Project Summary

We propose to continue the research activities of the Hubbard Brook Long-term Ecological Research project (HBR-LTER), expanding upon our theme, the effects of natural and anthropogenic disturbances on the structure and function of northern hardwood forest ecosystems. Through an integrated program of monitoring and process-level studies we will examine four principal categories of disturbance: (1) silviculture and land-use, (2) air pollution, (3) changes in atmospheric CO_2 and regional climate, and (4) irruptions of heterotrophic organisms. Monitoring of hydrometerology, ecosystem chemistry and biotic activity will be continued and expanded. Together with detailed, process-level studies this will allow us to test hypotheses concerning, (1) responses of vegetation, forest floor, organic debris dams and biogeochemistry to clearcut harvesting, (2) effects of land-use changes in the Hubbard Brook Valley and the larger Pemigewasset-Merrimack Basin on ecosystem structure and function, (3) changes in loading of acidic deposition and responses of biogeochemical cycles, (4) ecosystem processing of trace metals, (5) carbon budget effects on and responses to changing atmospheric CO_2 and regional climate, (6) interactions among breeding birds, phytophagous insects and vegetation structure and production, and (7) growth and longevity of fine roots and belowground herbivory. The research will be integrated using several new and existing ecosystem models.

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ABBREVIATIONS USED IN PROPOSAL

HBES - Hubbard Brook Ecosystem Study
HBR - Hubbard Brook Experimental Forest
USDA Forest Service - United States Department of Agriculture, Forest Service
USGS - United States Geological Survey
LTER - Long-Term Ecological Research
GIS - Geographic Information System
GPS - Global Positioning System
ML - Mirror Lake
NSF - National Science Foundation
DMSC - Data Management Subcommittee
IES - Institute of Ecosystem Studies
EDEX - Ecological Data Exchange
JARS - Jointly Accessible Research Samples
TSOB - The Source of the Brook
W - Watershed
dbh - diameter at breast height
Al_i - inorganic monomeric aluminum
Al_o - organic monomeric aluminum
ANC - acid neutralizing capacity
Ca^{2+} - calcium
C_B - basic cations (calcium, magnesium, sodium, potassium)
Cl^- - chloride
DIC - dissolved inorganic carbon
DOC - dissolved organic carbon
DIN - dissolved inorganic nitrogen (ammonium + nitrate)
DON - dissolved organic nitrogen
F^- - fluoride
H^+ - hydrogen ion
HNO_3 - nitric acid
H_2SO_4 - sulfuric acid
K^+ - potassium
Mg^{2+} - magnesium
Na^+ - sodium
N - nitrogen
NH_4^+ - ammonium
NO_2 - nitrogen dioxide
NO_3^- - nitrate
NO_x - nitrogen oxides (nitric oxide and nitrogen dioxide)
S - sulfur
SO_2 - sulfur dioxide
SO_4^{2-} - sulfate

RESULTS FROM PRIOR NSF SUPPORT

Long-term ecological research has been conducted at the Hubbard Brook Experimental Forest (HBEF) in New Hampshire since 1963. The HBEF was established in 1955 by the USDA Forest Service, as a center for hydrologic research in New England. In 1963 the Forest Service and Dartmouth College (through G.E. Likens and F.H. Bormann) developed a cooperative agreement to conduct ecological research at Hubbard Brook as the first step in what has become a comprehensive study of a northern hardwood forest ecosystem. In 1987 Hubbard Brook joined the group of sites selected for Long-Term Ecological Research (LTER) by the National Science Foundation (NSF). The association with the LTER program has been a critical component of the continued success of the Hubbard Brook Ecosystem Study (HBES). The HBES has made significant contributions to understanding of terrestrial and aquatic ecosystems (e.g. Likens et al. 1977; Bormann & Likens 1979; Likens 1985), which have influenced policy decisions regarding their management (e.g. Likens et al. 1978; Likens 1992). Throughout the study, the HBES has had the following research goals:

(1) **To evaluate the changing nature of biogeochemical inputs, storage pools and outputs, as well as the effects of these fluxes and cycles on terrestrial and interconnected aquatic ecosystems.**

(2) **To examine and compare the role of disturbance in governing the structure, function and development of the northern hardwood forest ecosystem. This research includes disturbances which are both anthropogenic (various types of forest harvesting, fire, road building, agricultural land clearing and abandonment, conversion to non-forest land use, and air pollutants) and natural (wind, fire, insect and disease outbreaks) in origin.**

(3) **To develop an understanding of ecological processes governing the structure, function and development of the northern hardwood forest ecosystem and associated aquatic ecosystems in order to provide a scientific basis for their management.**

Our research has utilized the small watershed-ecosystem approach, including long-term biogeochemical measurements of precipitation inputs, ecosystem element pools and transfers, and stream outputs, coupled with the experimental manipulation of whole ecosystems (Bormann & Likens 1967, 1979; Likens et al. 1970, 1977; Likens 1985). Research utilizing this conceptual model has yielded important ecological information on the structure, function and development of aggrading northern hardwood forests and associated aquatic ecosystems, as well as on the response of these ecosystems to disturbance. It is difficult to summarize all of the results from prior NSF support of the HBES because of the long-term and comprehensive nature of this study. However, a listing of all publications of the HBES, and a summary of the overall major findings can be found in Likens (1991) and USDA Forest Service (1991), respectively. Some of the major contributions, particularly those related to this proposal, are summarized below:

- **Developing and applying the small watershed approach to investigate and quantify element flux and cycling in forested ecosystems and their response to disturbance (Bormann & Likens 1967, 1979; Likens et al. 1970, 1977).**

- **Developing and applying computer models to simulate forest hydrology (Federer 1982a,b), biogeochemical processes (Johnson et al. 1969; Fuller et al. 1986a; Schecher & Driscoll 1987; Santore & Driscoll 1991; Aber et al. 1991); forest growth (Botkin et al. 1972; Botkin & Sobel 1975; Bormann & Likens 1979); spatial vegetation dynamics (Mou & Fahey, submitted); phytoplankton population dynamics (Lehman et al. 1975).**

- Developing experimental methodologies for studying the biogeochemistry of forest and aquatic ecosystems (Likens & Eaton 1970; Driscoll 1984; McDowell et al. 1987; Huntington et al. 1989; Johnson et al. 1990, 1991 a,b).

- Establishing patterns of biogeochemical cycles for major (Likens et al. 1977; Likens 1985) and trace (Smith et al. 1987; Driscoll et al. 1988, 1992) elements for northern hardwood forest ecosystems through measurements of element transport and soil/vegetation pools.

- Identifying and quantifying biogeochemical linkages between terrestrial, stream and lake ecosystems within the Hubbard Brook Valley (e.g. Fisher & Likens 1973; Hall et al. 1987; Likens 1984, 1985; McDowell & Likens 1988).

- Proposing a conceptual model of forest growth that divides ecosystem development following disturbance into four phases: Reorganization, Aggradation, Transition, and Shifting Mosaic Steady State (Bormann & Likens 1979). Several predictions are derived from this model,
  (a) total biomass peaks at the end of the Aggradation Phase;
  (b) ecosystem resistance to destabilizing forces peaks during the Aggradation Phase;
  (c) ecosystem patterns and processes across the landscape following sufficient time (ca. 150+ yr) after large-scale, exogenous disturbance are better described by the Shifting-Mosaic Steady State concept than by the traditional "Climax" concept;

  which have enhanced our understanding of the ecology, biogeochemistry and management of northern hardwood forest ecosystems.

- Establishing that the forest floor plays a central role in the biogeochemistry and ecology of northern hardwood forest ecosystems by: promoting infiltration and percolation of water into the soil, thus reducing erosion; storing a large portion of available nutrients during the Aggradation Phase; and, releasing nutrients during the Reorganization Phase (Bormann et al. 1974; Bormann & Likens 1979; Covington 1981).

- Showing that forest disturbance disrupts the nitrogen-cycle by decreasing vegetation assimilation, enhancing mineralization of forest floor and mineral soil N pools, and increasing nitrification. These responses result in large leaching losses of NO_3^- and gaseous losses of N_2O (Likens et al. 1969, 1970; Bormann & Likens 1979; Bowden 1986; Bowden & Bormann 1986; Duggin et al. 1991; Dahlgren & Driscoll 1992).

- Demonstrating that marked losses of critical elements (Ca^{2+}, K^+, Al) occur following disturbance by deforestation. These losses result from increased streamflow (due to reduced transpiration), from increased mineralization of soil organic matter and nitrification (Likens et al. 1970; Hornbeck et al. 1970; Bormann & Likens 1979; Dahlgren & Driscoll 1992), and decay of residual fine roots (Fahey et al. 1988).

- Showing that plant growth occurs rapidly following forest disturbance via a suite of regeneration mechanisms: buried seeds; recent seed dispersal; sprouting of damaged plants; accelerated growth of advanced reproduction; and, accelerated clonal expansion of a number of species (Hughes & Fahey 1988, 1992). Rapid regeneration of plants can quickly reestablish biotic control over biogeochemical processes following disturbance (Marks 1974; Bormann & Likens 1979).

- **Establishing that depletion of nutrients following clearcutting is mitigated by a series of homeostatic processes; such as rapid regrowth of plant biomass (Marks 1974; Bormann & Likens 1979), and adsorption of SO_4^{2-}, PO_4 and DOC on Al and Fe sesquioxide surfaces in soil (Wood et al. 1984; Nodvin et al. 1986; Fuller et al. 1987; McDowell and Likens 1988; Nodvin et al. 1988; Mitchell et al. 1989), which facilitate reorganization and recovery of the forest ecosystem.**

- **Proposing management protocols for the harvesting of northern hardwood forest ecosystems (Likens et al. 1978).**

- **Quantifying the role of atmospheric deposition as an important source of nutrients for forest and lake ecosystems (Likens et al. 1977; Likens 1985).**

- **Discovering "acid rain" in North America (Likens et al. 1972; Likens & Bormann 1974a).**

- **Establishing long-term trends in precipitation chemistry and the linkage of these trends with regional patterns of atmospheric emission in an effort to demonstrate the effects of air-quality legislation (Smith & Siccama 1981; Likens et al. 1984, 1990; Hedin et al. 1987; Likens 1985, 1990, 1992; Butler & Likens 1991).**

- **Quantifying the processes regulating the acidification of soil and drainage water (Driscoll & Likens 1982; van Breemen et al. 1983, 1984; Hedin et al. 1990), as well as the response of vegetation (Wood & Bormann 1976) and aquatic organisms (Hall et al. 1980) to acid stress.**

- **Understanding the processes regulating the release of Al from soil/sediments to surface water (Johnson 1979; Johnson et al. 1981; Driscoll et al. 1985; Hooper & Shoemaker 1985; Dahlgren et al. 1989; Driscoll 1990), the role of complexing ligands in regulating the chemical and biological availability of Al (Driscoll 1984; Lawrence et al. 1986; Driscoll & Schecher 1990) and the effects of elevated concentrations of aqueous Al on aquatic organisms (Hall et al. 1985; Havas & Likens 1985).**

Long-term studies have been invaluable in providing continuity for pursuit of critical questions, for identifying extreme observations and catalyzing significant new research questions. The HBES has involved more than 100 senior scientists and has been continuously productive during the past 29 yrs, resulting in over 1000 publications (Likens 1991). For example, as part of our current research effort supported by the NSF on "Long-Term Ecological Research at the Hubbard Brook Experimental Forest" several major papers were published (Forest Science 1988, Environmental, Science and Technology 1989, Journal of the Soil Science Society of America 1989,1991, Ecology in press, Journal of Ecology, in press), which address important research questions pertaining to 1) the biogeochemical response of forest ecosystems to clearcutting, 2) vegetation regrowth following clearcutting, 3) our analysis of long-term biogeochemical data and 4) bird and insect population studies. These papers are highly relevant to research proposed here, have broad scientific and management implications for ecosystems and are summarized below.

Research on a whole-tree clearcut watershed (watershed 5; W5) at the HBEF defined the role of soil processes in the reorganization of the ecosystem. Following clearcutting and leaching of HNO_3, soil and stream water concentrations and fluxes of basic cations (C_B; Ca^{2+}, Mg^{2+}, Na^+, K^+) increased, while concentrations and fluxes SO_4^{2-} decreased. Mitchell et al. (1989) showed that increased SO_4^{2-} adsorption in the lower mineral soil, due to protonation of soil surfaces, could explain the observed stream and soil solution patterns. Johnson et al. (1991a,b) found no change in

exchangeable C_B pools, and increased C_B concentrations in spodic horizons. These results indicate that processes other than leaching were responsible for the increased export of C_B (e.g., mineral weathering and net mineralization), and that spodic soil horizons were important agents in the retention of C_B in the ecosystem following clearcutting disturbance.

Through detailed measurements of decay and nutrient release from tree root systems following the whole-tree clearcut of W5, Fahey et al. (1988) observed that a significant portion of the N and K exported from forest ecosystems could be accounted for by this process. Also, the suspected importance of dead woody roots as a long-term sink for nutrients was discounted.

Major changes in precipitation and stream chemistry have occurred over the last 29 years at Hubbard Brook. Headwater streams are characterized by low pH (<5.0), negative values of acid neutralizing capacity (ANC) and elevated concentrations of inorganic monomeric Al (Al_i). Driscoll et al. (1989) showed that decreases in atmospheric inputs of SO_4^{2-} have resulted in equivalent declines in stream SO_4^{2-} concentrations. This change, however, did not result in increases in stream pH. Rather, decreases in stream SO_4^{2-} have coincided with a stoichiometric decrease in stream concentrations of basic cations, C_B . This decline in stream concentrations of C_B may be explained by reduced leaching of C_B from the soil exchange complex or decreases in atmospheric deposition of C_B, which have occurred during the past three decades. Both processes likely influence the acid-base status of soils and surface waters.

Vegetation recovery following large-scale disturbance was shown to be spatially variable, depending primarily upon physical disruption of the soil surface (and seed bed) and the availability of reproductive propagules (Hughes & Fahey, in press). This spatial variability affected patterns of nutrient retention across the sites (Mou et al., submitted) as well as the composition, biomass and nutrient content of vegetation after 17 years of succession (Thurston et al., in press). Surprisingly, the early dominant species, pin cherry (*Prunus pensylvanica* L.), does not appear to compete strongly with the slower growing, shade-tolerant species (Thurston et al., in press), probably because of severe nutrient limitation following canopy closure. The rate of biomass and nutrient accumulation in recovering vegetation was very high in dense pin cherry stands, but this ecosystem function was greatly impaired by the herbicide treatment, which was done following the clearfelling of W2 (Reiners, submitted).

Monitoring of breeding bird abundances at Hubbard Brook, along with studies of bird population and community dynamics, began in 1969 (Holmes et al. 1986, Holmes & Sherry 1988, Holmes 1990, studies in progress). This 23-year study provides perhaps the most quantitative, long-term data set on the abundances of breeding birds in unfragmented forest in eastern North America (see Askins et al. 1990), and coupled with the process studies on the factors affecting these populations, is yielding new insight into what causes population change in these species (e.g., Sherry & Holmes, in press). The long-term pattern in total numbers is one of decline, yet, population trends differ markedly among the individual species; some species have declined significantly (e.g., Swainson's Thrush), some have remained relatively constant, although fluctuating, in abundance (e.g., Red-eyed Vireo), with still others have increased significantly in abundance (e.g., Ovenbird).

The HBR-LTER is continuing to further the ecological understanding of the northern hardwood ecosystem, augmenting long-term analysis and helping to integrate this large and complex ecosystem project.

INTRODUCTION

Since its inception, the Hubbard Brook Ecosystem Study (HBES) has made major contributions to environmental science (e.g. Likens et al. 1977; Bormann & Likens 1979; Likens 1985; Likens 1992) which have facilitated policy decisions regarding the management of terrestrial and aquatic ecosystems (see summary of prior NSF support). In 1987 we initiated a Long-Term Ecological Research (LTER) program at Hubbard Brook (HBR) to help pursue the goals of the HBES (see summary of prior NSF support) and contribute to the broader goals of the overall NSF-LTER program. Hubbard Brook is particularly well-suited for long-term ecological research because:

(1) long-term measurements of meteorology, hydrology, precipitation, drainage water chemistry plant tissue chemistry, biomass, and productivity have been made using carefully standardized methods,

(2) drainage basins in the HBEF are virtually water-tight (Likens et al. 1977) allowing for accurate water and element budgets that are critical to verify ecosystem and plot-level process studies,

(3) the entire Experimental Forest is under the jurisdiction of the U.S. Forest Service, which maintains the site for long-term scientific research, and

(4) within the HBEF a series of whole-watershed and sub-watershed treatments have been made since 1965, facilitating the study of ecosystem recovery following disturbance,

(5) the HBEF is representative of northern hardwood-conifer forests in eastern North America, which are impacted by elevated loadings of atmospheric pollutants.

Theme and Justification

The theme of the ongoing HBR-LTER program is ecosystem response to both natural and anthropogenic disturbances. The research team at HBR has long recognized that the structure, function and development of an ecosystem scarcely can be understood in the absence of comprehensive knowledge of the historical and contemporary suite of disturbances to which it is exposed (Bormann & Likens 1979). The HBES has provided a quantitative basis for evaluating disturbance effects on energy flow and element cycling through an integrated set of surveys, experiments and simulation models, primarily at the small watershed scale.

This proposed renewal of the HBR-LTER program will allow us to continue to improve our understanding of disturbance effects on ecosystems by supporting four sets of activities. First, we propose to continue our ecosystem monitoring activities in and around HBR, and to

expand these activities to include some additional ecological processes for which long-term monitoring is particularly critical for quantifying ecosystem response to disturbance (Table 1; see Monitoring Programs). Second, we propose a major watershed-level manipulation experiment to advance our quantitative understanding of forest biogeochemistry and its response to the chronic disturbance of atmospheric pollution loading (see Changes in Loading of Acidic Deposition). Third, we will continue our ongoing, process-level investigations on effects of disturbance on ecological processes over long time intervals (see Research on Effects of Disturbance). Finally, we propose to expand our efforts to integrate the information from the HBES through the development and application of simulation models (see Integration of Ecological Research at Hubbard Brook.

The program of research supported by the HBR-LTER coincides with the rationale for the overall NSF-LTER program as identified on p. 2 of the LTER guidebook:

1. "That there are ecological phenomena that occur on time scales of decades or centuries..."

Within the HBR-LTER we are examining many phenomena that occur on long time scales: (i) the population dynamics of plants and heterotrophs, (ii) tree recruitment, growth and mortality across environmental and successional gradients, (iii) the dynamics and pool size changes of detrital organic matter and nutrients, and (iv) biogeochemical inputs and outputs and the dynamics of nutrient storage pools.

2. "That many experiments are performed without sufficient knowledge of year-to-year variability in the system..."

The application of long-term records of precipitation and streamflow chemistry at HBR show ample evidence of the need for understanding year-to-year variability of complex ecosystems to quantify biogeochemistry changes and provide information for management decisions (Likens 1990; Likens et al. 1991; Likens 1992). Together with our long-term records of climatic variability and surface hydrology (Federer et al. 1990), heterotroph populations (Holmes and Sherry 1988), and vegetation structure, composition and chemistry (Martin and Hornbeck 1990, Reiners, submitted), these data provide (i) insight into ecosystem structure and function, (ii) a record of extreme or unusual

events, (iii) empirical data for testing models and generating hypotheses and (iv) information that is relevant to regional, national and global environmental issues.

3. "That long-term trends in natural ecosystems were not being systematically monitored..."

It can be cogently argued that the importance of quantifying long-term trends in natural ecosystems was recognized at least in part from the observations of the HBES. Moreover, we would stress the importance of providing thorough documentation and careful standardization and cross-checking of long-term results to assure that systematic bias has been avoided. These remain a "stock in trade" of the HBES.

4. "That a coordinated network of sites was not available to facilitate comparative experiments..."

The HBR-LTER program has built upon a traditional strength of the HBES in the area of cross-fertilization of ideas and comparative studies. Our most productive cross-site activities are probably in the areas of simulation modeling and atmospheric pollution, but we are also participating in a number of cross-site experiments and workshops, and we anticipate the initiation of new, integrative LTER-wide activities in the coming years (see Intersite Activities).

5. "That examples of natural ecosystem were being converted to uses incompatible with ecological research."

Few truly virgin forest tracts exist in the eastern United States. Fortunately, an extensive, virgin forest catchment (the Bowl Natural Area) is protected as a research natural area within 2.5 km of HBR. In this renewal, we propose to expand our research activities at this valuable site.

6. "That as a result of advances in ecological research, phenomena at higher or lower levels of organization have been treated as insignificant or constant or have been oversimplified..."

In the HBR-LTER we attempt to span the levels of ecological organization, discovering how processes at various levels interact to explain the behavior of energy flow and biogeochemical cycles on a scale at which they can be accurately observed and experimentally altered (i.e. the small watershed).

Major Initiatives and LTER Core Areas

The five core areas, identified by the overall LTER program, have been integrated within the disturbance theme of the HBR LTER (Table 2). This renewal will allow us to continue to pursue research in each of these core areas. Within the framework of this proposed research, we would highlight the following major research initiatives in each of the core areas:

Core Area 1: Primary productivity

- Comparison of vegetation recovery following large-scale disturbance (p. 12).
- Macrocosm studies of vegetation responses to alterations in precipitation regimes (see p. 40).
- Vegetation responses to watershed chemical perturbation (p. 28).

Core Area 2: Populations representing trophic structure

- Population dynamics of breeding birds and phytophagous insects (p. 44).
- Effects of pathogen irruptions on stream communities (p. 48).
- Fine root herbivory in northern hardwood forest soils (p. 49).

Core Area 3: Organic matter accumulation

- Detailed carbon budgets for HBR: fine root dynamics, soil respiration, DOC flux (p. 36).
- Long-term forest floor dynamics following large-scale disturbance (p. 14).
- Studies of coarse woody debris (p. 16).

Core Area 4: Biogeochemistry

- Watershed chemical manipulation experiment (p. 28).
- Monitoring of water and element fluxes: inputs, outputs and internal recycling (p. 8).

Core Area 5: Disturbance

- Investigations of local and regional disturbance history (p. 22).
- The theme of the HBR-LTER.

Disturbance at Hubbard Brook

The natural disturbance regime in northern hardwood forests appears to be predominantly gap-phase replacement caused by the death of individual (or small groups of) trees and reflected in the abundance of soil microtopography owing to tip-ups (Bormann & Likens 1979). Since European settlement the northeastern forests have been subjected to repeated human disturbance. At HBR, intensive logging activities occurred during three distinct intervals -- 1880s, 1906-19, 1939-42 -- the latter interval associated with extensive blowdown by the 1938 hurricane (Cogbill 1989).

Currently, the principal disturbances affecting northern hardwood forest at HBR and region-wide fall into four classes: (1) silvicultural manipulations, especially clearcut harvesting, and other land-use changes (e.g. agricultural abandonment, urbanization); (2) pollution loading in the form of acid rain, nitrogen deposition, ozone and heavy metals; (3) regional climatic change; and (4) biotic disturbance agents, particularly fungal pathogens and insect pests. To understand the dynamics of these ecosystems and to predict changes in their structure, function and composition, we must improve our quantitative knowledge of the mechanisms of ecosystem response to each of these disturbance classes and we must comprehend how these disturbances could interact to drive ecosystem behavior. Clearly this is a daunting task. One might argue that we would be wiser simply to observe carefully ecosystem responses to this suite of disturbances and thereby draw inferences about cause and effect. The HBR-LTER takes the middle road: extensive observation (monitoring) supported by selected controlled experiments, coupled with modeling.

Integration of Ecological Research at Hubbard Brook

In the HBES models are used as research tools, to facilitate hypothesis testing and to integrate our ecosystem studies. The hydrologic model, BROOK, was developed for small forested watersheds, and was based on research at the HBEF (Federer and Lash 1978). BROOK simulates daily streamflow and changes in soil and snow water from daily inputs of precipitation and temperature. It has been used widely for teaching and research in both eastern North America and Europe (e.g., McKenna 1981; Focazio 1984; Laudelout et al. 1984; Forster & Keller 1986). BROOK is a critical tool in our research on disturbance at HBR and C.A. Federer of the USDA Forest Service is actively working on an updated version of this model.

We have developed a model (REGROW) to simulate the relationships between the growth of individual plants and the availability of essential resources (Mou & Fahey, submitted). The current version of REGROW simulates the dynamics of five dominant trees in the early stage of regrowth following clearcutting of northeastern hardwood forest at HBR. The model utilizes a 4 x 4 m grid of 1,600 0.1 x 0.1 m cells, including initial distribution of plant stems and soil resources. Resource availability (light, water and nutrients) is calculated for each cell and for each plant. Plant growth is

simulated using a continuous-time Markovian model which is parameterized using detailed empirical data on plant performance in the field site. REGROW was calibrated and verified using information from a sub-set of permanent plots established following whole-tree harvest of W5 at HBR. Validation was performed using field survey data from another sub-set of these permanent plots.

The model adequately tracks plant growth and changing community composition through 6 years of vegetation recovery on W5. The results illustrate the importance to plants growing on severely-disturbed soils of gaining access to adjacent, more fertile locations. Predictions of mortality under high-density conditions are inaccurate, reflecting a general problem with the current version of REGROW: most species parameters are either time invariant or vary in only a simple way. Differentiation in the size structure of populations and the overall community increases markedly when simulations include both spatial variation in the site and mixed species populations. Model performance will be improved during the next LTER funding cycle by utilizing new information on species autecology and interference competition being developed in fertilization experiments supported by the USDA-NRI (see Appendix V).

Dry deposition is one of the most difficult fluxes to measure in forest ecosystems. The widely-used dry deposition model developed by Hicks et al (1987) is being modified to predict deposition to W6 (see section 2.1). The model permits the integration of the various canopy and meteorological factors that influence dry deposition. The model has never been tested in complex terrain such as HBR, yet it is often applied to such terrain. We have an excellent opportunity to test the model using our throughfall and watershed mass balance methods for estimating S dry deposition. It will be necessary to parameterize the model for the species mixture on the watershed, and to adapt it to allow for steep slopes and the enhanced wind penetration into the canopy at HBR. Data are available from our meteorological measurements and from vegetation studies on the watershed to supply these parameters.

Numerous investigations have demonstrated complex linkages between individual element cycles (e.g. Likens & Bormann 1981; Kelly et al. 1982; Nodvin et al. 1986). To understand the acid-base chemistry of complex ecosystems, it is necessary to monitor the transfers of all major solutes and

integrate biogeochemical cycles. We use two approaches to integrate biogeochemical cycles: H^+ budgets and plant-soil-water simulation modeling.

A H^+ budget is a summary of the net transfers of H^+ occurring within an ecosystem (Sollins 1976; Sollins et al. 1980; Driscoll & Likens 1982; van Breemen et al. 1984). It is developed from the stoichiometry of all biogeochemical reactions involving ionic species (van Breemen et al. 1983; Binkley & Richter 1987). The long-term H^+ budget for W6 indicates that atmospheric deposition of H^+ and vegetation accumulation of nutrient cations have been the major H^+ sources, while supply of basic cations (C_B) from exchange/weathering reactions has been the major H^+ sink for the HBEF (Fig. 1). The forested watersheds at the HBEF show almost complete neutralization of H^+ sources; only 5.7% (116 eq/ha-yr) of the H^+ inputs are lost in streamwater. More importantly, there have been major changes in the H^+ budget since 1963. In the mid 1960's total inputs of H^+ were moderate (2.6 keq/ha-yr; 1965-69). They increased to a peak of 3.3 keq/ha-yr in 1974. In recent years total H^+ inputs have declined to the lowest values observed during the HBES (1.2 keq/ha-yr; 1985-90). Since about 1980, declines in the growth of vegetation (decreased cation uptake) have diminished this source of H^+ so that atmospheric deposition now provides more than 85% of the total H^+ inputs to the forest ecosystems at the HBEF (Fig. 1).

To better integrate and synthesize our work on biogeochemical cycles, we have developed a soil-water-vegetation element cycling model (VEGIE/CHESS; Aber et al. 1991, 1992; Santore & Driscoll 1991) as a research tool. This model includes linked modules of plant assimilation and decomposition of organic matter (VEGIE; Aber et al. 1991) and soil chemical process (e.g. solution acid-base chemistry, cation exchange, anion adsorption: CHESS; Santore & Driscoll 1991) and simulates the transfer of major solutes within forested watersheds. Unlike other biogeochemical models, the growth of vegetation is controlled by resource availability (i.e. light, water, nutrients) in soil and drainage water. As a result, VEGIE/CHESS can be used to evaluate the interactions between atmospheric deposition of S, C_B and N simultaneously (see section 2.1). Through the HBR-LTER, we also plan to use VEGIE-CHESS to integrate research on changes in biogeochemical processes

following clearcutting disturbance (see section 1.1.3) and processes regulating the speciation and release/immobilization of trace metals (section 2.2).

We have conducted a preliminary calibration of VEGIE/CHESS for Hubbard Brook and initial results appear promising (Fig. 2). Moreover, application of the model for W6 suggests that under current deposition of N the ecosystem is near conditions of "N saturation" (Fig. 2). At lower N loadings (50% of current and "pristine" deposition), model results suggest considerable delay to conditions of N saturation. However, the model has not been validated/verified. An important goal of this proposed research is to further develop, apply and validate/verify VEGIE/CHESS.

RESEARCH COMPONENTS

MONITORING PROGRAMS ONGOING AND NEW

A major strength of the HBES is the development of long-term records including: 1) meteorology and hydrology (since 1956); 2) precipitation and streamwater chemistry (1963); 3) forest vegetation (1965); and 4) forest floor (1968), for reference and experimentally manipulated watershed-ecosystems at the HBEF (Likens et al. 1977, 1984, 1985; Federer et al. 1990; Table 1). Annual quantitative surveys of bird and phytophagous insect populations within the forest have been conducted since 1969 (Holmes 1988). More recently, long-term studies of air chemistry, throughfall, litterfall, soil water and soils have been initiated, largely through the HBR-LTER, to develop a more comprehensive understanding of the ecology of the northern hardwood forest ecosystem. In this proposed study, we intend to build upon these activities through new monitoring studies of fine root activity and root-herbivore interactions, chemical characteristics of mineral soil and solution chemistry along a hillslope gradient from upland to near-stream zones.

Our long-term records show that short-term observations often are misleading and that decades may be required to detect real trends in complex ecosystems (Likens 1989, 1992). Long-term records at HBR are also extremely valuable for studying the structure, function and development of ecological systems. Our long-term studies have catalyzed critical research questions, and the monitoring activities described here will allow us to test some of the hypotheses in this proposal (e.g., see section 2.2).

Since the initiation of the HBES in 1963, special care has been taken to maintain the integrity of these long-term data (see Likens et al. 1984; Data Management). For example, our sampling locations and methods for the collection of bulk precipitation and streamwater chemistry have not been altered significantly since the beginning of the study. Necessary changes in sampling and analytical procedures have been implemented only after systematic comparison of methods has guaranteed that inconsistencies would not be introduced.

We have used the small watershed approach as an experimental tool to assess the response of forest and aquatic ecosystems to disturbance (Bormann & Likens 1967). Atmospheric inputs, stream outputs, and internal pools and transfers of solutes are monitored in several experimental watershed-ecosystems. We have integrated this information to develop detailed element budgets (Fig.3). Our research on the effects of disturbance has included whole-watershed experimental manipulations (i.e., devegetation and herbicide treatment of W2; strip-cut of W4; conventional commercial clearcut of W101; and whole-tree clearcut of W5) as well as the evaluation of anthropogenic influences (e.g., changes in atmospheric deposition of acids, C_B and trace metals; road construction in the NE watershed in the Mirror Lake basin; Fig. 4, Table 3). In addition, we are planning a chemical manipulation (Ca^{2+}-SO_4^{2-}-NO_3^--Cl^- addition) of W1 to evaluate the effects of changes in atmospheric inputs on soil and stream chemistry (see section 2.1).

The routine measurement of precipitation and stream chemistry in 12 experimental watersheds is the backbone of the biogeochemical monitoring program. All water samples are analyzed for all major solutes and a subset of these samples are measured for selected (11) trace metals. The Hubbard Brook Core project "Hydrologic-element cycle interactions in small undisturbed and human-manipulated ecosystems" project (see Appendix IV), funded by the NSF, provides about 60% of the funding for the routine collection and analysis of precipitation and stream samples described above. We are requesting here funds to support about 40% of this critical monitoring. Thus, both of these funding sources are necessary to sustain the long-term records of biogeochemistry at Hubbard Brook.

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, the biogeochemical reference watershed. Atmospheric chemistry monitoring has continued since 1984 at two sites in the HBEF, in cooperation with the EPA-sponsored National Dry Deposition Network. Dry deposition is being measured at W6 using three methods (inferential, throughfall, and watershed mass balance; Lovett et al. in press) to obtain comparative estimates of this important but difficult-to-measure flux. Throughfall and soil solution monitoring is done immediately west of W6 in order to minimize disturbance to this reference site. Bird and insect population monitoring is done in a large area west of W6. It is generally assumed that these research areas are representative of the experimental watersheds, including W6. For some measurements (forest biomass, forest floor) this assumption has been verified.

A number of investigations at the HBEF have revealed marked patterns in drainage water chemistry with elevation (Johnson et al. 1981; Lawrence et al. 1986; Driscoll et al. 1988). These patterns are attributed to elevational variations in climate, vegetation, soil and surficial geology. Our monitoring program includes monthly sampling of soil solutions and streamwaters at several sites in W1, W5 and W6 (Fig. 4). This approach has been instrumental in developing an understanding of the processes regulating stream chemistry at the gauging station (Lawrence et al. 1986) and stream chemical response to clearcutting disturbance (Lawrence et al. 1988; Fuller et al. 1988).

In addition to our ongoing monitoring activities (summarized in Table 1), several new monitoring initiatives are planned as part of this proposed research. We intend to expand the soil water monitoring program to evaluate patterns in drainage water chemistry with hillslope position. Currently soil solutions are collected monthly from tension-free lysimeters beneath the Oa and Bh horizons and within the Bs2 horizon (Driscoll et al. 1988) in upland plots located in three elevation zones in W5 and adjacent to W6: the spruce-fir zone (above 730 m), the upper-elevation hardwood zone (730-660 m), and the low-elevation hardwood zone (below 630 m). We propose to install additional lysimeters in plots located at midslope and near-stream positions of the hillslope, within each of these elevational zones west of W6. Shallow piezometers, screened within glacial till will also be installed within each plot. The number of piezometers will be increased for the near-stream plots to examine changes in stream chemistry as water enters the riparian zone. Two piezometers will be

placed about 20 m from the stream channel, while two piezometers will be installed adjacent to the channel. These piezometers will be located at two depths, 50 cm and within glacial till. Though not funded through the HBR-LTER, this effort will also occur at W1 to help assess changes in drainage water chemistry following the chemical manipulation experiment.

In an effort to quantify changes in chemical properties of the mineral soil, we propose a long-term study using small soil-bags (David et al. 1990). Five hundred kg of B horizon mineral soil will be excavated from west of W6, screened (2 mm), and homogenized. Aliquots of soil (100 g) will be placed in porous geotextile bags (15x15 cm). Sixty bags will be inserted in the upper mineral soil within each of the nine plots west of W6. Initially, four replicate soil bags will be retrieved yearly during each of the first three years to assess initial changes. From year 5 to year 50 bags will be collected at five year intervals. Samples will be analyzed for soil chemical parameters, including pH, cation exchange capacity, exchangeable cations, adsorbed anions and trace metals.

In recognition of the crucial role of fine roots in the energetics and nutrient cycles of forest ecosystems (Fahey, in press) we propose a monitoring program for fine roots in the northern hardwood forest at HBR. This monitoring program will consist of three complementary sets of measurements: biennial (spring and fall) fine root coring, and observation of root growth and longevity using minirhizotrons (mineral soil roots) and *in situ* screens (forest floor roots). This monitoring effort will contribute to testing hypothesis 10.3 and 13.1, and these methods are described in more detail in that section of the proposal (see p. 51).

RESEARCH ON THE EFFECTS OF DISTURBANCE

In the discussion of research on the effects of disturbance, we have indexed sub-sections numerically to facilitate understanding the organizational framework of the HBR-LTER. Moreover, the specific objectives of each phase of the study are numerically ordered and the hypotheses that are relevant to these phases are presented.

1.0 Silvicultural and Land-use Disturbance

1.1 Disturbance Associated with Silvicultural Practices: Clearcutting

Even-aged management, and attendant clearcut harvesting, dominates the disturbance regime of many temperate forest ecosystems, including the northern hardwoods of northern U.S. and southern Canada. Studies of the effects of clearfelling on the ecosystem have been the focus of much research at HBR, and watershed-level treatments have examined the following cutting regimes: whole-tree harvest (1983-4, W5), block clearcutting (1970, W101), strip-cutting over a multi-yr interval (1970-1974, W4), and forest felling followed by 3 yr of herbicide application (1966-1968, W2). Continued monitoring of these watersheds is a high priority of the HBR-LTER, and during the next funding cycle we will work toward an integration of organic matter, hydrologic and biogeochemical budgets of these four watersheds, and comparisons with the reference (W6) and the old-growth (the Bowl) watersheds. Our efforts will be concentrated on summarizing responses of vegetation dynamics, detrital organic matter, solution fluxes, H^+ budgets and weathering. These observations also will be used to parameterize three complementary models of ecosystem dynamics (REGROW, VEGIE-CHESS and ZELIG), and a limited regionalization effort also will be initiated.

1.1.1 Comparison of Vegetation Dynamics on Experimental Watersheds

OBJECTIVE 1: **(A) To compare the processes of vegetation regrowth and the recovery of conservative nutrient cycles following large-scale disturbance across the treated watersheds at HBR, and (B) to develop a mechanistic and spatially-explicit basis for understanding controls on the regional abundance of various pioneer tree species invading harvested sites.**

Forest vegetation exerts primary control over energy flow and nutrient flux cycling in terrestrial ecosystems, and a major component of the HBES and the HBR-LTER has been the development of both a conceptual and a quantitative understanding (Botkin et al. 1972; Bormann & Likens 1979) of the factors influencing forest composition and structure. Within the context of the theme of this proposal, we seek a better understanding of the process of vegetation recovery following large-scale disturbance in northern hardwood forests and its influence of watershed biogeochemistry.

During the first 4 years of the HBR-LTER our work on vegetation dynamics focused upon extending the detailed records from permanent plots on several treated watersheds at HBR and improving the accessibility of these data sets. This work is essentially complete, including the development of several manuscripts detailing vegetation patterns on four treated watersheds (Martin &

Hornbeck 1990; Hughes & Fahey 1988, 1992; Thurston et al., in press; Reiners, submitted; Mou et al., submitted). In addition, we initiated an experimental study of the response of early successional stands to changes in resource availability, capitalizing on the HBR-LTER research with funding from the USDA-National Research Initiative (a 3-year renewal is pending).

Because disturbance intensity and propagule availability appear to control the process of vegetation regrowth and the recovery of conservative nutrient cycles, it is essential that we gain a better understanding of the patterns of interaction between these variables at both a local (HBR) and regional scale. Our principal research initiative on vegetation dynamics during the coming LTER funding cycle is to integrate the detailed information on vegetation recovery following large-scale disturbance of four treated watersheds at HBEF (W2, W4, W5, W101) and to interpret this information on a regional basis using simulation models and GIS.

Intensive networks of permanent vegetation plots have been surveyed on four treated watersheds at HBR since these forests were cut (Table 4). Although the number, size and frequency of measurements on these plots are not identical, a quantitative comparison of vegetation recovery is possible and would improve our understanding of vegetation responses to large-scale disturbance in northern hardwood ecosystems. Time and funding limitations have prohibited such a comparison, and we propose support for this effort to begin in year 6 of the proposed LTER funding cycle. Ultimately, we hope to test the following null hypothesis:

Hypothesis 1.1. Despite large effects on initial growth, composition and nutrient content of recovering vegetation, four different watershed treatments (block clearcut, strip cut, whole-tree clearcut, forest felling and herbicide treatment) have only minor effects on the quasi-steady-state biomass, nutrient content and composition of northern hardwood forests.

In many forests short-lived, pioneer species dominate the initial stages of vegetation regrowth following large-scale disturbance, influencing both the recovery of conservative nutrient cycles (Marks & Bormann 1972) as well as the composition and growth of the tolerant, mature forest species. In northern hardwood ecosystems three principal species play this role (pin cherry, quaking aspen, white birch), but their abundance varies markedly across the region. The effects of these three species on the growth of the commercially valuable northern hardwoods probably differ, given their contrasting

physiological and morphological characteristics (Fowells 1965). For example, our results suggest that pin cherry does not compete strongly with the mature forest species, probably because of severe nutrient limitation following canopy closure, as revealed by fertilization experiments (Fig. 5). Expanded silvicultural activities in the northeastern region have accompanied the maturation of stands that were logged early in this century, and these activities will affect the abundance of both the pioneer and mature forest species in the next harvest rotation. We seek to improve our understanding of these effects both as a practical measure for optimizing silvicultural prescriptions and as a basic ecological problem regarding controls on the distribution, abundance and growth of forest trees.

We are working with the newest version of the forest growth simulator, ZELIG, an offspring of the well-known JABOWA and FORET models. While models of this type provide general estimates of patterns of change within a particular forest type, their predictions of responses to a given management or disturbance regime are weak. This weakness stems from the influence of the mosaic pattern of stands of different age and composition that usually comprises a complex watershed, and particularly from the ways this pattern affects availability of seeds, distribution of canopy gaps and consequent effects of one simulated plot on processes in adjacent plots. Thus, to accurately simulate a specific landscape, the model must be capable of accounting for spatial connections among plots. We propose to implement ZELIG on a spatially-distributed grid at HBR, to specify the mechanisms and magnitude of influence among plots, and to use this implementation to project the effect of different disturbance regimes on short- (25 yr) and long-term (500 yr) composition of the northern hardwood forest.

Hypothesis 1.2. The strength of connections across the landscape (e.g., via seed dispersal distance, expansion of disturbance gaps) determines the relative importance of the extent and frequency of disturbance in defining long-term pattern of forest vegetation composition.

After developing a spatially-distributed version of ZELIG, we will vary the scale and frequency of disturbance as well as plot interconnectedness to test this hypothesis. This research will be performed on the Cornell Supercomputer Facility in cooperation with staff from the Cornell NSF Theory Center.

1.1.2 Detrital Organic Matter on Experimental Watersheds

OBJECTIVE 2. **(A) To continue to refine estimates of the magnitude of organic matter and nutrient dissipation from forest floor horizons during the first two decades following large-scale disturbance, (B) to re-confirm the existence of steady-state forest floor in mature northern hardwoods and (C) to quantify the abundance and dynamics of coarse woody debris.**

Chronosequence studies of Covington (1981) and Federer (1984) suggested that the mass and nutrient content of forest floor horizons declines following large-scale disturbance of northern hardwoods, reaching a minimum of about 50% of original after 10-15 yr before slowly returning to steady-state values after 70-80 yr. During the first four years of the HBR-LTER we have been attempting to refine these estimates because both budgetary calculations and modeling exercises using VEGIE-CHESS (Fig. 2) do not concur with such large losses from forest floor horizons. Some of the C and N dissipated from the forest floor on W5 was mixed into the mineral soil during the whole-tree harvest operation (Huntington & Ryan 1990). Measurements of organic matter and nutrient content changes, using *in situ* forest floor blocks, indicated that about 20% of C and N was lost from forest floor horizons during the first 7 yr after harvest; however, this method excluded entry of roots which could affect mineralization rates. Forest floor mass and nutrient content also were measured 8 years after harvest of W5 on 80 randomly-chosen plots that were not disturbed during logging; forest floor organic matter pools were about 90% of pre-harvest values. Finally, we measured forest floor mass at 120 random points on W2, 22 years after large-scale disturbance. In this case no significant disruption of the forest floor occurred, and organic matter pools (excluding the downed bole wood) averaged 78% of the values for the forested reference watershed.

Hypothesis 2.1. Following large-scale disturbance of northern hardwood forests the forest floor pools of organic matter and nutrients decline to about 75% of steady-state values.

To further test and confirm this hypothesis, we propose to remeasure forest floor mass and nutrient content on randomly chosen, non-scarified sites within W5 in 1998, 15 years after the whole-tree harvest.

The existence of a steady-state forest floor mass in northern hardwoods ecosystems has been proposed (Bormann & Likens 1979) and partially confirmed (Covington 1981; Siccama unpublished).

Periodic remeasurements of forest floor mass on the reference watershed at HBR provide the best evidence for this phenomenon (Fig. 6). Measurement of forest floor mass is scheduled for summer 1992 and remeasurement in 1997 would be accomplished through funding from this proposal, to test the following hypothesis:

Hypothesis 2.2. Forest floor mass and nutrient content in northern hardwoods ecosystems reaches a steady-state after about 70 years of recovery following large-scale disturbance.

Limited information is available on the dynamics of coarse woody debris (CWD) in temperate deciduous forests even though the importance of CWD to the structure and function of temperate forest ecosystems has been clearly established (Harmon et al. 1986). During the first four years of the HBR-LTER we have been investigating (1) decay rates and nutrient content changes of aboveground CWD for five species on W2 (Fig. 7), (2) refinement of estimates of decay for coarse woody roots of four species on W5, and (3) decay rates of coarse woody debris under mature forest cover based upon incubation of logs available from forest clearing operations at HBR. The latter study was initiated in 1990 and consists of twenty logs of each of the three dominant species (beech, maple, birch) incubated in two sites in the lower elevation zone of the HBR forest. We plan to expand this effort during the coming LTER funding cycle, using the boles that are felled in our proposed forest manipulation experiment (section 3.4).

1.1.3 Biogeochemical Response to Clearcutting Disturbance

OBJECTIVE 3: To evaluate the biogeochemical response of soil, vegetation and drainage waters following clearcutting and during recovery.

Background and Research Approach: Clearcutting of mixed northern hardwood forests has been identified as a major cause of stream acidification and nutrient loss in the northeastern U.S. (Likens et al. 1970; Martin et al. 1976; Hornbeck et al. 1987). Stream acidification and mobilization of potentially toxic Al species are especially important concerns because many streams in the Northeast are already acidic and contain elevated Al concentrations (Johnson et al. 1981; Driscoll et al. 1991). The increased acidification caused by forest harvesting may therefore contribute additional stress to aquatic ecosystems.

The loss of plant nutrients in drainage waters following harvest is also a concern with regard to the sustainability of forest ecosystems (Hornbeck & Kropelin 1982; Waring & Schlesinger 1985). Sustainable forestry is based on the premise of removing essential nutrients at a rate less than or equal to that which can be replenished by natural processes (e.g., wet/dry deposition, N-fixation, mineral weathering). Since tree harvesting is superimposed on acidic deposition in the eastern U.S., it is essential to consider its effects on forest nutrient status, particularly as harvesting intensity increases (i.e., shorter rotations and biomass utilization).

There has been considerable research on the chemical response of the northern hardwood forest to clear-cutting disturbance and recovery at the HBEF, including stem only (W101), strip-cut (W4), devegetation and herbicide treatment (W2) and whole-tree clear-cut (Likens et al. 1970; Bormann & Likens 1979; Martin et al. 1986; Hornbeck et al. 1987; Lawrence et al. 1987). Shortly following clearcutting, drainage waters are characterized by elevated concentrations of H^+ and NO_3^-, due to mineralization of soil organic N and nitrification. Production of nitric acid, acidifies soil and drainage water (van Breemen et al. 1983), enhances leaching losses of C_B and, in base-poor ecosystems, Ali (Lawrence et al. 1987), and results in the immobilization of SO_4^{2-}(Fuller et al. 1987; Mitchell et al. 1989). Although these studies have yielded important information, additional studies are needed of this biogeochemical disturbance to forest and stream ecosystems in the Northeast.

We propose to continue our monitoring and analysis of recovery of watersheds from clearcutting disturbance (W2, W4, W5, W101; Table 3). This includes analysis of precipitation, dry deposition, throughfall soil solutions, forest floor, litterfall and mineral soil on W5, and streamwater and vegetation on W2, W4, W5 and W101. Results from the analysis of the biogeochemical response to clearcutting will be compared to data from the biogeochemical reference watershed (W6). Within this HBR-LTER we are particularly interested in integrating and synthesizing results from our ongoing analysis of the cut watersheds. This will be accomplished using three approaches. First, for watersheds for which considerable biogeochemical data are available (i.e., W2, W5), annual H^+ budgets will be developed to quantify changes in element transfer that have occurred following the disturbance and to determine the relative role of biogeochemical processes in the

acidification/alkalinization of soil and drainage waters. Second, the plant-soil-water model VEGIE-CHESS will be applied to the data collected from the clearcutting experiments. Because clearcutting has a marked effect on the biogeochemistry of forest ecosystem, this type of manipulation provides an excellent opportunity to verify/validate the processes represented in the model. As an initial exercise, we have applied VEGIE-CHESS to W5 after a preliminary calibration to simulate changes in the solution chemistry draining the lower mineral soil following the whole-tree clearcut of W5 (Fig. 8). These initial results seem promising. In the HBR-LTER, we will continue this modeling work, including an evaluation of the representation of biogeochemical processes regulating major chemistry parameters in soil, soil solutions and streamwater. Finally, we are currently developing a fifth synthesis volume on the results of the whole-tree clearcut experiment at W5 (The Impact of a Whole-Tree Clearcut on a Northern Hardwood Ecosystem: Scientific Results and Management Implications). This volume will include data collected from W5 through 1991 (eight years after the clearcut) and involve an analysis of the effects of the treatment and the initial recovery.

1.1.4 Organic Debris Dams

OBJECTIVE 4: To quantify long-term trends in the abundance and function of organic debris dams in a northern hardwood forest.

Background and Research Approach: Organic debris dams serve a variety of important roles in forested watersheds including: regulation of export of organic and inorganic sediments (e.g., Bilby & Likens 1980; Bilby 1981), erodibility and channel morphology of streams (e.g., Swanson et al. 1982), and control of aquatic habitat structure (e.g., MacDonald & Keller 1983; Hedin 1990). Despite their obvious importance, the factors regulating the formation and disruption of organic debris dams rarely have been determined (Swanson et al. 1984; Likens & Bilby 1982). In the HBES, we are taking advantage of several whole-watershed manipulations to evaluate the effects of deforestation on the abundance and function of organic debris dams. We seek an understanding of the immediate response of dams to deforestation and to quantify changes occurring during long-term development of the surrounding forest ecosystem.

Our results to date show a large, however somewhat delayed, effect of deforestation on the density (i.e., #/stream length) of organic debris dams. Densities in a first-order stream did not change significantly during the first two years following deforestation (13 dams/100 m) of W5 at the HBEF, but a sharp decline occurred in the third year (9 dams/100 m). A reference stream showed negligible change during the same period. Also, densities in a stream draining a watershed deforested 26 years ago (W2) are considerably lower (3 dams/ 100 m) today (Hedin et al, 1986).

We propose a long-term model describing the abundance and function of debris dams in northern hardwood-conifer watersheds during ecosystem development following large-scale disturbance (Likens and Bilby 1982; Hedin et al. 1986).

Hypothesis 4.1. Following deforestation, organic debris dams are depleted in first- and second-order streams because of continued dam destruction concurrent with an abrupt decline in input of coarse woody debris. A delay in this depletion is stochastic in nature, depending upon the occurrence of large storm-flow events.

Hypothesis 4.2. The number of debris dams continues to decline until a major input of large woody debris occurs following regrowth of the forest adjacent to the stream.

Because of the slow changes expected and the low frequency of catastrophic events (e.g., floods), long-term measurements are required to quantify the pattern and function of organic debris dams. We will continue to test our model by resurvey of organic dams on W6, W5 and W2 at 5-year intervals, with contingencies for extreme weather events. (The next sampling is scheduled for 1995). Sediment export and hydrologic discharge from the watersheds are measured in cooperation with the USDA Forest Service personnel as a component of the long-term biogeochemical studies. These studies are funded by a grant to G.E. Likens from The Andrew W. Mellon Foundation.

1.2 Disturbance Associated with Changes in Land-Use Changes

1.2.1 The Effects of Road Construction and Maintenance on the Mirror Lake Watershed

OBJECTIVE 5: To evaluate the disturbance of soil and drainage water due to road salting.

Background, Hypotheses and Research Approach: The Mirror Lake (ML) watershed has been the focus of a long-term study initiated in 1965 to investigate lake-watershed interactions (Likens 1985). Long-term trends in stream and lake chemistry have been analyzed to detect the response of the watershed to changing patterns of land-use, which we believe are characteristic of the northeastern

U.S. (see section 1.2.2). The most conspicuous effect of localized human activity has been the increase in concentrations of Cl^- and Na^+ resulting from road salt applications to highways during the winter (Fig. 9). Interstate 93, which traverses central NH, was constructed through the NE subcatchment of the ML basin during 1969-1971. Increasing salt concentrations in the ML-NE tributary became evident in 1975, despite construction efforts to divert the drainage from the highway away from the watershed. Since that time, Cl^- concentrations have continued to increase at a rate of about 90 µmol/L-yr. Marked seasonal variations in stream Cl^- are also evident following this disturbance. Concentrations reach very high values (1500-2500 µmol/L) during the winter and early spring, and decrease to lower concentrations (500-1000 µmol/L) in the summer and fall. Increasing salt concentrations in the lake outlet were not evident until 1978, but have increased continuously since that time.

There is evidence to suggest that NaCl inputs have altered the acid-base status of soil and drainage water in the ML-NE watershed. Increases in Cl^- have <u>not</u> coincided with stoichiometric increases in Na^+ in streamwater ($Na^+/Cl^- = 0.61$; $r^2 = 0.92$; Fig. 9). Rather, some of the increase in Cl^- appears to be associated with Ca^{2+} ($Ca^{2+}/Cl^- = 0.24$; $r^2 = 0.81$) and to a lesser extent with other C_B, suggesting displacement of Ca from soil exchange sites by inputs of Na^+. The increases in C_B coinciding with Cl^- increases are generally stoichiometric ($C_B/Cl^- = 0.95$; $r^2 = 0.95$). However, during the high flow winter/spring period Na^+ may exchange for acidic cations (H^+, Al) on the soil exchange complex and resulting in the acidification of these low ANC drainage waters.

Hypothesis 5.1. Concentrations of Na^+, Ca^{2+} and Cl^- will continue to increase in ML due to increases in the application of NaCl to roads in the watershed.

Hypothesis 5.2 Inputs of the neutral salt, NaCl, from road salting, displace Ca^{2+} and acidic cations from the soil exchange complex to solution. During spring snowmelt, this process contributes to short-term decreases in the acid neutralizing capacity (ANC) of streamwater entering ML.

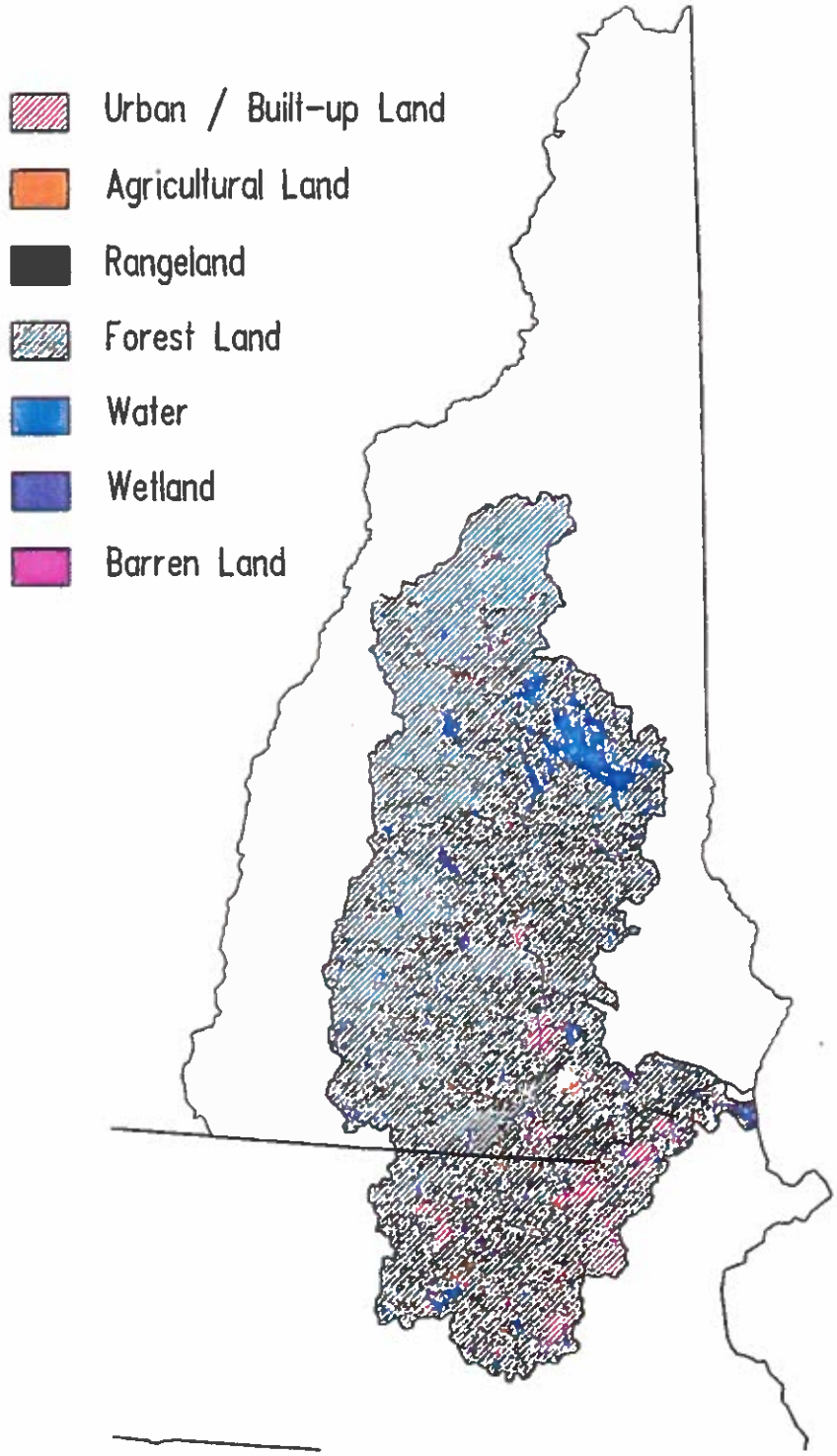
Through our ongoing monitoring activities, we will continue to assess changes in the chemistry of streamwater within the ML basin. We are obtaining records of road salt application rates, to determine if the increases in Cl^- observed for the ML-NE inlet reflect changes in road maintenance activities or attenuation of NaCl inputs by terrestrial processes (Hypothesis 5.1). We will supplement

these stream chemistry studies by doing a detailed sampling of soils in the ML watershed to test Hypothesis 5.2. Using an auger, organic and mineral soils will be sampled at 100 sites randomly located throughout the basin, with approximately one-third of the samples in each of the ML-NE, ML-NW and NL-W subbasins. These samples will be analyzed for pH, exchangeable cations, exchangeable acidity and PO_4 extractable anions (see Appendix III). Finally, during the spring of 1993, we intend to conduct a detailed sampling of ML inlets using flow activated automatic samplers. Analysis of water chemistry during this high flow period after winter salting, coupled with a partitioning of ANC loss according to changes in the chemistry of major solutes (Schaefer et al. 1990) should allow us to ascertain whether road salts are important to episodic acidification.

1.2.2 Land-Use Dynamics of the Pemigewassett-Merrimack Basin

OBJECTIVE 6: To evaluate processes contributing to longitudinal patterns in the chemistry of the Pemigewassett-Merrimack River system.

Background, Hypotheses and Research Approach: There is considerable concern and interest in the effects of increasing population densities and changes in land use on the environment, particularly water quality. These problems often are evident in large river basins. Through an NSF- sponsored Research Experience for Undergraduates (REU), a study of drainage water quality was initiated in 1990 to investigate patterns of water chemistry throughout the Pemigewassett-Merrimack River system in NH and MA (Fig. 10). These data were compared to results available from studies conducted at many of the same sampling stations 19 years ago (Likens and Eaton, unpublished data). Results showed increases in concentrations of NH_4^+, Cl^-, and NO_3^- as waters drained from the forested headwaters to highly urbanized areas in the lower reaches. These patterns are correlated strongly with population density in the basin. A comparison of these results with the previous study conducted in 1971 indicate Cl^- concentrations have increased in recent years, likely due to road salting practices. Reaches in the upland area were characterized by low values of ANC and potential sensitivity to strong acid inputs. There was a general increase in pH, ANC and C_B, and a decrease in concentrations of Al downslope within the basin. The within basin changes in ANC were largely due to variations in



NO.	NAME	MILES
1	Hancock Camp	0
2	Condominiums (Lincoln)	3
3	Tourist Information (Lincoln)	4
4	Middle River (No. Woodstock)	6
5	Lost River (No. Woodstock)	7
6	Woodstock	9
7	Storage Building (Campton)	10
8	Hubbard Brook (Campton)	12
9	Baker River (Plymouth)	25
10	Plymouth	26
11	Squam Lake	31
12	Newfound Lake	45
13	Flood Control Dam (Franklin)	52
14	Franklin Falls	58
15	Tilton	66
16	Contocook River	69
17	Concord	81
18	Suncook River	86
19	Piscataquog River	97
20	Manchester	101
21	Souhegan River	106
22	Nashua River	113
23	Nashua	114
24	Lowell, MA	127
25	Concord River, MA	128
26	Lawrence, MA	139
27	Haverhill, MA	161
28	Amesbury, MA	162
29	Newburyport, MA (before)	164
30	Newburyport, MA (after)	166
31	Plum Island, MA	167

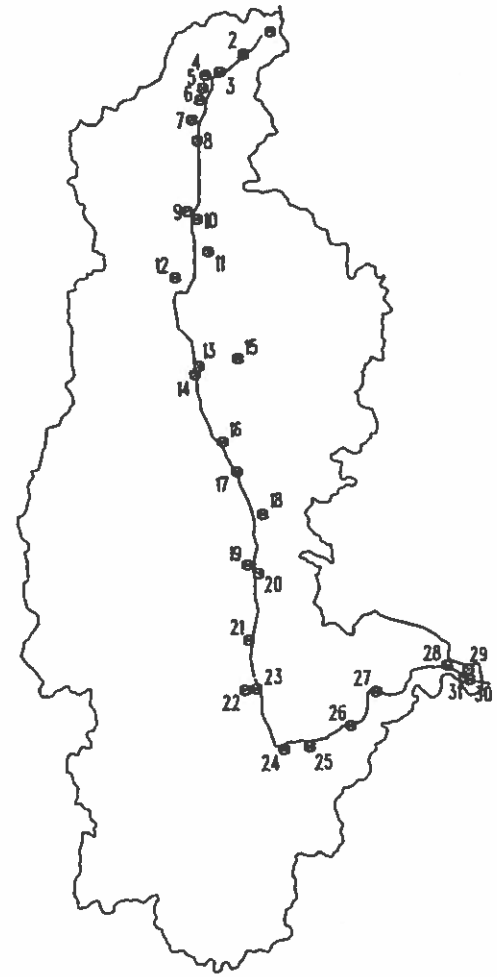


Figure 10. Map showing land classification and river sampling stations of the Pemigewassett-Merimack basin in NH and MA.

C_B. A comparison of 1990 SO_4^{2-} concentrations with 1971 values show a decline which likely is due to decreases in SO_2 emissions (Fig. 11).

We want to extend our analysis of factors regulating longitudinal patterns in water chemistry within the Hubbard Brook Valley (Johnson et al. 1981; Lawrence et al. 1986) to the entire Pemigewassett-Merrimack River system. We plan to develop a longitudinal, spatial database using a geographic information system (GIS) for the Pemigewassett-Merrimack River basin. The spatial database will include historical information on population density, vegetation, land use, atmospheric deposition and geology (both surficial and bedrock).

Multi-temporal land cover data for an extensive area can be derived from both existing sources and computer processing of digital imagery acquired by the Landsat Thematic Mapper (TM) sensor. The USGS digital land-use/land-cover data also are available for the basin (USGS 1986). The distribution of land cover types in the basin during the 1970's is shown in Figure 10. Approximately 78% of the basin was forested, 6% agricultural, 10% urban or built-up land, 5% water or wetlands, and 1% barren or transitional land. We plan to acquire current land cover data for the Pemigewassett-Merrimack River basin from the analysis of digital satellite imagery. We expect to use conventional image processing algorithms to partition digital values of relative multi-spectral scene reflectance into unique land cover types, and use the mapping classification scheme of Anderson et al. (1976).

This GIS will be coupled with a sampling of river water chemistry from historically monitored stations along the Pemigewassett-Merrimack River (Fig. 10) monthly during 1995 as part of the HBR-LTER. This integrated program should allow us to assess spatial and temporal changes in water quality and the factors responsible for these changes. Moreover, this analysis will provide important information to the Merrimack Basin Commission and other local water quality organizations concerned with management of regional water resources.

1.2.3 Land-use and disturbance history

OBJECTIVE 7. To quantify past patterns of forest composition and disturbance for intensive research sites (HBEF and The Bowl Natural Area).

At HBR we have begun to develop an historical perspective on natural and anthropogenic disturbance patterns in our intensive sites as part of a multi-site investigation of historical ecology, partially funded by the Mellon Foundation. Examination of the original presettlement forest composition using witness tree surveys (Hamburg and Cogbill 1988) and forest floor pollen stratigraphy (Davis et al. 1985) has indicated greater abundance of red spruce and beech prior to settlement (ca. 1787). A detailed cultural history (Cogbill 1989) has identified three periods (1880's, 1906-1919, and 1939-42) of intensive logging. In addition, the 1938 hurricane caused extensive canopy damage near the experimental watersheds (Peart et al. 1992) and in the Bowl Natural Area. Analysis of over 400 tree cores and cookies from two sites show sapling recruitment response in the 1880's, 1910's and 1938, with parallel growth releases in older remaining trees. Regeneration of early successional species such as pin cherry, white birch, and ash, indicates that there is a strong connection with the type and intensity of prior disturbances. Patterns of forest development, nutrient cycling, and regeneration are all dependent on site history. To understand the local and regional patterns of composition, growth, and successional change, it is necessary to complete site reconstructions of other areas of the Hubbard Brook Valley and The Bowl.

Hypothesis 7.1. The present forest at HBR is neither even-aged, second growth nor representative of the original forest composition.

Land-use histories will be expanded using a combination of historical methods, site surveys, and experimental testing. On-going studies of the cultural history of the valley will focus on 1880's river driving and 1938 salvage logging (including interviews with members of the logging crew). Clusters of trees will be cored to reconstruct stand history and the timing of past disturbance regimes and the corresponding growth responses. Both cut and broken stumps and tip-up mounds will be inventoried to document their pattern and relationship to blow-downs resulting from the 1938 hurricane and prior logging. Forest floor pollen analyses, in tandem with dendrochronology and dead wood surveys, will be done to reconstruct detailed stand level histories.

Hypothesis 7.2. Historical logging methods (horse skidding) result in different patterns of forest floor disturbance and consequent regeneration compared to modern mechanical methods.

Three plots will be logged in the winter of 1992-93 by horses using methods common to the early 1900's and three others by mechanical skidder. Initial planning and precut measurements have been supported by a grant from the Andrew W. Mellon Foundation. The density of pin cherry regeneration is predicted to differ in response to the logging methods and with the previous history of disturbance of the paired plots.

We are fortunate in the HBES to have a nearby site (The Bowl Natural Area) that has never been subjected to clearcutting disturbance. Previous and ongoing studies at this site have quantified vegetation composition and biomass (Martin 1977), temporal patterns in nutrient outputs (Martin 1979), and elevation patterns in the extent and sizes of natural forest gaps (Fig. 12) and consequent regeneration. As part of the HBR-LTER, we propose remeasurement of vegetation plots established at the Bowl to test the following hypothesis:

Hypothesis 7.3. Vegetation composition and biomass in an old-growth northern hardwood and mixed hardwood-conifer forest are not at steady-state but rather are changing as a result of shifts in disturbance patterns owing to unusually high mortality of beech (due to disease) and red spruce (unexplained decline).

These studies will aid our efforts at ground-truthing our regional model of vegetation dynamics (ZELIG). Our studies of past hurricane damage at HBR and the Bowl are being performed in conjunction with related efforts at the Harvard Forest and Luquillo Forest LTER sites.

2.0 Air Pollution

2.1 Changes in Loading of Acidic Deposition

2.1.1 General Patterns

There is much concern over the possible effects of elevated atmospheric inputs of acidic substances, including acidification of soil and surface waters (Galloway et al. 1983; Reuss & Johnson 1986), linkages to forest decline (McLaughlin 1985; Hinrichsen 1986; Schultz 1989) and changes in the biotic structure of aquatic ecosystems (Schindler et al. 1985). This concern resulted in the passage in 1990 of Amendments to the 1970 Clean Air Act. Part of this legislation was directed at reducing acid rain, mandating a 9.1 million metric ton reduction in emissions of SO_2 and a 1.8 million metric ton reduction in emissions of NO_x ($NO+NO_2$) by the year 2000. Because reductions in acid loading

will occur gradually, pollutant delivery to these ecosystems will continue for at least another decade. Moreover, the degree of recovery resulting from the reductions is difficult to predict (Likens 1992).

A major focus of the HBES, including the HBR-LTER has been determining inputs of acidic deposition, assessing changes in these inputs, and quantifying effects on terrestrial and aquatic ecosystems (see Results from prior NSF support). During this critical transitional period of mandated emission reductions, we propose to continue these activities.

OBJECTIVE 8. **(A) To continue to evaluate trends in wet and dry deposition inputs and stream outputs for small watershed ecosystems, (B) to develop detailed element budgets for forest ecosystems, (C) to assess changes in element transfer and cycling as the forest canopy matures, (D) to evaluate how the forest ecosystem responds to chemical addition of Ca^{2+}-SO_4^{2-}-NO_3^--Cl^-, with particular emphasis on studying changes in the N cycle through addition of ^{15}N, and (E) to use the H^+ budget approach and the biogeochemical model vegie/chess to evaluate and integrate studies on changes in chemical inputs to the forest and aquatic ecosystems.**

Background, Hypotheses and Research Approach. Following the passage of the Clean Air Act of 1970 there have been significant declines in emissions of SO_2 and particulates (Fig. 11; Butler & Likens 1991; Likens 1992). At the HBEF, a measured decline in precipitation SO_4^{2-} concentration (Fig. 13) is closely coupled with decreases in SO_2 emissions in the eastern U.S. (Likens et al. 1984; Hedin et al. 1987; Butler & Likens 1991; Likens 1992). Similarly, decreases in basic cations (C_B; $r^2 = 0.66$; Fig. 13) and particularly Ca^{2+} ($r^2 = 0.72$) in precipitation are correlated with declines in total particulate emissions. The decline in precipitation inputs of C_B is intriguing and has important management implication for base-poor ecosystems such as those of the HBEF (Driscoll et al. 1989).

Despite the decline in emissions of SO_2 and precipitation inputs of SO_4^{2-}, there has been little evidence of the recovery of acidic surface waters (Dillon et al. 1987; Morgan 1990; Driscoll & van Dreason 1991). At HBR, the long-term decline in SO_4^{2-} inputs is correlated with declines in stream SO_4^{2-}concentrations, but has not resulted in an increase in stream pH (Fig. 14; Driscoll et al. 1989). Rather, a stoichiometric decline in stream C_B has coincided with the decrease in SO_4^{2-}, preventing any long-term decrease in stream acidity. Between 77 to 85% of the decline in stream C_B can be explained by decreases in atmospheric deposition of C_B (1963-present; Driscoll et al. 1989).

Much of the recent research on surface water acidification in the U.S. focused on effects of atmospheric deposition of SO_4^{2-}. However, reports of elevated concentrations of NO_3^- in soil solutions and surface waters in central and northern Europe (van Breemen et al. 1982; Hauhs et al. 1990) have led to the hypothesis that elevated atmospheric inputs of N have caused a shift in forest ecosystems from conditions of N limitation of growth to limitation by some other resource (e.g. other nutrients, light, water; e.g. Nihlgard 1985; Aber et al. 1989; Tamm 1991). In the U.S. there have been no temporal trends in precipitation concentrations of NH_4^+ and NO_3^- in recent years (Simpson & Olsen 1990; Butler & Likens 1991; Driscoll & van Dreason 1991). Nevertheless, there have been reports of elevated NO_3^- in drainage waters in the eastern U.S. (Driscoll & Schafran 1984; Cronan 1985; Driscoll et al. 1990; Stoddard & Murdoch 1991; Driscoll et al. 1992).

Unlike SO_4^{2-}, there is not a strong relationship between atmospheric deposition of N and streamwater losses at the HBEF (Fig. 15). In fact, the long-term budget for N shows an initial interval of coincident increases in both inputs and outputs followed by an extended interval of ecosystem retention of N, despite near zero net ecosystem production. Regional patterns of N cycling suggest that HBR is located in a region of transition, between the western Adirondack Mountains that currently show elevated NO_3^-losses, and eastern New England which is characterized by very low NO_3^- export (Fig. 16). If vegetation biomass accumulation at HBR were to continue to decline, as it has recently (Driscoll et al. 1989), this change would likely contribute to increasing stream losses of NO_3^- and other solutes.

We anticipate that changes in atmospheric deposition of Ca^{2+} and SO_4^{2-} will continue to be a major influence on the biogeochemistry of forest ecosystems at HBR. Moreover, a small increase in N deposition at HBR may result in a dramatic response in the N cycle. We propose to couple our long-term biogeochemical studies, with a whole-watershed ecosystem manipulation experiment (not funded by the HBR-LTER) to evaluate the response to changes in atmospheric chemical inputs as well as provide a valuable opportunity to verify/validate process formulations of VEGIE/CHESS.

Hypothesis 8.1. Atmospheric inputs of SO_4^{2-} to the HBEF will continue to decline, in response to decreases in emissions of SO_2 in the eastern U.S.

Hypothesis 8.2 Concentrations of SO_4^{2-} will continue to decline in streamwater draining forest watersheds at HBR, but the rate of decrease will be slower than observed in atmospheric deposition due to release from soil S pools.

Hypotheses 8.3 Atmospheric deposition of C_B will continue to decline, reflecting decreases in particulate emissions as a result of the 1990 Amendments to the Clean Air Act.

Hypothesis 8.4 Stream concentrations of C_B draining forested watersheds at HBR will continue to decrease, reflecting deceases in atmospheric inputs and reduced leaching from the soil exchange complex.

Hypothesis 8.5 Atmospheric deposition of inorganic N at the HBEF will remain steady at current levels, reflecting constant emissions of NO_x. Under presumed constant rates of atmospheric N deposition, stream concentrations and total efflux of NO_3^- will increase in the long-term as a result of declining net ecosystem productivity, in the slightly aggrading forest of W6.

Hypothesis 8.6 As the W5 canopy matures, its capture of dry deposited material will increase, and its retention of deposited inorganic N will decrease. The consumption of inorganic N in the forest canopy is primarily a result of direct uptake by tree foliage.

Hypothesis 8.7 Under experimental increases in NO_3^- inputs, immobilization by microbial biomass will initially retain NO_3^- in surface soil horizons, so that NO_3^- cycle responses to added NO_3^- will be reflected primarily in microbial processes rather that plant processes. Increased release of organic N via forest floor leaching is anticipated in the mid-term (1-2 yrs).

Hypothesis 8.8 Significant amounts of N are lost via denitrification in near-stream saturated zones, and these losses will be stimulated by addition of NO_3^-.

Testing hypotheses 8.1 through 8.8 requires an integrated program of monitoring and processes investigations. The biogeochemical monitoring program, including chemical measurements of air, precipitation, throughfall, streamwater, forest floor and mineral soil, will enable us to test hypotheses 8.1-8.5. Throughfall monitoring and process-level canopy research are required to test hypothesis 8.6. Finally, hypotheses 8.7 and 8.8 will be tested through the intensive study of a chemically manipulated watershed (see section 2.1.4).

2.1.2 Atmosphere/canopy interactions

Comparisons of throughfall between W5 (clearcut in 1983) and W6 have revealed some interesting contrasts which we plan to study in more detail. Throughfall flux of SO_4^{2-} was higher under the W6 canopy than under the W5 canopy which is shorter and dominated by pin cherry (Fig. 17). Because the flux of SO_4^{2-} in throughfall has been found to reflect mainly wet and dry deposition inputs, as opposed to foliar leaching (Lindberg & Garten 1988), this pattern suggests that as the

canopy matures its ability to capture atmospheric SO_4^{2-} increases. Coincidently, the canopy of W5 appears to be more efficient in retaining the N from atmospheric deposition (i.e., it absorbs more NO_3^- and NH_4^+ from precipitation and releases slightly less organic N; Fig. 17). This pattern indicates that the role of pin cherry in retaining N following disturbance extends even as far as canopy scavenging deposited N. To test hypothesis 8.6, we plan to measure throughfall in W5 on a "two years on, two years off" schedule to monitor how the development of the canopy affects rates of dry deposition and the processing of N. Throughfall in W6 will be continuously monitored, including snow in the winter.

2.1.3 Chemical Manipulation Study

We intend to conduct a chemical manipulation of Ca^{2+}-SO_4^{2-}-NO_3^--Cl^- addition at W1. This investigation is a complicated whole-ecosystem manipulation. We do not have the resources in any single project to conduct a comprehensive evaluation of the biogeochemical response to the chemical treatment. As a result, this proposed research will be a joint initiative between the HBR-LTER and the HBES "core grant" (Hydrologic-nutrient cycle interaction in small forested and human manipulated ecosystems; see Appendix V). Through the HBES "core" study: (1) the manipulation will be done; (2) the response of soil, soil water and streamwater to the chemical manipulation will be evaluated; (3) watershed mass balances of major ions (e.g. Ca^{2+}, S, N, Cl^-, H^+, Al) will be developed; and (4) process-level studies on S and Ca using isotopic tracers will be done. Through the HBR-LTER, the effects of the chemical treatment on the N cycle (Hypothesis 8.7 and 8.8) will be studied. Detailed investigations of microbial and plant response to ^{15}N additions are a key component of this proposed HBR-LTER.

Stream chemistry of W1 (monitored since 1966) is similar to the biogeochemical reference watershed, W6 (Table 5). The similarity is remarkable, since W1 is small (11.8 ha), characterized by steep topography, and is hydrologically and chemically the most "flashy" of the experimental watersheds at the HBEF. A mixture of $CaSO_4$, $Ca(NO_3)_2$ and $CaCl_2$ will be added over a five-year period. The addition of Ca^{2+} provides an opportunity to evaluate the significance of changes in atmospheric deposition of C_B on soil and stream chemistry (Hypotheses 8.3, 8.4) and the acid-base chemistry of drainage waters. The S amendment will provide quantitative information about ongoing

and anticipated future changes in atmospheric deposition of S to the forest ecosystem (Hypotheses 8.1, 8.2). By increasing inputs of NO_3^-, we anticipate marked increases in leaching losses which would allow us to evaluate whether the ecosystem is at or near conditions of N saturation (Hypothesis 8.5). In the chemical manipulation, we plan to take full advantage of stable isotopes, a powerful tool in ecosystem research. Isotopically distinct Ca and Sr will be added to plots, while $CaSO_4$ will be obtained from a ^{35}S-rich source, and whole ecosystem additions of $Ca^{15}(NO_3)_2$ will be made in years 1 and 5.

The annual additions we propose for the chemical treatment are, Ca: 2.0 keq/ha-yr (40 kg Ca/ha-yr); Cl: 0.3 keq/ha-yr (10.6 kg Cl/ha-yr); SO_4^{2-}: 1.0 keq/ha-yr (16 kg S/ha-yr); NO_3-: 0.7 keq/ha-yr (9.8 kg N/ha-yr). These values correspond to a molar ratio of 1:0.7:0.3 for $CaSO_4$:$Ca(NO_3)_2$:$CaCl_2$. All additions will be applied in solid form by helicopter. Additions will be made every other month during each of five treatment years. Results from model simulations with VEGIE/CHESS suggest that chemical changes in soilwater, streamwater and soil pools should be detectable, given the natural variability (Johnson et al. 1990; Dahlgren & Driscoll 1992). Model simulations suggest that soil and drainage water will respond rapidly (< 1 yr) to Cl^-, at intermediate times (2-3 yr) to Ca^{2+} and SO_4^{2-} and probably longer (4-5 yr) to NO_3^- additions. When the treatment is completed after five years, we plan to monitor the "recovery" of the ecosystem to the lower ambient loading through our long-term biogeochemical studies.

2.1.4. Nitrogen Cycling Studies

The effects of the chemical perturbation on N cycling processes should be evaluated through a series of experiments and monitoring programs that encompasses the broad range of variables influencing N dynamics. These parameters include microbial and root uptake, microbial biomass and enzyme activity, fine root biomass and growth rate, net primary production, nutrient translocation, stochastic climatic events, soil organic matter concentrations and root penetration of soil profiles. This picture is further clouded by the fact that these parameters change over a wide range of time scales, from hours (microbial uptake) to decades (soil organic matter).

We will integrate a series of ^{15}N tracer additions with detailed process-level experiments and monitoring to permit a quantitative assessment of N cycle responses to increased NO_3^- inputs on W1. Comparisons with N cycling behavior under ambient N deposition will be facilitated through parallel studies in non-manipulated forest sites west of W6. These studies will allow us to test Hypotheses 8.7 and 8.8 and to quantify the mechanisms underlying watershed-level responses to NO_3^- deposition.

The watershed-level ^{15}N tracer additions will consist of approximately 1% atom enrichment of ^{15}N in the $Ca(NO_3)_2$ component of the chemical treatment. Experience from other regional sites indicates that this level of ^{15}N enrichment will be sufficient to quantify transformations of the added NO_3-within the soil and vegetation pools, when sampling protocols that control for spatial variability in ^{15}N natural abundance across the watershed are followed (K.Nadelhoffer, personal communication).

Patterns of natural abundance of ^{15}N in soil, vegetation and solution pools will be examined through comprehensive pre-treatment sampling of W1 and the reference forest. To assure detection of the ^{15}N tracer in the large soil pools, paired microplot sampling will be conducted within the macroplots that will be established for monitoring work. By reducing the scale of paired samples, uncertainties resulting from spatial variation in ^{15}N natural abundance will be minimized, and by sampling across the complex landscape, differential responses at contrasting landscape positions (i.e. upper vs. lower watershed, upper, mid and lower slope positions) can be detected.

Short-term responses of "fast" microbial and root uptake processes also will be examined at the small plot scale through experimental microinjection of high-enrichment (99% atom-enriched) ^{15}N tracer (in situ; Schimel & Firestone 1989). These tracer studies will augment the large-scale, low enrichment experiment by tracking the short-term fate of added NO_3^- at three different times through the annual cycle in three years. Thus, the combination of whole watershed and small plot additions of ^{15}N will allow us to calculate both the watershed mass-balance of the added NO_3^- (incorporation into soil and vegetation pools, and leaching and stream output) as well as the mechanisms that generate these budgetary responses.

Concurrently, we will quantify the responses of microbial processes (mineralization, nitrification, soil respiration, methanogenesis and methane oxidation, and specific enzyme activities),

root growth, root turnover, microbial biomass, and active soil N on the detailed study plots within W1 and the reference site. These measurements, to be conducted 6 times/yr, will allow us to evaluate both long-term responses to the chemical perturbation as well as the effects of likely unusual climatic events (e.g. soil freezing or drought). The measurements to be conducted in the N cycling research are summarized in Table 6. Detailed descriptions of the methodology are provided in Appendix III.

2.2 Trace metals

OBJECTIVE 9: To characterize and quantify the mechanisms regulating trace metal movement within the forest ecosystems at the HBEF.

Background, Hypotheses and Research Approach. A major effort at the HBEF, initiated in the mid-1970s, has been the investigation of the deposition and cycling of trace metals, including Al, Cd, Cu, Fe, Mn, Ni, Pb and Zn. To date, trace metal research at HBR has relied largely on the monitoring of forested (Smith & Siccama 1981; Smith et al. 1987; Driscoll et al. 1992) and clearcut watersheds (Fuller et al. 1988). In this phase of the HBR-LTER, we propose to continue monitoring of trace metal inputs and outputs in W5 (clearcut 1983-84) and W6 (reference), and to expand our trace metal research to include process-level research on plots and in the laboratory. The process-level studies will focus on the chemistry of Pb and Zn, which have shown interesting and contrasting behavior at HBR.

Lead and Zn differ in a number of ways. Lead is not a plant nutrient, while Zn is an important micronutrient (Bohn et al. 1985). Lead inputs at Hubbard Brook have exceeded outputs throughout the study period, while Zn outputs have exceeded inputs since 1981 (Fig. 18). Finally, clearcutting resulted in a marked increase in streamwater Zn concentrations at the HBEF, while Pb showed no response (Fuller et al. 1988).

The focus on Pb and Zn is further motivated by additional observations. First, legislation restricting the sale of leaded gasoline has resulted in reductions in Pb emissions (USEPA 1986). At HBR, the concentration of Pb in precipitation has declined from about 28 µg/L in the mid-1970s to about 1 µg/L today, a 95% decrease (Fig. 19). During this period, there has been a 30% decrease in the Pb content of the forest floor, and no change in Pb outputs in streamwater (Fig. 19), suggesting that Pb is immobilized in the mineral soil. Gaining an understanding of the mechanisms by which Pb

is mobilized, transported and immobilized is critical to determining the potential for future elevated streamwater concentrations.

Extensive plant tissue analyses have revealed that Zn concentrations in yellow and white birch are an order of magnitude higher than in other tree species at HBR. Also, the total and exchangeable pools of zinc in the soil are relatively small, compared to the current tissue Zn pool (Fig. 20). Patterns in Zn availability may thus be a factor in determining the species composition of the forest following clear-cutting. Another important factor may be the form in which Zn is found in the soil.

Hypothesis 9.1. Lead concentrations in precipitation will remain approximately at current levels. Lead content of the forest floor will continue to decrease as Pb accumulates in the mineral soil. Lead concentrations in streamwater will increase slightly during 1992-1998 as Pb is mobilized from the mineral soil.

Hypothesis 9.2. Zinc inputs in bulk precipitation will decrease as will the forest floor pool. Streamwater Zn concentrations will not change substantially.

Hypothesis 9.3. The concentration of Pb in the spodic soil horizons (Bh and upper Bs) have increased between 1976 and 1992. Concentrations in the E and lower Bs horizons have not changed.

Hypotheses 9.1 and 9.2 will be tested through our continuing trace metal monitoring program. These studies will be integrated with our proposed investigations concerning the processes regulating trace metal behavior (see hypotheses 9.4 and 9.5 below). Hypothesis 9.3 will be tested by measuring the Pb content of soil horizons collected in three efforts: excavation of a soil trench near W2 in 1976; extensive sampling on W5 in 1983, prior to clear-cutting; and extensive sampling on W1 in 1992, prior to chemical manipulation.

Hypothesis 9.4. Lead movement in the soil profile is strongly regulated by the formation and movement of Pb-organic matter complexes formed in the O horizon. The solubility of these complexes decreases with increasing soil and solution pH, resulting in the accumulation of Pb in the upper mineral horizons.

Hypothesis 9.5 Zinc movement is also strongly regulated by organic matter complexation in the absence of plant uptake.

Hypothesis 9.6. Under field conditions, Pb movement is regulated by the formation, transport, and precipitation of Pb-organic matter complexes. Zinc behavior is affected by plant uptake and organic matter complexation.

Laboratory studies with humic and fulvic acids have shown that both Pb and Zn (and most trace metals) form strong complexes with dissolved organic matter (e.g., Schnitzer & Kerndorff 1981; Stevenson 1982). At HBR, monitoring studies have shown that Pb concentrations in soil solutions and stream waters are correlated with dissolved organic carbon (DOC), while Zn is not correlated (Driscoll et al. 1988; Fuller et al. 1988). We propose to undertake process-level laboratory and field investigations to determine the extent to which organo-metallic complexes regulate Zn and Pb transport/immobilization through soil.

Initially, we will evaluate metal-DOC binding in batch laboratory experiments. Large forest floor lysimeters (Rascher et al. 1987) will be used to collect large quantities of solution enriched in DOC (concentrations 3,000 µmol C/L) for these experiments as well as organic solute immobilization experiments (see section 3.2). These solutions will be adjusted to a range of pH values (3.0 to 6.0), DOC concentrations (100 to 3,000 µmol C /L) and trace metal concentrations (10^{-9} to 10^{-5} mol/L), placed in batch reactors and equilibrated. Solutions will be monitored until equilibration occurs. Following equilibration, solutions will be analyzed for final values of pH, DOC and inorganic/organic forms of trace metals. We plan to use the approach of Driscoll (1984) to distinguish between inorganic and organic forms of dissolved Pb and Zn. While this methodology was developed for Al, we have applied it to other metals. We will attempt to verify the speciation procedure through comparison with measurement using ion selective electrodes. With these data, we intend to use the organic analog approach to simulate binding of trace metals with DOC (Driscoll et al. 1988; Schecher & Driscoll 1992).

To investigate trace metal sorption to HBR soils, samples of Oa, E, Bh, Bs1 and Bs2 horizon soils will be equilibrated with solutions containing varying amounts of Pb and Zn, using the approach of Harter (1979). These experiments will be conducted over a range of pH values (pH 3.0 to 6.0) and DOC concentrations (100 to 3000 µmol C/L) to quantify the pH-dependency and role of organic solutes in the immobilization of trace metals. With these data, partition coefficients (or surface complexation constants) will be determined to help quantify metal adsorption/desorption of forest soil.

These batch experiments will be supplemented by two series of soil-column experiments. In the first series, dilute solutions of $PbCl_2$ and $ZnCl_2$ will be drawn through various soil assemblages using a mechanical vacuum extractor. The soil columns will consist of a sequence of artificial profiles (Oa, Oa+E, Oa+E+Bh, Oa+E+Bh+Bs1, and Oa+E+Bh+Bs1+Bs2). Extracts will be analyzed for Pb (or Zn) species, DOC, and pH. These experiments will test the hypothesis (9.5) that organo-metallic complexes form in the O horizon and accumulate in the upper mineral horizons.

The second set of column studies will allow us to quantify conditions of trace metal immobilization. The extractant will be O horizon leachate with a total Pb (or Zn) concentration of 5×10^{-8} mol/L (twice the average concentration observed by Driscoll et al. [1988]), and initial pH adjusted to 3.0, 3.5, 4.0, 4.5, and 5.0. E, Bh, and Bs1 horizons will be pre-treated with dilute HCl or $CaCO_3$ to produce a range of soil pH values (3.0-5.5). After extraction, the leachates will be analyzed for Pb (Zn) species, DOC, and pH to determine the degree of immobilization by each horizon.

Hypothesis 9.6 will be tested through plot experiments using stable isotopes of Pb and Zn. Six 10m x 10m plots will be established at high, medium, and low elevations. Forest floor and mineral soils will be sampled and chemically characterized, and each site will be instrumented with duplicate tension-free lysimeters beneath the Oa, E, Bh and Bs1 horizons. The following year, the plots will be amended with solutions enriched in ^{210}Pb and ^{64}Zn. Following the addition, soils, forest floor, and litter will be collected annually and analyzed for isotopic content. Soil solutions will be collected quarterly and bulked for each site by horizon (i.e. 4 samples per site per quarter). Soil solutions will be characterized for inorganic and organic species of trace metals. Forest floor and mineral soil horizons will be extracted using a neutral salt (NH_4Cl) and Na-pyrophosphate to determine the degree to which Pb and Zn are "exchangeable" (NH_4Cl) or complexed with organic matter (Na-pyrophosphate). The presence of ^{210}Pb or ^{64}Zn in leaf litter would indicate an important biocycling component (as hypothesized for Zn).

Information on trace metal-DOC binding constants and trace metal surface complexation constants with forest soil will be used to parameterize the soil column model CHESS. The results of the laboratory column experiments and field isotope studies will be used to validate the model

formulations developed from batch laboratory data. These studies will provide a more quantitative understanding of trace metal cycling at HBR.

3.0 Disturbance by Changes in Atmospheric CO_2 and Climate

In recent years, scientific attention has focused on the possible effects of changes in the composition and properties of the atmosphere. Globally, the concentration of atmospheric CO_2 is steadily increasing (Keeling 1986). There is a consensus among scientists that CO_2 concentrations are likely to rise from their present level (350 ppm) to about 500 ppm by the early to mid-21st century (Ramanathan et al. 1985; Trabalka et al. 1986; National Academy of Science 1988). A number of climate models predict that the indirect effects of atmospheric CO_2 enrichment will include increases in the mean and variability of global temperatures and changes in global patterns of precipitation (Mitchell 1989; Schneider 1989). However, the extent and importance of CO_2-induced changes in global and regional climates remain subjects of considerable debate (e.g., Mitchell 1989; Karr 1989). Despite this uncertainty, much of the recent research in ecology has focused on the effects of climate change on ecosystems. The direct effects of changing atmospheric CO_2 concentrations have received much less attention.

Our ability to assess the potential effects of atmospheric change is further hampered by the lack of reliable quantitative information about some major components of the C cycle. In particular, rates of soil CO_2 efflux and CO_2 patterns within the soil are poorly understood, in spite of numerous attempts. The contribution of root turnover (particularly fine roots) is another key shortcoming.

Ecosystem processing of carbon has important influences on other element cycles (Fig. 21). Changes in C uptake (i.e., plant growth rates) affect element cycles through the production or consumption of acidity (e.g., van Breeman et al. 1983). A second major influence is through complexation reactions between humic substances and cations in the soil and drainage waters. These complexes are very sensitive to pH and the chemical/structural features of the humics involved (Stevenson 1982). Changes in the C cycle could thus profoundly affect the H^+ and metal cation cycles (including trace metals) through changes in drainage water pH, plant growth rates, and humic

chemistry or structure. We propose a course of study that focuses on these uncertainties in the ecosystem carbon budgets, as well as some analysis of the effects of possible climate changes.

OBJECTIVE 10: **(A) To develop a detailed C budget for the northern hardwood forest ecosystem at HBR, including reliable estimates of CO_2 fluxes, root litter, and forest floor mineralization; (B) to quantify the linkages between the C cycle and other element cycles, particularly those of metals and H^+; (C) to determine the effects of realistic changes in temperature, moisture, and atmospheric CO_2 on the structure and biogeochemistry of isolated macrocosms; (D) to assess the effects of changes in tree species composition on phytosociology, hydrology, and biogeochemistry.**

3.1 Carbon Budgeting

Background, Hypotheses, and Research Approach. As at many sites, the C cycle at HBR is at once extensively studied and poorly understood. The dynamics of C in vegetation (Whittaker et al. 1979; Bormann & Likens 1979), soils (Huntington et al. 1988, 1989), stream ecosystem metabolism (Fisher & Likens 1974; Bilby & Likens 1980), and drainage water chemistry (McDowell & Wood 1984; McDowell 1985; Lawrence et al. 1986; McDowell & Likens 1988) have received considerable attention. Through these efforts, we have constructed C budgets for undisturbed W6 and clearcut W5 (Fig. 22). Logging resulted in increases in soil water and stream fluxes of DOC. While these changes were probably critical in the transport of organo-metallic complexes, they were minor relative to the pools of C in the soil. Our understanding of C dynamics in both undisturbed and clear-cut forests is clouded by the lack of reliable estimates for three large fluxes: gaseous efflux, root litter, and root respiration. We propose to close these gaps through extensive and intensive sampling, and we offer the following hypotheses:

Hypothesis 10.1. Gaseous loss of CO_2 is highly variable in time and space. Carbon dioxide efflux is higher in recently clear-cut watersheds due to accelerated decomposition rates and higher root respiration. In the undisturbed forest, soil CO_2 evolution is closely tied to canopy conditions, with the highest rates occurring in gaps.

Hypothesis 10.2. In undisturbed forest ecosystems, root respiration is the dominant factor in mineral soil CO_2 production. Thus, CO_2 concentrations in the solum reflect fine root density, rather than organic matter mineralization rates.

Hypothesis 10.3. Root litter is a major flux in the carbon cycle at HBR. Input of C to the solum through root litter is greater in disturbed watersheds than in the undisturbed forest.

Existing data indicate that gaseous loss of CO_2 is greater in clearcut W5 than in undisturbed W6. However these estimates are based on relatively few observations (ca. 300). To test hypothesis 10.1. a reliable method for measuring CO_2 flux at a large number of locations is required. Frequently used methods include flux chambers and soda lime traps. Flux chambers are relatively expensive to install and maintain at a large number of sites. Soda lime traps (Edwards 1982) can be easily installed at a large number of sites, but there is concern that the traps induce a gradient in CO_2 partial pressure, resulting in over-estimation. We propose to test hypothesis 10.1. by measuring CO_2 evolution on an elevation-stratified, random set of 60 sites within W5 and just outside W6 using an infra-red CO_2 monitor.

To test hypothesis 10.2, CO_2 will be measured at several depths in the solum at each site, by installing PVC tubing screened at the desired depth, in much the same way as a piezometer. An access port is then installed in the tube to allow measurement of CO_2. Integration of this program with fine root monitoring studies will allow us to monitor CO_2 within the solum at locations with known fine root demographics. If hypothesis 10.2 is correct, the gradient in soil CO_2 concentrations will reflect the gradient in fine root density and/or biomass.

In addition to testing these hypotheses, the simultaneous measurement of CO_2 at several depths at many sites will allow us to estimate its mass transfer coefficient under a variety of ambient conditions and to cross-check flux estimates from CO_2 trap and flux chamber methods (DeJong and Schappert 1972). This is essential to the prediction of the compensatory response of soil CO_2 to increases in atmospheric CO_2 concentrations. A substantial increase in soil CO_2 concentrations would result in increased soil water acidity and, possibly, increased rates of soil acidification and chemical weathering.

3.2. Interactions between the cycles of carbon and other elements.

Changes in C dynamics may have profound effects on other element cycles through: (1) altered plant growth rates, resulting in changes in the uptake of nutrients and production of acidity (H^+); (2) altered soil water pH (due to changes in plant growth or soil CO_2 concentrations), resulting in

changes in chemical weathering rates and cation exchange reactions; and (3) induced changes in the proton and metal binding properties of soil and aquatic humic substances.

In spite of the acknowledged importance of humics in the acid-base and trace metal chemistry of drainage waters (Smith & Siccama 1981; Driscoll & Likens 1982; Lawrence et al. 1986; Driscoll et al. 1988), relatively little is known about the chemical and physical properties of soil and aquatic humic substances at HBR. In a study of the organic chemistry of precipitation and drainage waters at HBR, McDowell & Likens (1988) measured the concentrations of phenolics (lignin and tannin), carbohydrates, low molecular weight carboxylic acids, aldehydes and primary amines. They found that DOC in precipitation and throughfall was largely composed of carbohydrates and low molecular weight compounds, with a 10-fold enrichment of DOC in throughfall. At most, only 11% of the DOC in soil solutions and stream water was accounted for by carbohydrates, lignin and tannin. This strongly suggests that the organic chemistry of soil and stream water is dominated by humus leached from the forest floor (McDowell & Likens 1988).

We propose a research effort aimed at quantifying the binding properties of humic substances and their contributions to the organic chemistry of HBR drainage waters. This effort will fill a major gap in our understanding of the influence of the carbon cycle on other cycles. We plan to test the following hypotheses:

Hypothesis 10.4. Dissolved organic carbon (DOC) in HBR soil and stream waters has a distinctly acidic character and is dominated by hydrophobic and, to a lesser extent, hydrophilic acids. The hydrophilic acids in HBR drainage waters have a higher proton- and metal-binding capacity than the hydrophobic acid fraction.

Hypothesis 10.5. Soil humic substances at HBR have a higher humic acid/fulvic acid ratio (HA/FA) and a more basic and hydrophobic character than aquatic humics. Soil fulvic acids at HBR have significantly greater proton- and metal-binding capacities that humic acids.

Hypothesis 10.6. Humics in soils and waters in a recent clear-cut watershed have lower HA/FA and are more acidic than those of an undisturbed watershed, indicating that accelerated decomposition favors the formation of humics with higher acidity and binding capacities.

A number of methods have been proposed for the fractionation of organic matter in soils and waters. Separation into humic acid, fulvic acid, and humin fractions (Schnitzer & Khan 1972;

Stevenson 1982) is applicable to soils and water samples, is reasonably simple, and produces results which can be compared to a large data base. A major advantage is that the procedure produces fractions (humic and fulvic acid) with markedly different chemical properties. Recently, fractionation of aquatic humics into hydrophilic and hydrophobic acids, bases and neutrals (Leenheer 1981) has gained popularity. The advantages of this method are that it is somewhat more "gentle" chemically, it can be done on small samples, and it is not as operationally defined as the humic/fulvic acid fractionation. However, the method has not been widely used in the analysis of soil humics.

We plan to use both methods for two reasons. First, we have plans for numerous process-level investigations requiring isolation of DOC fractions. In spite of its many advantages, the method of Leenheer (1981) is not easily adapted to the isolation of gram quantities of humics. Second, the DOC of soil solutions and streams in New England appear to be dominated by hydrophobic and hydrophilic acids (Cronan & Aiken 1985; Vance & David 1991), which have similar chemical properties (Vance & David 1991). By using both methods, we can measure both the acid-base properties of DOC and make comparisons between soil and aquatic humics.

Hypothesis 10.4 will be tested by applying the method of Leenheer (1981), as modified by Vance and David (1991), to soil solution and stream samples collected through our ongoing monitoring efforts. Isolates of hydrophobic and hydrophilic acids will be collected from bulked solutions. Proton binding properties will be estimated by analysis of carboxyl group content and charge density using potentiometric titration. Metal binding studies using Al, Ca, Pb, and Zn will be conducted in the same manner as described in section 2.2.

The testing of hypothesis 10.5 requires the fractionation of soil and aquatic carbon into humic acid and fulvic acid (Schnitzer & Khan 1972; Stevenson 1982). Binding studies on isolated humic and fulvic acids will be conducted in parallel, using the same methods as those with hydrophobic and hydrophilic acids to allow direct comparison of the results.

Data from W5 support hypothesis 10.6. While DOC concentrations in soil solutions and stream waters did not change significantly (Lawrence et al. 1987; Fuller et al. 1987), organic monomeric Al (Al_o) concentrations in soil solutions and high-elevation stream waters increased. In the soil, where

organic matter is the major source of cation exchange capacity (CEC), there were significant increases in CEC per gram carbon in the organic-rich Bh and Bs1 horizons (Johnson et al. 1991b). These observations suggest that the chemical properties of soil and aquatic humics were altered following logging. To test hypothesis 10.6, we will analyze soil and water samples from W5, which was clearcut in 1983. Extraction of soil humic and fulvic acids will be done on archived samples collected in 1983, 1986, and 1991.

In addition to quantifying the chemical properties of HBR humics in undisturbed and clearcut watersheds, these experiments will provide critical information for modeling purposes. While there is some consistency to proton- and metal-binding constants, site-to-site variations may be a major source of uncertainty in chemical modeling efforts (Perdue et al. 1984; Driscoll et al. 1989). Also, efforts to incorporate organic complexation into models have largely been limited to H^+ and Al^{n+}. Our experiments are designed to provide similar information about Ca, Pb, and Zn complexation constants.

3.4. Vegetation Manipulation

The location and elevation of the HBEF is such that several tree species are at or near the edge of their ranges. These include red spruce, balsam fir, white birch, yellow birch, sugar maple, American beech, hemlock, white pine, and white ash. Increased CO_2 and possible associated climate change may result in changes in tree species composition of forests due to competitive response to increased CO_2 (Bazzaz 1991) or changes in species ranges (Pastor & Post 1982). For example, Bazzaz (1991) reported that beech and sugar maple showed significant increases in growth under high CO_2 conditions (700 ppm), while white birch showed no response. If yellow birch is similar to white birch, we might hypothesize that in a high-CO_2 environment, the HBR forest would be dominated by beech and sugar maple, with little yellow birch. Furthermore, paleoecological studies indicate that major compositional changes can occur in only a few years (Davis 1985). The possible effects of compositional changes on understory dynamics, hydrology, and biogeochemistry are difficult to predict. We propose to undertake three large-scale vegetation manipulation experiments in which all stems of one of the three dominant tree species in the northern hardwood forest (beech, yellow birch, and sugar maple) are

girdled. These experiments will be conducted on 1 ha plots within the mature northern hardwood forest at HBR.

Hypothesis 10.7. The principal immediate vegetation response to the individual elimination of each of the dominant overstory trees is an increase in growth and abundance of the dominant understory shrub (*Viburnum alnifoliam*) and tree (*Acer pensylvanicum*) species, as well as release of suppressed saplings of the tolerant overstory species.

Hypothesis 10.8. Elimination of each of the dominant overstory trees does not result in significant responses of biogeochemistry (esp. soil solution element concentrations).

Hypothesis 10.9. The long-term vegetation response to elimination of each of the dominant overstory species is a compensatory increase in the other two dominants.

Eight replicate 1 ha plots will be surveyed for vegetation using nested quadrats and randomly assigned to each of four treatments: girdling of (1) sugar maple, (2) beech, and (3) yellow birch, and (4) control. Sampling quadrats will be surveyed annually, and soil solutions will be sampled with zero-tension lysimeters to test hypotheses 10.7 and 10.8. This experiment is being initiated primarily as a long-term study to examine the potential effects of species loss and probable regional climate change on forest vegetation (Hypothesis 10.9). We also plan to follow the long-term pattern of bole decay of standing and fallen boles to augment our existing study of coarse woody debris.

4.0 Heterotroph Irruptions

Disruption of forest ecosystem structure and function by periodic irruptions of heterotrophic pests and pathogens has been documented widely (Mattson & Addy 1975, Morrow & LaMarche 1978). For eastern deciduous forests most attention has focused upon the pervasive effects on vegetation structure, growth and composition of several alien pests: chestnut blight, Dutch elm disease, gypsy moth and beech bark disease. The effects of native pests, including the ubiquitous phytophagous insects, have received less attention (Barbosa & Schultz 1988) and little is known about the interactions between heterotroph disturbance and other trophic groups in the northern hardwood ecosystem.

In keeping with the theme of the HBR-LTER program, we propose to examine the effects of irruptions of heterotrophic organisms on the structure and function of northern hardwood ecosystems. First, we will continue our efforts to document the relationships between the abundance of breeding

birds and their principal food source, phytophagous insects, and we will expand this effort to include consequent effects on primary production. Second, we will study the effects of high overstory mortality, resulting from the beech bark disease, on the structure and function of the stream ecosystem. Third, we will examine the magnitude and mechanism of herbivory on fine roots and attempt to identify the organisms involved.

4.1. Population dynamics of birds and insects and tree growth responses

OBJECTIVE 11: **(A) To quantify long-term patterns in population dynamics of birds breeding in northern hardwoods ecosystems and in their principal food supply, phytophagous insects, (B) to evaluate the mechanisms that regulate the bird populations, and (C) to determine the effects of bird-phytophagous insect interactions on tree growth.**

4.1.1. Breeding Birds

There is widespread concern that many species of passerine songbirds, especially those that migrate to the topics, are declining in abundance (Fig. 23; Holmes & Sherry 1988, Robbins et al. 1989, Askins et al. 1990, Finch 1991). The causes of these declines, however, are not well understood, and indeed are controversial. Current evidence based on the long-term data set from HBR indicates that diverse factors influence these abundance patterns, including (1) fluctuation in food availability, (2) effects of nest predators (but not brood parasites, which do not occur in these unfragmented forests), (3) natural changes in habitat structure that occur with succession, (4) competitive interactions between species, (5) weather on the breeding grounds (affecting breeding success), and (6) winter mortality. It is important to note that evidence for the latter has been obtained only for temperate zone residents and short-distance migrants, but not for Neotropical migrants (Holmes & Sherry 1988). Indeed, for the long-distance migrants, analyses of long-term demographic data from HBR show that recruitment of yearling males into breeding populations is significantly and positively correlated with nesting success in the previous summers (Sherry & Holmes, in press; Holmes et al. in press). Because recruitment essentially determines breeding population size, this finding strongly suggests that factors affecting reproductive output have a major impact on subsequent population dynamics and abundances of these species, and most importantly, these may override the impact of events happening on migration or in winter.

The two most important ecological factors affecting breeding success of birds at HBR appear to be food availability and nest predation. First, between 1986 and 1990, abundances of all foliage-gleaning birds on four replicate plots were correlated significantly with larval Lepidoptera (caterpillar) biomass in the preceding summers (Holmes et al. 1991, Fig. 24). This pattern suggests that food levels in the previous year influence reproductive success and subsequent survival into the following summer (i.e., recruitment). Second, both natural and experimental reductions in caterpillar abundance resulted in lowered nesting success, primarily through increased starvation of young (Rodenhouse & Holmes, in press) and failure to double brood (Holmes et al. in press). Third, between 1986 and 1990, the annual reproductive output of an intensively studied species (Black-throated Blue Warbler) was significantly correlated with caterpillar biomass (Holmes et al. 1991, Fig. 25). And fourth, nest predation was found to be the single most important mortality factor during the breeding season, and to vary significantly from year-to-year and place-to-place, even within this unfragmented forest (Reitsma et al. 1990, Sherry & Holmes, in press). Thus, knowledge of annual changes in food availability and predator populations contribute much to understanding fluctuations in bird abundances. As far as we know, such information, especially the long-term record, on the ecological factors potentially affecting neotropical migrant bird populations is not available from any other site in North America.

Hypothesis 11.1. Fluctuations in the abundances of birds breeding in northern hardwoods forests are related to changes reproductive success which is in turn related to changes in food supply, predation, habitat structure, and other ecological factors operating in the breeding season.

Our approach will be (1) to monitor bird populations, using the same methodology employed since 1969 (see Holmes et al. 1986), on four replicate study sites within relatively homogeneous, unfragmented northern hardwoods forests in and near the HBEF, and (2) to monitor simultaneously environmental factors (food availability, predator populations, forest structure, weather) that will help explain long-term population trends and that will be used to explain or to develop hypotheses concerning the factors causing population fluctuations. Experimental studies will be funded separately (Holmes & Sherry, BSR-pending).

4.1.2. Phytophagous Insects

In terms of potential impacts on ecosystem structure and function, phytophagous insects are probably the most important group of heterotrophs (e.g., Mattson & Addy 1975). Lepidopteran defoliators increase dramatically in abundance at periodic intervals, and at these times they can remove a large proportion (up to 100%) of photosynthetic leaf tissue (Barbosa & Schultz 1988). The periodicity of these defoliator irruptions in northern hardwood forests and their effects on forest ecosystem dynamics have not been well studied. For temperate deciduous forests as a whole, there are surprisingly few long-term records of outbreak frequency or magnitude. From the few available (Barbosa & Schultz 1988, Holmes 1988), it appears that irruptions occur on average about every 10 years, but the variability is high (5-15 years). Locally, the variability can be even higher, in that some areas may "escape" the outbreak for long periods of time (see below for HBR). Finally, almost no information exists on the abundance of defoliating Lepidoptera between outbreaks, nor on the periodicity of outbreaks in any single forest ecosystem.

Since 1969, we have sampled defoliators at HBR, and over this period only two major Lepidoptera irruptions have occurred, one of the saddled prominent (*Heterocampa guttivita:* Notodontidae) which peaked in mid summer of 1970 and one of an inchworm, *Itame pustularia* (Geometridae), which appeared in late May and early June of 1982 and 1983 (Holmes et al. 1986, Holmes 1988). No outbreak occurred during the last 5 years although *H. guttivita* did show initial signs of increase in 1987-1989 before collapsing in 1990 (Fig. 26). In the periods between outbreaks, caterpillar densities have been extremely low (e.g., an average of 5.2 larvae/1000 leaves on American beech; Holmes 1988, Holmes & Schultz 1988).

We propose to continue monitoring defoliating Lepidoptera in the HBR forest to document the long-term pattern of density and outbreak frequency in this northern hardwood forest ecosystem and to determine the local and regional patchiness in these populations. This work contributes to the avian ecology studies described above.

Hypothesis 11.2. Lepidoptera defoliators enter outbreak phase periodically, but while synchronous over large areas, these outbreaks are locally patchy.

Our approach for phytophagous insect monitoring will include visual censuses, frass collectors, and malaise traps, techniques which have been tested and used successfully at HBR (Holmes et al. 1986, Holmes & Schultz 1988, Holmes et al. 1991). A reference collection of adult and larval Lepidoptera from HBR is housed at Dartmouth. Monitoring will be done during the in-leaf period of each year, with detailed sampling at 2-week intervals. Measurement within permanent plots within the Hubbard Brook Valley and at three locations at replicate sites in the southern White Mountains will permit detection of the scale of any outbreaks.

4.1.3. Tree Growth Responses

The direct consumer role of birds in ecosystem processes (e.g., nutrient cycling) is considered to be minor (Wiens 1973, Holmes 1990). However, their indirect role, as consumers of phytophagous insects that influence plant processes, may be much greater. For example, recent experiments with *Quercus alba* have shown that insect herbivores can significantly reduce plant growth, and also that birds reduce the abundance of insects enough to counteract this effect (R. Marquis & C. Whelan, unpublished). A similar effect has been observed with eucalyptus trees, homopteran herbivores and insectivorous birds (*Manorina melanophry*) in Australia (Loyn et al. 1983). At HBR, caterpillars have defoliated up to 40% of leaf biomass during irruptions (Gosz et al. 1978, Holmes et al. 1988), and avian populations respond to these irruptions (Holmes et al. 1986). Birds also have significant impacts on non-irruptive insect populations (Holmes 1990), but consequent effects on forest production and nutrient cycling are unknown. In view of the alarming population declines of Neotropical migrant birds, both at HBR (Sherry & Holmes, in press) and throughout North America (Askins et al. 1990), the importance of such interactions takes on added significance.

Hypothesis 11.3. Foliage-gleaning birds consume sufficient biomass of herbivorous insects to have a beneficial effect on tree growth.

Our proposed experiment will consist of three treatments with 30 replicates per treatment on sugar maple saplings: (1) bird (but not insect) removal via exclosures of mesh netting, (2) insect removal via application of a pyrethroid insecticide, and (3) control. We will assess shoot extension, increment in stem diameter, leaf size and number, and estimated biomass increment. Insect

abundances will be examined throughout the experimental period (May-August), and birds will be censused in the vicinity of the treatments to assess relative abundances of migratory and resident species. The experiment will be conducted during two different growing seasons in the proposed LTER.

4.2 Long-Term Changes in the Biota of the Bear Brook Ecosystem

Objective 12. To assess factors that are responsible for long-term changes in stream biota.

Background and Research Approach: Early studies in the 1960's showed that benthic algae were extremely rare or nonexistent in headwater sections of Bear Brook (Eaton, 1968, unpublished report; Mahall, 1967, unpublished report; Fisher & Likens, 1972). Moreover, Thornton (1974) showed that insect species dependent of algae for food (e.g., *Neophylax* spp.) were limited in abundance in headwater streams at the HBEF. More recently Mayer (1986) and Mayer & Likens (1987) observed significant benthic algal production in the headwaters of Bear Brook, and found that ingested benthic algae supported between 50% to 87% of the annual growth of abundant *Neophylax* spp. in the stream (Mayer & Likens, 1987).

Additional anecdotal information may be relevant to these observations: 1) American beech and sugar maple have declined since the 1960's, and annual biomass increment currently is very small (USDA 1991). As a result, the amount of solar radiation reaching the stream likely has increased. Experimental illumination of Norris Brook within the HBEF and other data suggest that algal production in Bear Brook may be limited by light. 2) The chemistry of headwater streams has changed since the 1960's (Driscoll et al. 1989; Likens 1992). In particular, inorganic N concentrations are generally higher today than in the 1960's. It is not known, however, whether NH_4^+ and NO_3^- are limiting to benthic algal production in Bear Brook.

We will quantify changes in streamside forest canopy and light penetration between the mid-1960's and today, using historical data and vegetation surveys. Experimental tests will be done to determine the limiting factors on periphyton growth in headwater streams. This research will be conducted using funds provided to G.E. Likens by The Andrew W. Mellon Foundation.

4.3 Belowground herbivory and fine root dynamics

OBJECTIVE 13. (A) To document and quantify the importance of belowground herbivory and (B) to quantify fine root longevity in organic and mineral soil horizons in the northern hardwood forest ecosystem.

As noted earlier, a fundamental anomaly in the organic matter budgets of hardwood forest soils is illustrated by observations of fine root turnover rates (Aber et al. 1985; Nadelhoffer et al. 1985) and decay rates (McClaugherty et al. 1984, Fahey et al. 1988); i.e. decay rates are too low to account for turnover rates unless organic matter is accumulating rapidly, which does not appear to be the case at HBR. Three possible explanations of this anomaly have been suggested (Fahey, in press): (1) the techniques for measuring fine root decay yield serious underestimates; (2) the techniques for measuring fine root turnover yield overestimates; and (3) a significant proportion of fine root mortality is associated with herbivory which would accelerate oxidation rates.

Although the food webs of forest soils usually have been regarded as primarily detritus based (Wallwork 1976), the quantitative importance of belowground herbivory in forest ecosystems is poorly known. In the forestry literature the most prominent belowground herbivores are the white grubs (especially *Phyllophaga* spp.), which can cause significant damage to forest plantations (Stone & Swardt 1943, Shenefelt & Simkover 1950). The other potentially important root herbivores in forests (other arthropod larvae, nematodes, and rodents) have received very limited attention. Ausmus et al. (1978) concluded that belowground herbivory by insect larvae probably is a minor component of fine root dynamics in deciduous forests in Tennessee, but they noted that their conclusion must be interpreted with caution because of many assumptions that entered into the calculations.

We have observed apparent herbivory on fine roots over the past 3 yr in the mature northern hardwood forest at HBR. Our technique involves direct observation of roots that have grown through *in situ* mesh screens inserted into the Oe horizon. After removing the overlying Oi layer, screens are placed on top of the rooting zone in the Oe and the Oi litter replaced. A few weeks later we record the exact location and morphology of roots that have grown through the screens. This cohort of roots is then re-surveyed periodically. We have demonstrated that observation of the roots does not affect their growth or survivorship when precautions are taken to avoid dessication (i.e., misting). We

followed cohorts of several hundred roots by this method in 1989-1991. Results were significantly different among years as 45% to 81% of the mapped roots were still alive at the end of the growing season over the three years (Table 7).

Our evidence for the occurrence of fine root herbivory was the rapid disappearance of roots from the screens, particularly during summer 1990 (Table 7). The *in situ* rates of microbial decomposition of dead fine roots are much too slow (e.g. 22% dry weight loss; Fahey et al. 1988) for such rapid disappearance to occur, suggesting herbivory instead. Summer of 1990 was unusually wet at HBR (Federer et al. 1991) and white grubs, and other insects and larvae were abundant (personal observation) as would be expected (Ritcher 1966, Andersen 1987). In the first and third years of survey (1989, 1991) only 5% and 24% disappearance was observed in the same study plots. High variation in root longevity both among and within 0.2 x 0.2m sampling screens was observed, indicating high spatial variation at both small scale (<0.05 m^2) and mid-scale (ca. 10 m^2, Table 7). Unfortunately, only one stand has been surveyed so that large-scale spatial variation is unknown.

The abundance of potential root herbivores in eastern deciduous forests appears to be highly variable both spatially and temporally (Ferris & Ferris 1974, Ausmus et al. 1978, Karban 1984, Andersen 1987). Periodic irruptions of some insect larvae result from the effects of abiotic conditions on survivorship and reproduction, and the likelihood of pronounced irruptions is greatest outside the natural range of the insects (Andersen 1987). Very high densities of white grubs (*Phyllophaga* spp.) and cicadas have been observed in eastern deciduous forests, but their quantitative role as fine root herbivores has never been measured in the field. Ridsdill Smith (1977) observed consumption of 15% of fine root biomass by beetle larvae in greenhouse pot experiments, illustrating their potential importance. The high spatial and temporal variability in abundance and difficulties of quantifying metabolic activities have precluded accurate estimates of the chronic role of insect larvae as root herbivores in forest ecosystems.

Hypothesis 13.1. Chronic herbivory of fine roots in northern hardwood forests is relatively low (<15% of mortality) but during occasional irruptions of herbivore populations, this proces is the principal cause of fine root mortality.

We propose to add observations of fine root growth, longevity, and biomass to the baseline monitoring program of the HBR-LTER program (Table 1). Our fine root monitoring program will consist of three complementary sets of measurements: (1) coring for fine root biomass at the annual maximum (late summer) and minimum (late spring); (2) direct observations of fine root longevity in forest floor horizons using *in situ* screens; and (3) minirhizotron (Taylor 1987) sampling of fine root growth and longevity in mineral soil horizons. Together with measurements of annual litterfall and soil respiration (section 3.1), these results will provide confirming evidence for the magnitude of C flow through the fine root soil food chains, as well as the importance of herbivory in this food chain.

PROGRAM INTEGRATION AND MANAGEMENT

Five Core Areas

There are five "core areas" of research/monitoring (primary production, population trophic structure, organic matter, biogeochemistry and disturbance) that are required of all NSF LTER projects. In the HBR-LTER, we have integrated these "core areas" across our theme of disturbance to northern hardwood forest and associated aquatic ecosystems (see Table 2).

Long-Term Experiments

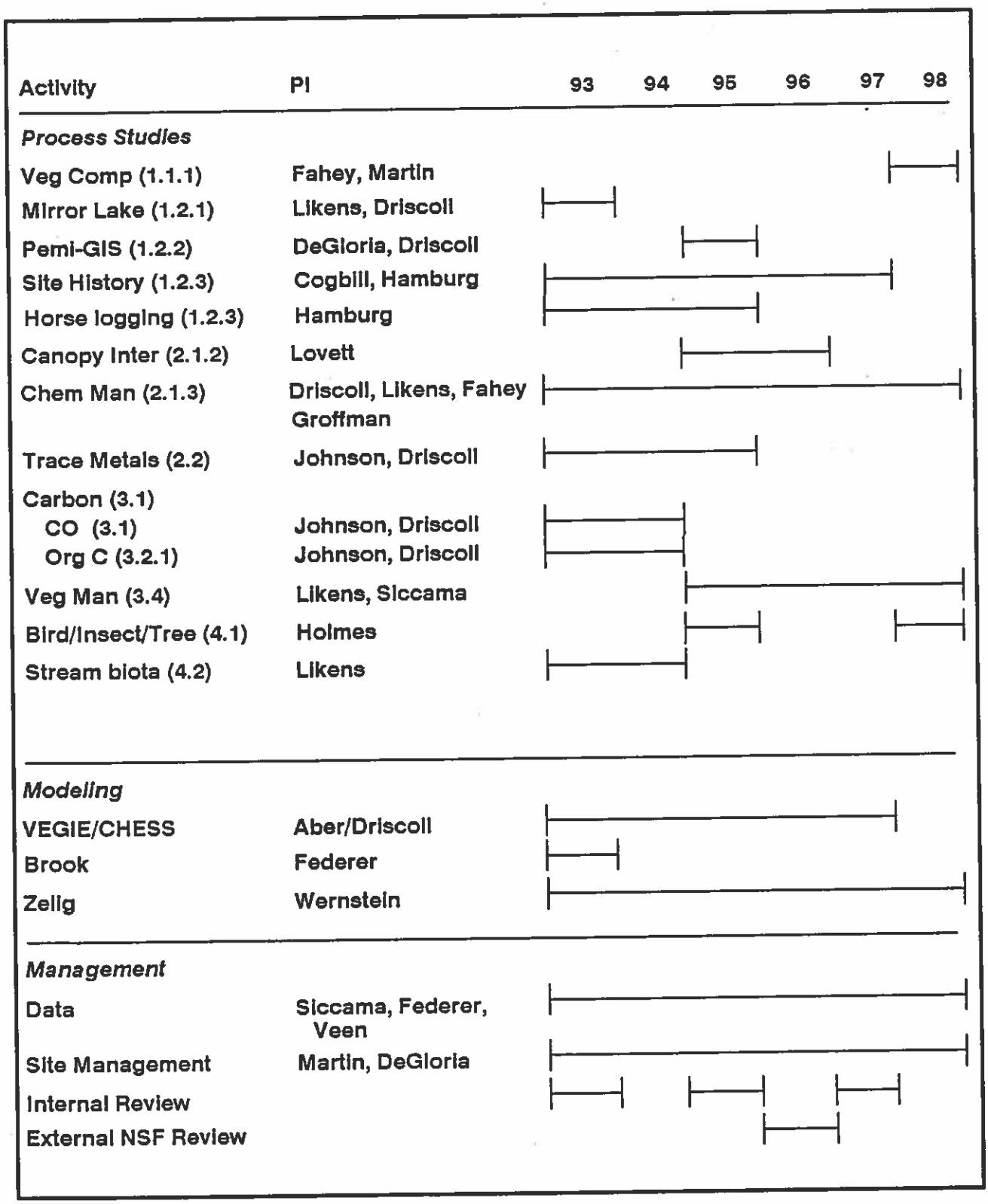
At HBR long-term experiments are a major research focus (Likens et al. 1977; Bormann & Likens 1979; Likens 1985; Likens 1992) and these activities are discussed throughout sections 1 and 2 of the HBR-LTER proposal. Our long-term experiments include our continued monitoring of manipulated watersheds (W2, W4, W5, W101; see Monitoring Programs) and the site of highway construction in the Mirror Lake watershed (ML-NE; section 1.2.1; Table 2). In addition, we consider our long-term studies of meteorology, hydrology, precipitation chemistry, soil solution, streamwater, lakewater, forest vegetation, forest floor, and bird and phytophagous insect populations to be long-term experiments (Table 1).

Long-Term Data Sets

Long-term data sets of the HBES are summarized in Table 1. A major accomplishment of the past 5 years is the systematic assembly of the long-term chemical data from the HBES. In 1990, the

FIGURE 27 (continued)

Time line continued.



USDA Forest Service completed a publication documenting techniques and results from 30 years of routine hydrometeorological studies at Hubbard Brook (Federer et al. 1990). These data were also loaded to "the Source of the Brook" (TSOB). In 1991, the precipitation and streamwater chemical data for HBES W6 from the period 1963 to 1980 were added to this public access system. In both these cases, considerable effort was expended to cross check all the original raw data using computer programs to identify outliers and missing values, to document all past methods and current techniques, and to uniformly process data to formats that can be used immediately by most investigators.

In addition, vegetation and soils data from periodic surveys on the manipulated and reference watersheds have been compiled and entered onto computer media, as well as long-term data on heterotroph population trends. Much of this information now is available on TSOB.

Data management

Efforts to develop and refine a data management system for the HBES have continued during the last 5 years. The four primary data management goals identified in our last proposal were: (1) to set policy for data requests from researchers within and outside the HBES; (2) to compile and review current and past long-term hydrometeorologic, chemical, and physical (soils and vegetation) data; (3) to create a uniformly-formatted computer storage and retrieval system for those data; (4) to provide a cataloged archival system and storage facility for physical samples of soil, water and vegetation.

Although there have been some unforeseen setbacks due to loss of key personnel, these basic goals have been met (Table 1). The Data Management Subcommittee (DMSC) of the SAC, consisting of D.C. Buso (IES), C.A. Federer (USDA Forest Service), T.G. Siccama (Yale Univ.), and the USDA Forest Service Data Management Specialist (C. Veen), as well as members from Cornell Univ. and Syracuse Univ. have met several times each year to address problems, priorities, and progress with respect to each task. All HBES cooperators have been advised of the existence, ongoing evolution, and importance of the HBES data management system in letters, brochures, and formal discussions at meetings. Appropriate data sets have been solicited from these cooperators, and in some cases funds have been allocated to assist HBES researchers in data compilation efforts.

Since 1987, striking changes have occurred in the processing of the raw data at all facilities. Considerable funds have been expended to purchase new computers, both stand-alone and network systems, so that data can be collated, checked, analyzed, and transferred as efficiently as possible. Each cooperator currently has responsibility for quality assurance of their own data sets.

As was expected, some changes in published values from previous HBES findings did occur in 1990-91. This underscores the importance of that massive review effort, and clearly demonstrates the need to retain data management in a priority position in the future. Because of this need, IES, Yale, Cornell, Syracuse, and the USDA Forest Service currently have personnel dedicated partly or full-time to HBES data management activities. Moreover, it will be necessary to continue to update computer equipment in the future to take advantage of changes in data management software, and to maintain the ever-larger databases more efficiently.

Synthesis and Modeling

Integration/synthesis of the HBR-LTER occurs through a number of activities including: 1) the development of synthesis volumes (Likens et al. 1973; Bormann & Likens 1979; Likens 1985; Likens 1992); 2) annual cooperator meetings; and 3) development and application of computer models (see Integration of Ecological Research). We are currently developing a synthesis volume on the W5 whole-tree clearcut experiment "Impact of a Whole-Tree Clearcut on a Northern Hardwood Ecosystem: Scientific Results and Management Implications." Modeling activities involving vegetation, hydrology, air-canopy interactions and biogeochemistry are used as research tools to facilitate project integration and hypothesis development/testing.

Intersite and Network Activities

A natural outgrowth of the long-term research activities at HBEF has been linkages with scientists at ecological research sites and institutions in the U.S. and around the world. The degree of interaction ranges from informal or formal advisory status to direct comparative experiments and surveys. Within the LTER program our most direct research ties have been, not surprisingly, with the other forest ecosystem sites, but we are expanding our linkages in the LTER network and consider the

stimulus towards intersite research to be one of the many positive aspects of our participation in the network.

Ongoing Activities. Currently, our most important inter-site comparative work is with the Luquillo EF LTER site in Puerto Rico. These projects have grown from the visualization that many parallels exist between watershed structure and function on the HBEF and Bisley (Luquillo EF) catchments. We are contrasting geochemical and vegetation ecological patterns and processes between these sites to develop a better understanding of the contrasting phenomena regulating ecosystem behavior in these differing forest environments. The first efforts along these lines have been to quantify soil pools at Bisley with the same methods as applied at HBEF, to compare soil chemical responses to block clearcutting (Bisley clearcut performed in summer 1989), to examine regeneration mechanisms and plant tissue chemistry following clearcutting, to compare the patterns of plant distribution along the similar topographic gradients from stream to ridgetop, and to expand the analysis of the distribution and cycling of Zn. We propose to continue these synthesis efforts in the coming years.

Our ongoing research on vegetation-soil-water modeling includes an international effort to compare and evaluate these models. John Aber (Harvard Forest LTER) and Charles Driscoll are participating in a series of workshops in which plant-soil-water models will be applied to databases from a few intensive study sites. This initiative is directed toward evaluating the application of these models to quantify critical loads of air pollutants to forest ecosystems. This initiative is funded by the Dutch Climate Program, the United Kingdom Department of the Environment and the U.S. Environmental Protection Agency. Phil Sollins (Andrews LTER) is participating in this initiative using the model Steadyql.

Together with D.L. Urban and H.H. Shugart, we are working actively on a comparative study applying a single forest growth simulator (ZELIG) to several forest sites, both LTER and non-LTER. We also propose to expand this effort to include the development of spatial connections among plots in these FORET-type models, and thereby improve their capacity to predict regional vegetation dynamics.

The HBR-LTER is participating in the LTER-wide inter-site decomposition experiment, and some personnel support for that effort will be provided by this proposed grant. We are also involved with inter-site comparisons on decay of coarse woody debris. An LTER cross-site comparison of fine root dynamics was not funded by NSF last year, but we hope to re-submit a revised version of this proposal. The HBES will continue to play a central role in several ecosystem monitoring networks, established and funded outside the LTER program, but including several LTER sites. These include National Atmospheric Deposition Program, the National Dry Deposition Network, the Global Precipitation Chemistry Project, the worldwide Cloudwater Project and the MAP3S program. Through these and a variety of other cooperative projects at both the national and international level, the HBES is making a continuing and concerted effort to foster the synthesis and integration of ecosystem-level research.

Related Research Projects

The HBES encompassed many researchers and research projects. Some of the major ongoing projects are summarized in Appendix V.

Archives and Inventories

In 1990, the USDA Forest Service built a physical storage facility at HBEF, designed to provide organized protection of the many samples of water, soil and vegetation taken for the HBES. The USDA Forest Service Data Management Specialist supervises this facility, the purpose of which is to preserve samples without degradation, and to allow access for reanalysis at a later date. The HBES DMSC has developed approaches and protocols used by this large project.

Samples of precipitation and streamwater (IES), vegetation (USDA Forest Service, Yale Univ.), and soils (Univ. of Pennsylvania) collected since the 1960's have been moved to this facility, and presently are undergoing cataloging and entry into a dBase-driven data base system that uses bar codes to identify each sample with complete background documentation (Table 1). Along with the HBES samples, a physical library of regional vegetation material, Jointly Accessible Research Samples (JARS), will be housed in this building. A library of HBES publications is maintained at the Pleasant View Farm Facility (see Appendix II).

Leadership, Management and Organization

The HBES has evolved during the past 29 yr from a relatively small project involving a handful of investigators to a large, complex one including with time over 100 principal investigators. In response to this complexity, we initiated a formal management structure to administer both the scientific program and associated facilities of the HBR forest.

Scientific Advisory Committee

The scientific management of the HBES is governed by the Scientific Advisory Committee (SAC). The SAC is advisory to the USDA Forest Service which has ultimate responsibility for the site. Under the direction of SAC are three standing committees -- LTER, Facilities and Data Management.

The agenda of the SAC consists of:

(1) **Reviewing proposals for research within the HBEF and giving advice on these proposals to the USDA Forest Service chair, who has the authority to decline or accept proposals.**

(2) **Integration of results and projects of the HBES; promoting integration of these results toward larger synthesis of forest ecosystem processes and suggestions for practical management.**

(3) **Education of undergraduate and graduate students and the public.**

The SAC is composed of six members, including a non-voting chairperson (who must be a USDA Forest Service employee, presently Dr. R.S. Pierce), and a non-voting Executive Director (presently Dr. J.J. Cole). The four voting members are senior researchers with a demonstrated long-term interest and participation in research at the HBEF. The chairperson is charged with calling meetings, calling votes and may cast a vote in the event of a tie. Additional members are added by majority vote. The SAC meets at least three times per year. The meetings occur once in early summer near the time of the Annual Cooperator's meeting, in late fall and in early spring.

Internal Advisory Committee

This committee (Chris Cronan, Ken Cummins, Jerry Franklin, and George Hornberger) will continue its important role in the HBR-LTER during the coming funding cycle. We plan to convene the Committee during years 1, 2, 4 and 6 of this funding cycle. Many of the recommendations of both

this Internal Advisory Committee and the NSF-appointed review team (D. Binkley, H. Gholz, P. Mulholland, J Sedell and E. Rykiel) have been incorporated into this proposal.

Transitions

Dr. F. Herbert Bormann, co-founder of the HBES, is close to retirement. He will continue as an active member of the SAC. Dr. R.S. Pierce, the USDA Forest Service Project Leader at Hubbard Brook for over two decades, will be stepping down this year. While he reduces his work share at the HBES, he will be guiding Dr. Chris Eagar, the new USDA Forest Service Project Leader at HBR, in his new responsibilities in the HBES. The SAC has, and will continue to work with the USDA Forest Service to make this transition as smooth as possible.

The Hubbard Brook Foundation

To assist with continuity of research at the HBES over the long term, we have begun to establish the Hubbard Brook Foundation. The responsibilities of the Foundation include (1) providing continuity for scientific leadership of the HBES; (2) raising, receiving and disbursing additional funds to support research and/or facilities of the HBES; (3) providing legal and financial advice; (4) maintaining physical facilities; and (5) providing and promoting public awareness of the research of the HBES. The structure of the Foundation has been drafted and presently is receiving legal scrutiny. During the timeframe of the research proposal here, the Foundation will form its first Board of Directors and begin to operate.

Site and Facilities Management

Facilities Management: Cornell, Yale, IES and NSF have made sizeable investments in purchasing and renovating dormitory facilities and in building a new laboratory as a part of the Pleasant View Farm complex (see Appendix II). These facilities now provide living space with a permanent, high-quality laboratory. Additionally, the Trust for Public Land, with the assistance of the Mary Flagler Cary Charitable Trust and the USDA Forest Service, has purchased an 8-ha tract of land surrounding a portion of Mirror Lake, which includes six cabins. This tract, in addition to preserving part of Mirror Lake, provides housing for up to 12 HBES researchers. The management and operation of these facilities is the responsibility of IES and the Facilities Committee (see above).

Site Management: The HBES operates in the HBEF with the understanding and cooperation of the USDA Forest Service. Coordination is provided by Dr. R.S. Pierce (the Site Coordinator) and C.W. Martin (the Site Manager) for the USDA Forest Service and by Dr. J.J. Cole (Executive Director) for the HBES. The responsibilities of this group are to integrate new projects during their planning stage, to coordinate the various activities within the HBEF, and to promote communication. Dr. Pierce provides liaison between this group and the SAC.

New Projects and Technologies

Geographic Information Systems

The Hubbard Brook Geographic Information System (HBGIS) is a shared computing resource for the HBES. The system was purchased with funds from an LTER technology supplement and is located in the USDA Forest Service headquarters building at the HBEF (Fig. 28).

The purpose of the HBGIS is to help researchers and site managers to manage and analyze spatially distributed environmental data relevant to HBR. An automated site management information system is also being developed which integrates historical and on-going field experiments with the relational descriptive information.

Over the past year, we have developed a digital version of the HBR base map with nested management compartments linked to a relational database management system. The location and characteristics of significant ecological and cultural boundaries, streams, roads, weather stations, data collection transects and plots, land treatments, weirs, and research areas are being encoded for use in the site management.

Global Positioning Systems

We are working with site managers to improve the precision of planimetric control at the HBEF. The HBR basemap does not have adequate control points to geo-reference environmental databases.

We propose to conduct a GPS-based land survey of new and established benchmarks and permanent data collection systems at the HBEF. The objectives of the survey will be to: (1) improve the positional accuracy of basemaps at the HBEF; (2) provide accurate three-dimensional positions of

permanent data collections systems (e.g. weirs, plots); (3) test the precision of both field-portable and survey-grade GPS instruments.

A series of permanent benchmarks will be installed to augment the existing network established by the USGS. We plan to install additional benchmarks and resurvey existing benchmarks in selected locations within the HBEF.

The field survey activities will be conducted during May 1992, including selecting benchmark locations, installing monuments, recording position coordinates, data processing and map generation. This field survey will be conducted based on previous experience as well as information and training received at the LTER-wide GPS workshop held during October 1991.

We expect this project to result in (1) a digital watershed-wide basemap with improved positional accuracy, (2) a network of benchmarks from which traditional and GPS land surveys can be based, and (3) a set of robust control points to geo-reference environmental data within the HBEF site management information system.

Dissemination of Information

Considerable effort is made to disseminate information and data from the HBES. This past year Publications of the Hubbard Brook Ecosystem Study was updated (Likens 1991). This document summarizes all of the publications of the HBES, over 1000 listings, and is available to anyone for the asking. Within Publications of the Hubbard Brook Ecosystem Study is information on how to order any of the reprints available from the HBES. In addition, this past year we developed The Hubbard Brook Ecosystem Study: Site Description and Research Activities. This guidebook is a brief summary of the HBES. Both the guidebook and publication list are distributed to people who visit the HBEF.

The policy for acquisition of HBES data has been designed to allow for relatively rapid sharing of recent data within the HBES research group, careful verification and documentation of public-access data sets, and timely consideration of individual requests for data from outside the HBES. Within the HBES, researchers may request in writing any up-to-date data necessary to their studies. Data managers for individual PIs coordinate these internal requests, and attempt to provide colleagues with last minute corrections and/or additions. Requests made external to the HBES group

are routed to each PI for specific permission to release. It is anticipated that as more data are available on the computerized public bulletin board, "The Source of the Brook" (TSOB) most inquiries and requests from non-HBES researchers will be processed through electronic mail and the bulletin board medium.

Supplemental Support

To date, NSF Technology Supplements to the HBR-LTER have contributed to four related activites, (1) initial establishment of the HBR-GIS at Cornell University, (2) expansion of the HBR-GIS to the field site at HBEF, (3) research activities on spatial dynamics of vegetation, trace gas emissions, and soil temperature in the Hubbard Brook Valley, and (4) contributions to application of the Global Positioning System (GPS). The first two activities are essentially complete and both stations of the HBR-GIS are very active in data management, meeting mapping needs and participating in spatially-explicit research. The research activities are partially completed, and two manuscripts have been developed (Mou et al., submitted; Yavitt and Fahey, in press). The studies of soil temperature are still in progress with completion planned for this year. No funds are requested for this activity. Continued testing of the GPS also is planned for 1992.

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APPENDIX II: SITE DESCRIPTION

The Hubbard Brook Experimental Forest (HBEF) in the White Mountains of central NH is administered by the USDA Forest Service. The site is a 3,160-ha forested area, with a series of experimental watershed ecosystems. Soils at the site are acidic, well-drained Spodosols (Haplorthods), with a well-developed and well-drained surface organic layer (3-15 cm). Soils are shallow at high elevations and increase in depth with decreasing elevation (Likens et al. 1977; Lawrence et al. 1986). The Hubbard Brook Valley has variable depths of glacial till and metamorphic rock of igneous and sedimentary origin (schists and quartz monzonite; Likens et al. 1977; Johnson et al. 1981).

Climate at the HBEF is cool-temperate, humid-continental with mean July and January temperatures of 19°C and -9°C, respectively (at 450 m elevation). Mean annual precipitation for the biogeochemical reference Watershed 6 (W6) is approximately 1390 mm (SD = 188), with 25-33% of the total occurring as snow (Federer et al. 1990). Mean annual streamflow from W6 is 869 mm (SD = 175).

Northern hardwood forest covers the HBEF, with American beech (Fagus grandifolia Ehrh.), yellow birch (Betula alleghaniensis Britt.) and sugar maple (Acer saccharum Marsh.) dominating from 500-730 m. Red spruce (Picea rubens Sarg.) and balsam fir (Abies balsamea (L.) Mill) largely dominate at elevations above 730 m. The HBEF was logged between 1909-1917, and there is no evidence of recent fire (Bormann et al. 1970; Whittaker et al. 1974; Bormann & Likens 1979; Davis et al. 1985). Forest biomass has been monitored at the HBEF since 1965. Initially, the forest showed significant rates of biomass accumulation and associated element uptake (5.8 ton/ha-yr; 1965-1977; Likens et al. 1977; Bormann & Likens 1979; Whittaker et al. 1979). However, in recent years forest growth has declined to almost zero (0.2 ton/ha-yr; 1982-1987).

APPENDIX III: METHODS

Solution Chemistry

1. Analyses performed by atomic absorption spectroscopy (AAS):
   Ca, Mg, K, Na - Flame atomization.
   Al, Sr - Graphite furnace atomization.

2. Analysis performed by ion exchange chromatography:
   NO_3^-, SO_4^{2-}, Cl^-.

3. Analysis performed by autoanalyzer

   NH_4^+ - A green colored compound, closely related to indophenol, occurs when ammonium salt is added to sodium phenoxide followed by the addition of sodium hypochlorite. Potassium sodium tartrate is added to the sample stream to eliminate the precipitation of metal hydroxides.

   PO_4^{3-} - Formation of a phosphomolybdenum blue complex. Uses a single reagent solution consisting of acidified solution of ammonium molybdate containing ascorbic acid and a small amount of antimony.

   SiO_2 - Reduction of a silicomolybdate complex in acidic solution to "heteropoly blue" by aminonaphtholsulfonic acid. Oxalic acid is introduced before addition of ANSA to eliminate interference from phosphate.

Organic N - Alkaline persulfate oxidation with detection of NO_3^- by hydrazine reduction. This procedure has been calibrated with the method of Suzuki and co-workers (Suzuki et al. 1985; Sugimura and Suzuki 1988).

4. Analysis performed by IR spectroscopy

   Dissolved organic carbon (DOC) - Solutions are filtered with a glass fiber filter, acidified and purged of any dissolved inorganic carbon by He. Organic carbon is oxidized by persulfate enhanced UV oxidation. Detection of CO_2 is made by IR spectroscopy.

   Dissolved inorganic carbon (DIC) - Solutions are filtered, acidified and detection of CO_2 is made by IR spectroscopy.

5. Potentiometric analysis

   pH - glass electrode.

   Acid Neutralizing Capacity (ANC) - strong acid titration and Gran plot analysis.

   F^- - Fluoride ion selective electrode.

Field Methods

1. Tension free lysimeters - 10 cm diameter, quartz-sand or teflon chip filled collectors. Triplicate sets (below Oa, Bh and Bs2 horizons) are at three elevations in each watershed.

2. Throughfall collectors - 15 cm diameter funnels with fine mesh nylon screening to remove particulate matter.

3. Soil bags - to monitor changes in soil parameters, 500 kg of mineral soil has been excavated from the HBEF, screened (2 mm) and homogenized. One hundred gram aliquots of soil were placed in 0.25 mm mesh Nitex bags (15 x 15 cm), marked and inserted in the upper mineral soil. Soil bags are retrieved over selected intervals and monitored for soil parameters.

Soil Chemical Methods

1. Soil pH - 1:1 soil:water ratio; 1:1 soil:0.01 M $CaCl_2$ ratio, with glass electrode.

2. Ion Exchange Components

   Cation exchange capacity - 1N NH_4Cl/KCl extraction.

   Exchangeable acidity - 1N KCl extraction, NaOH titration.

   Exchangeable cations - Extraction with 1N NH_4Cl, measurement of Ca, Mg, Na, K, Al by AAS.

   Exchangeable anions (SO_4^{2-}, Cl^-) - Extraction with 0.016 M NaH_2PO_4 and measurement by IC.

3. Free Fe, Al and Si

Pyrophosphate extractable - Extraction with 0.1 M sodium pyrophosphate (approximates organic fraction).

NH_4 - Oxalate extractable - Extraction with 0.2 M ammonium oxalate (subtraction of pyrophosphate extractable fraction approximates amorphous fraction).

Dithionite extractable - Extraction with citrate - dithionate - bicarbonate (substraction of NH_4 - oxalate extractable fraction approximates crystalline fraction).

Allophane/imogolite - An acid oxalate extraction will be used to estimate the content of allophane/imogolite in Hubbard Brook Spodosols. If the presence of allophane/imogolite is indicated by oxalate extraction, it will be verified by electron microscopy and infrared spectroscopy.

4. Sulfur fractions

Soluble SO_4 - Deionized water extractable SO_4, 1:10 soil:solution ratio.
Absorbed SO_4 - 0.016 M NaH_2PO_4 extract, 1:10 soil:solution ratio

Sulfide - HCl digestion

Inorganic non-SO_4 S - Zn/HCl reduction

Ester SO_4 - HI reduction less inorganic S fractions

C-bonded S - Total S by wet oxidation minus HI reducible

5. Organic C

Total carbon - Dry combustion train (CHN analyzer).

Humic and fulvic acids - Extraction with 0.1 M sodium pyrophosphate (from free Fe, Al procedure), precipitation of humic acids with H_2SO_4, measurement of DOC.

6. Total N - Dry combustion train (CHN analyzer).

Soil Physical Methods

1. Grain size analysis - wet sieve, dry sieve and hydrometer techniques.

2. Permeability - estimated from grain size distribution.

Nitrogen Cycle Measurements

The N cycling portion of the proposed Chemical Manipulation study (section 2.1.4) will be supported primarily by this HRB-LTER project. Thus, we describe in detail the N cycling methods in the following section.

Natural ^{15}N abundance survey and microplot soil sampling. Large and small scale spatial variability in the abundance of ^{15}N in soil and plants arises as a result of natural $^{15}N/^{14}N$ fractionation mechanisms (e.g., nitrification, denitrification, etc.) and soil mixing processes. To provide a detailed background framework in which to interpret short- and long-term responses of ecosystem N pools and fluxes using the watershed ^{15}N tracer, we require information on ^{15}N natural abundance in soils and vegetation collected across the complex landscape of W1 and within intensively sampled microplots. Soils, plant tissues (foliage, fine roots, woody) and litterfall will be collected in the summer prior to watershed treatment from each of three elevation zones and four landscape positions within each zone (ridgetop, mid-slope, toe slope and alluvial). Twenty soil samples (5 cm diameter) will be collected within each stratum, and samples will be separated by genetic horizons (Oi, Oe, Oa, E, Bh, Bs) and analyzed for total C and N and $^{15}N/^{14}N$ ratio. Foliage, litterfall, fine roots and woody plant tissues (wood, bark, twigs) will be collected for each of the dominant species (beech, sugar maple, yellow birch), with standardization of sampling time and position on trees. Six samples of each tissue type will be pooled for each of the 12 strata for ^{15}N determinations. Finally, pretreatment sampling of soil solutions, groundwater and streams also will be carried out during summer 1992 to characterize $^{15}N/^{14}N$ ratios.

Detection and recovery of the low ^{15}N enrichment tracer will be facilitated by paired microplot sampling to be carried out within the detailed sampling plots on W1. In conjunction with the ^{15}N natural abundance survey, an array of paired sampling points will be established in each of the sampling strata (twenty pairs per plot). Following ^{15}N addition, four of the paired samples will be collected on each sampling data (see Table 6), and changes in ^{15}N abundance will be quantified by comparison with the values obtained in the earlier natural abundance survey. We will also measure changes in ^{15}N abundance of samples incubated in soil bags. Together, these techniques should allow us to track the short- and long-term patterns of $^{15}NO_3$ retention in soil and vegetation pools at the beginning (year 1) and end (year 5) of the chemical manipulation.

Microbial biomass and active soil nitrogen (ASN). Two complementary approaches will be used to quantify changes in microbially-active soil N pools. Microbial biomass C and N will be measured using the chloroform fumigation and incubation/extraction techniques (Jenkinson and Powlson 1976). Following chloroform fumigation, CO_2 evolution from incubated samples will be measured directly by gas chromatography. Soil extracts of fumigated samples will be digested by a Kjeldahl method and total N and ^{15}N determined as described below. Corrections for N and C recovery from microbial biomass will be applied (Voroney and Paul 1984).

The pool of soil N which participates in short-term biological cycling will be quantified using a ^{15}N technique (Duxbury et al. 1991). A known quantity of ^{15}N-enriched NH_4 is injected into the soil N cycle, and microbial cycling is stimulated until the ^{15}N is isotopically mixed with the ASN pool. Measurement of the inorganic ^{15}N pool after KCl extraction allows calculation of the ASN pool. The ASN assay will be employed in conjunction with measurement of microbial biomass C, N and ^{15}N to characterize the responses these important "fast" N pools to the chemical perturbation.

Enzyme activities. Although the activities of specific enzymes involved in N transformations respond to short-term changes in the soil environment, they show less variation than actual microbial process rates (Groffman 1987). We will the activity of nitrification and denitrification enzymes. Nitrification enzyme activity will be measured by a short-term incubation technique described by Schmidt and Belser (1982). An anaerobic assay of denitrification enzyme activity will be employed following the procedures of Smith and Tiedje (1979).

^{15}N microinjection tracer experiments. To examine in detail the short-term fate of added NO_3 and long-term trends in the processing of N, we propose small-scale and short-term studies using highly-enriched $^{15}NO_3$ on field plots in the treated and control watersheds. We will employ a microinjection technique in which 99% atom enriched $^{15}NO_3$ is injected uniformly through an intact soil profile (i.e. *in situ*) and the movement of this tracer pulse to various pools is measured via destructive harvest after a brief period of incubation (Schimel and Firestone 1989). Recovery of ^{15}N will be measured for fine roots, soil organic matter, microbial biomass and extractable pools. We propose to perform ^{15}N tracer experiments in the intensive study plots on treated and control watersheds at three times (late spring, mid-summer, fall) during three years of the chemical perturbation (yr 1, 3 and 5). Two random plots will be treated within each of the six intensive research plots on W1 and the control forest. To minimize convective transport in soil and plant, the tracer solutions will be added at night and samples will be collected 6-8 h later at dawn. We have observed very high recovery of added ^{15}N (over 90%) and significant responses of root and microbial NO_3 assimilation in field experiments with this technique under high and low NO_3 loading to red spruce ecosystems.

Soil cores from the treated plots will be returned to the laboratory for subsampling, oven drying, and extractions. For each sample we will measure ^{15}N content of four classes of roots (very fine, fine, large and moribund), extractable NO_3, soil organic matter and microbial biomass, using techniques described below. These measurements of short-term kinetics of NO_3 utilization will complement the long-term estimates derived from watershed-wide ^{15}N addition and pool size determinations.

Gaseous fluxes rate and nitrification potential. On six sampling dates in each year we will collect 12 random soil cores from each of 8 sampling sites (outside intensive plots) chosen to represent the range of slope position and elevation in the treated and control watersheds (including riparian zones). The cores will be returned to the laboratory and incubated at *in situ* temperatures to measure gas production rates. Six cores will be treated with acetylene and N_2O production will be measured to quantify denitrification rates. The other six cores will be unamended and production of CO_2, CH_4 and N_2O will be measured. These unamended cores will then be incubated at *in situ* temperatures for 10 days to measure potential N mineralization and nitrification. Sample times will include a mid-winter and early spring dates because many microbial processes are significant at low temperatures beneath snow cover.

Gas fluxes between soil and the ambient atmosphere also will be estimated by measuring the time-series change in concentration within the headspace of open-bottom boxes constructed of welded aluminum. The boxes (10-cm tall and covering 0.082 m^2) will be inserted to a 1-cm soil depth. Plastic syringes (30-mL volume with an attached needle) will be used for sampling gases at 5 to 20-min intervals during a 20 to 60-min deployment. The sampling syringes also serve as storage vessels until analyses can be conducted within 24 h of collection. Field gas fluxes will be measured at five random locations within each of the 6 plots in the control and treated watersheds on at least 6 dates.

Denitrification in streams and hyporheic zone. The large observed difference in NO_3 concentration between subsoil solutions and streams at HBEF suggests either significant NO_3 losses via denitrification or NO_3 assimilation by stream biota. Direct measurement of denitrification has proven to be difficult. We propose to utilize the large $^{15}N/^{14}N$ fractionation that accompanies denitrification as indirect evidence for streambed and hyporheic zone denitrification. By comparing the magnitude of ^{15}N enrichment along the pathway from soil to riparian zone groundwater to stream in both the treated and control sites, we will provide indirect evidence to help substantiate budgetary estimates based upon fluxes at various locations in the watershed (i.e. upland soils, variable-source areas, and longitudinal stream sampling). To avoid obvious problems associated with the whole watershed ^{15}N tracer, these measurements will be carried out in W1 in the pretreatment year and in the 5th year of treatment, when the signal from the first-year ^{15}N treatment is expected to be gone.

Determination of ^{15}N in soils, tissues and solutions. All measurements of $^{15}N/^{14}N$ ratios for samples collected in this proposed study will be analyzed under the supervision of J. Duxbury in facilities supported by an NSF Research Instrumentation award. The Europa ANC-MS system in our laboratories consists of a Dumas/combustion C-N elemental analyzer coupled via a capillary interface to a triple collector mass spectrometer. Detailed controlled measurements on soil and tissue standards indicates a precision of $\pm$ 1 per mil for our current applications of this instrumentation. After thorough mixing and milling through a 30-mesh screen, samples are powdered in a micro-ball mill and carefully weighed into sampling cups. Duplicate samples and standards are included in every measurement run.

To quantify the $^{15}NO_3$ in soil solution, groundwater and surface water samples, the samples must be processed to extract and reduce the NO_3 from solution. Over the past year we have been exploring two approaches for this purpose and both appear promising: use of anion exchange resins followed by NO_3 reduction and distillation (Valenske 1989) and a diffusion technique (Adamson and Reader 1983, MacKown et al. 1987). The former technique will be used for soil solutions and surface waters and the latter for soil extracts.

High volume water samples (2-10L) will be filtered through 0.45 um glass fiber filters and the filters composited by sample type to obtain sufficient material for determination of ^{15}N in particulates by the standard combustion technique. The filtrate will be passed through Dowex anion exchange resin in columns to quantitatively extract NO_3. The adsorbed NO_3 will be extracted from the resin with dilute HCl and reduced to NH_4 using Devardas' alloy. The distillation procedure of Valenske (1989) will be used to prepare samples for combustion analysis. This procedure has been used successfully to quantify $^{15}NO_3$ in streamwaters and potential problems with deammination from exchange resins has been discounted on the basis of NO_3 standards with known ^{15}N values (P. Mulholland, personal communication).

Soil extracts will be prepared by a diffusion technique. Extraction solutions will be placed in flasks with threaded lids. For $^{15}NO_3$ analysis, Devardas' alloy will be added to reduce NO_3 to NH_4 and the extracts will be made basic by adding 13N NaOH. A vial containing 2 mL of 0.05N H_2SO_4 will be placed in the flasks and the sealed flasks heated to 75°C for 48 h. After cooling, the vials will be removed and the acid will be evaporated to dryness in a forced-air heating system.

APPENDIX IV: EXISTING FACILITIES AND EQUIPMENT

Because of the multidisciplinary nature of the proposed research, we plan to draw upon the resources of several institutions. These principal investigators have collaborated successfully on previous research projects.

A. Institute of Ecosystem Studies

The Institute of Ecosystem Studies (IES) is located at the Mary Flagler Cary Arboretum (MFCA), an 800-ha tract of land west of the village of Millbrook, New York. In addition, the Tompkins Farm, acquired in late 1989, is a 34-ha parcel located in the towns of Pleasant Valley and Clinton near Salt Point, New York (approximately 11.3 km from the Arboretum). The Institute is a division of The New York Botanical Garden. The Plant Science Building at the MFCA currently has 3350-m^2 of floor area containing nine research laboratories, a library (8000 volumes and about 300 journals), scientific staff offices, classroom, herbarium, administrative and business offices. In addition, there are 24 other buildings on the Arboretum grounds used for maintenance, administration, housing for students and staff, carpentry and a 1370-m^2 greenhouse with adjacent cold storage facility, a lath house, storage buildings, and irrigated nursery grounds. A new rearing facility offers a Model TB-500 Grieve truck oven for drying of plant materials, Prescott Pierson walk-in refrigeration and environmental chambers, a plant growth room, animal rearing facility, and laboratory area. Dormitory facilities are available to

house students while in residence at IES. Data on ambient air quality, air temperature, relative humidity, total incoming solar radiation, indirect solar radiation, net solar radiation, and precipitation amount are collected continuously at an environmental monitoring station on the property. In addition, samples of precipitation are collected from this station for chemical analysis.

Three small boats are available for use on local lakes and the Hudson River as well as several vehicles for transport to and from the field. Analytical facilities at the Institute are state-of-the-art and make possible a wide variety of new as well as ongoing research programs. Instrumentation includes a Varian 6000 gas chromatograph with autosampler equipped with TCD, FID, and N-P TSD detectors; Varian 6500 satellite gas chromatograph; Varian 5500 ternary gradient liquid chromatograph (UV-visible) with autosampler, Pharmacia fraction collector and Kratos fluorescence detector; Varian 402 chromatography data system; Tekmar liquid sample concentrator; Shimadzu model GC-8 gas chromatograph with thermal conductivity detector; Perkin-Elmer 2380 atomic absorption spectrophotometer; Perkin-Elmer 6000 inductively coupled plasma emission spectrophotometer with graphite furnace, autosampler, and a model 7500 data station; Carlo-Erba NA 1500 CNS analyzer; two Dionex ion chromatographs; two high-quality UV-visible PE 332 dual-beam spectrophotometers; two Technicon autoanalyzers; Turner Designs fluorometer; Shimadzu UV 160 gas analyzer for determination of dissolved and particulate carbon; Astro TOC analyzer; leaf area meter; optical microscopes; inverted microscope; fluorescence microscopes; glove box; Olympus image analyzer; Beckman scintillation counter; ultra centrifuge; drying ovens; rotary evaporators; incubators; walk-in cold room; ultra-low freezer; muffle furnace; soil processing equipment; field sampling equipment; electronic balances (including microbalance); pH meters and electrical conductivity meters. Computers include a Digital Equipment Corporation Micro VAX II, numerous IBM compatible microcomputers, three Macintosh SE/30's, and direct access through four terminals to an IBM 3090-200E mainframe computer.

A field laboratory at the MFCA includes a necropsy facility for animal examination. A variety of animal capturing and tagging equipment are available as well as a 36-channel external/internal telemetry system, a Clay-Adams Blood Chemistry Accustat (modular) and freezing microtomes.

IES owns and operates a regional precipitation chemistry site located 15 km southwest of Ithaca, New York (42•24' lat., 76•39' long.), at an elevation of 503 m above sea level. The site is a 5.6-ha tract of land surrounded by deciduous forest, pasture, and old field, with no local major pollution sources nearby. The site is used for continuous monitoring of regional-scale precipitation chemistry (since 1977), and is part of a national dry deposition network (NDDN). Data collection at the site includes precipitation amount and chemistry, continuous ozone, wind speed, wind direction, temperature at 2 and 10 m above ground, relative humidity, solar radiation, visibility, and weekly concentrations of SO_2, particulate SO_4, NO_3, and nitric acid vapor. There is a small climate-controlled shelter supplied with electric and telephone connections, and data acquisition equipment.

B. Syracuse University

The Department of Civil and Environmental Engineering currently has 1,400 m^2 of laboratory space for research and analytical chemistry. These facilities include three constant temperature rooms, two analytical equipment rooms and a soil chemistry laboratory. The analytical and research equipment available to students and faculty include: two atomic absorption spectrophotometers with graphite furnaces, automatic samplers, and deuterium background correctors; a gas partitioner; an ampoulator; three autoanalyzers; a gas chromatograph with electron capture, thermal conductivity and flame ionization detectors; two visible-ultraviolet scanning spectrophotometers; an infrared spectrophotometer; a dissolved carbon analyzer; a solid carbon/nitrogen analyzer; an ion chromatograph with automatic sampler and microcomputer interface; an automated pH/ion selective electrode measurement unit; two automatic titrators; two fluorometers; a particle counter and microelectrophoresis unit; and extensive equipment for wet chemical determinations.

Field equipment includes a snowmobile; field pH, dissolved oxygen and specific conductance meters; a fluorometer; sequential water samplers; data loggers; and a stream velocity meter.

C. Cornell University

Fully-equipped chemical laboratories are available in the Department of Natural Resources at Cornell University. Instrumentation includes four gas chromatographs, continuous flow analyzer with automated data analysis system, carbon analyzer, atomic absorption spectrophotometer and automatic titrator. An analytical laboratory in the Department of Pomology is equipped with an inductively-coupled argon plasma spectrophotometer. An NSF-funded laboratory in the Department of Soil, Crop and Atmospheric Sciences (SCAS) is available to this project for analysis of C and N stable isotopes. The Europa ANC-MS system consists of a Dumas combustion C-N elemental analyzer coupled via a capillary interface to a triple collector mass spectrometer. Also in SCAS is the Cornell Laboratory for Environmental Applications of Remote Sensing where the HBG GIS is based. Finally, the Cornell

National Supercomputer Facility is available for simulation modeling in the HBR-LTER through existing cooperative agreements as a strategic user.

D. Yale University

Yale School of Forestry and Environmental Studies has approximately 3,250 m^2 of research, classroom and office space in Greeley Memorial Laboratory, Marsh Hall and Sage Hall. Two laboratories in Sage Hall have been converted for wildlife work. The School has 353 m^2 of greenhouse space and eight walk-in controlled environment rooms. Four of these may be programmed for control of light, temperature and humidity. In addition to the usual laboratory equipment, the School owns a Parr bomb calorimeter, several cabinet environmental growth chambers, a Tractor Model MT150-G gas chromagraph with an electron capture detector, a Perkin-Elmer atomic absorption spectrophotometer, a Shimadzu Model GC-8 gas chromatograph with a thermal conductivity detector and a photosynthesis laboratory. Two fully-equipped laboratories are dedicated to soil and soil biology research.

Computing facilities include several terminals that provide access to IBM 3083, IBM 4341 and VAX 8600 mainframe computers maintained by the Yale Computer Center (YCC). In addition, there are more than a dozen IBM and Apple microcomputers at the Greeley Laboratory for general research use. Also, there is an Apple II+ equipped with dual disk drives and an Adalab A/D converter that is dedicated to gas chromatograph data acquisition and analysis.

Additional laboratory facilities are available in Kline Biology Tower, Kline Biology Laboratory, Peabody Museum of Natural History, Bingham Oceanographic Laboratory, the Ornithological Laboratory and the Eaton Herbarium located in Osborn Memorial Laboratory. There is also a genetic garden located at Union, CT. Yale University has excellent library strength in biology, forest science, ecology and other subjects related to the structure and function of ecosystems.

E. USDA Forest Service at Hubbard Brook

The Hubbard Brook Experimental Forest consists of the 3076-ha Hubbard Brook watershed in the Pemigewasset District of the White Mountain National Forest. There are 16 km of gravel roads within the Experimental Forest maintained by the White Mountain National Forest. Except for entry to the field laboratory storage area, snow is not removed from these roads in winter. Travel into the Forest in winter is either on foot with snowshoes and/or skiis or by motorized over-snow vehicles. The Forest Service has two snowmobiles for such use and the HBES has two others. A trail system allows access to major research installations such as precipitation stations. A class-A weather station, 22 additional weather stations and nine gauged watersheds are distributed throughout the Experimental

Forest. Generally these precipitation stations are located at lower, middle and upper elevations in the Experimental Watersheds and have a density of about one station per 13 ha. Snow depth and water content are measured each winter at four locations on south-facing and three on north-facing slopes.

The Forest Service operates a year-round field laboratory and office building at the HBEF. This building provides 334-m^2 of space, including four offices, one laboratory, one conference room, four dormitory rooms, a kitchen, bath and shower. In addition, there are 280-m^2 of maintenance, storage, garage and shop facilities.

F. Pleasant View Farm Facility

A field research facility is operated jointly by IES, Yale and Cornell Universities, at the HBEF in West Thornton, NH. With the help of an NSF facilities grant, the Pleasant View farmhouse was completely renovated into an attractive dormitory building that houses 14-16 persons. In addition, a 2-bay garage and the 200-m^2 Henrietta Kendall Towers Laboratory facility were constructed adjacent to the renovated farmhouse to provide research space for personnel on a year-round basis. This housing and laboratory facility is very convenient for researchers, being only 0.5 km from Mirror Lake and 1.6 km from the HBEF. Equipment at the site includes a Perkin-Elmer atomic absorption spectrophotometer, Technicon autoanalyzers, UV-visible spectrophotometer, fluorescence microscope, Packard scintillation counter, Shimadzu gas chromatograph, pH meters, distillation and deionizing equipment, a muffle furnace, drying ovens, microcomputers, refrigerator and freezer. Two small boats, diving equipment, a portable generator, and two snowmobiles are also available.

APPENDIX V. COOPERATIVE STUDIES

A. Long-Term Biogeochemical Studies - The project "Hydrologic-nutrient cycle interactions in small undisturbed and human-manipulated ecosystems" has been funded by NSF for 29 years and represents the HBES "core" project. The principal investigators are G.E. Likens, F.B. Bormann and C.T. Driscoll. This investigation initiated and currently includes many of our long-term biogeochemical and ecological studies. For example, much of the funding (60%) for our long-term precipitation and stream chemistry record is obtained through this project. The "core" study is also responsible for the integration and synthesis of the HBES (Likens et al. 1977; Bormann and Likens 1979; Likens 1985, 1992), the compilation and distribution of "Publications of the Hubbard Brook Ecosystem Study" (Likens 1991), the organization of the annual cooperators' meeting and the maintenance of Pleasant View Farm facility (see Appendix IV).

B. Atmospheric Deposition Monitoring Programs - During the past 14 years, the HBES has been part of two national networks that were established to measure the spatial and temporal trends in the deposition of chemical elements in precipitation and dry matter. These are the National Atmospheric Deposition Program (NADP)/National Trends Network (NTN) and the Multi-State Atmospheric Power Production Pollution Study (MAP3S). Through the USDA Forest Service and IES, the HBES has participated in the NADP since its initiation in July 1978. In addition, we have participated throughout the 14-yr history of the MAP3S program through cooperative funding from the DOE, EPA and NOAA.

C. NDDN - A National Dry Deposition Network site is being operated at the HBEF in cooperation with the U.S. Environmental Protection Agency (EPA). Basic meteorological parameters are being measured as well as atmospheric concentrations of ozone, S and N-containing particles, SO_2 and HNO_3. Funding is provided by EPA and NSF.

D. Long-Term Precipitation Chemistry - To broaden the scale of our studies of precipitation chemistry, we are comparing the HBEF data to similar records of bulk precipitation in Sweden, The Netherlands, various locations in North America and remote sites in the Southern Hemisphere. This

comparison, conducted in cooperation with scientists at the Univ. of Stockholm and elsewhere, allows us to use various long-term records of precipitation chemistry to explore several fundamental questions about the regulation of major ions in precipitation. Funding is provided by the A.W. Mellon Foundation and NOAA.

E. Dynamics of Bird, Small Mammals and Insect Populations in the HBEF - The structure, productivity and bioenergetics of several important components of the animal communities of the HBEF have been under intensive investigation since 1969. These studies, which are largely concerned with birds, mammals and insects, are integrated with the larger program of ecosystem research at Hubbard Brook, but are funded separately by the NSF through grants to Dr. R.T. Holmes and colleagues at Dartmouth College.

F. Cooperative Studies Related to Whole-Tree Harvest of Watershed 5 - Several outside investigators are involved in the whole-tree harvest experiment of Watershed 5 (W5) at the HBEF. Researchers use both the experimental manipulation itself and our baseline measurements of chemical inputs and outputs. The effects of the whole-tree harvest on the reorganization of nutrient pools within the ecosystem is being studied by Drs. A.H. Johnson (Univ. Pennsylvania), T.G. Siccama (Yale Univ.), T. Fahey (Cornell Univ.), and D. Ryan (Univ. Pennsylvania). The objective of this study is to investigate changes in nutrient sources and sinks in the soil, soil solution and vegetation following disturbance by whole-tree harvest. Funding has been provided by the NSF.

G. Weathering Studies - Studies are underway with collaborators to determine the mechanisms and rates of weathering in two base-poor forest watersheds in New Hampshire. The project is designed to study weathering on the scale of individual minerals, the soil profile and the watershed. Several methods of estimating weathering rates will be used and compared, including geochemical mass balances, mineral depletion estimates, watershed element balances and Sr isotope analysis. Funding is provided by the NSF.

H. Organic Debris Dams - Long-term monitoring of organic debris dams is being done in several streams of the HBEF following watershed disturbance. Factors influencing the origin and maintenance of these dams are being studied. Funding is provided by the A.W. Mellon Foundation.

I. Response of Early Successional Northern Hardwoods to Changes in Resource Availability - This detailed, long-term study was initiated in 1988 and planned for continuation until 1996. In each of three true replicate stands of each of three ages, four treatments were initiated: complete, continuous fertilization, nutrient depletion, thinning and control. Physiological, population, community and ecosystem responses are monitored for 5 dominant tree species (see Fig. 5). Funding is provided primarily by USDA-NRICGP (Ecosystems Program).

J. Mirror Lake Studies - Mirror Lake lies within the Hubbard Brook Valley and until 7 yr ago, studies of the lake and its watershed were included sporadically in the NSF funding to the HBES. Studies on Mirror Lake are now funded separately. These include studies of groundwater and surface-water interactions with the lake, nutrient cycling, residence time and mixing models. Numerous colleagues of the USGS are engaged in cooperative studies of groundwater in the Hubbard Brook Valley. Geophysical data are collected to provide information on the hydraulic and mineralogic characteristics of the geologic substrate through which water flows. Because of its geologic setting and research activity, Mirror Lake was chosen in 1978 by the USGS for an intensive geophysical and hydrological study to provide a complete hydrologic budget for the lake (no terms estimated by difference). Elaborate instrumentation has been installed to accomplish this goal. Funding for Mirror Lake studies is provided by the USGS, NSF and A.W. Mellon Foundation.

K. The Sandbox Experiment - The objective of the sandbox experiment is to determine, by direct measurement, the rate at which ecosystems populated by monospecific communities of plants accumulate nitrogen. Collaborators from the USDA Forest Service, U. of Vermont, U. of New Hampshire, and Yale U. are conducting these long-term experiments in numerous boxes located near the USDA Forest Service Headquarters at Hubbard Brook. Funding is provided by the A.W. Mellon Foundation.

L. HBEF Biosphere Reserve - Biosphere Reserves are part of an international program sponsored by UNESCO, whose primary objectives are conservation of genetic diversity, environmental research and monitoring, and education (Franklin 1977). In 1976, the HBEF was designated a Biosphere Reserve (MAB - Biosphere Reserve Program) representative of the northern hardwood-spruce forest (Küchler vegetation type). This area is presently the only Biosphere Reserve in the northeastern U.S. Hubbard Brook was further recognized in 1977 by The Institute of Ecology as a potential site as part of a network of National Experimental Ecological Reserves, representing northern hardwood forest ecosystems.

M. USDA Forest Service - The Northeastern Forest Experiment Station, U.S. Forest Service, during the first eight years following the establishment of the HBEF, developed a network of stream gauging and precipitation stations and other weather monitoring installations on the experimental waters. Data from these installations combined with numerous studies have formed the hydrometerological foundation for much of the biogeochemical research at Hubbard Brook. Forest Service researchers are active participants in many of the cooperative studies described above.