1998.** Flow modeling and permeability estimation using borehole flow logs in heterogeneous fractured formations. Water Resour. Res. 34(5):997-1010.

**Sherry, T.W., and R.T. Holmes. 1998.** Migrants wintering in the Caribbean: vacation time? Jamaican Naturalist 5:16-19.

**Sloan, S. S., R. T. Holmes and T. W. Sherry. 1998.** Depredation rates and predators at artificial bird nests in an unfragmented northern hardwoods forest. J. Wildlife Manage. 62(2):529-539.

**Tierney, G. L. and T. J. Fahey. 1998.** Soil seed bank dynamics of pin cherry in a northern hardwood forest, New Hampshire, USA. Can. J. For. Res. 28:1471-1480.

**Wuethrich, B. 1998.** Songbirds stressed in winter grounds. Science 282:1791-1794.

**Yanai, R. D. 1998.** The effect of whole-tree harvest on phosphorus cycling in a northern hardwood forest. For. Ecol. Manage. 104:281-295.

**Zhang, Y., M. J. Mitchell, M. Christ, H. R. Krouse and G. E. Likens. 1998.** Stable sulfur isotopic biogeochemistry at Hubbard Brook Experimental Forest, New Hampshire. Biogeochemistry 41:259-275.

**Book Chapters**

**Hornbeck, J. W. and S. W. Bailey. 1998.** Factors controlling streamwater chemistry in upland forested catchments of northeastern United States. pp. 59-67. In: M. J. Haigh, J. Kÿeÿek, G. S. Rajwar, M. P. Kilmartin (eds.). IAHC Headwaters: Water Resources and Soil Conservation. Proc. Headwater '98, Fourth Internat. Conf. On Headwater Control, Merano, Italy.

**Johnson, D. W. and M. J. Mitchell. 1998.** Responses of forest ecosystems to changing sulfur inputs. pp. 219-262. In: D. Maynard (ed.). Sulfur in the Environment. Marcel Dekker, Inc., New York, New York.

**Mitchell, M. J., H. R. Krouse, A. C. Stam and Y. Zhang. 1998.** Use of stable sulfur isotopes in evaluating biogeochemistry of forest ecosystems. pp. 489-518. In: C. Kendall and J. McDonnell (eds.). Isotope Tracers in Catchment Hydrology. Elsevier, The Netherlands.

**Dissertations and Theses**

**Goode, D. J. 1998.** Ground-water age and atmospheric tracers: simulation studies and analysis of field data from the Mirror Lake site, New Hampshire. Ph.D. Thesis, Dept. Civil & Environmental Engineering, Princeton University. 194 pp.

**Joyce, E. M. 1998.** Incubation patterns of female black-throated blue warblers. Senior Honors Thesis, Dartmouth College.

**Lewis, G. P. 1998.** Response of stream chemistry to forest insect defoliation on the Allegheny High Plateau, PA. Ph.D. Thesis, Cornell University. 158 pp.

**Marra, P. P. 1998.** Causes and consequences of sexual habitat segregation in a migrant songbird during the non-breeding season. Ph.D. Dissertation Dartmouth College .

**Medori, A. 1998.** Seasonal and habitat changes in the diet of a neotropical migrant warbler, with special emphasis on the conservation value of shade coffee plantations. Senior Honors Thesis, Tulane University. 57 pp.

**Nielsen, C. B. 1998.** Changes in microbial respiration and nitrogen cycling following soil freezing. Senior Honors Thesis, Brown University. 26 pp.

**Nuengsigkapian, P. 1998.** Have our forests stopped growing? Detecting changes in forest productivity through analyzing 150 years of aboveground biomass accumulation in the White Mountains of New Hampshire. Senior Honors Thesis, Brown University. 43 pp.

**Rodgers, B. 1998.** Studies of molecular size of soil organic matter in a northern hardwood forest soil. M.S. Thesis, Syracuse University.

**Teeling, L. M. 1998.** The floristic diversity of the experimental watersheds of the Hubbard Brook Experimental Forest, New Hampshire. M.S. Thesis, University of New Hampshire, Durham. 117 pp.

**Wright, B. 1998.** Song rate variation and the function of song in the black-throated blue warbler (Dendroica caerulescens). Senior Honors Thesis, Dartmouth College.

**Other**

**Amthor, J. S. 1998.** Searching for a relationship between forest water use and increasing atmospheric CO2 concentration with long-term hydrologic data from the Hubbard Brook Experimental Forest. Oak Ridge National Laboratory, Environmental Sciences Division Publication No. 4833. ORNL/TM-13708. 25 pp.

**Johnson, C. D. and A. H. Dunstan. 1998.** Lithology and fracture characterization from drilling investigations in the Mirror Lake area, Grafton County, New Hampshire. USDI Geological Survey Water Resources Investigations Report 98-4183. 211 pp.

**Winter, T. C., J. W. Harvey, O. L. Franke and W. M. Alley. 1998.** Ground water and surface water - a single resource. U.S. Geological Survey Circular 1139. 79 pp.

## 1999

**Journal Articles**

**Alewell, C., M. J. Mitchell, G. E. Likens and R. H. Krouse. 1999.** Sources of stream sulfate at the Hubbard Brook Experimental Forest: Long-term analyses using stable isotopes. Biogeochemistry 44:281-299.

**Arthur, M. A., T. G. Siccama and R. D. Yanai. 1999.** Calcium and magnesium in wood of northern hardwood forest species: relations to site characteristics. Can. J. For. Res. 29:339-346.

**Becker, M. W., P. W. Reimus and P. Vilks. 1999.** Transport and attenuation of carboxylate-modified latex mircospheres in fractured rock laboratory and field tracer tests. Groundwater 37(3):387-395.

**Berger, T. W. and G. E. Likens. 1999.** Effects of acid anion additions (trifluoroacetate and bromide) on soil solution chemistry of a northern hardwood forest soil. Water Air Soil Pollut. 116:479-499.

**Christ, M. J., C. T. Driscoll and G. E. Likens. 1999.** Watershed- and plot-scale tests of the mobile anion concept. Biogeochemistry 47(3):335-353.

**Chuang, H. C., M. S. Webster and R. T. Holmes. 1999.** Extra-pair paternity and local synchrony in the Black-throated Blue Warbler (Dendroica caerulescens ). Auk 116:727-736.

**Dai, K. H. and C. E. Johnson. 1999.** Applicability of solid-state 13NMR analysis in Spodosols: Chemical removal of magnetic materials. Geoderma 93:289-310.

**Erickson, J. D., D. Chapman, T. J. Fahey and M. J. Christ. 1999.** Non-renewability in forest rotations: implications for economic and ecological sustainability. Ecol. Econ. 31(1):91-106.

**Groffman, P. M. 1999.** Carbon additions increase nitrogen availability in northern hardwood forest soils. Biol. Fert. Soils 29:430-433.

**Holberton, R. L., P. P. Marra and F. R. Moore. 1999.** Endocine aspects of physiological condition and habitat quality in migrant birds during the non-breeding period. In: N. Adams and R. Slotow (eds.). Proc. 22nd Int. Ornithol. Congr., University of Natal, Durban, South Africa.

**Joyce, L. A., J. J. Landsberg, M. Stafford Smith, J. Ben-Asher, J. R. Cavazos Doria, K. Lajtha, G. E. Likens, A. Perevolotsky and U. Safriel. 1999.** Ecosystem-level consequences of management options. pp. 97-116. In: T. W. Hoekstra and M. Shachak (eds.). Arid Lands Management -- Toward Ecological Sustainability. Univ. Illinois Press, Urbana and Chicago.

**Lajtha, K., C. T. Driscoll, W. M. Jarrell and E. T. Elliott. 1999.** Soil phosphorus: characterization and total element analysis. In: G.P. Robertson, D.C. Coleman, and P. Sollins (eds.) Standard Soil Methods for Long Term Ecological Research, Oxford University Press, New York, pp. 115-142.

**Likens, G. E. 1999.** Afterword: Reflections and Needs. pp. 269-272. In: T. W. Hoekstra and M. Shachak (eds.). Arid Lands Management -- Toward Ecological Sustainability. Univ. Illinois Press, Urbana and Chicago.

**Rodenhouse, N.L., T.W. Sherry, and R.T. Holmes. 1999.** Multiple mechanisms of population regulation: contributions of site dependence, crowding, and age structure. In: Adams, N. and R. Slotow (eds.). Proc. 22nd Int. Ornithol. Congr., University of Natal, Durban, South Africa.

**Dissertations and Theses**

**Atlee, J. R. 1999.** The effects of whole tree harvest on soil carbon and nitrogen after 15 years. Senior Honors Thesis, Brown University. 34 pp.

**Ferrarese, J. 1999.** A comparison of the forest floor macroarthropod communities in the spruce-fir and upper hardwood zones of two watersheds in the Hubbard Brook Experimental Forest, New Hampshire. Senior Honors Thesis, Cornell University. 26 pp.

**Grissemann, N. 1999.** Depositionsmessungen in zuckerahornbestanden (Acer saccharum) auf standorten des Hubbard Brook Experimental Forest unterschiedlicher kalziumverfugbarkeit in New Hampshire, USA. Diplomarbeit, Institut fur Forestokologie, Universitat fur Bodenkultur, Vienna, Austria. 108 pp.

**Henson, J. A. 1999.** Does JABOWA work? A verification study of the first gap model using data from the Hubbard Brook Experimental Forest, and some potential policy implications. M.A. Thesis, Brown University. 30 pp.

**Houlton, B. Z. 1999.** The effects of ice storm damage on the biogeochemistry of northern forest ecosystems. M.S. Thesis, Syracuse University.

**Johnson, M. 1999.** Habitat suitability for canopy-foraging warblers wintering in Jamaica: patterns, determinants, and conservation implications. Ph.D. Dissertation, Tulane University.

**Pardo, L. H. 1999.** Natural abundance of 15N as a tool for assessing patterns of nitrogen loss from forest ecosystems. Ph.D. Dissertation, Massachusetts Institute of Technology. 136 pp.

**Randall, J. A. 1999.** Patterns of ice damage in a young northern hardwood forest. Senior Honors Thesis, Cornell University. 24 pp.

**Rubenstein, D. R. 1999.** Using stable-carbon isotopes to determine the breeding origin and extent of population mixing in Black-throated Blue Warblers wintering in the Caribbean. Senior Honors Thesis, Dartmouth College.

**Strobridge, D. M. 1999.** Chemical weathering in the unsaturated zone: the effect of plant type on porewater residence time. M.S. Thesis, Washington State University, Pullman, WA. 136 pp.

**Other**

**Burton, W. C., T. R. Armstrong, and G. J. Walsh. 1999.** Bedrock geologic framework of the Mirror Lake research site, New Hampshire. pp. 705-713. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Buursink, M. L. and J. W. Lane, Jr. 1999.** Characterizing fractures in a bedrock outcrop using ground-penetrating radar at Mirror Lake, Grafton County, New Hampshire. pp. 769-776. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Day-Lewis, F. D., P. A. Hsieh, A. M. Shapiro and S. M. Gorelick. 1999.** Geostatistical simulation of high-transmissivity zones at the Mirror Lake site in New Hampshire: Conditioning to hydraulic information. pp. 685-693. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Ellefsen, K. J., P. A. Hsieh and A. M. Shapiro. 1999.** Relation between seismic velocity and hydraulic conductivity at the USGS Fractured Rock Research Site. pp. 735-745. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Goode, D. J. 1999.** Modifications to the solute-transport model MOC3D for simple reactions, double porosity, and age, with application at Mirror Lake, New Hampshire, and other sites. pp. 821-832. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Goode, D. J., E. Busenberg, L. N. Plummer, A. M. Shapiro, and D. A. Vroblesky. 1999.** CFC's in the unsaturated zone and in shallow ground water at Mirror Lake, New Hampshire. pp.

809-820. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Holmes, R. T. and G. E. Likens. 1999.** Organisms of the Hubbard Brook Valley, New Hampshire. USDA Forest Service, Northeastern Research Station, General Tech. Report NE-257. 32 pp.

**Hornbeck, J. W., S. W. Bailey, D. C. Buso and J. B. Shanley. 1999.** Streamwater chemistry: A useful tool for forest managers. Wildland Hydrology, Amer. Water Resources Assoc., June/July, pp. 361-367.

**Hsieh, P. A., A. M. Shapiro, and C. R. Tiedeman. 1999.** Computer simulation of fluid flow in fractured rocks at the Mirror Lake FSE well field. pp. 777-781. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Johnson, C. D. 1999.** Effects of lithology and fracture characteristics on hydraulic properties in crystalline rock: Mirror Lake research site, Grafton County, New Hampshire. pp. 795-802. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Lane, J. W. Jr., D. L. Wright and F. P. Haeni. 1999.** Borehole radar tomography using saline tracer injections to image fluid flow in fractured rock. pp. 747-756. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Paillet, F. L. 1999.** Geophysical reconnaissance in bedrock boreholes – finding and characterizing the hydraulically active fractures. pp. 725-733. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Paillet, F. L. and J. W. Lane, Jr. 1999.** Integrating surface and borehole geophysics – examples based on electromagnetic sounding. pp. 715-723. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Powers, C. J., K. Singha, and F. P. Haeni. 1999.** Integration of surface geophysical methods for fracture detection in bedrock at Mirror Lake, New Hampshire. pp. 757-768. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Shapiro, A. M., J. W. Lane, Jr., and J. R. Olimpio. 1999.** Borehole packers for in situ geophysical and microbial investigations in fracture rock. pp. 841-845. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Tiedeman, C. R., and P. A. Hsieh. 1999.** Analysis of an open-hole aquifer test in fractured crystalline rock. pp. 783-793. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Vroblesky, D. A., P. M. Bradley, J. W. Lane, Jr., and J. F. Robertson. 1999.** Microbial processes and down-hole mesocosms in two anaerobic fractured-rock aquifers. pp. 695-703. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

**Winter, T. C., D. C. Buso, R. S. Parkhurst, D. O. Rosenberry and M. L. Martinez. 1999.** Hydrographs of lake stage, stream discharge, and hydraulic head in ground water for the Mirror Lake area, New Hampshire, 1979-1995. U.S. Geological Survey Open-File Report 99-239. 52 pp.

**Wood, W. W., T. F. Kraemer, and A. M. Shapiro. 1999.** Exchangeable ions, fracture volume, and specific surface area in fractured crystalline rocks. pp. 681-684. In: U.S. Geological Survey Toxic Substance Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999. U.S. Geological Survey Water-Resources Investigations Report 99-4018C Volume 3.

## 2000

### Journal Articles

**Aitkenhead, J. A. and W. H. McDowell. 2000.** Soil C:N ratio as a predictor of annual riverine DOC flux at local and global scales. Global Biogeochem. Cy. 14(1):127-138.

**Alewell, C., M. J. Mitchell, G. E. Likens and R. Krouse. 2000.** Assessing the origin of sulfate-deposition at the Hubbard Brook Experimental Forest. J. Environ. Qual. 29:759-767.

**Arthur, M.A., and R.D. Yanai. 2000.** Distinguishing the effects of environmental stress and forest succession on changes in the forest floor. Korean J. Ecol. 23(2):83-88.

**Battles, J. J. and T. J. Fahey. 2000.** Gap dynamics following forst decline: A case study of red spruce forests. Ecol. Appl. 10(3):760-774.

**Blum, J. D., E. H. Taliaferro, M. T. Weisse and R. T. Holmes. 2000.** Changes in Sr/Ca, Ba/Ca and 87Sr/86Sr ratios between trophic levels in two forest ecosystems in the northeastern U.S.A. Biogeochemistry 49:87-101.

**Campbell, J. L., J. W. Hornbeck, W. H. McDowell, D. C. Buso, J. B. Shanley and G. E. Likens. 2000.** Dissolved organic nitrogen budgets for upland, forested ecosystems in New England. Biogeochemistry 49:123-142.

**Cramer, J., T. J. Fahey and J. J. Battles. 2000.** Patterns of leaf mass, area and nitrogen in young northern hardwood forests. Amer. Midl. Nat. 144:253-264.

**Goodale, C. L., J. D. Aber and W. H. McDowell. 2000.** The long-term effects of disturbance on organic and inorganic nitrogen export in the White Mountains, New Hampshire. Ecosystems 3:433-450.

**Hall, R. O., Jr. and G. E. Likens. 2000.** Ecological implications of high discharge variability in streams of the Hubbard Brook Experimental Forest. Verh. Internat. Verein. Limnol. 27:2353-2358.

**Johnson, C. E., C. T. Driscoll, T. G. Siccama and G. E. Likens. 2000.** Element fluxes and landscape position in a northern hardwood forest watershed-ecosystem. Ecosystems 3:159-184.

**Johnson, M. D. 2000.** Effects of shade-tree species and crop structure on the winter arthropod and bird communities in a Jamaican shade coffee plantation. Biotropica 32:133-145.

**Johnson, M. D. 2000.** Evaluation of an arthropod sampling technique useful for measuring food availability for forest insectivores. J. Field Ornithol. 71:66-87.

**Johnson, M. D. and A. M. Strong. 2000.** Length-weight relationships of Jamaican anthropods. Entomol. News 111:270-281.

**Likens, G. E. 2000.** A long-term record of ice-cover for Mirror Lake, NH: effects of global warming? Verh. Internat. Verein. Limnol. 27(5):2765-2769.

**Marra, P. P. 2000.** The role of behavioral dominance in structuring habitat occupancy of a migrant bird during the non-breeding season. Behav. Ecol. 11:299-308.

**Martin, C. W., C. T. Driscoll and T. J. Fahey. 2000.** Changes in streamwater chemistry after 20 years from forested watersheds in New Hampshire, USA. Can. J. For. Res. 30(8):1206-1213.

**Martin, C. W., G. E. Likens and D. C. Buso. 2000.** Comparison of long-term precipitation chemistry measurements at the Hubbard Brook Experimental Forest, New Hampshire. Water Air Soil Pollut. 120(3-4):359-379.

**Martin, C. W., J. W. Hornbeck, G. E. Likens and D. C. Buso. 2000.** Impacts of intensive harvesting on hydrology and nutrient dynamics of northern hardwood forests. Can. J. For. Res. 57 (Suppl. 2):19-29.

**Reitsma, L. R. and C. J. Whelan. 2000.** Does vertical partitioning of nest sites decrease nest predation? Auk 117:409-415.

**Rodenhouse, N. L., T. W. Sherry and R. T. Holmes. 2000.** Site-dependent regulation of population size: Reply. Ecology 81:1168-1171.

**Sherry, T. W. 2000.** Overview: A good brew even in small doses. Auk 117:563-568.

**Sillett, T. S., R. T. Holmes and T. W. Shery. 2000.** Impacts of a global climate cycle on population dynamics of a migratory songbird. Science 288:2040-2042.

**Steinhart, G. S., G. E. Likens and P. M. Groffman. 2000.** Denitrification in stream sediments in five northeastern (USA) streams. Verh. Internat. Verein. Limnol. 27(3):1331-1336.

**Strong, A. M. 2000.** Divergent foraging strategies of two Neotropical migrant warblers: implications for winter habitat use. Auk 117:381-392.

**Strong, A. M. and T. W. Sherry. 2000.** Habitat-specific effects of food abundance on the condition of Ovenbirds wintering in Jamaica. J. Anim. Ecol. 69:883-895.

**Strong, A. M., T. W. Sherry and R. T. Holmes. 2000.** Bird predation on herbivorous insects: indirect effects on sugar maple saplings. Oecologia 125:370-379.

**Tank, J. L., P. J. Mulholland, J. L. Meyer, W. B. Bowden, J. R. Webster and B. J. Peterson. 2000.** Contrasting food web linkages for the grazing pathway in three temperate forested streams using 15N as a tracer. Verh. Internat. Verein. Limnol. 27(5):2832-2835.

**Winter, T. C., S. E. Mallory, T. R. Allen and D. O. Rosenberry. 2000.** The use of principal component analysis for interpreting ground water hydrographs. Ground Water 38(2):234-246.

**Yanai, R. D., M. A. Arthur, T. G. Siccama and C. A. Federer. 2000.** Measuring forest floor organic matter dynamics: repeated measures from a chronosquence. For. Ecol. Manage. 138:273-283.

**Book Chapters**

**Castro, M. S., C. T. Driscoll, T. E. Jordan, W. G. Reay, W. R. Boynton, S. P. Seitzinger, R. V. Styles and J. E. Cable. 2000.** Contribution of atmospheric deposition to the total nitrogen loads to thirty-four estuaries on the Atlantic and Gulf Coasts of the United States. In: R. Valigura et al. (eds.) Nitrogen Loading in Coastal Water Bodies: An Atmospheric Perspective. American Geophysical Union, Washington, DC, pp. 77-106.

**Hornbeck, J. W. and J. H. Kochenderfer. 2000.** Forestry effects on water quality. pp. 15-18. In: R. G. Wagner and J. M. Hagan (eds.). Conference Proceedings, Forestry and the Riparian Zone. Cooperative Forestry Research Unit, Univ. Maine, Orono and Manomet Center for Conservation Sciences.

**Hornbeck, J. W. and J. H. Kochenderfer. 2000.** Linkages between forests and streams: a perspective in time. pp. 89-97. In: E. S. Verry, J. W. Hornbeck and C. A. Dolloff (eds.). Riparian Management in Forests of the Continental Eastern United States. Lewis Publishers, CRC Press, New York.

**Paerl, H. W., W. R. Boynton, R. L. Dennis, C. T. Driscoll, H. S. Greening, J. N. Kremer, N. N. Rabalais and S. P. Seitzinger. 2000.** Atmospheric deposition of nitrogen in coastal waters: biogeochemical and ecological implications. In: R. Valigura, et al. (eds.) Nitrogen Loading in Coastal Water Bodies: An Atmospheric Perspective. American Geophysical Union, Washington, DC, pp. 11-52.

**Sherry, T. W. and R. T. Holmes. 2000.** Demographic modeling of migratory bird populations: The importance of parameter estimation using marked individuals. USDA Forest Service Proc. RMRS-P-16:211-219; and In R. Bonney, D. N. Pashley, R. J. Cooper and L. Niles (eds.). Strategies for bird conservation: the Partners in Flight Planning Process; proceedings of the 3rd Partners in Flight Workshop; 1995 October 1-5; Cape May, NJ. Proceedings RMRS-P-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 281 pp.

**Dissertations and Theses**

**Aitkenhead-Peterson, J. A. 2000.** Source, production and export of dissolved organic carbon and nitrogen. Ph.D. Thesis, Univ. New Hampshire, Durham. 304 pp.

**Coleman, K. 2000.** An assessment of the possible importance of species composition to calcium cycling in young northern hardwood forest stands. Senior Honors Thesis, Brown University. 44 pp.

**Douglas, L. 2000.** Effects of human habitat disturbance on resident and migrant bird communities, Caribbean tropical dry forest, Jamaica. Master's Thesis, University of the West Indies.

**Fredericks, R. 2000.** From farm to forest: The land-use history and carbon stocks of a reforested farm in central New Hampshire. Senior Honors Thesis, Brown University. 51 pp.

**Fitzhugh, R. 2000.** Canopy tree-soil-microbial interactions in a northern hardwood ecosystem: Effects of soil freezing disturbance on soil solution chemistry and nutrient loss. Ph.D. Thesis, Syracuse University. 245 pp.

**Gbondo-Tugbawa, S. S. 2000.** Modeling the response of forest and aquatic ecosystems to changes in atmospheric deposition. Ph.D. Thesis, Syracuse University. 149 pp.

**Hogan, J. F. 2000.** Solute isotopes as hydrologic tracers: Examples from the Glacial Lake Agassiz Peatlands, MN, Hubbard Brook, NH and the Fresh Kills Landfill, NY. Ph.D. Thesis, Dartmouth College. 271 pp.

**Kaban, J. 2000.** Food resources used by three Neotropical migrant warblers wintering in a Jamaican shade coffee plantation. Senior Honors Thesis, Tulane University.

**Mahar, E. M. 2000.** Foraging behavior as an indicator of habitat quality in the Black-throated Blue Warbler Dendroica caerulescens. Senior Honors Thesis, Dartmouth College.

**O'Brien, R. 2000.** Unsaturated flow and hydrogeochemistry beneath different plant covers: field observations from the Hubbard Brook Sandbox Experiment. Ph.D. Dissertation, Washington State University, Pullman, WA. 255 pp.

**Sillett, T. S. 2000.** Long-term demographic trends, population limitation, and the regulation of abundance in a migratory songbird. Ph.D. Dissertation, Dartmouth College.

**Tilley, J. 2000.** Manipulating forests to increase soil carbon sequestration: calcium and nitrogen fertilization of red spruce stands. Ph.D. Dissertation, Yale University. 106 pp.

**Other**

**Burton, W. C., Walsh, G. J. and Armstrong, T. R. 2000.** Bedrock geology map of the Hubbard Brook Experimental Forest, Grafton County, New Hampshire. U.S. Geological Survey, Open File Report 00-45. Platel.

**Buso, D. C., G. E. Likens and J. S. Eaton. 2000.** Chemistry of precipitation, stream water and lake water from the Hubbard Brook Ecosystem Study: A record of sampling protocols and analytical procedures. General Tech. Report NE-275. Newtown Square, PA: USDA Forest Service, Northeastern Research Station. 52 pp.

**Verry, E. S., J. W. Hornbeck and A. H. Todd. 2000.** Watershed research and management in the Lake States and northeastern United States. pp. 81-92. In: Land Stewardship in the 21st Century: The Contributions of Watershed Management. Proc. USDA Forest Service Proceedings RMRS-P-13.

## 2001

**Journal Articles**

**Arthur, M. A., S. P. Hamburg and T. G. Siccama. 2001.** Validating allometric estimates of aboveground living biomass and nutrient contents of a northern hardwood forest. Can. J. For. Res. 31:11-17.

**Berger, T. W., C. Eagar, G. E. Likens and G. Stingeder. 2001.** Effects of calcium and aluminum chloride additions on foliar and throughfall chemistry in sugar maples. For. Ecol. Manage. 149:75-90.

**Blum, J. D., E. H. Taliaferro and R. T. Holmes. 2001.** Determining the sources of calcium for migratory songbirds using stable strontium isotopes. Oecologia 126:569-574.

**Bohlen, P. J., P. M. Groffman, C. T. Driscoll, T. J. Fahey, and T. G. Siccama. 2001.** Plant-soil-microbial interactions in a northern hardwood forest. Ecology 82(4):965-978.

**Butler, T. J., G. E. Likens and B.J.B. Stunder. 2001.** Regional-scale impacts of Phase I of the Clean Air Act Amendments: The relation between emissions and concentrations, both wet and dry. Atmos. Environ. 35(6):1015-1028.

**Chuang-Dobbs, H. C., M. S. Webster and R. T. Holmes. 2001.** Paternity and parental care in the Black-throated Blue Warbler (Dendroica caerulescens). Anim. Behav. 62:83-92.

**Chuang-Dobbs, H. C., M. S. Webster and R. T. Holmes. 2001.** The effectiveness of mate guarding by male Black-throated Blue Warblers. Behav. Ecol. 12: 541-546.

**Dai, K. H., C. E. Johnson and C. T. Driscoll. 2001.** Organic matter chemistry and dynamics in clearcut and unmanaged hardwood forest ecosystems. Biogeochemistry 54(1):51-83.

**Driscoll, C. T., G. B. Lawrence, A. J. Bulger, T. J. Butler, C. S. Cronan, C. Eagar, K. Fallon Lambert, G. E. Likens, J. L. Stoddard and K. C. Weathers. 2001.** Acidic deposition in the northeastern United States: sources and inputs, ecosystem effects, and management strategies. BioScience 51(3):180-198.

**Fisk, M. C. and T. J. Fahey. 2001.** Microbial biomass and nitrogen cycling responses to fertilization and litter removal in young northern hardwood forests. Biogeochemistry 53(2):201-223.

**Fitzhugh, R. D., C. T. Driscoll, P. M. Groffman, G. L. Tierney, T. J. Fahey and J. P. Hardy. 2001.** Effects of soil freezing disturbance on soil solution nitrogen, phosphorus, and carbon chemistry in a northern hardwood ecosystem. Biogeochemistry 56(2):215-238.

**Gbondo-Tugbawa, S. S., C. T. Driscoll, J. D. Aber and G. E. Likens. 2001.** Evaluation of an integrated biogeochemical model (PnET-BGC) at a northern hardwood forest ecosystem. Water Resour. Res. 37(4):1057-1070.

**Groffman, P. M., C. T. Driscoll, T. J. Fahey, J. P. Hardy, R. D. Fitzhugh and G. L. Tierney. 2001.** Effects of mild winter freezing on soil nitrogen and carbon dynamics in a northern hardwood forest. Biogeochemistry 56(2):191-213.

**Groffman, P. M., C. T. Driscoll, T. J. Fahey, J. P. Hardy, R. D. Fitzhugh and G. L. Tierney. 2001.** Colder soils in a warmer world: A snow manipulation study in a northern hardwood forest ecosystem. Biogeochemistry 56(2):135-150.

**Hall, R. O., Jr., G. E. Likens and H. M. Malcom. 2001.** Trophic basis of invertebrate production in two streams at the Hubbard Brook Experimental Forest. J. N. Amer. Benthol. Soc. 2093):432-447.

**Hall, R. O., Jr., K. H. Macneale, E. S. Bernhardt, M. Field and G. E. Likens. 2001.** Biogeochemical responses of two forest streams to a two-month calcium addition. Freshwater Biology 46(3):291-302.

**Hardy, J. P., P. M. Groffman, R. D. Fitzhugh, K. S. Henry, T. A Welman, J. D. Demers, T. J. Fahey, C. T. Driscoll, G. L. Tierney and S. Nolan. 2001.** Snow depth manipulation and its influence on soil frost and water dynamics in a northern hardwood forest. Biogeochemistry 56(2):151-174.

**Holmes, R. T. and T. W. Sherry. 2001.** Thirty-year bird population trends in an unfragmented temperate deciduous forest: importance of habitat change. Auk 118(3):589-609.

**Johnson, M. D. and T. W. Sherry. 2001.** Effects of food availability on distribution of migratory warblers among habitats in Jamaica. J. Anim. Ecol. 70:546-560.

**Joyce, E. M., T. S. Sillett and R. T. Holmes. 2001.** An inexpensive method for quantifying incubation patterns of open-cup nesting birds, with data for Black-throated Blue Warblers. J. Field Ornithol. 72(3):369-379.

**Likens, G. E. 2001.** Biogeochemistry, the watershed approach: Some uses and limitations. Mar. Freshwater Res. 52(1):5-12.

**Likens, G. E., T. J. Butler and D. C. Buso. 2001.** Long- and short-term changes in sulfate deposition: Effects of The 1990 Clean Air Act Amendments. Biogeochemistry 52(1):1-11.

**Marra, P. P. and R. T. Holmes. 2001.** Consequences of dominance-mediated habitat segregation in a migrant passerine bird during the non-breeding season. Auk 118(1):94-106.

**McPeek, M. A., N. L. Rodenhouse, R. T. Holmes and T. W. Sherry. 2001.** A general model of site-dependent population regulation: population-level regulation without individual-level interactions. Oikos 94:417-424.

**Mitchell, M. J. 2001.** Linkages of nitrate losses in watersheds to hydrological processes. Hydrol. Proc. 15:3305-3307.

**Mitchell, M. J., B. Mayer, S. W. Bailey, J. W. Hornbeck, C. Alewell, C. T. Driscoll and G. E. Likens. 2001.** Use of stable isotope ratios for evaluating sulfur sources and losses at the Hubbard Brook Experimental Forest. Water Air Soil Pollut. 130:75-86.

**Nielson, C. B., P. M. Groffman, S. P. Hamburg, C. T. Driscoll, T. J. Fahey and J. P. Hardy. 2001.** Freezing effects on carbon and nitrogen cycling in northern hardwood forest soils. Soil Sci. Soc. Am. J. 65(6):1723-1730.

**Ohte, N., M. J. Mitchell, H. Shibata , N. Tokuchi, H. Toda and G. Iwatsubo. 2001.** Comparative evaluation on nitrogen saturation of forest catchments in Japan and North America. Water Air Soil Pollut. 130:649-654.

**Pardo, L. H., H. F. Hemond, J. P. Montoya and T. G. Siccama. 2001.** Long-term patterns in forest-floor nitrogen-15 natural abundance at Hubbard Brook, NH. Soil Sci. Soc. Am. J. 65(4):1279-1283.

**Schwarz, P. A., T. J. Fahey, C. W. Martin, T. G. Siccama and A. Bailey. 2001.** Structure and composition of three northern hardwood-conifer forests with differing disturbance histories. For. Ecol. Manage. 144:201-212.

**Scott, N. S., G. E. Likens, J. S. Eaton and T. G. Siccama. 2001.** Trace metal loss following whole-tree harvest of a northeastern deciduous forest, USA. Biogeochemistry 54:197-217.

**Shapiro, A. M. 2001.** Effective matrix diffusion in kilometer-scale transport in fractured crystalline rock. Water Resour. Res. 37(3):507-522.

**Strong, A. M. and M. D. Johnson. 2001.** Exploitation of a seasonal resource by Plain and White-crowned pigeons in southern Jamaica: implications for conservation of tropical dry forests. Wilson Bull. 113:73-77.

**Strong, A. M. and T. W. Sherry. 2001.** Body condition of Swainson's Warblers wintering in Jamaica and the conservation value of Caribbean dry forests. Wilson Bull. 113: 410-418.

**Taliaferro, E. H., R. T. Holmes and J. D. Blum. 2001.** Eggshell characteristics and calcium demands of a migratory songbird breeding in two New England forests. Wilson Bull. 113(1):94-100.

**Teeling, L. M., G. E. Crow and G. L. Wade. 2001.** Floristic diversity of the Experimental Watersheds of the Hubbard Brook Experimental Forest, New Hampshire, USA. Rhodora 915:263-292.

**Tiedeman, C. R. and P. A. Hsieh. 2001.** Assessing an open-well aquifer testing fractured crystalline rock. Ground Water 39(1):68-78.

**Tierney, G. L. and T. J. Fahey. 2001.** Evaluating minirhizotron estimates of fine root longevity and production in the forest floor of a temperate broadleaf forest. Plant Soil 229(2):167-176.

**Tierney, G. L., T. J. Fahey, P. M. Groffman, J. P. Hardy, R. D. Fitzhugh and C. T. Driscoll. 2001.** Soil freezing alters fine root dynamics in a northern hardwood forest. Biogeochemistry 56(2):175-190.

**Webster, M. S., H. C. Chuang-Dobbs and R. T. Holmes. 2001.** Microsatellite identification of extra-pair sires in a socially monogramous warbler. Behav. Ecol. 12:439-446.

**Whelan, C. J. 2001.** Foliage structure influences foraging of insectivorous forest birds: an experimental study. Ecology 82:219-231.

**Winter, T. C., D. O . Rosenberry, D. C. Buso and D. A. Merk. 2001.** Water source to four U.S. wetlands: implications for wetland management. Wetlands 21(4):462-473.

**Book Chapters**

**Likens, G. E. 2001.** Ecosystems: Energetics and Biogeochemistry. pp. 53-88. In: W. J. Kress and G. W. Barrett (eds.). A New Century of Biology. Smithsonian Institution Press.

**Likens, G. E. 2001.** Eugene P. Odum, the ecosystem approach, and the future. pp. 309-328. In: G. W. Barrett and T. L. Barrett (eds.). Holistic Science: The Evolution of the Georgia Institute of Ecology (1940-2000). Taylor & Francis, New York.

**Ussiri, D. A. and C. E. Johnson. 2001.** Effects of clear-cutting on structure and chemistry of soil humic substances of the Hubbard Brook Experimental Forest, New Hampshire, USA. pp. 271-286. In: E. A. Ghabbour and G. Davies (eds.). Humic Substances: Strucrtures, Models and Functions. Royal Society of Chemistry, Cambridge, England.

**Dissertations and Theses**

**Bernhardt, E. S. 2001.** Nutrient demand and nitrogen processing in streams of the Hubbard Brook Experimental Forest. Ph.D. Thesis, Cornell University. 185 pp.

**Erickson, B. 2001.** Effects of food supplementation on nestling feeding rate and parental time budgeting in a Neotropical migrant bird. Senior Honors Thesis, Dartmouth College.

**Hane, E. N. 2001.** Multi-factor interactions in the decline of Acer saccharum regeneration in the White Mountains of New Hampshire. Ph.D. Thesis, Brown University. 155 pp.

**Schwarz, P. A. 2001.** Spatial patterns of abundance of northern hardwood-conifer tree species in a forested valley in the White Mountains, New Hampshire, USA. Ph.D. Thesis, Cornell University. 145 pp.

**Other**

**Day-Lewis, F. D., J. W. Lane, P. A. Hsieh and S. M. Gorelick. 2001.** Characterization of fractured rock aquifers using radar, tracer, and hydraulic data. In: Fractured Rock 2002 Conference, Proceedings, Toronto, Ontario, March 2001: CD-ROM.

**Driscoll, C. T., G. B. Lawrence, A. J. Bulger, T. J. Butler, C. S. Cronan, C. Eagar, K. Fallon Lambert, G. E. Likens, J. L. Stoddard and K. C. Weathers. 2001.** Acid Rain Revisited: advances in scientific understanding since the passage of the 1970 and 1990 Clean Air Act Amendments. Hubbard Brook Research Foundation. Science Links Publication. Vol. 1, No. 1. pp. 1-20.

**Haeni, F. P., J. W. Lane, J. W. Williams and C. D. Johnson. 2001.** Use of a geophysical toolbox to characterize groundwater flow in fractured rock. In: Fractured Rock 2002 Conference, Proceedings, Toronto, Ontario, March 2001: CD-ROM.

**Hornbeck, J. W. and J. N. Kochenderfer. 2001.** A century of lessons about water resources in northeastern forests. pp. 31-37. In: Proceedings Society of American Foresters, 2000 National Convention, Washington, DC.

**Hornbeck, J. W., M. A. Alexander, C. Eagar, J. Y. Carlson and R. B. Smith. 2001.** Database for chemical contents of streams on the White Mountain National Forest. USDA Forest Service, Northeastern Research Station, General Tech. Report NE-282. 12 pp.

**Hornbeck, J. W., M. A. Alexander, C. Eagar, J. Y. Carlson and R. B. Smith. 2001.** Database for chemical contents of streams on the White Mountain National Forest. USDA Forest Service, Northeastern Research Station, General Tech. Report NE-282. 12 pp.

**Johnson, C. D., F. P. Haeni and J. W. Lane. 2001.** Importance of discrete-zone monitoring systems in fractured-bedrock wells - a case study for the Univeristy of Connecticut Landfille, Storrs, CT. In: Fractured Rock 2002 Conference, Proceedings, Toronto, Ontario, March 2001: CD-ROM.

**Shapiro, A. M. 2001.** Characterizing groundwater chemistry and hydraulic properties of fractured-rock aquifers using themultifunction bedrock-aquifer transportable testing tool (BAT3). U.S. Geological Survey Fact Sheet FS0075-01. 4 pp.

## 2002

### Journal Articles

**Aber, J.D., S.V. Ollinger, C.T. Driscoll, G.E. Likens, R.T. Holmes, R.J. Freuder and C.L. Goodale. 2002**. Inorganic N losses from a forested ecosystem in response to physical, chemical, biotic and climatic perturbances. Ecosystems 5:648-658.

**Bernhardt, E. S. 2002.** Lessons from kinetic releases of ammonium in streams of the Hubbard Brook Experimental Forest. Verh. Internat. Verein. Limnol. 28(1):429-433.

**Bernhardt, E. S. and G. E. Likens. 2002.** Dissolved organic carbon enrichment alters nitrogen dynamics in a forest stream. Ecology 83(6):1689-1700.

**Bernhardt, E. S., R. O. Hall, Jr. and G. E. Likens. 2002.** Whole-system estimates of nitrification and nitrate uptake in streams of the Hubbard Brook Experimental Forest. Ecosystems 5(5):419-430.

**Blum, J. D., A. Klaue, C. A. Nezat, C. T. Driscoll, C. E. Johnson, T. G. Siccama, C. Eagar, T. J. Fahey and G. E. Likens. 2002.** Mycorrhizal weathering of apatite as an important calcium source in base-poor forest ecosystems. Nature 417:729-731.

**Bormann, B. T., C. K. Keller, D. Wang and F. H. Bormann. 2002.** Lessons from the Sandbox: Is unexplained nitrogen real? Ecosystems 5:727-733.

**Castro, M. S. and C. T. Driscoll. 2002**. Atmospheric nitrogen deposition to estuaries in the mid-Atlantic and northeastern United States. Environ. Sci. Technol. 36:3242-3249.

**Driscoll, C. T., G. B. Lawrence, A. J. Bulger, T. J. Butler, C. S. Cronan, C. Eagar, K. F. Lambert, G. E. Likens, J. L. Stoddard and K. C. Weathers. 2002.** Response to W. E. Sharpe's "Acid deposition explains sugar maple decline in the East". BioScience 52(1):5-6.

**Ellefsen, K. J., P. A. Hsieh and A. M. Shapiro. 2002.** Crosswell seismic investigation of hydraulically conductive, fractured bedrock near Mirror Lake, New Hampshire. J. Appl. Geophys. 50:299-317.

**Gbondo-Tugbawa, S. S., C. T. Driscoll, M. J. Mitchell, J. D. Aber and G. E. Likens. 2002.** A model to simulate the response of a northern hardwood forest ecosystem to changes in S deposition. Ecol. Appl. 12(1):8-23.

**Gbondo-Tugbawa, S.S. and C.T. Driscoll. 2002**. A retrospective analysis of the response of soil and stream chemistry of a northern forest ecosystem to atmospheric emission controls from the 1970 and 1990 Amendments of the Clean Air Act. Environ. Sci. Technol. 36:4714-4720.

**Gbondo-Tugbawa, S. S. and C. T. Driscoll. 2002**. Evaluation of the effects of future controls on sulfur dioxide and nitrogen oxide emissions on the acid-base status of a northern forest ecosystem. Atmos. Environ. 36:1631-1643.

**Gilliland, A. B., T. J. Butler and G. E. Likens. 2002.** Monthly and annual bias in weekly (NADP/NTN) versus daily (AIRMoN) precipitation chemistry data in the Eastern USA. Atmos. Environ. 36:5197-5206.

**Hall, R. O., Jr., E. S. Bernhardt and G. E. Likens. 2002.** Relating nutrient uptake with transient storage in forested mountain streams. Limnol. Oceanogr. 47(1):255-265.

**Johnson, C. E. 2002.** Cation exchange properties of acid forest soils in the northeastern United States. Eur. J. Soil Sci. 53:271-282.

**Johnson, M. D., D. R. Ruthrauff, J. G. Jones, J. R. Tietz and J. K. Robinson. 2002**. Short-term effects of tartar emetic on re-sighting rates of migratory songbirds in the non-breeding season. J. Field Ornitho. 73:191-196.

**Kobe, R. K., G. E. Likens and C. Eagar. 2002.** Tree seedling growth and mortality responses to manipulations of calcium and aluminum in a northern hardwood forest. Can. J. For. Res. 32:954-966.

**Lawrence, G. B. 2002.** Persistent episodic acidification of streams linked to acid rain effects on soil. Atmos. Environ. 36:1589-1598.

**Likens, G. E., D. C. Buso and J. W. Hornbeck. 2002.** Variation in chemistry of stream water and bulk deposition across the Hubbard Brook Valley, New Hampshire, USA. Verh. Internat. Verein. Limnol. 28(1):402-409.

**Likens, G. E., C. T. Driscoll, D. C. Buso, M. J. Mitchell, G. M. Lovett, S. W. Bailey, T. G. Siccama, W. A. Reiners, C. Alewell. 2002**. The biogeochemistry of sulfur at Hubbard Brook. Biogeochemistry 60:235-316.

**Macneale, K. H., G. E. Likens and B. L. Peckarsky. 2002.** Feeding strategy of an adult stonefly (Plecoptera): implications for egg production and dispersal. Verh. Internat. Verein. Limnol. 28(2):1140-1146.

**Palmer, S. M. and C. T. Driscoll. 2002.** Acidic deposition. Decline in mobilization of toxic aluminum. Nature 417:242-243.

**Pardo, L. H., H. F. Hemond, J. P. Montoya, T. J. Fahey and T. G. Siccama. 2002.** Response of the natural abundance of 15N in forest soils and foliage to high nitrate loss following clear-cutting. Can J. For. Res. 32:1126-1136.

**Paul, M. J. and R. O. Hall, Jr. 2002.** Particle transport and transient storage along a stream-size gradient in the Hubbard Brook Experimental Forest. J. N. Am. Benthol. Soc. 21(2):195-205.

**Rhoads, A. G., S. Hamburg, T. J. Fahey, T. G. Siccama, E. N. Hane, J. Battles, C. Cogbill, J. Randall and G. Wilson. 2002.** Effects of an intense ice storm on the structure of a northern hardwood forest. Can. J. For. Res. 32:1763-1775.

**Rubenstein, D. R., C. P. Chamberlain, R. T. Holmes, M. P. Ayres, J. R. Waldbauer, G. R. Graves and N. C. Tuross. 2002.** Linking breeding and wintering ranges of a migratory songbird using stable isotopes. Science 295:1062-1065.

**Sillett, T.S., and R.T. Holmes. 2002.** Variation in survivorship of a migratory songbird throughout its annual cycle. J. Anim. Ecol. 71:296-308.

**Stelzer, R. S., G. E. Likens, D. C. Buso and J. H. McCutchan. 2002.** Seasonal variation of phosphorus in precipitation at Hubbard Brook Experimental Forest. Verh. Internat. Verein. Limnol. 28:1211-1215.

**Strong, A. M. and T. W. Sherry. 2002.** Body condition of Swainson's Warblers wintering in Jamaica, and the conservation value of Caribbean dry forest. Wilson Bull. 113:410-418.

**Tierney, G. L. and T. J. Fahey. 2002.** Fine root turnover in a northern hardwood forest: a direct comparison of the radiocarbon and minirhizotron methods. Can. J. For. Res. Rapid Communication 32:1692-1697.

**Webster, M. S., P. P. Marra, S. M. Haig, S. Bensch and R.T. Holmes. 2002.** Links between worlds: unraveling migratory connectivity. Trends Ecol. Evol. 17:76-83.

## Book Chapters

**Currie, W. S., R. D. Yanai, K. Piatek, C. Prescott and C. L. Goodale. 2002.** Processes affecting carbon storage in the forest floor and in downed woody debris. Chapter 9. In: J. M.

Kimble et al. (eds.). The Potential for U.S. Forests to Sequester Carbon and Mitigate the Greenhouse Effect. Lewis Publishers, Boca Raton, FL.

**Dissertations and Theses**

**Douglas, L. 2002.** Impact of human habitat degradation on resident and Neotroopical migratory birds occupying the Tropical Dry Forest Life zone of southern Jamaica. M.S. Thesis, University of the West Indies, Jamaica.

**Fiorentino, I. 2002.** Early response of phosphorus cycling to an experimental addition of calcium in a northern hardwood forest. M.S. Thesis, Cornell University. 59 pp.

**Gulezian, P. 2002.** Reproductive success in forest birds: a test of the mobbing playback method. Senior Honors Thesis, Dartmouth College.

**Nagy, L. R. 2002.** Causes and consequences of individual variation in reproductive output in a forest-dwelling Neotropical migrant songbird. Ph.D. Thesis, Dartmouth College.

**Stanculescu, D. 2002.** Weight loss in breeding female Black-throated Blue Warblers: a result of energetic stress or an adaptive physiological trait? Senior Honors Thesis, Dartmouth College.

**Tierney, G. L. 2002.** Fine root dynamics in a northern hardwood forest. Ph.D. Thesis, Cornell University. 116 pp.

**Other**

**Miller-Weeks, M. and C. Eagar. 2002**. The Northeastern ice storm 1998: A forest damage assessment. USDA Forest Service and Northeast State Foresters Association. 32 pp.

## 2003

**Journal Articles**

**Bailey, S. W., D. C. Buso and G. E. Likens. 2003.** Implications of sodium mass balance for interpreting the calcium cycle of a forested ecosystem. Ecology 84(2):471-484.

**Bernhardt, E. S., G. E. Likens, D. C. Buso and C. T. Driscoll. 2003.** In-stream update dampens effects of major forest disturbance on watershed nitrogen export. P. Natl. Acad. Sci. 100(18):10304-10308.

**Butler, T. J., G. E. Likens, F. M. Vermeylen and B.J.B. Stunder. 2003.** The relation between NO emissions and precipitation $NO_3^-$ in the eastern USA. Atmos. Environ. 37(15):2093-2104.

**Cogbill, C. V., J. Burk and G. Motzkin. 2003.** The forests of presettlement New England, USA: spatial and compositional patterns based on town proprietor surveys. J. Biogeography 29:1279-1304.

**Castro, M. S., C. T. Driscoll, T. E. Jordan, W. G. Reay and W. R. Boynton. 2003**. Sources of nitrogen to estuaries in the United States. Estuaries 26: 803-814.

**Driscoll, C., D. Whitall, J. Aber, E. Boyer, M. Castro, C. Cronan, C. Goodale, P. Groffman, C. Hopkinson, K. Lambert, G. Lawrence and S. Ollinger. 2003**. Nitrogen pollution in the Northeastern United States: sources, effects and management options. BioScience 53:357-374.

**Driscoll, C., D. Whitall, J. Aber, E. Boyer, M. Castro, C. Cronan, C. Goodale, P. Groffman, C. Hopkinson, K. Lambert, G. Lawrence and S. Ollinger. 2003**. Nitrogen Pollution: Sources and Consequences in the U.S. Northeast. Environment 45: 8-22.

**Driscoll, C. T. 2003**. Elevated inputs of reactive nitrogen in the environment: causes, consequences, and controls. BioScience 53:311.

**Fiorentino, I., T. J. Fahey, P.M. Groffman, C. Eagar, C. T. Driscoll and T. G. Siccama. 2003.** Initial responses of phosphorus biogeochemistry to calcium addition in a northern forest ecosystem. Can. J. For. Res. 33:1864-1873.

**Fitzhugh, R. D., G. E. Likens, C. T. Driscoll, M. J. Mitchell, P. M. Groffman, T. J. Fahey and J. P. Hardy. 2003**. The role of soil freezing events in interannual patterns of stream chemistry at the Hubbard Brook Experimental Forest, New Hampshire. Environ. Sci. Technol. 37:1575-1580.

**Fitzhugh, R. D., C. T. Driscoll, P. M. Groffman, G. L. Tierney, T. J. Fahey and J. P. Hardy. 2003**. Soil freezing and the acid-base chemistry of soil solutions in a northern hardwood forest. Soil Sci. Soc. Am. J. 67:1897-1908.

**Gbondo-Tugbawa, S. S. and C. T. Driscoll. 2003**. Factors controlling long-term changes in soil pools of exchangeable basic cations and stream acid neutralizing capacity in a northern hardwood forest ecosystem. Biogeochemistry 63:161-185.

**Goodale, C. L., J. D. Aber and P. M. Vitousek. 2003.** An unexpected nitrate decline in New Hampshire streams. Ecosystems 6(1):75-86.

**Hall, R. O., Jr. 2003.** A stream's role in watershed nutrient export. P. Natl. Acad. Sci. 100(18):10137-10138.

**Hamburg, S. P., R. D. Yanai, M. A. Arthur, J. D. Blum and T. G. Siccama. 2003.** Biotic control of calcium cycling in northern hardwood forests: Acid rain and aging forests. Ecosystems 6(4):399-406.

**Hane, E. N. 2003.** Indirect effects of beech bark disease on sugar maple seedling survival. Can. J. For. Res. 33:807-813.

**Hane, E. N., S. P. Hamburg, A. L. Barber and J. A. Plaut. 2003.** Phytotoxicity of American beech leaf leachate to sugar maple seedlings in a greenhouse experiment. Can. J. For. Res. 33:814-821.

**Hogan , J. F. and J. D. Blum. 2003.** Tracing hydrologic flow paths in a small forested watershed using variations in $^{87}Sr/^{86}Sr$, [Ca]/[Sr], [Ba]/[Sr] and $\delta^{18}O$. Water Resour. Res. 39(10):1282.

**Houlton, B. Z., C. T. Driscoll, T. J. Fahey, G. E. Likens, P. M. Groffman, E. S. Bernhardt and D. C. Buso. 2003**. Nitrogen dynamics in ice storm damaged forest ecosystems: implications for nitrogen limitation theory. Ecosystems 6:431-443.

**Johnson, C. E. 2003.** Reply on comments on 'Cation exchange properties of acif forest soils of the northeastern USA' by G. Limousin & D. Tessier. Eur. J. Soil Sci. 54(3): 645-647.

**Jones, J., P. J. Doran and R. T. Holmes. 2003.** Effects of climate and food on regional synchrony of forest bird population abundances. Ecology 84:3024-3032.

**Kauffman, S. J., D. L. Royer, S. B. Chang and R. A. Berner. 2003.** Export of chloride after clear-cutting in the Hubbard Brook sandbox experiment. Biogeochemistry 63(1):23-33.

**Likens, G. E. 2003.** Use of long-term data, mass balances and stable isotopes in watershed biogeochemistry: The Hubbard Brook model. Gayana Botanica 60(1):3-7.

**Peters, S. C. and J. D. Blum. 2003.** The source and transport of srsenic in a bedrock aquifer, New Hampshire, USA. Appl. Geochem. 18(11):1773-1787.

**Peterson, G. 2003.** Hubbard Brook: Making watershed links. Geotimes 48(8):22-25.

**Richardson, A. D., E. G. Denny, T. G. Siccama and Xuhui Lee. 2003.** Evidence for a rising cloud ceiling in eastern North America. Am. Meteorolog. Soc. 16: 2093-2098.

**Rodenhouse, N. L., T. S. Sillet, P. J. Doran and R. T. Holmes. 2003.** Multiple density-dependence mechanisms regulate a migratory bird population during the breeding season. P. Roy. Soc. Lond. B. 270(1529):2105-2110.

**Schwarz, P. A., T. J. Fahey and C. E. McCulloch. 2003.** Factors controlling spatial variation of tree species abundance in a forested landscape. Ecology 84(7):1862-1878.

**Smith, T. B., P. P. Marra, M. S. Webster, I. Lovette, H. L. Gibbs, R. T. Holmes, K. A. Hobson and S. Rohwer. 2003.** A call for feather sampling. Auk 120:218-221.

**Stelzer, R. S., J. Heffernan and G. E. Likens. 2003.** The influence of dissolved nutrients and particulate organic matter quality on microbial respiration and biomass in a forest stream. Freshwater Biol. 48:1925-1937.

**Tierney, G. L., T. J. Fahey, P. M. Groffman, J. P. Hardy, R. D. Fitzhugh, C. T. Driscoll and J. B. Yavitt. 2003.** Environmental control of fine root dynamics in a northern hardwood forest. Global Change Biol. 9:670-679.

**Ussiri, D. A. and C. E. Johnson. 2003.** Characterization of organic matter in a northern hardwood forest soil by $^{13}C$ NMR and chemical methods. Geoderma 111:123-149.

**Venterea, R. T., G. M. Lovett, P. M. Groffman and P. A. Schwarz. 2003.** Landscape patterns of net nitrification in a northern hardwood-conifer forest. Soil Sci. Soc. Am. J. 67:527-539.

**Winter, T. C., D. C. Buso, D. O. Rosenberry, G. E. Likens, A. M. Sturrock, Jr. and D. P. Mau. 2003.** Evaporation determined by the energy-budget method for Mirror Lake, New Hampshire. Limnol. Oceanogr. 48(3):995-1009.

**Yanai, R. D., W. S. Currie and C. L. Goodale. 2003.** Soil carbon dynamics following forest harvest: An ecosystem paradigm reviewed. Ecosystems 6(3):197-212.

**Yanai, R. D., S. V. Stehman, M. A. Arthur, C. E. Prescott, A. J. Friedland, T. G. Siccama and D. Binkley. 2003.** Detecting change in forest floor carbon. Soil Sci. Soc. Am. J. 67(5):1583-1593.

**Book Chapters**

**Forman, R. T. T., D. Sperling, J. A. Bissonette, A. P. Clevenger, C. D. Cutshall, V. H. Dale, L. Fahrig, R. France, C. R. Goldman, K. Heanue, J. A. Jones, F. J. Swanson, T. Turrentine and T. C. Winter. 2003.** Road salt and lake ecosystems. pp. 215-219. In: Road Ecology: Science and Solutions. Island Press.

**Dissertations and Theses**

**Doran, P. J. 2003.** Intraspecific spatial variation in bird abundance: patterns and processes. Ph.D. Thesis, Dartmouth College.

**Macneale, K. H. 2003.** Life history and dispersal of a stonefly, Leutra ferruginea (Plecoptera; Leuctridae), in the Hubbard Brook Experimental Forest, New Hampshire. Ph.D. Thesis, Cornell University. 216 pp.

**Palmer, S. M. 2003.** Spatial and temporal patterns in the biogeochemistry of aluminum at the Hubbard Brook Experimental Forest, New Hampshire. Ph.D. Thesis, Syracuse University. 162 pp.

**Reynolds, L. V. 2003**. Effects of climatic variation on lepidopteran communities in a northern hardwood forest. Undergraduate Honors Thesis, Dartmouth College. 37 pp.

**Ussiri, D. 2003.** Organic matter characterization and evaluation of effects of forest clear-cutting on organic matter chemistry at the Hubbard Brook Experimental Forest. Ph.D. Dissertation, Syracuse University. 193 pp.

**Winter, J. M. 2003.** Response of streamwater chemistry in a calcium treated watershed to hydrologic events. Senior Honors Thesis, State University of New York College of Environmental Science and Forestry. 37 pp.

**Other**

**Bailey, A. S., J. W. Hornbeck, J. L. Campbell and C. Eagar. 2003**. Hydrometeorological database for Hubbard Brook Experimental Forest: 1955-2000. USDA Forest Service, Northeastern Research Station, Gen. Tech. Report NE-305. 36 pp.

**Lambert, K. F. and C. T. Driscoll. 2003**. Nitrogen pollution: from the sources to the sea. Hubbard Brook Research Foundation, Science Links™ Publication, Hanover, NH, 24 pp.

## 2004

**Journal Articles**

**Campbell, J. L., J. W. Hornbeck, M. J. Mitchell, M. B. Adams, M. S. Castro, C. T. Driscoll, J. S. Kahl, J. N. Kochenderfer, G. E. Likens, J. A. Lynch, P. S. Murdoch, S. J. Nelson and J. B. Shanley. 2004.** Input-output budgets of inorganic nitrogen for 24 forest watersheds in the northeastern United States. Water Air Soil Pollut. 151:373-396.

**Journal Articles in Press**

**Bailey, S. W., B. Mayer and M. J. Mitchell. (in press).** The influence of mineral weathering on drainage water sulfate in the northeastern United States. Hydrol. Proc.

**Campbell, J. L., J. W. Hornbeck, M. J. Mitchell, M. B. Adams, M. S. Castro, C. T. Driscoll, J. S. Kahl, J. N. Kochenderfer, G. E. Likens, J. A. Lynch, P.S. Murdoch, J. B. Shanley and S. J. Vidito. (in press).** A synthesis of nitrogen budgets from forested watersheds in the northeastern United States. Water Air Soil Pollut.

**Groffman, P. M., C. T. Driscoll, G. E. Likens, T. J. Fahey, R. T. Holmes, C. Eagar and J. D. Aber. (in press).** Neither snow, nor rain, nor heat, nor gloom of night: a new conceptual model for the Hubbard Brook Ecosystem Study. BioScience.

**Johnson, C. E., R. J. Petras, R. H. April and T. G. Siccama. (in press).** Post-glacial lead dynamics in a forest soil. Water Air Soil Pollut.

**Likens, G. E. (in press).** Biogeochemistry: Some opportunities and challenges for the future. Biogeomon Special Issue. Water Air Soil Pollut.

**Lovett, G. and M. J. Mitchell. (in press).** The critical role of sugar maple in nitrogen retention by forested watersheds in northeastern North America. Frontiers Ecol. Environ.

**Palmer, S. M., C. T. Driscoll and C. E. Johnson. (in press).** Long-term trends in soil solution and stream water chemistry at the Hubbard Brook Experimental Forest: relationship with landscape position. Biogeochemistry.

**Palmer, S. M., B. I. Wellington, C. E. Johnson and C. T. Driscoll. (in press).** Landscape influences on aluminum and dissolved organic carbon in streams draining a northern hardwood forest. Hydrol. Proc.

**Pardo, L. H., C. Kendall, J. Pett-Ridge, and C. C. Y. Chang. (in press).** Evaluating the source of streamwater nitrate using ä$^{15}$N and ä$^{18}$0 in nitrate in two watersheds in New Hampshire, USA. Hydrol. Proc.

**Peters, S., J. Blum, C. T. Driscoll and G. E. Likens. (in press).** Dissolution of wollastonite during the experimental manipulation of Hubbard Brook Watershed 1. Biogeochemistry.

**Rhoads, A. G., S. P. Hamburg, T.J. Fahey, T.G. Siccama and R. Kobe. (in press).** Comparing direct and indirect methods of assessing canopy structure in a northern hardwood forest. Can. J. of For. Res.

**Rodenhouse, N. L., R.T. Holmes and T. S. Sillett. (in press).** Contribution of site-dependence to regulation of population size: evidence and consequences for biological monitoring of populations. Proc. Internat. Ornithological Congress (Beijing).

**Rosenberry, D. O. and R. G. Morin. (in press).** Use of an Electromagnetic seepage meter to investigate temporal variability in lake seepage. Ground Water.

**Sillett, T. S., R. T. Holmes and N. L. Rodenhouse. (in press).** An experimental test of behavioral mechanisms regulating a migratory songbird population. Ecology.

**Ussiri, D. A. and C. E. Johnson. (in press).** Sorption of organic carbon fractions by Spodosol mineral horizons. Soil Sci. Soc. Amer. J.

**Wellington, B. I. and C. T. Driscoll. (in press).** The episodic acidification of a stream with elevated concentrations of dissolved organic carbon. Hydrol. Proc.

**Yanai, R. D., D. G. Ray, and T. G. Siccama. (in press).** Lead deposition and disappearance in forest floors of northern hardwoods. J. Environ. Qual.

**Book Chapters in Press:**

**Mitchell, M.J. (in press).** Episodic Acidification. In: Jay H. Lehr (ed). Encyclopedia of Water. John Wiley and Sons Publishing.

**Mitchell, M. J. and C. Alewell. (in press).** Sulfur transformations and fluxes. The Encyclopedia of Soil Science and Technology. Van Nostrand Reinhold Co., New York.

**Sillett, T. S. and R. T. Holmes. (in press).** Long-term demographic trends, limiting factors, and the strongeth of density dependence in a breeding population of a migratory songbird. In: R. Greenberg and P. Marra (eds.). Birds of Two Worlds: Advances in the Ecology and Evolution of Temperate-Tropical Migration Systems. Smithsonian Institution Press, Washington, DC.