# I.0 RESULTS FROM PRIOR RESEARCH

**NSF Award: 0423259**

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

**Summary:** The overall goal of the HBR-LTER program is to improve understanding of the response of Northern Forest ecosystems to natural and anthropogenic disturbances. Hubbard Brook serves as a central hub for basic research and ecosystem monitoring, as well as for a suite of educational, policy and outreach activities in the Northern Forest region. Our activities include: 1) collection, management and analysis of long-term data sets (Table 1 – see Supplementary Documents); 2) small-watershed- and plot-scale manipulation experiments; 3) ecological process studies on hydrology, soil, vegetation, soil microbes and other heterotrophs; 4) cross-site surveys and experiments across the Northern Forest region; 5) development and application of ecosystem models; and 6) educational, outreach and natural resource management projects coordinated by the Hubbard Brook Research Foundation (HBRF). These studies are supported directly by the HBR-LTER and indirectly in conjunction with numerous research grants from NSF, USDA and other funding agencies and foundations.

There have been many accomplishments during the current HBR-LTER in science, outreach, and education. Science highlights include developing a better understanding of the controls on weathering supply of nutrient cations at the HBR and regionally, particularly focusing on the role of forest biota (Blum et al. 2008, Nezat et al. 2008, Schaller et al. 2010). Regional studies have also demonstrated the importance of weathering supply of Ca and the long-term depletion of soil available Ca (Warby et al. 2009) to the health of sugar maple and red spruce and to the recovery of surface waters following emission controls on sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_x$; Warby et al. 2009). We have continued our long-term experimental wollastonite addition to W1 to evaluate the role of Ca supply on the structure and function of Northern Forest ecosystems. Through this experimental treatment, we have gained insight on soil (Cho et al. 2009), vegetation (Dasch et al. 2006), and stream (Peters et al. 2004) response to changes in Ca supply. We have observed marked improvement in the health of sugar maple (Juice et al. 2006), red spruce (Hawley et al. 2006) and snails (Skeldon et al. 2007) following the Ca treatment. Through site and regional modeling (Chen and Driscoll 2005a,b) and critical load analysis (Wu and Driscoll, in press), we have quantified ecosystem response to potential future controls on emissions of $SO_2$ and $NO_{x,}$ in combination with changing climate.

Our research has included a major initiative on effects of climate change in the Northern Forest. This work has involved analysis of long-term meteorological and hydrologic trends (Campbell et al. in review), a series of experiments on effects of snowpack reduction on ecosystem structure (Templer et al. in prep., Christenson et al. 2007) and function (Cleavitt et al. 2008, Groffman et al. in press), and regional projections of the effects of future climate change on hydrology, biogeochemistry and heterotroph populations of Northern Forest ecosystems (Ollinger et al. 2008, Campbell et al. 2009, Rodenhouse et al. 2009).

Under the leadership of the HBRF, we have continued the successful *Science Links* program. Two outreach projects were completed on long-term monitoring (Lovett et al. 2007) and mercury contamination (Driscoll et al. 2007a, Evers et al. 2007). We are completing a project on local-scale carbon management in the Northeast (Fahey et al. 2010). Each *Science Links* project includes a scientific synthesis of an issue of regional or national concern by a team of science experts, which results in one or more peer-reviewed journal articles. Projects also involve outreach activities, including the development of a report for a general audience, and policy and media briefings on the projects (e.g., Driscoll et al. 2007b).

We have also initiated an NSF-funded Research Experience for Undergraduates (REU) program that is led by Plymouth State University and is affiliated with the HBR-LTER. The REU involves three components in the research experience: a seminar and science exchange series, a traditional student research project, and a student outreach project. The student outreach project is a unique component of our program: students are teamed with governmental and non-governmental organizations to develop a science communication product, such as a poster, web site or Power Point presentation, pertaining to an issue of interest to both the student and the client organization.

**Publication and leveraging research funding.** We continue our consistent record of publishing the results of research findings in high quality peer-reviewed journals. Since 2004, the Hubbard Brook Ecosystem Study has produced 204 journal articles, 26 book chapters, 2 books, 54 theses and dissertations and 52 reports and abstracts (Table 2, Supplementary Documents). In the HBR-LTER, we emphasize developing student research and publications. Our research, education and outreach activities are highly leveraged through funding from government agencies and foundations. During the last LTER funding cycle we received major funding for over a dozen different projects from various agencies and foundations including NSF, USDA-NRICGP, USEPA and Mellon Foundation. These externally funded projects included studies of climate change, soil freezing, mercury dynamics, root nutrient uptake, sugar maple health, interaction of soil Ca and C, denitrification, critical loads of pollutants, and long-term studies of precipitation, stream chemistry and birds and other heterotrophs. We are also supported by cooperative funding for long-term measurement of climate and hydrology by the USDA Forest Service (UDSA FS). Our outreach and Schoolyard programs have been supported by co-funding from a variety of private foundations, the USDA FS and by a NSF-REU site project, all coordinated through the HBRF.

**Biogeochemical processes.** We have continued the development of a monograph series detailing the behavior of key chemical elements at HBRF (Lovett et al. 2005, Fahey et al. 2005a); additional monographs (N, P) are in development as well as a synthetic overview. Our understanding of primary mineral weathering has been substantially advanced by a series of studies at the plot level (Balogh-Brunstad et al. 2008a, 2008b; Keller et al. 2006a, 2006b), small watershed (Nezat et al. 2004, 2007; Dasch et al. 2006) and regional scale (Nezat et al. 2008). For example, we demonstrated significant landscape-scale variation in weathering rates (3-fold higher in upper slope than toe slope positions), as well as the significant role that vegetation disturbance plays in controlling chemical denudation rates (Schaller et al. 2010). Study of the dynamics of Si (Stelzer and Likens 2006; Conley et al. 2008; Saccone et al. 2008) has also demonstrated a key role of disturbance in redistributing amorphous Si in the soil profile. Recent work focusing on the dynamics of C in soil (Fahey et al. 2005b; Ussiri and Johnson 2004, 2007) and surface waters (Palmer et al. 2005; Bernhardt and McDowell 2008; Warren et al. 2007; Fierer et al. 2007; Jaffe et al. 2008; Demers et al. in press; Dittman et al. in press) has produced new insights into both forest-stream coupling and interactions between C and N (Dittman et al. 2007) and between C and Fe (Fuss et al. in review).

**Winter climate change.** Building on earlier observations of the role of winter climate and soil freezing in controlling landscape and temporal patterns in ecosystem pattern and process, we conducted a series of plot-level manipulations to evaluate mechanisms of response involving such key features as frost heaving and damage to fine roots (Cleavitt et al. 2008a), soil aggregation (Steinweg et al. 2008), microbial production of trace gases (Groffman et al. 2006, in press), microbial retention of N and S (Campbell et al. 2007) and herbivory by moose (Christenson 2007). A key factor in nutrient dynamic responses to soil freezing is direct physiological impairment of root nutrient uptake function (Socci and Templer, in prep.), but the extrapolation of this response across large landscapes remains uncertain. Our insights on winter climate were summarized in regional syntheses (Campbell et al. 2005, 2009).

**Atmospheric deposition and ecosystem responses.** We continue to track long-term deposition of air pollutants and responses of ecosystem processes. Despite marked decreases in S deposition and stream $SO_4^{2-}$ (Likens et al. 2002), current levels of acidic deposition result in net depletion of soil nutrient cations (Ca, Mg), and surface water recovery from acidification has been modest (Driscoll et al. 2001, Palmer et al, 2004). Ongoing process studies continue to provide new insights into the mechanisms responsible for these responses (Campbell et al. 2007, Mitchell et al. 2008). In recent years, there have also been marked decreases in atmospheric N deposition (Butler et al. 2005). Stream N losses at HBR and other watersheds in the region have declined to extremely low values (Goodale et al. 2003; Driscoll et al. 2007a). The connection of this behavior with soil and vegetation processes (Judd et al. 2007; Groffman et al. 2006; McLauchlan et al. 2007; Campbell et al. 2007) and stream ecosystems (Conley et al. 2008) is of continuing interest. Most recently we have expanded our air pollution research to include mercury (Driscoll et al. 2007b; Evers et al. 2007; Butler et al. 2008; Han et al. 2008; Dittman et al. in press; Demers et al. in press), a contaminant of considerable concern throughout the U.S.

**Soil available calcium depletion.** Our earlier mass-balance calculations indicated that acidic deposition and forest harvest caused marked depletion of ecosystem Ca (Likens et al. 1998), and the local and regional implications of this depletion are the subject of ongoing studies. Specifically, we augmented soil Ca supply on plots and on a small watershed (W1) (Peters et al. 2004, Cho et al. in press; Nezat et al. in review), and we evaluated a regional Ca gradient (Yanai et al. 2005, Warby et al. 2009). These ongoing studies have revealed valuable insights regarding Ca effects on forest production and fine root turnover (Park et al. 2008), soil Ca sources (Nezat et al. 2008), sugar maple decline (Huggett et al. 2007; Juice et al. 2006), red spruce decline (Hawley et al. 2006, Halman et al. 2008), soil microbial processes (Groffman et al. 2006) and soil invertebrates (Skeldon et al. 2007, Fisk et al. 2006). For example, fine root production and turnover increased with soil Ca availability (Park et al. 2008), and reproductive failure of sugar maple on Ca-depleted soils was associated with limited formation of mycorrhizal associations (Juice et al. 2006). The ability of young forests to access Ca despite severe depletion of soil available Ca may be associated with “mining” of recalcitrant soil organic matter or primary minerals (Yanai et al. 2005). New approaches to the problem of Ca biogeochemistry also have been developed, such as using Ca/Sr ratios corrected for biological fractionation (Dasch et al. 2006, Page et al. 2008, Blum et al. 2008).

**Regional synthesis.** We have expanded our efforts to apply the results from HBR in regional syntheses of understanding of ecological patterns and processes and response to disturbance. In addition to using models as a synthetic tool (described below), we have coordinated a variety of such regional syntheses, including climate change effects on forest fauna, hydrology and biogeochemistry (Ollinger et al. 2008, Campbell et al. 2009, Huntington et al. 2009, Rodenhouse et al. 2009); acidic, N and Hg deposition (Whitall et al. 2003, Campbell et al. 2004, Chen and Driscoll 2005, Evers et al. 2007, Driscoll et al. 2007c, Butler et al. 2008); sugar maple dynamics (Lovett and Mitchell 2004); potassium biogeochemistry (Tripler et al. 2006); soil nitrification (Ross et al. 2009); and atmospheric S deposition (Mitchell et al., in review).

**Quantitative ecosystem modeling.** We utilize a variety of hydrologic, energy and ecosystem models to interpret data, evaluate theory and regionalize research results. Models are also used to inform natural resource management. At the core of our modeling work is the PnET family of models which are used to examine hydrologic-element response to land disturbance and changes in atmospheric deposition, climate, and $CO_2$ (Ollinger and Smith 2005; Ollinger et al. 2002, 2008; Chen and Driscoll 2005a,b). In addition to PnET, we apply a number of models to address more focused research questions including the energy balance model SNTHERM (Frankenstein et al. 2008) to examine snowpack accumulation and loss, BROOK90 to examine watershed hydrology, MEL to evaluate element stoichiometry and nutrient limitation (Rastetter and Shaver 1992) and DALEC (Richardson et al. in review) to quantify ecosystem C fluxes.

**Ecology of heterotrophic organisms.** The centerpiece of our animal studies is the 40-year continuous record of breeding bird populations, a record that continues to provide new insights (Rodenhouse et al. 2006, 2008; Sillett and Holmes 2005; Holmes 2007, in review; Holmes et al. 2005) and serves as the basis for demographic and behavioral research. Examples of research that build on long-term observation include occupancy modeling (Betts et al. 2008; Sherry et al. 2006), a test of the energetic stress hypothesis (Nagy and Holmes 2005; Nagy et al. 2007), singing, foraging and social behaviors (Dobbs et al. 2007; Betts et al. 2008), habitat quality assessment (Johnson et al. 2006), and tests of heterozygosity theory (Smith et al. 2005). We have also expanded the scale of our bird research to encompass both the elevation gradient and the complex landscape gradient at HBR thereby providing new insights on spatial scaling (Jones et al. 2007, Doran and Holmes 2005) and climatic effects (Rodenhouse et al. 2008, 2009). Our heterotroph studies also included exciting new work on salamanders and stream and soil invertebrates (Lowe et al. 2006, 2008; MacNeale et al. 2005; Greene et al. 2008; Fisk et al. 2006), small mammals (Nagy and Holmes 2004), and moose (Christenson 2007). Finally, we have increased efforts to link heterotrophic processes with vegetation and nutrient dynamics (Stange 2009).

**Forest dynamics.** We monitor forest demographics at a variety of scales and for a variety of purposes, including support of biogeochemical budgets. Together with manipulation experiments and natural disturbance events, these surveys have provided valuable insights into the dynamics of the Northern

Forest. We demonstrated that the decline of biomass on W6 at HBR has been associated with decreased growth and increased mortality of sugar maple, American beech, and birches (Siccama et al. 2007) owing to stresses such as soil available Ca depletion (Juice et al. 2006), beech bark disease (Lovett et al. 2006), and drought (Battles et al., in prep.). These declines are patchily distributed across the complex wider HBR landscape (Solomonoff et al., in review) and are accompanied by increased abundance of conifers and beech. A severe ice storm caused significant changes in the trajectories of forest development, favoring American beech expansion in 100-yr-old forests and accelerating succession in 30-40-yr-old forests (Weeks et al. 2009). Experimental studies determined that recruitment of beech is co-limited by light and soil resources (Cleavitt et al. 2008b), while broad-scale surveys indicated that sugar maple recruitment is regulated by complex biotic and environmental factors (Cleavitt et al., in prep.).

**New Techniques and Approaches**. We have continued to develop new methods to improve our ecosystem measurements. Study of root dynamics remains challenging, and we have adapted or perfected several novel approaches including an *in situ* nutrient depletion method for quantifying root uptake (Yanai et al. 2009, Templer et al., in prep.); morphological and genetic approaches for quantitative sorting of fine roots by species (Yanai et al. 2008, Fisk et al., in press); and a combined root-window and genetic method for identifying and quantifying root decay fungi (Fisk et al., submitted). Similarly, measurement of denitrification is plagued by methodological problems, and we have developed and tested a new soil-core gas-flow system (Burgin et al., submitted, Kulkarni et al, submitted) that can be used in conjunction with *in situ* $O_2$ sensors to improve denitrification estimates. We are currently field testing a novel, near-real-time dissolved $CO_2$ sensor, developed by the late B. Browne, which could resolve 3-D patterns of $CO_2$ flux in linked terrestrial-aquatic systems. We have used the W1 wollastonite treatment to refine isotopic approaches for tracing watershed Ca dynamics by precisely quantifying Ca/Sr fractionation in ecosystem processes (Dasch et al. 2006), an approach with promise for improving resolution of weathering estimates. Finally, HBR has "gone wireless" for many hydrometerological measurements, utilizing a new transmitter network across the HB valley to relay signals.

**Education and outreach.** Our vigorous program of outreach and public education is coordinated through the HBRF with co-funding from NSF Schoolyard Supplements, USDA FS and several private foundations. During the past few years, several prominent projects have been undertaken under the Environmental Literacy Program of the HBRF in conjunction with the USFS Northern Research Station: 1) *Science Links* teaching guides that build upon our public policy program (described below); 2) teacher-training events involving teachers, who pilot-test lessons, prospective users, and HBRF and USFS staff; 3) school partnerships with six nearby high schools as well as additional schools that visit the HBR for tours. We are also partnering with A Forest for Every Classroom, NH, which is a year-long professional development collaboration among HBRF, USDA FS, National Wildlife Federation and Project Learning Tree.

Our major outreach and public education program is *Science Links*. Together with policy and management experts from the region, LTER scientists translate scientific information from the HBR and related research projects for use by natural resource managers and policymakers at regional and national levels. In 2009 we continued to work on the fifth *Science Links* project, a regional analysis of C sources, sinks, and mitigation strategies. In conjunction with colleagues from the BES, HFR and PIE LTER sites, we are comparing the costs and potential for C emission reductions across several settings in the Northeast. In addition, organization of the next *Science Links* project, which will focus on long-term migratory bird data, was begun in 2009. Our Schoolyard educational activities are coordinated with the *Science Links* program. We have developed a series of science teaching modules that are "field-tested" with our affiliated high school science teachers. To date we have completed modules on acid rain and birds, with a new module on mercury currently in development.

Another outgrowth of the *Science Links* program is the Hubbard Brook Roundtable, initiated in 2006. The Roundtables incorporate a broad range of stakeholders and bring an ecosystem perspective to identify and discuss threats and opportunities in the Northern Forest region. For example, a Roundtable discussing the formation of wood-fuel cooperatives was held in September of 2009.

**Network and cross-site activities**. The HBR-LTER has taken a leadership role in Network and cross-site activities. P. Groffman has served on the LTER Executive Board. P. Groffman and C. Driscoll are on the LTER EcoTrends editorial committee. They have led the Biogeochemistry component of EcoTrends, conducted two EcoTrends workshops, and are developing an EcoTrends biogeochemistry database and an associated LTER synthesis article. T. Fahey together with A. Knapp (SGS) led a network initiative on primary productivity which has resulted in a synthesis volume (Fahey and Knapp 2007). J. Campbell participates in the IM Executive Committee. P. Templer served on the organizing committee for the 2009 All Scientist's Meeting (ASM). J. Campbell and C. Driscoll are participating in the LTER Network initiative on the Disappearing Cryosphere. S. Hamburg has participated in the leadership of the International LTER (ILTER). M. Mitchell and S. Hamburg have been active in the Asian ILER program, participating in Asian LTER All-Scientists meetings and cross-site studies. The HBRF manages the children's book fund for NSF and the LTER program.

The HBR-LTER has promoted cross-site and synthesis activities in the Northeast and Northern Forest region. Several of these initiatives have been conducted in conjunction with the LTER sites in the region (HFR, PIE, BES). We have conducted two workshops with Northeast LTERs to discuss and promote cross-site Network activities. We have taken a leadership role in the Northeastern Ecosystem Research Cooperative (NERC, www.ecostudies.org/nerc), which is a regional collaborative of ecosystem scientists dedicated to sharing data and other information, promoting regional synthesis, and enhancing outreach to land managers and policy makers. The NERC is led by G. Lovett, funded by a NSF RCN grant, and involves many HBR-LTER scientists and students. The NERC promotes cross-site analysis and synthesis of environmental issues across the Northeast.

**Site Review.** On 29-30 May 2007, the NSF conducted a site visit and review of the HBR-LTER. This review provided important constructive feedback to our efforts in research, education and outreach to advance understanding of the Northern Forest region. There were several specific suggestions that have especially influenced our thinking and changed our activities over the past 2.5 years. The review team suggested that we could a better job of putting the HBR-LTER in an integrated theoretical framework that would guide the development and testing of models. We held a workshop to discuss theory associated with the response of the northern forest to disturbance. We reviewed *Pattern and Process in a Forested Ecosystem* (Bormann and Likens 1979), discussing whether recent research were consistent with this theoretical framework. We propose to continue to address this issue by improving understanding of the influence of press disturbances, such as air pollution and climate change, on forest development; the role of stoichiometric constraints on element cycling and loss; and the manifestation of processes across the landscape of the HB valley and the Northern Forest region. The mid-term review team also suggested that we advance modeling work through the use of "intelligent" data assimilation approaches. We held a workshop on data assimilation and have started projects that couple observations with models to improve parameterization and predictions of ecosystem C dynamics and hydrology. The mid-term review team challenged us to look critically at our long-term monitoring efforts. This is a difficult problem as long-term monitoring is at the heart of much of the research of the HBR-LTER. We held a workshop to critically review our monitoring activities and examine the cost-effectiveness of these programs. As a result of this review, we have reduced the frequency of some of our measurements and decreased overall monitoring costs. Several important suggestions were provided for our information management (IM) program. The most important of these is to provide support in the LTER budget for a full-time information manager. As discussed with the mid-term review committee, we have implemented a successful REU site project through Plymouth State University; we plan to submit a new REU site proposal for continuation next year. The REU program has helped in the recruitment of under-represented students to work at the HBR. We also sent a team of graduate students and PIs to the LTER ASM in 2009. The HBR group had a fruitful experience at the meeting, including organizing and participating in a number of workshops. As suggested in the mid-term review, the HBR-LTER team is aggressively pursuing Network and synthesis activities. Recently, Winter and Likens (2009) published a new synthesis volume on the Mirror Lake ecosystem at HBR.

## 2.0 PROPOSAL NARRATIVE

## I. Introduction

### A. General

Since its establishment in 1955 by the USDA FS, the Hubbard Brook Experimental Forest (HBR) has been a focal site for research on the structure and function of northern temperate forest ecosystems. In the early 1960s, Bormann, Likens and colleagues initiated the Hubbard Brook Ecosystem Study (HBES) with the goal of advancing understanding of the interaction among structural, functional and dynamic aspects of ecosystem organization. Early studies in the HBES led to the development of a theoretical framework and approach for characterizing the patterns and processes in the Northern Forest ecosystem (Likens et al. 1977, Bormann and Likens 1979). These studies have guided continuing research and influenced the wider development of ecosystem theory. At the core of the HBES were (1) the concept of ecosystem development following large-scale disturbance expressed as four sequential stages: reorganization, aggradation, transition and shifting-mosaic steady state; (2) the use of the small watershed as a unit for monitoring and experimental manipulation to facilitate precise mass-balance calculations for material fluxes in linked terrestrial-aquatic ecosystems; and (3) providing guidance in the development of environmental policies related to our program of scientific research.

As a result of continuing study at the HBR, supported by NSF as a LTER site since 1988, we have elaborated upon the theoretical framework and approaches of the HBES, contributing to and learning from the further development of ecosystem science. The complexity of the suite of patterns and processes that underlies ecosystem behavior at each successive stage in ecosystem development has become apparent (Groffman et al. 2004), especially the interactions among chemical elements and key populations in food webs; the linear, “single-patch” model of the HBES is not sufficient. The key role of the landscape template (Johnson et al. 2000) in determining energy, water and element fluxes and population distributions across the HB valley has become clear; the implicit assumption of uniformity in small watersheds is inadequate. Moreover, the effect of compounded and interacting disturbances on ecosystem structure and function has become a dominant theme in community ecology and ecosystem biology; feedbacks and interactions among disturbance agents and landscapes are crucial to ecosystem behavior. The overarching theme of the HBR-LTER project is the response of ecosystem structure and function to disturbances: air pollution and atmospheric deposition; forest pulse events and land-use change; and regional climate change. The continuing challenges we face in explaining forest ecosystem responses to disturbance are illustrated by some surprising observations that have emerged from our long-term studies at the HBR, observations that run counter to existing ecological theory.

- Live biomass in the ~100-yr-old forest is steadily declining (Fig. 1) and net ecosystem productivity (NEP) is negative.

This observation departs radically from predictions of the original ecosystem development concept of the HBR (Bormann and Likens 1979), and from widespread reports of positive NEP in mature forests based on eddy flux measurements (Bonan 2008). Moreover, key anthropogenic drivers of NPP, such as warming climate and $CO_2$ and N fertilization from atmospheric deposition, should stimulate greater tree growth, yet forest NPP at HBR is clearly declining (Fahey et al. 2005a).

- Nitrogen loss is extremely low in streamwater draining mature watersheds at the HBR, the lowest in the 45+-yr record.

This observation coincides with patterns in other watersheds in the region (Goodale et al. 2003; Driscoll et al. 2007), but conflicts with the theory of N saturation (Aber et al. 1989) and predictions of biogeo-chemical models (Aber et al. 2002). Stream N decreases coincident with declining and negative NEP are also in striking contrast with theories of ecosystem biogeochemistry (Vitousek and Reiners 1975).

- 25 yrs following whole-tree harvest, Ca loss in streamwater draining watershed 5 (W5) continues to exceed that in reference W6 (Fig.2).

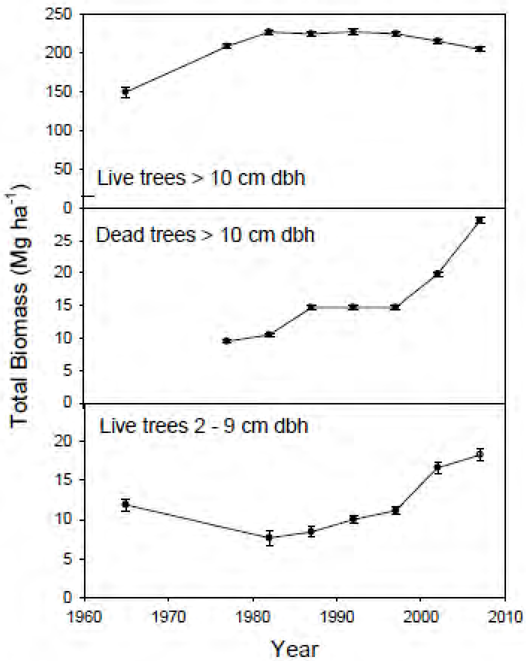



**Figure 1.** Time series of aboveground biomass in W6 at the HBR, including total live trees (≥ 10 cm dbh), dead trees (≥ 10 cm dbh) and total live saplings (2-9 cm dbh). Error bars derived by Monte Carlo uncertainty analysis.

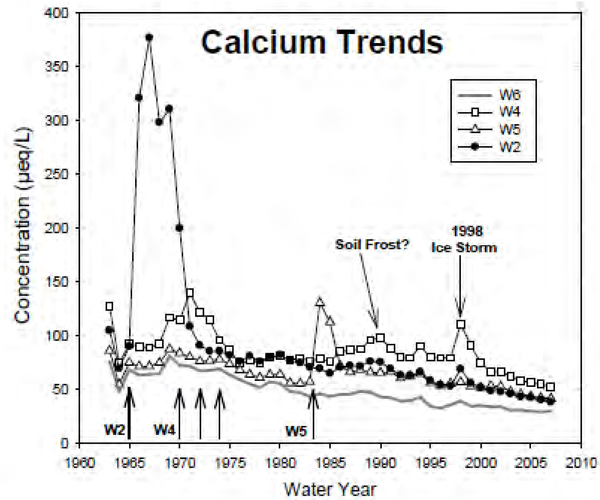



**Figure 2.** Time series of annual volume-weighted concentrations of $Ca^{2+}$ in stream water in W2 (clear-fell and herbicide), W4 (strip-cut), W5 (whole-tree harvested) and W6 (reference). The cutting periods for W2, W4 and W5 are indicated. Note that following the W5 clear-cut, stream $Ca^{2+}$ has increased relative to W6 values.

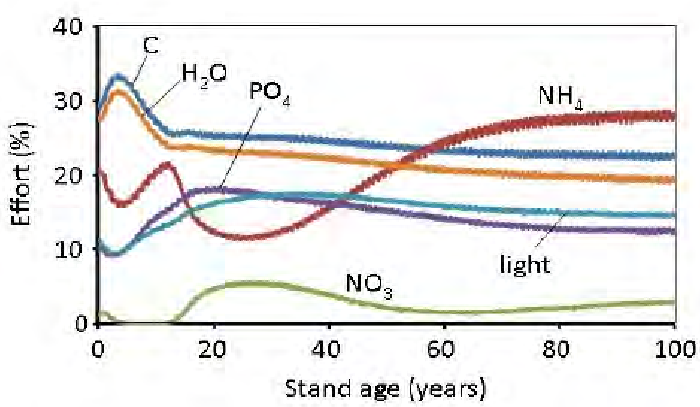



**Figure 3.** Results from Multiple-Element Limitation (MEL) model output illustrating changes with stand age in the relative demand for resources by the forest ecosystem at HBR.

Accepted biogeochemical theory predicts that depletion of soil Ca pools by intensive harvest and subsequent rapid aggradation of vegetation biomass would decrease stream Ca losses with cascading effects on solution pH, Al, and acid-neutralizing capacity (ANC). The stoichiometric coupling among these and other soil constituents apparently departs from current theory.

- Despite gradually increasing air temperature, the abundance of northern conifer trees has been steadily increasing at the HBR.

Simple models of forest response to global warming project recession in the range of northern conifers that occupy the highest elevation in the HB valley (Loehle and LeBlanc 1996). Apparently, other features of the landscape template and biotic environment are as important as temperature in predicting forest compositional change.

These unexpected observations, together with the unprecedented pace of human-accelerated environmental change, suggest the need to revisit fundamental aspects of ecosystem theory. Our findings indicate the need to elaborate and integrate concepts of ecological stoichiometry and ecosystem resilience to accommodate such features as resource interchangeability and the synchronization of resource supply, to recognize systematic variation across the landscape template, and to identify the feedbacks inherent in coupled systems. For example, the coupling between C and N likely explains strong N retention in HBR soils, yet the mechanisms of excess N retention on soil organic matter remain unclear (Hobbie 2008), impeding the development of models to predict future C and N cycling. The possible role of P availability in limiting forest production and its stoichiometric relationships with C and N are suggested by our recent parameterization and expansion of the Multiple Element Limitation (MEL) model (Rastetter and Shaver 1992, Yanai et al. in prep., Fig. 3), but current theory does not recognize the dynamics underlying the supply of these resources. Soil nutrient cation depletion associated with forest harvest and acid deposition is implicated in forest dynamic responses (Gbondo-Tugbawa and Driscoll 2003), but the mechanisms contributing to maintenance of high base cation supply in aggrading forests are not understood, and could be linked with P demand (Blum et al. 2002). Moreover, the coupling of S, N, base cations, Al, DOC and pH as $SO_4$ deposition declines (Likens et al. 1998, Driscoll et al. 2007, Montief et. al. 2008) certainly contributes to the long-term patterns of biogeochemical fluxes at the HBR (Figs. 4,5). Clearly, complex stoichiometric interactions among these chemical constituents must be considered to explain the trajectory of community and ecosystem responses to disturbance.

An important advance in our conceptualization of forest ecosystem dynamics in the HBR-LTER has been the recognition of patterns and processes at the landscape scale. A repeating pattern of variation in the glaciated landscape of the Northern Forest is the substrate sequence from ridgetop to lower slopes in headwater catchments (Johnson et al. 2000). For example, although well-drained Spodosols are the dominant soils over the larger landscape, other hydropedological processes (Lin 2003) governed by local topography result in complex interactions between soil characteristics and transient water tables (Fig. 6). In response to wetting events (heavy rains, snowmelt episodes) a soil transmissivity feedback may govern hillslope activation leading to threshold effects on hydrologic behavior (Detty and McGuire, in review). Moreover, key biogeochemical processes and ecological patterns are shaped by these hydropedological phenomena, including processes such as redox reactions, mineralization, denitrification, and root uptake and patterns such as soil base status, sugar maple decline, ecotones between forest types, storm hydrographs, and even vertebrate and invertebrate populations.

These landform features also affect patterns at the larger scale of the entire HB valley and thus inform our expectations for the response of ecosystem structure and function to climate change and other disturbances. For example, complex patterns of stream chemistry variation at the HB valley-wide scale (Palmer et al. 2005, Likens and Buso 2006, Fig. 7) may be governed primarily by hillslope hydrology, and the stoichiometry of C and N varies systematically with vegetation composition and landscape position (Table 3). Moreover, although we might imagine the 800 m range of elevation in the HB valley as a proxy for future global climate change drivers, such that hardwood forest should move upslope in a warmer, wetter climate, the reality is more complex. The competitive interactions between conifers and hardwoods are occurring on a complex landscape where feedbacks between soils, nutrient availability and disturbance result in departures from simple models. A key role in these interactions is played by

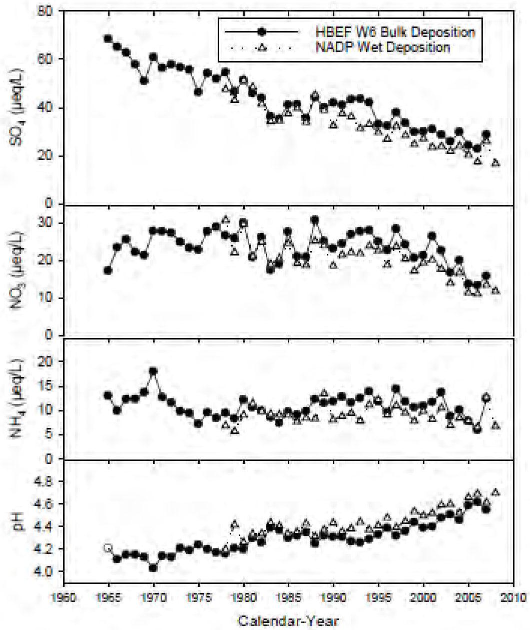



**Figure 4.** Annual volume-weighted concentrations of $SO_4^{2-}$, $NO_3^-$, $NH_4^+$ and pH in bulk precipitation in W6 and wet-only precipitation at the HBR over the period of record. Note there have been significant decreases in $SO_4^{2-}$ and $NO_3^-$, and increases in pH. Bulk deposition shows slightly higher concentrations than wet deposition.

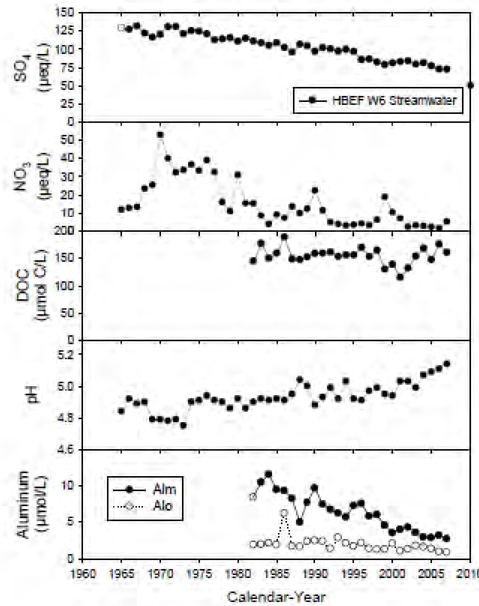



**Figure 5.** Annual volume-weighted concentrations of $SO_4^{2-}$, $NO_3^-$, dissolved organic carbon (DOC), pH and Al species in stream water in W6 at the HBR over the period of record. Note that Al measurements include monomeric Al ($Al_m$) and organic monomeric Al ($Al_o$). Inorganic monomeric Al ($Al_i$) is the difference between $Al_m$ and $Al_o$, There have been significant decreases in $SO_4^{2-}$, $NO_3^-$, DOC and $Al_i$, and increases in pH.

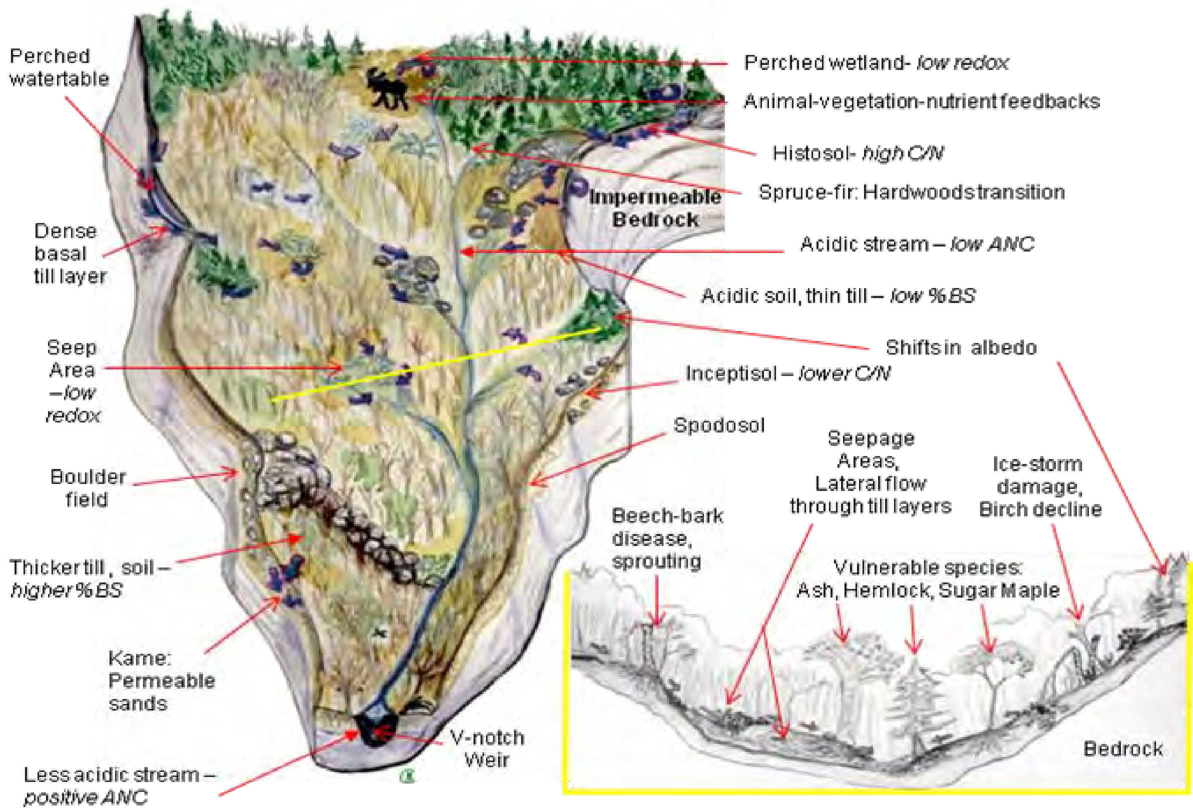



**Figure 6.** Diagrammatic representation of the HBR landscape. Patterns in topography, vegetation, soils and surficial geology across the landscape, result in systematic variations in hydrology, tree species distribution, nutrient, redox and acid-base stoichiometry that influence watershed biogeochemical dynamics.

**TABLE 3. Ecosystem organic C:N molar ratios across landscape subcatchments of Watershed 6 (after Dittman et al. 2007). Oa refers to forest floor horizon.**

| | Molar C:N ratios by ecosystem compartment | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Soil | | Microbial | | Soil solution | | |
| Subcatchment | Precipitation | Above-ground litter | Oa | Mineral | Oa | Mineral | Oa | Mineral | Stream |
| Spruce Fir Birch | 15.7 | 66.8 | 24.1 | 23.7 | 5.8 | 9.6 | 64.8 | 60.8 | 68.0 |
| High Elevation Hardwood | 20.9 | 50.1 | 21.9 | 21.7 | 6.6 | 8.2 | 39.9 | 42.0 | 47.5 |
| Low Elevation Hardwood | 16.9 | 46.8 | 22.3 | 22.4 | 5.3 | 7.1 | 38.5 | 36.6 | 38.0 |

exotic insect pests, such as that responsible for beech-bark disease (Houston 1994), and by the recent return of a keystone herbivore species, the moose (*Alces alces*), whose range and activities are in part governed by landforms. The return of moose has effects on soil C and N availability (Christenson 2007), tree and shrub layer vegetation dynamics, and consequently bird and lepidopteran populations. These observations illustrate the need to further develop a concept of landscape demography, applied to key taxa in the forested ecosystem and both dependent upon and influencing the underlying biogeochemical and hydrological landscape.

Long-term research at HBR has very important management implications (e.g., Driscoll et al. 2001). In its early stages the HBES utilized a "passive" model of science-policy interaction; in the past decade we developed a highly regarded "active" effort of outreach and engagement of key audiences. Now, we recognize the need for better bi-directional linkages between the realms of science and natural resource management. Recently, the Research Initiatives Sub-committee of the LTER network proposed a framework for "Integrative Science for Society and Environment (LTER 2007)" that advanced a model for interdisciplinary research, linking changes in ecosystem structure and function, with feedbacks to ecosystem services and social systems, under external drivers including "press" and "pulse" disturbances. We have adopted that framework to describe our overall program of research and to help conceptualize the connections between our scientific research and the societal drivers that influence ecosystem dynamics (Fig. 8). Although the core funding requested in this proposal does not include specific allocations to support social science research, we plan to use the LTER project to leverage funding in support of a new initiative in science and society. For example, the burgeoning and controversial demand for solid biofuels in forested regions of the world provides an exemplary case for studying the coupling between human and ecological systems in the context of a complex and timely public policy problem, and a proposal to NSF Coupled Human-Ecological Systems is currently in review.

## B. Research Themes and Questions

The overall theme of the HBR-LTER is the response of ecosystem structure, function and composition to disturbance. With this proposal we seek to advance the integration of our long-term program around the interactions among biogeochemical stoichiometry, the geophysical landscape template and biotic populations. We have organized our research around three types of disturbance: 1) press disturbances associated with air pollution, 2) pulse and press disturbances related to tree mortality and land use change, and 3) press disturbance resulting directly or indirectly from regional climatic change (Fig. 8). Although we recognize that there are important interactions among these disturbance types, this segregation provides a convenient organizing framework for describing our proposed research.

### *Theme 1: Disturbance from Air Pollution*

Forest ecosystems downwind of urbanized and industrialized regions are exposed to high levels of chronic air pollution. Our research has long included acid deposition and N pollution, which have overriding effects on ecosystem structure and function. Air pollution work at HBR led to an early example of the coupled socio-ecological approach that is now gaining ground throughout the LTER network: observations of acid rain at HBR (Likens et al. 1972) played a role in the development of the 1990 Amendments to the Clean Air Act and the cap and trade program for controlling sulfur dioxide emissions. Monitoring the response of ecosystems at HBR to ongoing emission controls has perpetuated a socio-ecological "loop" where response and recovery data have provided guidance to further changes in air quality management (Likens et al. 1996, Driscoll et al. 2001; USEPA 2009; Wu and Driscoll 2010).

We are increasingly confronted by challenges to our earlier concepts of biogeochemical interactions (Likens and Bormann 1995) as we seek explanations for biogeochemical behavior and trends that involve complex interactions among chemical elements. In forests, stoichiometric relationships among major elements depart in fundamental ways from the paradigm for aquatic ecosystems (Sterner and Elser 2002), with consequences for predicted responses to changing atmospheric deposition. Through coordinated ecosystem monitoring, experimental manipulations, remote sensing and modeling, we propose to address hypotheses about acidic deposition and N saturation in the Northern Forest organized under four integrated sub-themes: **1. Long-term biogeochemical responses and stoichiometric interactions; 2. Soil calcium depletion and ecosystem function; 3. Nitrogen deposition and**

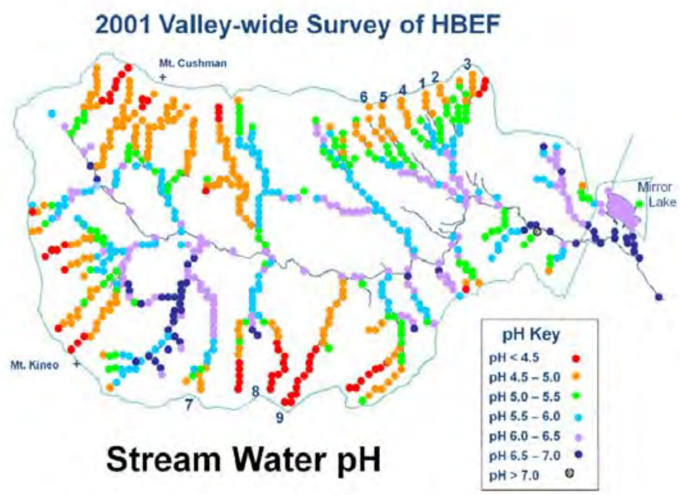



**Figure 7.** Spatial patterns of stream pH across the Hubbard Brook valley.

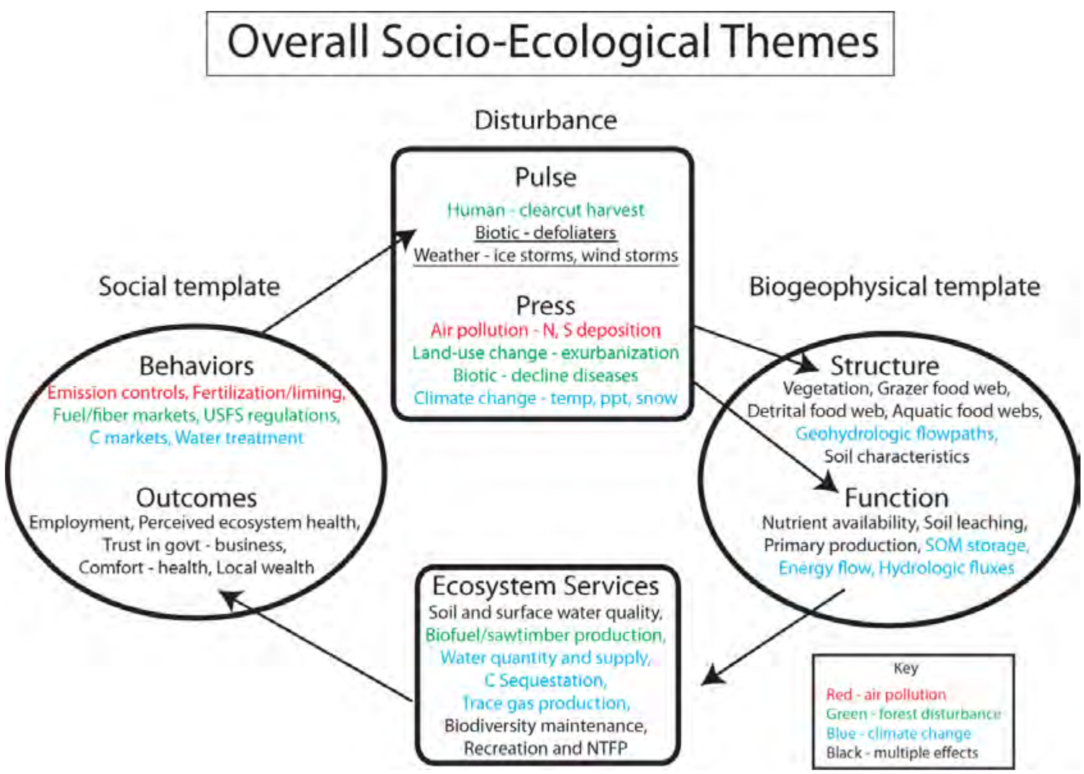



**Figure 8.** Conceptual figure illustrating the interactions between the response of the structure and function of the Northern Forest ecosystem to pulse and press drivers discussed in this HBR-LTER, associated effects on Ecosystem Services (ES), and the feedback to societal outcomes and activities. Note that the disturbance drivers are color coded to correspond to the three research themes of the proposal: air pollution, forest disturbance and climate change. Clear effects of these drivers are also shown in these same colors the Biophysical template, Ecosystem services and Social template. Natural disturbance drivers are underlined. Effects from multiple perturbations are shown in black.

**retention; and 4. Interactions of C, N and P in forest production.** This work will address some overarching questions in biogeochemistry and environmental change.

- *How do the stoichiometric relationships among key elements – C, N, P, Ca, S and Al – respond to the continuing press disturbance associated with decreasing deposition of $SO_4$ and $NO_3^-$, and how does the legacy of historic pulse disturbance (forest harvest) modify these responses?*
- *How do landscape-scale hydrologic features interact with biogeochemical processes to regulate element fluxes at the headwater catchment and HB valley-wide spatial scales?*
- *Are critical loads/dynamic loads an effective and appropriate approach to guide future emission controls to protect ecosystems from the effects of air pollution?*

***Theme 2: Forest Disturbances***

Although Northern Forest ecosystems in the past were subjected to a wide variety of natural disturbances and stresses, we have observed recently and can anticipate in the future an unprecedented combination of disturbances associated with intensified forest harvest, exotic pests and diseases, and weather and climatic phenomena. These multiple and compounding forest disturbances challenge our traditional conceptions of forest ecosystem development (Bormann and Likens 1979) and demand a more encompassing model that incorporates their spatial and temporal components. While continuing to monitor key ecosystem features, we plan to initiate a new experiment and to use remote sensing and modeling to scale up our local investigations to the Northern Forest region. We organize this work under three integrated sub-themes, **1. Forest decline and population demography; 2. Forest compositional change and biogeochemical feedbacks; and 3. Intensified forest harvest**, to address such intriguing questions as:

- *Can a concept of landscape-scale population demography combined with multiple, compounding disturbances help to account for spatial and temporal patterns of changing forest production, nutrient cycling and population abundances of plants and key heterotrophs?*
- *If intensified forest harvest pushes the ecosystem beyond its resilience capacity, will public policy be influenced by the social feedback associated with human perception of changing environmental quality?*

***Theme 3: Regional Climate Change***

The Hubbard Brook ecosystem is positioned at the interface between the broadleaf deciduous and evergreen needleleaf biomes, an ecotone that could be particularly sensitive to climate change in the Northeast (Beckage et al. 2008). The water balance at HBR has already been significantly altered by surprisingly large, long-term increases in annual precipitation (Fig. 9) and declining duration of snow and ice cover (Likens 2000, Figs. 10, 11). We propose to continue to explore winter climate effects through snowpack manipulations (Groffman et al. 2001) and gradient studies (Groffman et al. 2009a), monitor responses to gradually changing climate drivers, and apply simulation models to provide insights into climate change effects and responses (Campbell et al. 2009). These studies will expand our developing concepts of landscape-scale patterns and processes in the Northern Forest ecosystem and are organized in this proposal under five integrated sub-themes: **1. Winter climate change; 2. Hydropedology and landscape ecohydrology; 3. Landscape demography of trees; 4. Landscape demography of heterotrophs; and 5. Regionalization.** Our climate change work will address such exciting questions as:

- *Do biogeochemical and population responses exhibit non-intuitive, "tipping point," behaviors in response to climate change as a result of landscape-scale feedbacks?*
- *How might hydrology, forest productivity and biogeochemical processes of the Northern Forest respond to different scenarios of climate change and increasing $CO_2$ and interact with anticipated land use and air pollution change?*
- *On a regional basis, what is the comparative strength of climate change feedbacks associated with C sequestration, other trace gas emissions, latent and sensible heat flux, and albedo changes, and how might these respond under different scenarios of land use, pollution and climate change?*

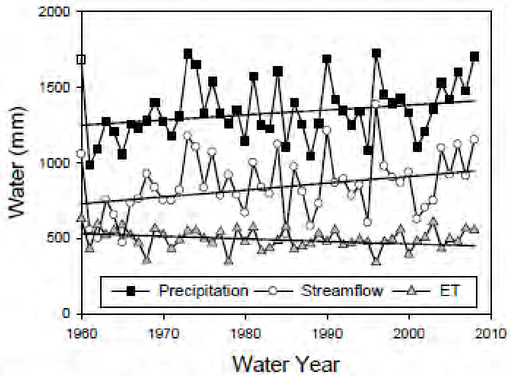



**Figure 9.** Long-term trends in annual precipitation, stream discharge and evapotranspiration (ET) for W3 at the HBR.

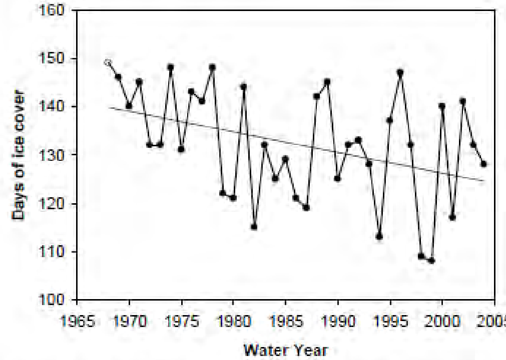



**Figure 11.** Time series of significant decreases in the duration of ice cover in Mirror Lake.

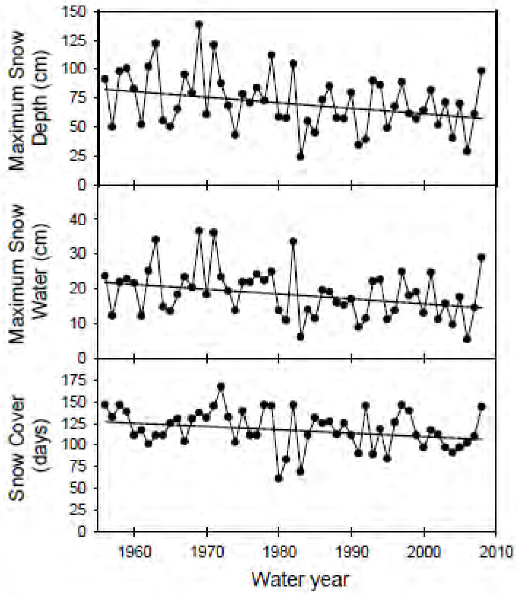



**Figure 10.** Long-term decreases in annual maximum snow depth, maximum water content and duration of snow cover at HBR. Note that all measurement show significant decreases.

- *Are the “green” and “brown” food webs responding in non-linear and heterogeneous ways to changing climate across the elevation gradient within the HBR?*

## C. Research Sites

Most of the research in the HBR-LTER project is located at the HBR in the White Mountains of central NH. Because of space limitations we refer readers to detailed descriptions of the climate, soils, vegetation, and history of the HBR at our website (http://www.hubbardbrook.org). At the HBR, we have used the small watershed approach to quantify the response of forest and aquatic ecosystems to disturbance, and several experimental watersheds on the south-facing slope have been manipulated for this purpose (Table 4). Increasingly we have broadened the scope of our studies to encompass the wider HB valley including north-facing experimental watersheds and additional landscape elements in the large HB valley (3,000 ha).

The HBR-LTER also encompasses other forested sites in the region that provide further context for studies at the HBR. For example, we conduct complementary research at the Bartlett Experimental Forest (BEF), located about 30 km east of the HBR, where silvicultural treatment of forests on similar sites provides a valuable resource for experimental work (Leak and Smith 1996). At the BEF, eddy covariance methods are used to examine C fluxes, which are compared with biomass and modeling approaches at the HBR and across the region. This facility is part of the AmeriFlux network. In addition to these intensive study sites, HBR-LTER researchers work cooperatively with researchers from other regional study sites, including Cone Pond (NH), Bowl Natural Area (NH), Sleepers River (VT), Bear Brook (ME), and Huntington Forest (NY).

## D. Long-term Data Sets

A major component of the HBR-LTER is the development of long-term records for reference and experimentally manipulated watershed ecosystems, including 1) meteorology and hydrology (since 1956), 2) precipitation and streamwater chemistry (1963), 3) forest vegetation (1965), and 4) forest floor mass and chemistry (1965) (Likens et al. 1977, Likens and Bormann 1995). Annual quantitative surveys of bird and phytophagous insect populations within the forest have been conducted since 1969 (Holmes and Sherry 2001; Fig. 12) coordinated with surveys of tree mast production and small mammal populations (Fig. 13). Long-term studies of air chemistry, throughfall, litterfall, fine root activity, microbial activity, soil water and soils have been maintained, largely through the HBR-LTER, to develop a more comprehensive understanding of the ecology and biogeochemistry of the Northern Forest ecosystem. An important value of these monitoring efforts is as background information for quantifying responses to weather and other disturbance events (Rhoads et al. 2002, Houlton et al. 2003, Bernhardt et al. 2003).

Most of our long-term measurements have focused on the south-facing experimental watersheds (i.e., W1-6); however, in the previous funding cycle we expanded this effort to include north-facing experimental watersheds and the wider HB valley (Fig. 14). The north-facing watersheds at the HBR are characterized by a cooler climate and a greater proportion of coniferous vegetation, which influences biogeochemical behavior (Wellington and Driscoll 2004, Palmer et al. 2004, 2005). The wider HB valley encompasses a broader range of elevation, physiography, and habitat types, supporting a more diverse assemblage of populations (Jones et al. 2007).

The routine measurement of precipitation and stream chemistry in the experimental watersheds is the backbone of the biogeochemical monitoring program. Water samples are analyzed for all major solutes following carefully documented routines (Buso et al. 2000). Complete forest surveys (all stems > 10 cm dbh) and forest floor collections are made periodically in W6. Vegetation surveys also are conducted periodically in other watersheds (W1, W2, W4, W5, W101) and on a grid of plots across the wider HB valley (Fig. 14). Atmospheric chemistry monitoring has continued since 1989 at two sites in the HBR. Litterfall, microbial activity (Bohlen et al. 2001, Groffman et al. 2006) and soil solution monitoring are conducted immediately west of W6 and in W1 (Ca treated) (Fig. 14). Bird, insect and small mammal population monitoring is conducted in a large area west of W6 (Fig. 14) as well as on the HB valley-wide grid. A summary of our monitoring program is provided in Table 1 (Supplementary documents).

**TABLE 4. Characteristics of monitored watersheds at the HBR and related sites.**

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

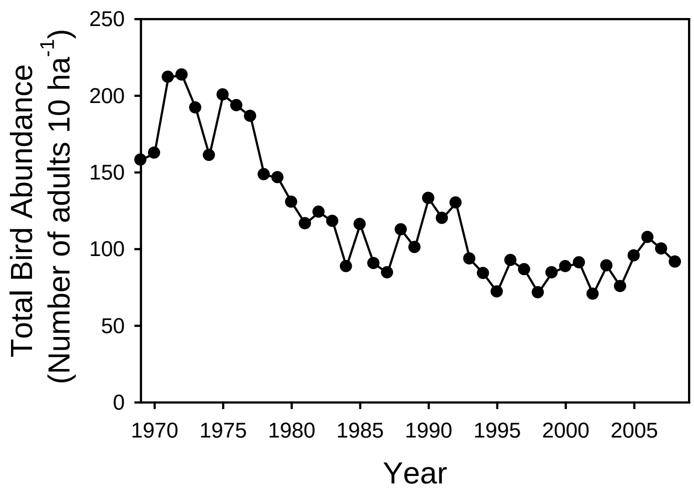
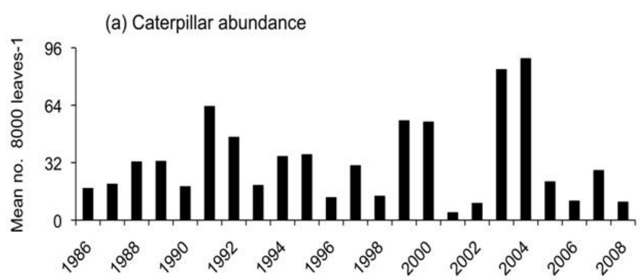



**Figure 12.** Long-term trends in total bird abundance at the HBR. Data show a long-term decline in bird populations.



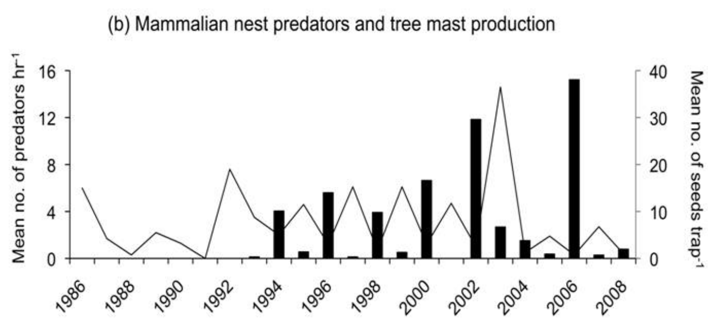




**Figure 13.** Long-term trends in caterpillar abundance (a), and tree mast production (bars) and abundance of mammalian nest predators (b) at HBR.

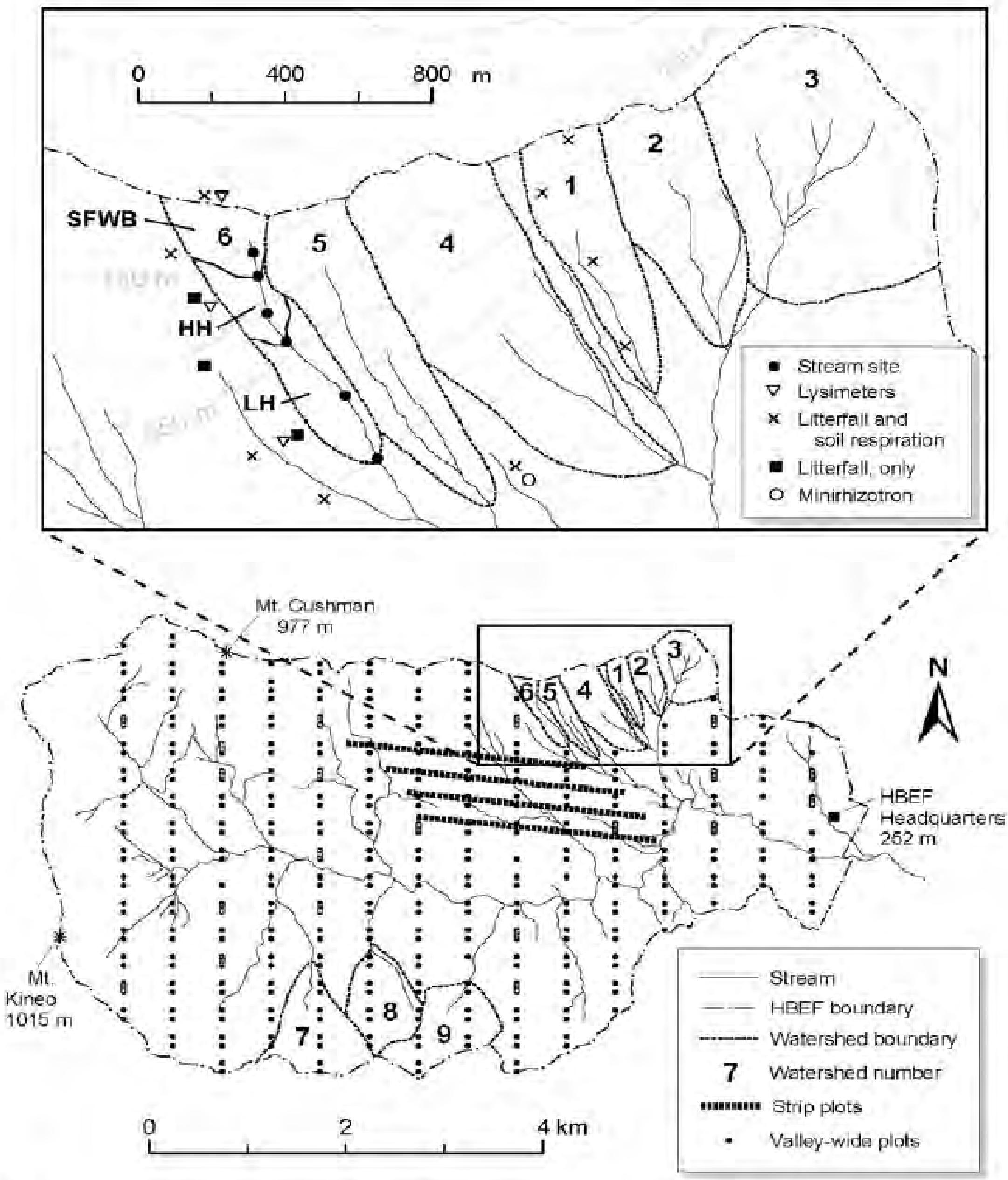



**Figure 14.** Map of the Hubbard Brook Experimental Forest (HBR), including experimental watersheds. Shown are valley-wide transects in which vegetation, soil and microbial processes have been characterized in plots, and bird and insect survey lines. A detailed map of the north-facing experimental watersheds is also shown with location of monitoring sites.

## E. Models and Data Analysis

Development, testing and application of models is an integral part of HBR-LTER research. We use models to test current understanding, to integrate ecosystem studies, to analyze population demography and to develop hypotheses that feed back into new field manipulations. We also use models as predictive tools to help inform and guide natural resource management (e.g., Driscoll et al. 2001), such as those pertaining to the theme areas addressed in this proposal: air pollution (Chen and Driscoll 2005a), forest disturbance (Aber et al. 2002) and climate change (Ollinger et al. 2008). In this proposed HBR-LTER, we focus on the use of models to improve understanding of hydrology, element transport and transformations, element-element interactions, and landscape variation in ecosystem pattern and process. We will also advance data assimilation approaches by coupling field observations with models to enhance model parameterization and prediction.

We use the PnET (Aber et al. 1997; Gbondo-Tugbawa et al. 2001) family of models (PnET-CN, PnET-BGC) to integrate hydrologic and biogeochemical research, support process and ecosystem-level studies, and evaluate management issues. For example, use of both PnET models continues to be an integral part of efforts to explain why long-term patterns in streamwater $NO_3^-$ export deviate from patterns predicted by prevailing ecosystem theory (e.g. Aber et al. 2002). For this HBR-LTER, we propose to add gaseous N fluxes into future versions of PnET, capitalizing upon a new NSF-supported project. We are also using spatially downscaled atmosphere-ocean global circulation model (AO-GCM) output as input to PnET to examine how the Northern Forest might respond to changing climate and to interactions with atmospheric deposition. Reconstructions of past climate and atmospheric deposition allow us to hindcast hydrologic and biogeochemical conditions prior to the Industrial Revolution (Ollinger et al. 2002). Comparisons of model predictions with measured observations (such as stream $NO_3^-$ in Fig. 15) enable us to test theory and, where theory is inadequate, to design process studies to improve understanding. Model forecasts will also predict future hydrochemistry in W6 under changing conditions of temperature, precipitation, and solar radiation with and without forest fertilization by $CO_2$. An important hypothesis that has emerged from this work suggests that forest fertilization associated with rising $CO_2$ could offset the effects of accelerated N cycling and acidification caused by future increases in temperatures (Fig. 15).

We will use a suite of models to help assess landscape dynamics in hydrology and biogeochemistry, particularly pursuing questions pertaining to effects of changing climate (described under section IV Disturbance to Climate Change). Our soil climate modeling system is capable of simulating the development and melting of the snowpack; temperatures at the snow-soil interface; soil profile temperatures, water, ice and vapor contents; soil freezing; and forest floor drainage. In addition to SNTHERM (discussed in Results in Prior Support), a more detailed vegetation, snow and soil physics model, FASST (Fast All-season Soil STrength, Frankenstein et al. 2008), will be used for advanced soil climate simulations, as well as improved canopy energy balance modeling. Both FASST and SNTHERM are driven by locally collected temperature, precipitation, radiation, wind, and humidity data that are modified for forest cover and complex landscape elements.

Model-data synthesis is a systematic and rigorously quantitative method of combining process models and data in a manner that utilizes the information contained in each (Raupach et al. 2005, Williams et al. 2005), yielding both an optimal agreement between model and data and full characterization of posterior uncertainties in model parameterization and model predictions. In response to comments from the mid-term NSF LTER review, we have initiated a number of such data-assimilation activities in the HBR-LTER. These projects leverage long-term inventory and biogeochemical data and tower-based $CO_2$ and $H_2O$ flux data from BEF to constrain the ED2 (Dietze et al., in prep.), DALEC (Richardson et al. in review), and PnET models. Current work (funded by DOE NICCR) is showing how using multiple constraints (rather than just the tower-measured fluxes) greatly reduces the likelihood of over-fitting the model to any single data stream, thereby resulting in improved representation of internal dynamics and better model predictions (Richardson et al. in review).

We plan to use data-assimilation approaches in modeling applications of hydrology and C dynamics in this HBR-LTER. We will apply spatially distributed and semi-distributed hydrologic model structures that are coupled with biogeochemical models (e.g., MEL combined with TOPMODEL or DHSVM, Rebel et al.

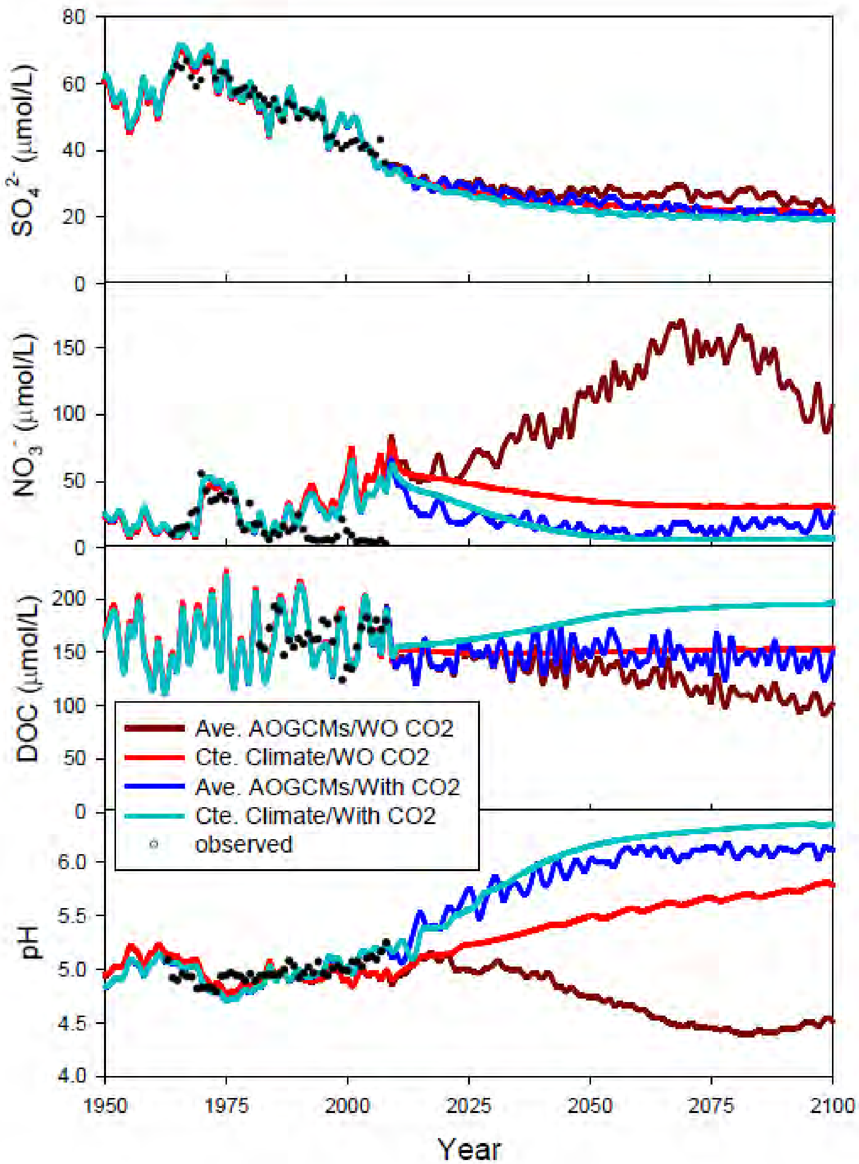



**Figure 15.** Predictions of annual volume-weighted concentrations of $SO_4^{2-}$, $NO_3^-$, dissolved organic carbon (DOC), and pH in stream water for W6 at the HBR for the period 1950-2100 using PnET-BGC. Also shown are measured values. Future projections are based on watershed response to scenarios of changes in temperature, precipitation and solar radiation obtained from mean output from downscaled projections from three AO-GCMs for HBR, with and without forest fertilization by $CO_2$ (2010-2100). Future projections are in comparison to scenarios of constant climate from current values. Note the PnET-BGC projects marked increases in $NO_3^-$ loss and acidification due to mineralization and nitrification associated with future increases in temperature. The magnitude of $NO_3^-$ loss is diminished under the forest fertilization due to $CO_2$.

2009) to W1, W3, W6 and W7 to examine landscape and temporal variations in soil moisture, drainage, and solute transport. Hydrologic processes such as lateral redistribution of water and transient hydrologic connections between hillslopes and streams control much of the export of nutrients from the terrestrial landscape. We will develop process-based data-fusion models that utilize a new shallow groundwater monitoring network to capture the hydrologic connection of hillslopes and the spatial production of runoff within the watershed (Detty and McGuire, in review).

## II. Disturbance from Air Pollution

**A.** ***Objective 1.*** *Describe and explain spatial and temporal patterns in the response of forest vegetation and ecosystem pools and fluxes of elements to changing air pollution loading.*

### B. Introduction

Emissions of air pollutants in the eastern U.S. have changed markedly during the decades since monitoring began at HBR (Driscoll et al. 2001). The 1970 and 1990 Amendments to the Clean Air Act (CAAA) resulted in decreases in emissions of $SO_2$ (~50%) and associated decreases in atmospheric deposition of $SO_4^{2-}$ at HBR (Likens et al. 2002; Figs. 4,16) and elsewhere in the eastern U.S. (Lehman et al. 2005). In contrast, there were limited changes in annual volume-weighted concentrations of $NO_3^-$ in bulk or wet deposition from the 1960s through the 1990s, but this period was followed by marked decreases since 2002 due to $NO_x$ emission controls on electric utilities (Figs 4, 16). These patterns have resulted in a profound shift in the composition of precipitation (Fig. 17). Early in the study, the anion composition of bulk precipitation was dominated by $SO_4^{2-}$. Over time, the relative contribution from $NO_3^-$ increased, but this overall pattern may be reversing due to recent decreases in $NO_3^-$ emissions.

Decreases in atmospheric S deposition have coincided with decreases in concentrations of $SO_4^{2-}$ in soil solutions and streamwater in the biogeochemical reference watershed at HBR (W6; Likens et al. 2002, Palmer et al. 2004, Fig. 18). Sulfate is the dominant anion in throughfall, soil water and streamwater at HBR and is critical in regulating the acid-base chemistry of drainage waters. We have also observed intriguing temporal patterns in stream $NO_3^-$ in W6, which do not seem directly related to N deposition. Annual volume-weighted concentrations of $NO_3^-$ in stream water increased early in the record, remained elevated from the late 1960s to the mid-1970s and have greatly decreased in recent years (Fig. 5). The trend of decreasing $NO_3^{--}$ in W6 was interrupted by two disturbance events: a severe soil freezing event in 1989 (Mitchell et al 1996, Fitzhugh et al. 2003) and an ice storm in 1998 (Houlton et al. 2003, Bernhardt et al. 2003). These disturbances produced relatively short (2-3 yr) periods of elevated $NO_3^-$ within the context of the overall record, primarily due to decreases in root N uptake (Houlton et al. 2003, Groffman et al. 2001). The dynamics of N retention in experimentally cut watersheds also provided unexpected patterns. During the 10-15 year aggrading phase following experimental harvesting of W2 and W4, inputs of N were strongly retained and $NO_3^-$ leaching losses were low (Fig. 19). Over the following intermediate period, this pattern shifted such that $NO_3^-$ loss in cut watersheds exceeded values observed in the reference watershed (Fig. 19). Following the ice-storm of 1998 and the recent decreases in atmospheric N deposition, the strong retention of $NO_3^-$ has resumed in the cut watersheds. Changes in watershed N retention have strongly influenced the acid-base chemistry of drainage waters. In W6 the long-term decrease in stream $NO_3^-$ is contributing to increases in acid-neutralizing capacity (ANC). In contrast, W2 and W4 had shown a period of marked ANC increase after the cut, followed by ANC decrease and most recently ANC increase, which coincide with the shifts in watershed $NO_3^-$ retention (Fig. 19).

Historically, elevated inputs and leaching of $SO_4^{2-}$ and $NO_3^-$ have contributed to the depletion of available $Ca^{2+}$ and $Mg^{2+}$ and the mobilization of Al from forest soils at the HBR (Likens et al. 1996, 1998, Gbondo-Tugbawa and Driscoll 2003) and elsewhere (Lawrence et al. 1999, Huntington et al. 2000). This disturbance may have long-term effects on the forest vegetation and aquatic biota (Driscoll et al. 2001). It is difficult to establish unequivocal evidence for the relationship between acidic deposition and ecosystem damage; however, studies in eastern North America suggest that red spruce (DeHayes et al. 1999, Schaberg et al. 2000) and sugar maple (Horsley et al. 2000, St. Clair et al. 2005) have been injured by elevated inputs of acidic deposition. Long-term observations at the HBR indicate that sugar maple biomass has decreased markedly (Fig. 20).

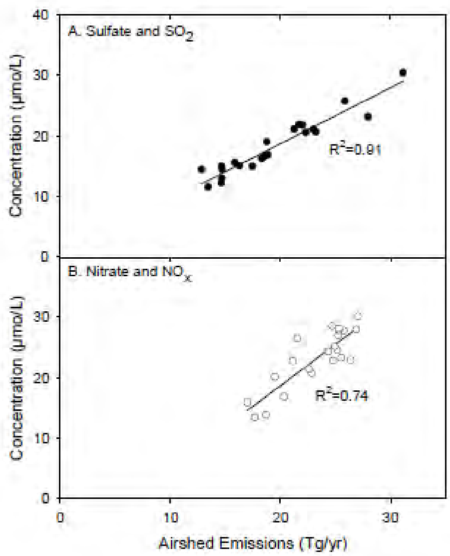



**Figure 16.** Relationship between annual volume-weighted concentrations of $SO_4^{2-}$ and $NO_3^-$ in bulk precipitation at the HBR and emissions of $SO_2$ and $NO_x$, respectively, from the airshed of the northeastern U.S. defined from 24 hr back-trajectory analysis (Butler et al. 2001).

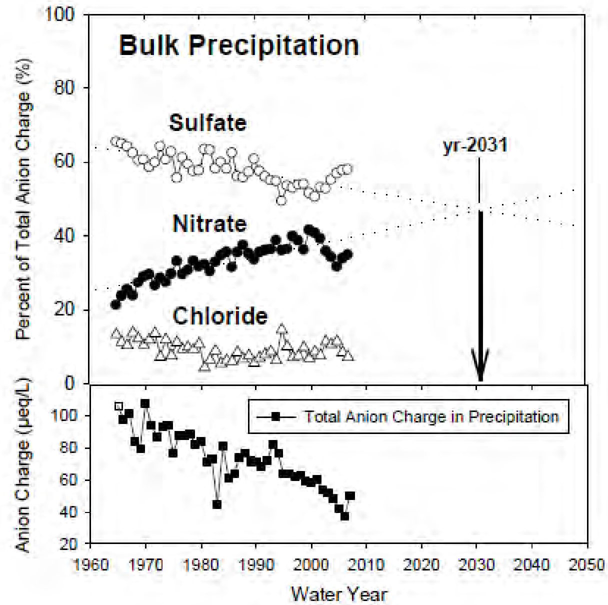
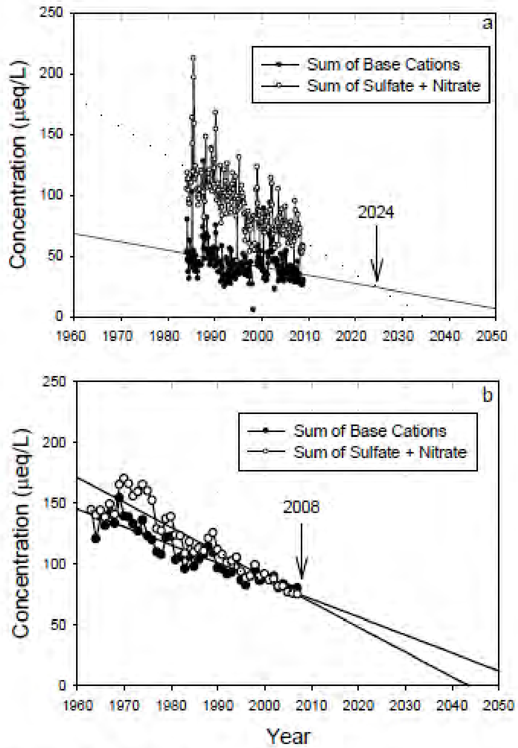



**Figure 17.** Long-term trends in the relative distribution of anions (on an equivalence basis) and total anion concentration (in µeq/L) in bulk precipitation at the HBR. Note that $SO_4^{2-}$ and $Cl^-$ have decreased in importance over the long-term, while $NO_3^-$ has increased. However, recent declines in $NO_3^-$ may be altering this long-term pattern. At current rates of change $SO_4^{2-}$ and $NO_3^-$ concentrations will be equivalent in 2031.



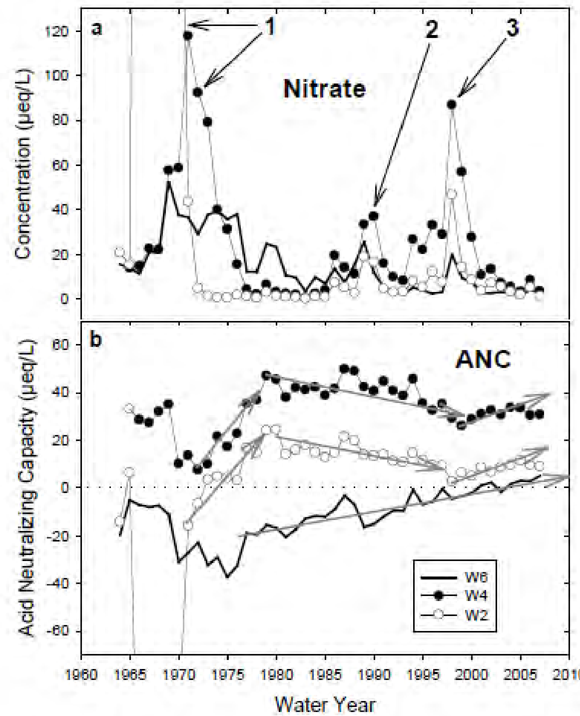




**Figure 18**. Annual volume-weighted concentrations of the sum of base cations ($C_B$) and the sum of concentrations of $SO_4^{2-}$ plus $NO_3^-$ in soil solution and stream water of W6 at the HBR. Concentrations of $C_B$ decrease with decreases in $SO_4^{2-}$+$NO_3^-$. Mineral soil solutions of the high elevation hardwood zone are highly acidic ($SO_4^{2-}+NO_3^- >> C_B$). This zone coincides with the elevation of marked sugar maple decline. In streamwater draining the entire watershed long-term declines in $SO_4^{2-}$+$NO_3^-$ are approaching $C_B$ and we anticipate positive values of acid neutralizing capacity in the future.

**Figure 19.** Long-term trends in annual volume-weighted concentrations of $NO_3^-$ and acid neutralizing capacity (ANC) in reference (W6), and cut (W2: devegetation and herbicide treatment; W4: strip-cut) watersheds at the HBR. Note there has been a long-term decrease in concentrations of $NO_3^-$ in W6 in recent years with increasing ANC. In contrast $NO_3^-$ concentrations have varied in cut watersheds (W2, W4) corresponding with changes in ANC. The large initial increase in $NO_3^-$ in W2 and W4 was the result of the experimental cutting (1). The increase in $NO_3^-$ in the late 1980s was the result of a soil freezing event (2), and the increase in the late 1990s was the result of an ice storm (3).

Over the last 45 years, significant declines in strong acid anion concentrations in drainage waters have been balanced to some degree by declines in concentrations of base cations (Likens et al. 1996, Palmer et al. 2004). Interestingly, the stoichiometry of these changes varies with landscape position (Johnson et al. 2000). In the high elevation hardwood zone where sugar maple decline is clearly evident, concentrations of $SO_4^{2-}$+$NO_3^-$ in mineral soil solution greatly exceed the sum of base cations ($C_B$) (Fig. 18). ANC is highly negative and not expected to reach positive values for some time. For the watershed as a whole, declining stream $SO_4^{2-}$+$NO_3^-$ now balance $C_B$, and positive ANC is anticipated in the near future. Recovery from acidification is indicated by increasing ANC and decreasing concentrations of inorganic monomeric Al (Ali) in drainage waters throughout W6. However, persistently low $Ca^{2+}$/Ali ratios (<1) in mineral soil solutions and tree fine roots on upper slopes may be evidence of continuing Al stress to trees (Cronan and Grigal 1995; Palmer et al. 2004).

## C. Background and Hypotheses on Air Pollution Disturbance

**1. Long-term Biogeochemical Processes and Stoichiometric Interactions.** Future changes in atmospheric deposition of S and N are difficult to predict. The 1990 CAAA will be fully implemented in 2010, and emission reduction targets have already been met. A number of proposals have been advanced to further reduce emissions of $SO_2$ (50-75% reduction) and $NO_x$ (66-70% reduction; Driscoll et al. 2001). We will continue to track atmospheric deposition and major ion chemistry in soil solutions and stream water. As a result, we will be well positioned to assess the response of this acid-sensitive site to anticipated decreases in acidic deposition when additional control measures are implemented.

The dynamics of S across forested landscapes at the HBR remain somewhat mysterious. Rates of long-term decreases in $SO_4^{2-}$ concentrations in forest floor leachate are greater than rates observed in atmospheric deposition. The cause of this discrepancy is unclear. One possibility is dry deposition; estimates of dry S deposition are not well constrained. Our record of dry deposition does not yet resolve this discrepancy, but measurements over a longer period and improved methods may help. Another possibility suggested by both mass balance (Likens et al. 2002) and PnET-BGC calculations (Gbondo-Tugbawa et al. 2002) is that atmospherically deposited S can be retained in watersheds by vegetation uptake and soil adsorption and subsequently released under conditions of lower S deposition. Watershed S retention is greatest on lower slopes of the experimental watersheds due to thicker soils and deeper surficial deposits (Fig. 8). Analyses of stable isotopes of $SO_4^{2-}$ ($\delta^{34}$S and $\delta^{18}$O) at HBR and elsewhere have strongly suggested that additional internal sources of S have influenced $SO_4^{2-}$ loss to surface waters (Alewell et al. 1999, Mitchell et al. 2001, Likens et al. 2002, Bailey et al. 2004). Gbondo-Tugbawa et al. (2002) modified the PnET-BGC model to account for different stable S isotopes, confirming that uncertainties in predicting the contributions of dry S deposition, S mineral weathering, and mineralization of soil organic S are critical in making long-term predictions of $SO_4^{2-}$ concentrations in surface waters. A key question for ecosystem recovery resulting from decreases in atmospheric S deposition is whether inputs of S will be reversibly released to drainage waters or irreversibly retained.

Model calculations using PnET-BGC suggest that recovery of W6 from decreases in acidic deposition will occur slowly over a period of several decades (Driscoll et al. 2001). Several watershed processes influence the rate of ANC response to decreases in atmospheric deposition, including depletion of exchangeable base cations from soil, watershed N retention, desorption of previously adsorbed $SO_4^{2-}$, and net mineralization of soil organic S. As decreases in inputs of strong acids from atmospheric deposition continues to decrease concentrations of $SO_4^{2-}$ and $NO_3^-$ to lower and lower levels, we anticipate that naturally occurring organic acids will play a more prominent role in regulating the acid-base and elemental chemistry of drainage waters. Concentrations of DOC are higher in soil solutions and stream reaches on upper slopes, declining to low levels at gauging stations (Palmer et al. 2005). The episodic acidification of stream water in W6 is due in part to the supply of naturally occurring organic acids delivered through shallow hydrologic flowpaths especially at higher elevations (Fig. 8).

***H1.1:*** *Soil solution and surface water pH will become increasingly sensitive to acid pulses (e.g., snowmelt) as the ionic strength of these solutions continues to decline with additional emission controls.*

***H1.2:*** *As soil solution and streamwater $SO_4^{2-}$ decline, the stoichiometry of C, S and Ca (and other base cations) will shift to reflect the composition of the dominant organic sources.*

**2. Soil Calcium Depletion and Ecosystem Function.** To examine ecosystem response to long-term depletion of $Ca^{2+}$ from acidic deposition, we initiated a $Ca^{2+}$ addition experiment (W1). 45 tons of $CaSiO_3$ (wollastonite) was added to W1 by helicopter in 1999. This long-term experiment was designed to gradually replenish the $Ca^{2+}$ depleted from the soil exchange complex since the advent of acidic deposition. The added wollastonite has unique $^{87}Sr/^{86}Sr$ and Ca/Sr ratios, facilitating the tracking of the added $Ca^{2+}$ in soil, soil water, vegetation and stream water. To date, most of the added $Ca^{2+}$ has been retained in the forest floor. However, we have detected significant amounts of the added $Ca^{2+}$ in vegetation (Dasch et al. 2006), soil solutions (Cho et al in press), and stream water (Nezat et al. in review). The treatment response has been most evident in the upper reaches of the watershed, due to shallow, more acidic soils (Cho et al. 2009). We have observed marked changes in the Ca/Al of soil and soil solutions in response to the experimental treatment (Cho et al. 2009). Moreover, there has been a marked improvement in sugar maple health, survival and mycorrhizal colonization (Juice et al. 2006; Fig. 20) and reduced winter injury of red spruce (Hawley et al.2006) in W1 compared to the reference watershed. Concomitant changes in the detrital and herbivore food web (Fisk et al. 2006, Skeldon et al. 2007) also are likely to drive responses in soil chemistry and forest nutrition. For example, feedbacks between changes in soil pH, the soil microbial community, and foliar nutrition (e.g., protein and fiber content) could have cascading consequences for Lepidopteran larvae and their predators (e.g., Stange 2009, Schwenk et al. 2009). Moreover, new studies funded by USDA-NRICGP suggest that $Ca^{2+}$ additions decrease C flow through the detrital food web and could increase C stabilization in soil organic matter.

***H1.3:*** *Addition of $Ca^{2+}$, replacing that lost from historical acidic deposition, will promote the ability of trees to form normal mycorrhizal associations, mitigating the effects of long-term acidification and restoring the health of Northern Forests.*

***H1.4:*** *Increased $Ca^{2+}$ recycling through detritus and soil organic matter will promote the stabilization of soil C and retention of N in soil organic matter.*

**3. Nitrogen Deposition and Retention.** Current N losses in streamwater in our biogeochemical reference watershed are near the analytical detection limit for $NO_3^-$, and are at the lowest level in the 45+ year history of measurements at the site (Fig. 19). This low level of $NO_3^-$ leaching contradicts two hypotheses based on ecosystem theory. First, as a forest ages and NEP declines to zero, $NO_3^-$ leaching should increase until $NO_3^-$ outputs roughly equal N inputs (Vitousek and Reiners 1975). NEP is negative for the HBR ecosystem (Fahey et al. 2005a), suggesting that $NO_3^-$ leaching should be high. Second, the theory of N saturation (Aber et al. 1998) proposes that under elevated N deposition, N will accumulate until it meets or exceeds biological N demand, when high $NO_3^-$ leaching should commence. Nitrogen deposition at HBR has been elevated over background levels for the entire period of record (Fig. 4) and most deposited N is retained in the ecosystem (Dittman et al. 2007), yet the stream record shows a long-term pattern of decreasing $NO_3^-$ (Fig. 5). Stream $NO_3^-$ has also declined at other sites in the region, in both old-growth and successional forests (Martin et al. 2000, Goodale et al. 2003, Driscoll et al. 2007).

Because the low level of $NO_3^-$ leaching contradicts expectations based on these theories, this situation provides an opportunity to better understand the N cycle in temperate forests. Our modeling studies suggest that neither climate variation, fertilization by $CO_2$, nor recovery from insect infestation suffice to explain the protracted $NO_3^-$ decline (Aber et al. 2002, Hong et al. 2005). Our field studies discount the importance of changes in stream denitrification losses as an explanation for this temporal pattern (Bernhardt et al. 2005, Warren et al. 2007). Denitrification from soils could contribute to the low stream $NO_3^-$ losses at HBR (Groffman et al. 2006), but soil denitrification estimates are poorly constrained (see Section III. Press and Pulse Disturbance of Forests). Accumulation in soil organic matter seems to be the principal fate of the retained N (Dittman et al. 2007); this sink may wax and wane with ecosystem development following pulse disturbances.

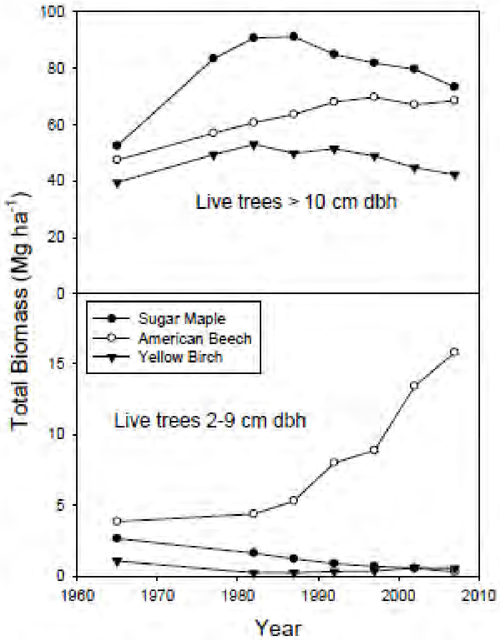



**Figure 20.** Time series of biomass by major hardwood tree species in W6 at the HBR, including total live trees (≥ 10 cm dbh) and total live trees (2-9 cm dbh).

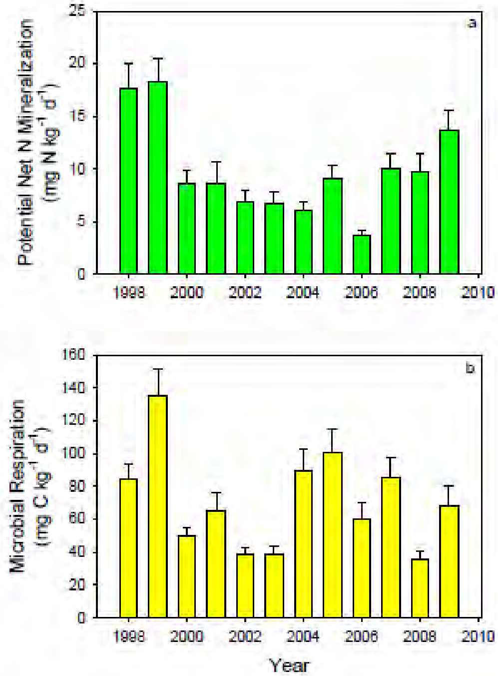



**Figure 21.** Long-term trends in annual average potential net N mineralization (a) and microbial respiration (b) in W6 at the HBR.

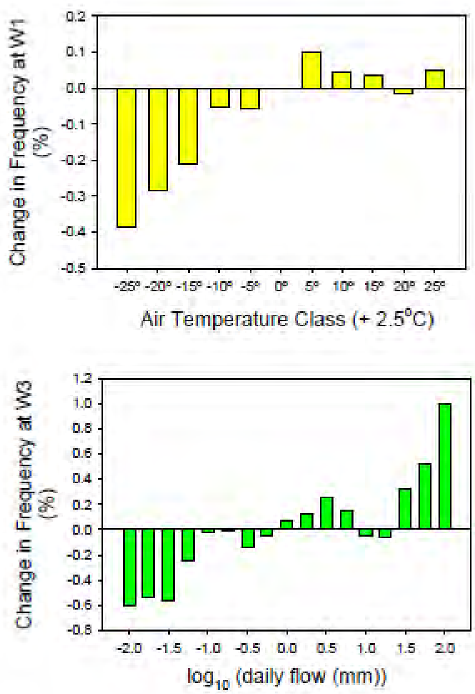



**Figure 22.** Histograms of long-term change in air temperature by temperature class (a) and change in frequency of discharge for classes of daily discharge in W3 at the HBR.

Accumulation of N in soil could be occurring through three possible mechanisms. First, organic C and N (solid or dissolved) from litter decomposition could be accumulating together in soils. Second, inorganic N from atmospheric deposition could be taken up by microbes and subsequently stabilized in soil organic matter. Third, N could be accumulating without corresponding C accumulation, such as by processes of abiotic $NO_3^-$ incorporation onto soil organic matter (SOM) (Dail et al. 2001). The first two mechanisms predict coupling between C supply, microbial activity and N retention. We have observed striking seasonal and annual variation in microbial biomass and N mineralization over 12 years of monitoring at HBR (Fig. 21), despite a relatively stable supply of C by aboveground litterfall. This pattern would imply that C supply from roots (turnover and rhizosphere C flux) might interact with climatic variation to influence soil microbial activity. The research we propose is targeted at revising current theories of N retention and resolving the mystery behind the current low N export in stream water from these forests.

***<u>H1.5</u>:*** *The current low N export is caused by N retention in mineral soil, restoring N previously depleted during rapid biomass accumulation.*

***<u>H1.6</u>:*** *As C and N are released in organic forms from the detrital complex, they are co-stabilized in mineral soil organic matter. Alternatively, N accumulates primarily by microbial immobilization and subsequent conversion to recalcitrant forms.*

**4. Interaction of C, N, P and Ca in Forest Production.** The stoichiometric coupling among key elements – C, N, P, Ca – may be disrupted by the combined press and pulse disturbances associated with air pollution and forest harvesting. Ecosystem theory predicts that productivity should be co-limited by multiple resources (Bloom et al. 1985), but limits of biological responses to the disruption of element balances are expected (e.g., in N saturation theory; Aber et al. 1998). Most of the P supply to vegetation in the organic-rich soils at the HBR is from mineralization of forest floor P (Yanai 1992), an observation that also applies to $Ca^{2+}$ (Blum et al. 2008), while the supply of both nutrients can be augmented by weathering of the ubiquitous primary mineral apatite. Moreover, $Ca^{2+}$ availability regulates soil pH which strongly modulates soil P availability (Schlesinger 1997), in part through effects on phosphatase enzyme activity (Carreira et al. 2000). We have extended the Multiple-Element Limitation model (Rastetter and Shaver 1992) to include P limitation and applied it to the Hubbard Brook forest to evaluate changes in plant allocation to resource acquisition during ecosystem development under chronic N deposition (Yanai et al., in prep.). The results suggest that young aggrading forests are more P limited than mature forests (Fig. 3), under current N deposition rates. Following disturbance, the changing nutrient supply and demands of accumulating biomass alter the balance between N and P supply and demand. This imbalance could be mitigated by plant allocation of effort for resource acquisition, for example by enhanced mycorrhizal weathering of P minerals (van Breemen et al. 2000, Landeweert et al. 2001) or by production of phosphatase enzymes to obtain P from soil organic matter.

***<u>H1-7</u>:*** *Under current atmospheric N deposition rates, young aggrading northern hardwood forests are primarily P limited whereas mature forests are primarily N limited.*

***<u>H1-8</u>:*** *Nitrogen fertilization exacerbates soil P limitation, an effect that is ameliorated by promotion of mineral weathering and mineralization of organic P.*

### D. Approaches to Objective 1: Air Pollution Disturbance

We propose to continue to examine long-term changes in the acid-base chemistry of soil solutions and stream water in response to decreases in atmospheric deposition of $SO_4^{2-}$ and $NO_3^-$ to test H1.1 and H1.2. We will compare trends during base-flow and high-flow snowmelt periods. We will also use hydrologic tracers and end-member mixing analysis coupled with hydrologic models to examine the mechanisms driving changes in stream chemistry during high-flow conditions (e.g., Chen and Driscoll 2005b, Demers et al. in press). Studies of solute fluxes, soils, and vegetation dynamics on Ca-treated W1 are supported by LTER funding, augmented by several grants from NSF, USDA-NRI, and the Mellon Foundation. Continuing measurements including isotopic analyses of solutions, soils, and tissues will contribute to addressing H1.3 and H1.4 and further advancing our understanding of $Ca^{2+}$ dynamics on the base-depleted soils of HBR and other Northeastern forests.

Continued vigilance in the monitoring of stream chemistry, soil N transformations, and foliar and litter N is needed to document the appearance of N saturation symptoms at HBR. Further, we propose new studies employing stable isotopes to evaluate the mechanisms of N accumulation in soil and thereby test H1.5 and H1.6. First, we will examine abiotic nitrosation (Fricks et al. 2009) by applying double-labeled $NO_3$ ($^{15}N$, $^{18}O$) to isolated soil cores of organic and mineral soil horizons. Retention of both $^{15}N$ and $^{18}O$ with SOM would indicate direct, abiotic incorporation of $NO_3^-$ into SOM because oxygen is microbially assimilated during $NO_3$ reduction and hence involves chemical incorporation of both labeled N and O. Second, we will add double-labeled ($^{13}C$, $^{15}N$) plant litter to *in situ* soil mesocosms and measure the accumulation of the labels in various SOM fractions (light, humic, humim, microaggregates) (Bird et al. 2008). Third, we will add $^{15}NO_3$ to separate microcosms and recover $^{15}N$ in various SOM pools to quantify the kinetics of N incorporation into various SOM fractions.

We propose to use a field experiment in conjunction with the Multiple Element Limitation model (Rastetter and Shaver 1992) to address H1.7 and H1.8. The field experiment has been designed as a factorial study (control, N, P, and N + P fertilization) in young (30-yr old) and mature (100-yr old) stands across a range of site quality conditions (especially soil chemistry), including BEF, HBR and one other site in White Mountain NF, thereby allowing a rigorous, general test of the hypothesis. Experimental plots have been established and comprehensive pre-treatment measurements completed. We intend to begin fertilization treatment in August 2010, continuing through the duration of this proposed LTER funding. A proposal under review at NSF would permit detailed process measurements to augment the tree growth response work supported by this LTER project.

## III. Press and Pulse Disturbances of Forests

**A.** ***Objective 2.*** *Describe and explain the response of ecosystem structure, function and community composition across the complex HBR landscape to multiple and compounded disturbances associated with forest harvest, exotic pests, and weather events.*

### B. Introduction

The idealized model of ecosystem development described by Bormann and Likens (1979) involved a sequence of stages of recovery following catastrophic disturbance and the ecosystem structural and functional attributes associated with these stages. A shifting mosaic of stands with differing attributes was predicted to characterize the mature steady-state forest ecosystem. However, these predictions have not played out in the ~100-yr-old reference watershed W6 (Siccama et al. 2007, Fig. 1), because of unexpected growth declines and increased mortality of key dominant species (especially sugar maple and birches; Fig. 20). At the broad scale of the wider HB valley, biomass accumulation has also stopped unexpectedly (Solomonoff et al., in review).

We propose a new concept of landscape-scale population demography for forest trees that recognizes how geomorphic and hydropedologic phenomena interact with climate and pulse-disturbance drivers to shape the environmental complex. Such a concept is an essential extension of the HBR ecosystem development model. Key habitat features of heterotrophs also depend upon this landscape-vegetation-disturbance nexus, shaping the trophic structure of both herbivore and detrital food webs. The complex spatial patterning of vegetation also affects heterotroph distributions (Jones et al. 2007) and influences the top-down and bottom-up food-web feedbacks that regulate their population dynamics (see Fig. 12, 13). A more spatially explicit view of the HBR ecosystem that considers linkages between geohydrology, biogeochemistry, and ecological patterns and processes is essential for advancing our understanding of forest response to human-accelerated environmental change.

The Northern Forest is being assaulted by an unprecedented suite of perturbations that could exceed the resilience of forest ecosystems and threaten the normal structure and functions that provide many valuable ecosystem services (ES; Fig. 8). In addition to climate change and unusual weather events, like the exceptional 1998 ice storm and 2002 summer drought, the Northern Forest could be struck by devastating native or exotic insect pests (Lovett et al. 2006). Moreover, the burgeoning demand for low-grade wood products associated with developing solid biofuel markets (Richter et al. 2009) could result in intensified forest harvest and shortened rotation lengths. Bormann and Likens (1979) anticipated the possibility of these increasing pressures on Northern Forests and predicted in their conceptual model the progressive deterioration of ecosystem function in the face of compounded disturbances.

We propose a quantitative test of these ideas in the context of intensified forest harvest and soil $Ca^{2+}$ depletion. By our calculations, the combined effects of chronic leaching associated with elevated acidic deposition and two cycles of forest harvest have pushed the experimental watersheds (W2, W4, W5, W101) at HBR near the limit of Ca-supplying power, and we anticipate that a third harvest cycle could exceed that limit. Moreover, the shortened cycle could promote a forest community composition that will suppress the abundance of valuable sawtimber species (Tierney and Fahey 1998) resulting in drastic rearrangement of ES and economic values (Erickson et al. 1999). These combined changes would represent an ecosystem state shift (Scheffer et al. 2009).

The HBR-LTER has a long history of providing scientific information to influence public policy. With this proposed experiment we plan to integrate social science and policy aspects into our research agenda. Although landowner decisions might be expected to determine the amount and impacts of wood energy use in the Northern Forest, progressive deterioration in ES could influence local and regional policy makers to alter regulatory priorities and override parcel-specific management decisions. We propose to explore this nexus of interactions between ecological and social systems through a small watershed-scale field experiment, surveys of the local public, and observations of regional policy processes.

## C. Background and Hypotheses on Forest Disturbance

**1. Forest Decline.** Declines in the abundance of any population result from systematic changes in one or more of the three key demographic processes: recruitment, growth and survival. For forest trees, population growth is most sensitive to the survival of adults (Silvertown et al. 1993, Franco and Silvertown 2004). Moreover, there is a direct connection between tree growth and survival (Manion 1981, Franklin et al. 1987). Growth of a tree can be understood as an integrated measure of the physiological influences that contribute to its likelihood of survival (Kyto et al. 1996). Manion (1981) incorporated this connection between growth and survival in the concept of the decline spiral, in which various stresses reduce tree growth rates and predispose them to decline-inciting factors. Press and pulse disturbances, both natural and anthropogenic, can serve as predisposing stresses and inciting factors. For example, a press disturbance of nutrient limitation or drought may be exacerbated by soil deterioration from acidic deposition. The Northern Forest is experiencing a broad suite of these press and pulse disturbances, yet the potential impacts on tree survival remain largely unexplored. Both the frequency and intensity aspects of these perturbations and the sensitivity of trees to their effects will vary across the complex landscape due to factors such as elevation, soils, drainage, and exposure.

The long-term, multi-scale network of permanent forest plots at HBR provides an exceptional opportunity to explore these interactions in our rapidly changing environment (Fig. 14). Our inventory of canopy tree survival in unmanaged forests through space (small watershed, vegetation community, entire HB valley) and time (44 years) are explicitly linked to measured environmental conditions (nutrient supply, temperature gradients, disturbance history) and biological interactions (competition, disease incidence) that are known to influence tree growth and survival. The drivers of demography for long-lived organisms are complex, but sufficient information exists to build predictive models (Das et al. 2008). The analysis of these models will help identify the key stressors, and the failure of these models when confronted with the empirical record from our forest monitoring network will direct our subsequent efforts to quantify unrecognized or underappreciated aspects of tree growth and survival.

Northern Forests have been affected by a variety of native (e.g., forest tent caterpillars, spruce budworm, bark beetles) and exotic pests and pathogens (e.g., gypsy moth, beech bark disease). Within the next funding cycle of the HBR-LTER, we can anticipate the possible arrival at the HBR of two devastating insect pests: the hemlock wooly adelgid (McClure 1987) and the emerald ash borer (Haack et al. 2002). These pests are rapidly expanding their ranges from the south and west, and there seems to be little native resistance in the eastern hemlock or white ash populations. Although hemlock is confined to the lower elevation zones of the HBR, it is especially abundant in riparian areas where the effects of sudden mortality could significantly alter biogeochemistry and stream processes.

***H2.1*:** *The decline in live biomass in W6 (Fig. 1) will continue and it will be observed more broadly across the HB valley, associated with the decline of dominant species (sugar maple, beech, birches) and the anticipated arrival of new decline agents.*

***H2.2*:** *Landscape-scale variation in mortality rates of trees in the Northern Forest can be explained by the combination of chronic stress and multiple pulse disturbance events.*

**2. Forest Compositional Changes and Biogeochemical Feedbacks.** Sugar maple and American beech are co-dominant, extremely shade tolerant tree species in the shifting-mosaic steady-state forest. The widespread mortality of beech caused by the beech bark disease complex (Houston 1994) and the sporadic decline of sugar maple (associated in part with soil available nutrient cation depletion, Horsley et al. 2000) are profoundly altering the dynamics of the Northern Forest. In some but not all settings, increased beech mortality facilitates expansion of sugar maple populations, and ongoing research at the HBR and other sites in the region seeks to explain and predict the patterns of response (Griffin et al. 2003, Wheat et al., in review). These two species have quite different effects on surface soil properties; for example, sugar maple litter decays more rapidly than beech and promotes nitrification beneath its canopy (Lovett and Mitchell 2004). Hence, shifts in dominance between these species may have consequences for key biogeochemical processes, as well as feedbacks to future responses of forest composition to human-accelerated environmental change.

These interactions between beech and maple are being played out on the larger stage of the complex landscape at the HBR, and several key demographic features of the populations vary across the landscape. For example, beech reproduces both by sprouting and seed (Cleavitt et al. 2008b), and the contribution of these modes to future abundance varies with elevation and with decline status of beech (Wheat et al., in review). Our broad-scale surveys of sugar maple reproduction suggest higher seedling survivorship in landscape positions where subsurface hydrologic flowpaths ameliorate surface soil acidification by transporting more base-rich groundwater to the surface (Cleavitt et al., in prep.). In addition, higher N availability increases susceptibility of beech to beech bark disease (Latty et al. 2003). Sorting out these influences on the future balance between maple and beech at the HBR and generalizing these relationships across the Northern Forest region requires continued surveys, building upon our recent work. Extrapolating these findings to the landscape scale and determining the consequences for watershed biogeochemistry will require a model in which tree species composition can shift over time and species have different effects on ecosystem processes such as production, decomposition, and nutrient cycling (Lovett et al. 2006).

***H2.3*:** *Variation in key demographic parameters of sugar maple populations across the HB valley are explained not only by climatic factors, but also by landscape-scale patterns of hillslope hydrology and biogeochemistry.*

***H2.4*:** *Changes in tree species composition caused by exotic pests, climate change and other disturbances will be a primary driver of C and N cycle responses across the landscape.*

**3. Intensified Forest Harvest.** Interest in wood energy has increased recently, and the prospects for this energy source are particularly good in the Northeast (Kroetz and Friedland 2008), where several scenarios for increased wood energy use (e.g., power plants, home heating, and “fuel for schools” programs) are already being developed. Increasing wood energy production in the Northeast raises serious concerns about sustainability and trade-offs among ES (Likens and Franklin 2009). Earlier research at the HBR produced recommendations for the sustainable management of Northern Forests, suggesting harvest cycles of at least 80-100 yr (Likens et al. 1978), but rapid growth in wood energy demand would likely lead to shortened harvest cycles. Particular concern revolves around soil base cations, which have been seriously depleted on many sites as a result of the combined effects of acid deposition and forest harvest (Likens et al. 1998, Warby et al. 2009). How far can these ecosystems be pushed before radical shifts in system state result in serious deterioration of ES (Scheffer 2009)?

At the nexus of interactions between social and ecological systems, ES are a function of both the provision capacity of the ecosystem and the human demand for ES benefits (Beier et al. 2008). Forest management and land use practices strongly influence how ES are provided (Lambin et al. 2003), and management for bioenergy will change ES provision in complex ways, distributed over various time and spatial scales. Inaccurate accounting of these changes in ES in current legislation could create incentives for large-scale forest clearing that have myriad ES effects (Wise et al. 2009). A key challenge at the frontier of coupled natural-human systems is to evaluate how changes in ES interact both with larger-scale issues like energy security and with local energy production to influence decision making processes (Liu et al. 2007). Our proposed studies of socio-ecological feedbacks in the context of intensified forest harvest will move the HBR-LTER into a new arena of discovery and public policy analysis (Fig. 8).

***H2.5**: Intensified harvest associated with expanding biofuel markets can push forest ecosystems beyond their capacity for resistance to pulse disturbances, resulting in an "ecosystem state change" and consequent productivity decline, compositional shifts and severe surface water acidification.*

***H2.6**: Human perceptions of deterioration of ecosystem structure and function, and resulting changes in provision of ES, can result in pressure on policy makers that override market forces.*

## D. Approaches for Objective 2: Forest Disturbances

We have established a suite of permanent forest plots in the HBR in conjunction with watershed experiments and other studies; these plots allow us to quantify forest change at a variety of scales. Periodic remeasurements of tagged trees allow us to characterize tree growth, mortality and recruitment, and by applying site-specific allometric equations, we are able to estimate biomass with known precision and accuracy (Fahey et al. 2005a). We will evaluate H2.1 with re-census of W6 in 2012 and the entire HB valley in 2015-16; these surveys are augmented by permanent plots in several other experimental watersheds (W1, W2, W4, W5, W101), as well as other mapped and intensive plots (Siccama et al. 2007). Inevitably, the forest on these plots will be affected by pulse disturbances – during the last LTER cycles by an intense ice storm (1998; Rhoads et al. 2002), severe drought (2002), and a localized frontal windstorm (2001) – as well as chronic stresses. These remeasurements will allow us to continue to evaluate causes of tree mortality and to test H2.2. We will also monitor the low-elevation forest annually for evidence of the appearance of the hemlock wooly adelgid and the emerald ash borer.

During the last LTER cycle we evaluated forest change associated with canopy gaps created by mortality of American beech due to beech bark disease (Cleavitt et al., in prep., Lovett et al., in prep.), and we documented the patterns of sugar maple recruitment across the HBR landscape. These observations suggested a level of complexity in these patterns not heretofore recognized in northeastern forests. We suspect that these observations may be explained in part by landscape-scale variation in soils and hillslope hydrology. To test H2.3 we propose to monitor patterns of beech and maple regeneration (seed production and germination, sprouting, and survivorship) on selected plots across the complex landscape gradient within the HB valley. To examine H2.4 we propose to use our information on the physiographic, geologic and soil features that influence the distribution of these competing species to forecast compositional changes across the HBR landscape. Then we will employ a biogeochemical model parameterized for individual species to predict consequences for C and N dynamics within the HBR.

We propose a small watershed-scale experiment coupled with regional wood-energy production scenarios and landowner surveys to address H2.5 and H2.6; separate funding is being sought to provide support for establishment of the proposed experiment, and LTER funds will be used to continue monitoring of the study for the longer time scale (i.e., beyond 3 yrs post-treatment). This work would be conducted in collaboration with regional social science experts. The proposed experimental treatment will be a whole-tree harvest of an early-succession experimental watershed, simulating the effects of short-rotation forestry on ecosystem dynamics and health. Detailed measurements of soils, vegetation, heterotrophs and surface water will be conducted to quantify the response of ES. Wood energy production scenarios will be developed for the region in conjunction with our ongoing HBRF *Science Links* project. A questionnaire will be used to assess environmental attitudes, knowledge, intention and behavior related to forest management, energy resources and land-use change among representative stakeholders. A "forest ecosystem services toolbox" will be developed to integrate ES responses, land-use change, and energy production scenarios and socioeconomic information to test H2.6 and related questions regarding the feedbacks among intensified forest harvest, ES and socioeconomic systems.

## IV. Disturbance from Climate Change

**A.** ***Objective 3.*** *Quantify the responses of ecosystem structure and function and biotic community composition and phenology to the press disturbances associated with changing climate.*

### B. Introduction

The long-term record from HBR provides clear evidence of a changing climate in the northeastern U.S. Over the 55 years of record, annual average temperature at HBR has increased by about 0.5$^{o}$C. This increase has been more pronounced in the winter than the summer. Over the same time period, total annual precipitation also has increased significantly, by about 100 mm/yr (Fig. 9). Surprisingly, the changes in these two key drivers have been accompanied by a slight reduction in annual evapotranspiration in our hydrologic reference watershed, W3 (Fig. 9). The warming winter climate has resulted in a significant reduction in the depth and duration of the snowpack (Fig. 10), with likely consequences for the frequency and extent of soil freezing (Henry 2008). Although we cannot conclusively ascribe recent extreme climatic events (e.g., ice storm, drought) to global climate change, these events are in accord with expectations of climate change science (Hayhoe et al. 2007). We have noted marked decreases in extreme cold temperatures (Fig. 22), which may have implications for the success of anticipated insect pests such as the hemlock wooly adelgid. We have also seen an increased frequency of high-flow events and a decreased frequency of low-flow events due to the long-term increases in precipitation at HBR (Fig.22). We would anticipate that these trends will continue and probably accelerate in coming years (Meehl et al. 2000).

How will ecosystem structure and function and the provision of ES in the Northern Forest respond to continuing climatic change? The HB valley lies at the interface between the broadleaf deciduous forest biome and the evergreen needleleaf biome (Fig. 23). Recent evidence suggests that climate change responses are occurring in this ecotone (Beckage et al. 2008), but we anticipate that complex feedbacks between vegetation and environment will influence ecosystem dynamics (Siccama 1974). Although elevation might be considered as a spatial surrogate for changing climate (Fukami and Wardle 2005, Korner 2007), the elevation gradient encompasses a complex hydrogeologic and biogeochemical template over which physical conditions and soil resources exhibit complex patterns (Fig. 6). Predicting the responses of vegetation dynamics and productivity, heterotroph populations and food webs, and nutrient cycling and hydrology to the changing climatic drivers presents a challenge that requires a new level of study of ecosystems in a large landscape context. We would anticipate that a variety of possible feedbacks could lead to "tipping-point" behaviors in ecosystem structure and function, and our proposed conceptual model of the landscape ecosystem may be particularly relevant for identifying these phenomena. Evaluating and testing the mechanisms that underlie ecosystem responses to climate change at the HBR will also allow us to translate patterns and processes to the regional scale.

We propose an integrated suite of new and continuing studies to improve understanding of climate change disturbance at the HBR. In the mid-1990s we expanded the scale of monitoring over the 3,000-ha HB valley (Fig. 14), where we periodically measure vegetation, soils, surface water, and bird and small mammal populations (Schwarz et al. 2003, Jones et al. 2007, Betts et al. 2008). We propose to expand this monitoring to include additional key environmental parameters (especially soil freezing and stream temperature) and biotic populations (salamanders, arthropods and moose) to allow us to formulate and test predictions of spatially explicit landscape-scale responses to climate change. This work will be integrated with high resolution mapping of landform shape and landscape position based on Lidar and other imagery. This large landscape work will facilitate extrapolations from hillslope-scale studies of hydropedologic and linked biogeochemical processes within our intensive reference watersheds (e.g., W3; Fig. 24). We will employ data assimilation approaches to improve data-model linkages in these studies as well as to link long-term measurements of ecosystem C dynamics (Fahey et al. 2005b) to continuous records of tower-based NEP at our nearby affiliated station, BEF, a NEON relocatable site. Finally, we will employ linked ecosystem simulation modeling and remote sensing to translate our

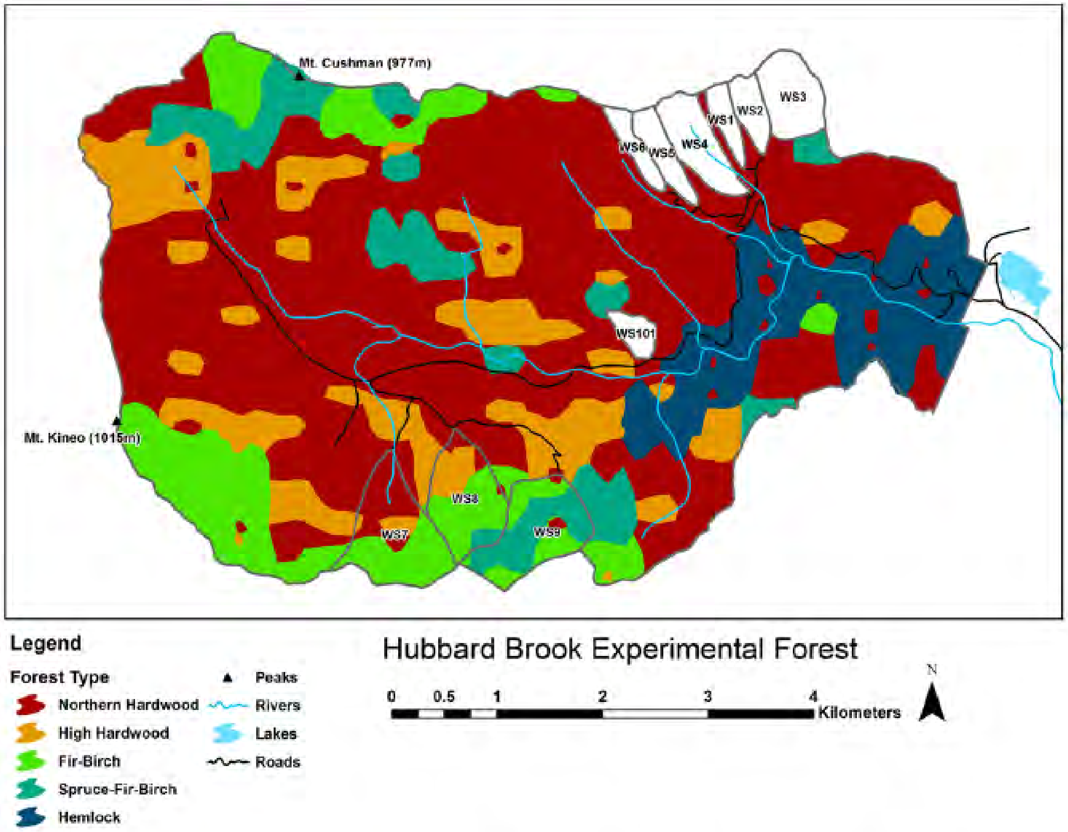



**Figure 23**. Map of forest types across the Hubbard Brook valley based on analysis of 450+ permanent plots (see Figure 14).

research results into predictions across the region.

## C. Background and Hypotheses on Regional Climate Change

**1. Winter Climate Change.** Winter processes play a key role in the biogeochemistry and hydrology of Northern Forest ecosystems (Campbell et al. 2005, 2009). A cohesive analysis of the influence of winter climate change on ecosystem dynamics has been hampered by a disconnect among laboratory, plot and watershed-scale studies (Henry 2007). We have conducted plot-level studies of soil freezing at the HBR over the past decade (Groffman et al. 2001, Cleavitt et al. 2008a, Steinweg et al. 2008), and building on that work we now propose additional mechanistic, landscape and modeling research.

For example, we ask where and why soil freezing might increase in a warmer world. "Tipping points" in soil freezing across a complex landscape can be expected because of the spatial distribution of snowpacks too shallow to insulate the soil and air temperatures too warm to freeze the soil (Henry 2008). These factors interact with canopy radiative properties and the insulating properties of the forest floor, both of which are influenced by forest composition (e.g., hardwood vs. conifer), resulting in landscape-scale variation in freezing response. These biophysical features of winter climate likely influence biogeochemical and hydrologic responses at the catchment scale. Our previous studies showed that mobilization of N in frozen soils was associated with damage to fine roots (Cleavitt et al. 2008a) and soil freezing had effects on DOC, POC and DON (Steinweg et al. 2008). The role of root N uptake during high streamflow in early spring has received limited study, but the high capacity of the ecosystem to retain N in spring suggests that this mechanism may be important. How spring N retention will change in a warmer world depends upon complex interactions among soil freezing, duration of snowmelt, and plant and microbial processes that are currently poorly characterized.

***H3.1:*** *A winter climate "tipping point" can be identified, associated with non-linear response of soil freezing to warming temperatures across the complex landscape. As a consequence, soil processing of C and N will exhibit complex behavior in response to warming winter temperatures.*

***H3.2:*** *Winter climate change effects on soil microbial activity are mediated by C flux and the movement of DOC and POC from litter to soil organic matter.*

***H3.3:*** *Tree root uptake of N plays a significant role in N retention during spring snowmelt, a key function that will respond to winter climate change.*

**2. Hydropedology and Landscape Ecohydrology.** We propose continued development of hydropedologic research (Lin et al. 2003) focused on feedbacks between hydrology, soil characteristics, and catchment biogeochemistry in the hydrology reference W3 (Fig. 24). The classic description of HBR refers to soils as well-drained Spodosols developed in dense basal till (Likens and Bormann 1995). However, recent monitoring of hillslopes shows a transient water table at most sites, with duration and height varying with hillslope position (Detty and McGuire, submitted). The dominant drainage class in W3 is moderately well drained, with spodic horizon development, base saturation, and mineral soil C content all showing relationships with duration and height of water table development. Analysis of shallow water tables showed that above a critical depth in the soil profile, saturation increases transmissivity due to improved drainage efficiency and activation of near-surface preferential flowpaths. The observed threshold is best explained as a transmissivity feedback mechanism that allows for a rapid expansion of the runoff contributing area onto hillslopes. Further work to determine timing and transport characteristics of hillslope activation relative to location in the landscape and biogeochemical characteristics of preferential flowpaths by soil horizon is needed to understand the timing and chemistry of watershed runoff. Landform classes and topographic indices derived from a digital elevation model were predictive of soil morphology and chemistry, suggesting a method that may be capable of predicting spatial patterns in plant root uptake activity and in redox processes such as denitrification. For example, denitrification may occur primarily during "hot moments" of activity following rainfall events large enough to reduce soil oxygen conditions enough to foster high rates of denitrification. These conditions are most likely to occur in particular locations in the landscape (hotspots) where particular soil (forest floor depth) and hydrologic (water table) factors converge (McClain et al. 2003, Groffman et al. 2009b).

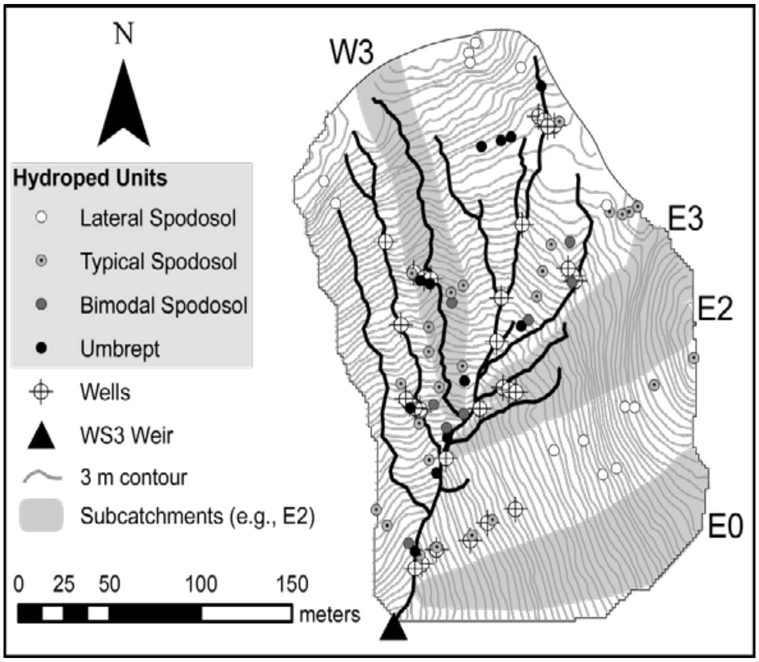



**Figure 24.** Map of hydrologic reference W3, the focus of ongoing and proposed work on geohydrology and hydropedology studies.

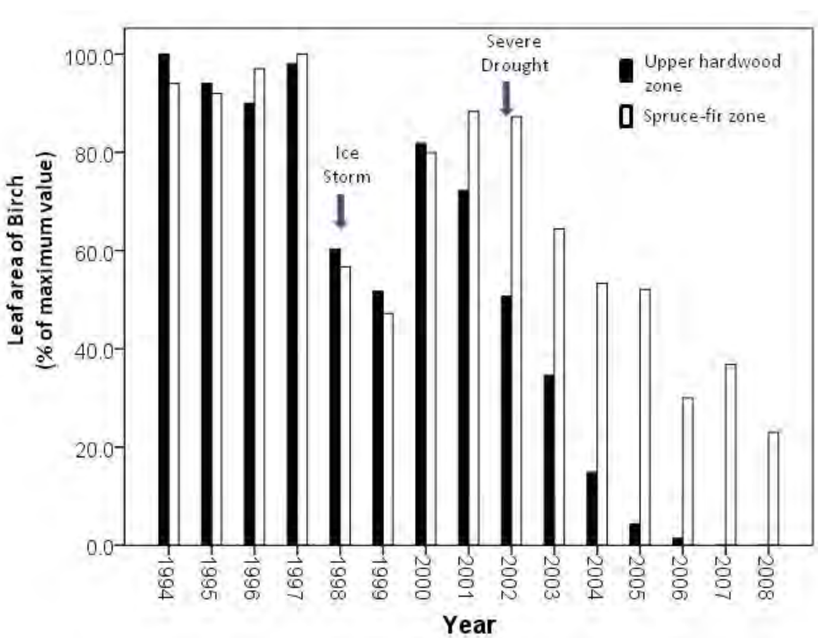



**Figure 25.** Time series of the relative leaf area (as a % of maximum value) of paper birch in the high elevation hardwood zone and spruce-fir- paper birch zone of W6 at the HBR. Severe birch decline followed a sequence of disturbance by an ice storm (1998) and summer drought (2002).

***H3.4*:** *A soil transmissivity feedback controls hillslope hydrologic activation, such that the effects of changing precipitation and evapotranspiration patterns on streamflow generation will exhibit complex behavior.*

***H.3.5*:** *Hydropedologic processes associated with transient water tables regulate the spatial and temporal dynamics of soil redox processes, tree nutrient uptake, and C and N processing.*

**3. Landscape Demography of Trees.** The population demography of trees across the HB valley – reproduction, growth and mortality – cannot be explained on the basis of our classical conceptions of ecosystem patterns and processes (Bormann and Likens 1979). We propose to explore a concept of landscape-scale demographic patterns and processes to evaluate the mechanisms controlling forest compositional responses to climate change and connections with press and pulse disturbances. Increasing temperature and precipitation will be distributed across the array of soils, plant communities, and landforms (Fig. 6), resulting in spatially complex changes in the environmental conditions and resources that mediate forest dynamics.

We have already seen some evidence to support this landscape demography concept. A recent severe decline of paper birch in the HBR (Fig. 25), attributed to the inciting effect of an extreme late-summer drought, was largely confined to the shallow soils of ridgetops and upper slopes, where additional disturbance by the 1998 ice storm may have predisposed paper birch to drought stress. Similarly, as noted earlier, one of the principal tree demography changes at the HBR and in the region is the decline of sugar maple attributed in part to depletion of available soil $Ca^{2+}$ (Horsley et al. 2000). At HBR, this decline includes reduced growth, increased mortality and reproductive failure, especially in restricted landscape positions (Juice et al. 2006). In contrast, across the wider HB valley, sugar maple decline is not clearly evident (Solomonoff et al., submitted), and successful maple reproduction may exhibit localized patterns related to hillslope hydropedologic processes (Cleavitt et al., in prep.). Future expansion of hardwood tree populations at tension zones with the subalpine conifers in a warming climate may be restricted primarily by underlying soils and landforms. In addition, expansion or contraction of transient high water tables in a changing climate, described above, will influence the susceptibility of canopy trees to windthrow and influence spatial patterns of canopy turnover (Battles et al. 1996).

***H3.6*:** *Landscape-scale hydropedologic and linked biogeochemical patterns influence the demographics of dominant forest trees thereby altering the response of ecotonal tension zones to changing climate.*

***H3.7*:** *Recent expansion in the abundance of subalpine conifers at HBR, in spite of warming climate, results from the elevational distribution of soils and landforms in combination with declines of competing hardwood species.*

**4. Landscape Demography of Heterotrophs.** During the most recent LTER funding cycle, we initiated studies to bridge the two principal strengths of the HBR, long-term biogeochemistry and population dynamics research. For example, initial studies of moose, which have recently returned to the HBR, demonstrated that they could accelerate the cycling of N, an effect that is sensitive to variations in snowpack depth and duration (Christenson et al. 2007). Selective feeding by moose also appears to influence vegetation dynamics, including effects on vegetation structure that influence habitat quality for shrub-layer nesting birds like the black-throated blue warbler (*Dendroica caerulescens*). Similarly, interannnual variation in soil N and P availability appears to be driven in part by climatic variation, as warm, wet conditions stimulate N and P flux (Judd et al. 2007), with consequent effects on foliar nutrition. In turn, performance of insect herbivores is stimulated by higher nutritional quality (Stange 2009), with likely consequences for higher trophic levels, including insectivorous birds (Nagy and Holmes 2005).

These interactions between biogeochemistry and population dynamics may be played out on the landscape template in ways analogous to those described for the vegetation. For example, invertebrate productivity in the HBR exhibits patterns related to elevation, stream channel networks, and patch structure of the vegetation, with cascading effects on salamander feeding (Greene et al. 2008). In the detrital food web, microinvertebrates exhibit landscape-scale patterns of abundance (highest in lower slope and ridgetop habitats) that appear to be related primarily to fine root production and turnover (Fisk et al., in review; Fig. 26). Although the complexity of food webs in the forest would prohibit a comprehensive analysis of such landscape demographic phenomena, we propose to expand our HB valley-wide monitoring program to encompass additional key taxa and to initiate experimental studies to resolve the linkages among the geohydrologic template, soil processes, vegetation dynamics and food web structure.

***H3.8*:** *Landscape-scale changes in snowpack depth and duration will modify population dynamics and behavior of a keystone herbivore, moose, with consequences for N cycling, vegetation dynamics and populations of understory-nesting birds and their insect prey.*

***H3.9*:** *The spatial distribution of heterotrophs at the landscape spatial scale can be explained by geohydrologic patterns interacting with vegetation, climate, and disturbance variables that characterize the shifting-mosaic steady state.*

**5. Regionalization.** Our work to regionalize the HBR-LTER has helped place our site-level studies into a broader context (e.g., Rodenhouse et al. 2008, Campbell et al. 2009), and additional development along these lines is proposed. In particular, whereas most of our focus to date has been on forest responses to environmental change, forests also have the potential to shape future regional and global environmental conditions. For example, forests can affect climate through a combination of biophysical (albedo, turbulence, latent and sensible heat exchange) and biogeochemical (C sequestration, $N_2O$ and $CH_4$ emissions) factors. To date, most of the attention in forest policy related to climate has focused solely on C sequestration, without consideration of consequences for albedo and other processes that could either enhance or counteract the intended effects on climate (Betts et al. 2000). Models that couple C, N and $H_2O$ cycles are needed to evaluate the net radiative forcing effects of changes in disturbance, land use, climate and nutrient cycling at a regional scale.

The impacts of multiple environmental stressors on terrestrial ecosystems, particularly under future scenarios of change, are complex and poorly understood (Aber et al. 2002). While it is known that elevated $CO_2$ stimulates photosynthesis (Norby et al. 2002, Korner 2003), several studies suggest that long-term effects may be restricted by increased N limitation (Oren et al. 2001). Similarly, $CO_2$-fertilization can be offset by increased tropospheric ozone (Karnosky et al. 2003), although the effect of ozone can itself be reduced by $CO_2$-induced declines in stomatal conductance. The future role of N deposition is also important in nutrient-limited systems, as elevated $CO_2$ increases plant demand for N and as N deposition rates change in response to emissions regulations, agricultural practices, and industrial activities. Land-use and forest management have been considered in studies of present C and N cycling (Vetter 2005), but are rarely examined as part of future scenarios.

Coupled water, C and N cycles play a major role in controlling climate-C cycle interactions, but field sites that are suited to measurement of surface-atmosphere exchange by eddy covariance are mostly unsuitable for measurement of hydrologic inputs and outputs in gauged watersheds (and vice versa). Since January 2004, a tower-mounted eddy covariance system has continuously measured surface-atmosphere exchange of $CO_2$, $H_2O$ and energy at BEF, located 30 km from the HBR. The forests at these two study sites are similar in age, structure and composition, and they experience essentially the same climate forcing at time scales from hours to years. Thus, these two sites represent an exceptional opportunity to merge knowledge of C, water and nutrient cycles into a common analytical framework, using data-model fusion to enhance our understanding of biogeochemical coupling.

***H3.10*:** *Significant climate feedbacks at the regional scale result from changes in ecosystem C sequestration, canopy albedo, and trace gas emissions under various land-use, climate change, and atmospheric deposition scenarios.*

***H3.11*:** *A data assimilation approach can be used effectively to link tower measurements of C and water fluxes from the NEON relocatable site at BEF to detailed plot- and catchment-level measurements at the HBR.*

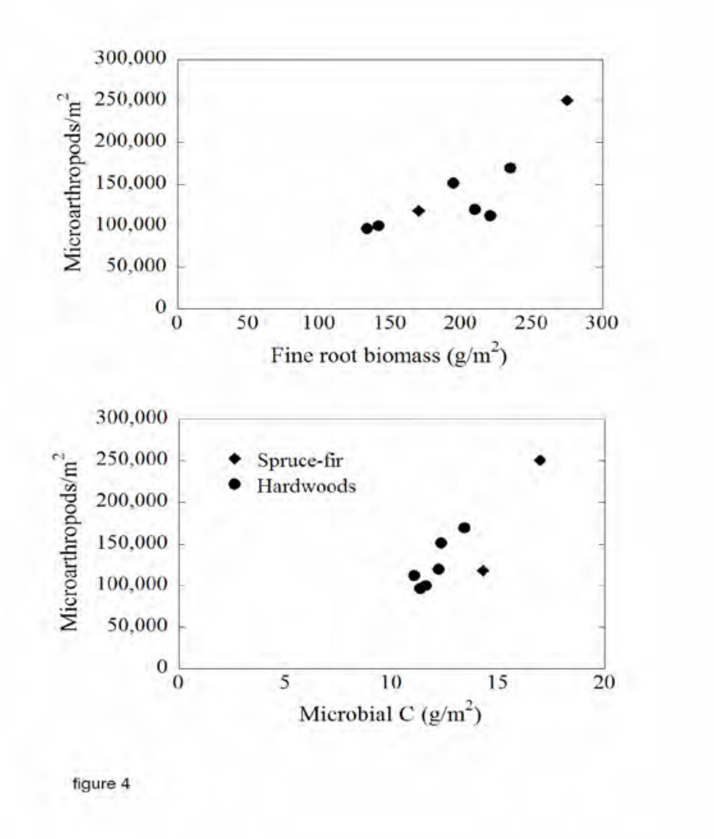



**Figure 26.** Dependence of soil microinvertebrate density on fine root biomass and microbial C at HBR across eight study plots in W1 and W6.

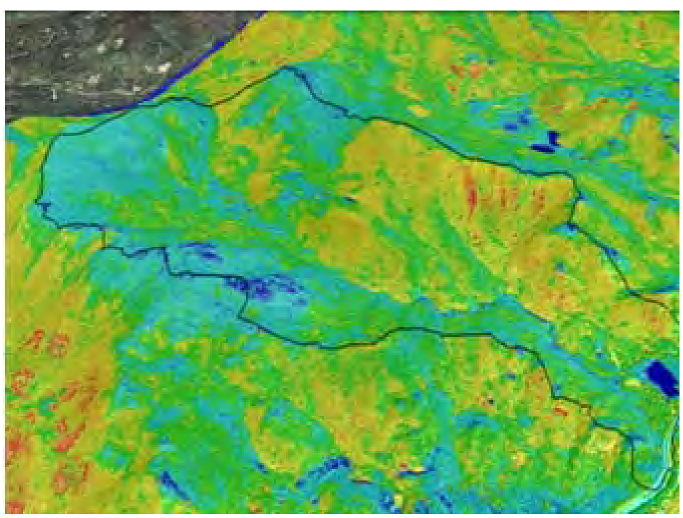


**Figure 27.** A high resolution map of mid-summer canopy albedo for the HBR, derived from AVIRIS imaging spectrometer data and an atmospheric radiative transfer model. Future improvements will involve BRDF correction and estimation of full hemispheric albedo.

## D. Approaches

We have conducted two sets of snowpack manipulations to alter soil freezing (Groffman et al. 2001, Cleavitt et al. 2008a); these studies allowed us to identify mechanisms of ecosystem responses and to parameterize models of local soil freezing effects (Hardy et al. 2001). Now, we propose to evaluate landscape-scale responses of biogeochemical phenomena to natural interannual and spatial variation in soil freezing, to better understand watershed-level responses and test H3.1 and H3.2. We have submitted a proposal to NSF Ecosystems to support many aspects of this proposed research, including extensive monitoring plots, intensive isotope tracer studies, and distributed modeling and measurement of catchment responses. Our LTER project would supplement that proposed research by maintaining long-term records of meteorology, hydrology and soil freezing and describing landscape patterns of soil solution and stream chemistry. In addition, LTER would support mechanistic studies of the response of root N uptake to soil freezing, building on previous work that suggested a critical role of root damage in regulating biogeochemical response (Tierney et al. 2001, Cleavitt et al. 2008a). We will utilize an *in situ* nutrient depletion method (Yanai et al. 2009) to quantify root nutrient uptake activity during and immediately following spring snowmelt under naturally varying conditions of soil freezing (H3.1, H3.2). The proposed research would be integrated by a combination of extensions of soil climate modeling work (SNTHERM and FASST; Frankenstein et al. 2008) and small catchment responses to natural soil freezing events.

Our hydrology reference watershed, W3, is the site of intensive measurements of hillslope hydrology and hydropedological processes (Fig. 24). Based on soil morphology and hydrology, we have identified four hydropedologic mapping units, each of which is confined to certain combinations of land surface shape and depth and type of subsurface restriction. We utilize a combination of groundwater wells with water level recorders, lysimeters, soil temperature and moisture sensors, and soil gas collectors to characterize the hydrologic and biogeochemical processes in each of these mapping units. We propose to quantify biogeochemical redox processes (denitrification, Fe forms, $CH_4$) and C storage in mineral horizons in this network. Responses of tree root uptake to these changing redox conditions will also be quantified using *in situ* nutrient depletion measurements, as described above. A high-resolution Lidar-derived digital elevation model will be used to extrapolate from monitoring sites to the watershed and eventually to the entire HB valley. The landscape model will then be used to investigate relationships among soil properties, hydrologic flowpaths and ecological patterns at a variety of scales. For example, we will evaluate the relationship between vegetational ecotones (Fig.23) and geohydrological phenomena (H3.6).

We surveyed moose abundance in the upper-elevation conifer forest in 2008 and 2009 using fecal pellet counts. Moose density (0 = 1.4/km$^2$) showed extreme spatial variation that was strongly related to browse damage. After controlling for forest structure and composition, we found that moose congregated in winter in topographic hollows. In coming years we will quantify the interactive effects of landscape position, vegetation composition and snow depth on moose abundance and herbivory. Study sites will be co-located with measurements of N availability and bird and insect abundances to test H3.8.

We conduct annual surveys of all bird species and diurnally active small mammals at two spatial scales: a permanent 10-ha plot that has been surveyed continuously since 1969 (Holmes and Sherry 2001) and HB valley-wide points that have been surveyed beginning in 1999 (see Betts et al. 2008). To test H3.9, we will continue landscape-scale surveys of birds, diurnally active small mammals (primarily chipmunks, *Tamias striatus*, and red squirrels, *Tamiasciurus hudsonicus*) and moose (from pellet and browse counts) at the valley-wide points. To better characterize the forest food web, we will expand these surveys to include arthropods (*Lepidopteran* larvae), representing a mid-trophic level, and red-backed salamanders (*Plethodon cinereus*), which are key predators in the detrital food web. Replicate samples within elevation bands will be used to evaluate correlations among hydropedology, vegetation and food web structure across the climate gradient.

Our regionalization work builds upon previous simulations of climate-pollution interactions using PnET-CN and PnET-BGC (Ollinger and Smith 2005). We now propose to extend model predictions into the future using an improved version of the model and downscaled AO-GCM output as model drivers and validate these predictions against data from experimental manipulations and biomass inventory. Model simulations will focus on the 246 counties within the domain of the Regional Greenhouse Gas Initiative, an area including all of New England and the northern Mid-Atlantic states. Emphasis on county-level estimates of C cycle dynamics reflects both the interests of regional planners and the resolution of available FIA data for model evaluation. Future climate, air pollution, and land-use scenarios will be used to test the individual and combined effects of these environmental stressors on forest above- and below-ground production, C biomass storage, and canopy chemistry.

We also plan to couple PnET to a radiative transfer model to evaluate both the C cycle and biophysical effects of changes in forest structure and function. This effort will allow us to contrast the relative importance of biogeochemical change versus changes in land management as future drivers of regional ecosystem function and ecosystem-climate interactions.

**Synthesis**

The HBR-LTER strives to advance basic understanding of ecosystem dynamics in response to disturbance and inform and guide the management of forest and aquatic resources. We hypothesize that the response of forest ecosystems to disturbance is regulated by stoichiometric constraints of elements which are manifested across the landscape template due to interconnected variations in climate, surficial geology, soils and hydrology. These constraints alter nutrient availability and transport, as well as acid-base and redox conditions, which, in turn, define temporal and spatial patterns in ecosystem function and biotic populations. In this proposed research, we focus on three interrelated disturbance themes which encompass press and pulse drivers that are important in the management of the Northern Forest: air pollution, forest disturbance and climate change. A deeper understanding of these basic processes and phenomena is necessary to improve predictions of how ecosystem services will be altered in the face of unprecedented environmental change. The ability of society to adapt in cost-effective ways to these changes and to efficiently manage natural resources depends upon an improved conceptual and quantitative basis for ecosystem dynamics and the feedbacks with social systems. By leveraging additional funding and engaging experts in the social science realm, we anticipate that the HBR-LTER will make important contributions to the solution of environmental problems.

Our continuing work on ecosystem recovery following controls on emissions that contribute to elevated atmospheric deposition represents the cutting edge of global research on this widespread problem. The maintenance of comprehensive long-term biogeochemical records, experimental manipulations, and associated testing and advancement of models provide a framework to transfer a basic understanding of this disturbance to other biomes and regions. We will obtain new insights into the acidification and eutrophication of ecosystems that is relevant to conditions observed in other LTER sites. Our research will contribute to robust evaluation of critical loads approaches to pollution management (USEPA 2009).

A hallmark of research at HBR has been quantifying the response of ecosystems to forest cutting. Our experiments not only help characterize the short-term effects of cutting disturbance, but also frame the science and discussion of sustainable forestry. We propose to expand this sustainable forestry theme by initiating a new forest cutting experiment to evaluate intensive forest harvesting for biofuel markets. We will assess if short rotation harvesting will push the ecosystem into a state change resulting in a long-term decline in site productivity. An important driver of this new line of research will be impacts of intensive harvesting on related ecosystem services. There is considerable regional and national interest C offsets, and land management strategies to maximize C sequestration.

Over the past 55 years, we have observed marked changes in meteorology and hydrochemistry at HBR that appear linked to winter climate change. Model calculations suggest that these patterns will accelerate and affect the structure and function of the Northern Forest. Process research in winter climate change, ecohydrology, and demography of trees and heterotrophs, coupled with the application of process models will enable us to characterize and quantify ecosystem response to changing climate. Our focus on winter climate change is relevant to new research done with other LTER sites (e.g., NWR, AND, CWT, BNZ, PIE), including a cross site analysis of the hydrochemical response of high elevation watersheds to future climate change and the Network’s Disappearing Cryosphere initiative. This work will advance our regionalization efforts and help inform management strategies to mitigate the effects of changing climate on Ecosystem Services.

## 3.0 – SITE MANAGEMENT

**Site Management and Facilities.** Primary and ultimate responsibility and authority for administering the Hubbard Brook Experimental Forest (HBR) is the Chief of the U.S. Forest Service (FS) who in turn delegates authority to the Director of the Northern Research Station (NRS), the Project Leader of NRS-07, and the Team Leader for the Hubbard Brook Experimental Forest. The FS has agreed to share the management of the overall Hubbard Brook Ecosystem Study (HBES) and the HBR with cooperating research and education institutions, recognizing the need for all parties to commit funds, personnel, and equipment to attain common long-term objectives in research, education and outreach. Because of the remote location, general supervision of the HBR is under the FS Team Leader (currently Lindsey Rustad), as delegated by the Director of the NRS. Day-to-day operations of the HBR are supervised by the resident Research Forester-Manager of the NFES (currently Ian Halm).

The FS operates a year-round field laboratory and office building at HBR. The Robert S. Pierce Ecosystem Laboratory provides 835 $m^2$ of space, including six offices, four laboratories, one conference room, six dormitory rooms, a kitchen, baths and showers. A sample archive building was constructed in 1990 to house and archive samples of soil, water, plant tissue, and other materials (see section 4.0 Information Management). In addition, there are 280 $m^2$ of maintenance, storage, garage and shop facilities. In 1983, Yale and Cornell University's purchased Pleasant View Farm (PVF), the 200-yr-old dormitory and laboratory complex, which had been rented for 18 years for use by graduate students and senior researchers, working at the HBR. In 1993, the Hubbard Brook Research Foundation (HBRF), a non-profit 501(c) (3) charitable organization was established to facilitate the housing, project logistics, education and outreach of the HBES (also see section 5.0 Outreach and Education). The HBRF assumed control of PVF and oversees the operation and maintenance of the dormitory and laboratory complex. PVF includes housing for 14 and kitchen facilities. In 2004 The HBRF purchased the Mirror Lake Hamlet, which is located adjacent to the HBR on Mirror Lake. The Hamlet provides 977 $m^2$ of high quality housing, cooking and workspace (computing, internet, meeting) facilities for an additional 50 PIs, students and visitors. The maintenance of the Hamlet is provided by a caretaker. Currently, we primarily house undergraduate students participating the HBR REU program (see section 5.0 Outreach and Education) at PVF, and PIs, visiting scientists, post-doctoral associates, graduate students, other undergraduate students and technicians are housed at the Hamlet.

**Site Governance.** At the center of the governance structure of the HBES is the "Committee of Scientists (COS)," which consists of PIs conducting research, education or outreach in the HBR (Fig. 3.1; Groffman et al. 2004). The membership of the COS is reviewed at three-year intervals. There are currently 48 members of the HBES COS. The Scientific Coordinating Committee (SCC) provides leadership for the COS, overseeing a series of committees, providing vision and scientific leadership to the research program, fostering integration and synthesis across diverse projects, encouraging new scientists to work at the site and as part of the HBES, enhancing diversity among the HBR community, and promoting interactions and communication among HBES scientists. The "visioning" function of the SCC is considered to be particularly important as governance activities for large projects can become mired in detail. The SCC has 10 members, five of which are elected by the COS (currently Groffman, chair, Bailey, Rustad, Rodenhouse and Campbell). Other members include one of the two HBR LTER PIs (rotating every 2 years, currently Fahey); a senior scientist (chosen from amongst a group of the five investigators with the longest experience in the HBES, currently Likens); a scientist not associated with the HBES (chosen and invited by the SCC members as an external reviewer, currently Scott Collins from the University of New Mexico); a representative from the HBRF Board of Trustees (a non-scientist, currently vacant); the USFS Project Leader for the HBR (*ex-officio*, currently Scott Bailey); and the Executive Director of the HBRF (*ex-officio*, currently David Sleeper). Note, Collins was added as our external scientist after he served on our last mid-term site review, so that we could benefit from his insights and constructive suggestions on an ongoing basis.

The Research Approval Committee (RAC) is advisory to the USFS Team Leader, who bears ultimate responsibility for research activities at the HBR (also see section 4.0 Information Management). This committee evaluates and approves proposed projects, facilitates coordination and prevents conflicts among different research projects at the site. Anyone wishing to conduct research at HBR must submit a brief proposal to the RAC (proposals are accepted three times per year). The Information Oversight Committee (IOC) is responsible for the content of the HBR web site (www.hubbardbrook.org), data management and maintenance of the HBES data, sample and document archives (also see section 4.0 Information Management). The Program and Meetings Committee (PMC) organizes a series of COS meetings (four per year) as well as the annual HBES Cooperators' Meeting. The Education and Outreach Committee (EOC) facilitates links among HBRF, HBR-LTER and HBES research and learning groups ranging from K – 12 to undergraduates to local residents to management and policy communities (see section 5.0 Outreach and Education).

The quarterly COS meetings are a key venue for project management; with time allocated for logistical issues (25%) and discussion of overarching scientific topics (75%). All investigators (i.e., PIs, post doctoral associates, students) working at HBR are required to make presentations at the annual Cooperators' Meeting in early July which is attended each year by approximately 150 people and includes a keynote speaker sponsored by the HBRF (in 2009 the speaker was Jim Collins of NSF), group dinner, barn dance and midnight swim that facilitate project morale and cohesion.

To date, our governance structure has been effective and we anticipate that it will help maintain the vitality of the HBR-LTER and HBES for decades to come. We expect that this approach to governance will help maintain the integrity of the long-term data and experiments, attract new people to the project, facilitate transitions in the study, encourage and enhance diversity among scientists working at the site, help us to develop new ideas and experiments, and increase participation in project leadership. This structure has enabled us to focus more on our vision for the future of the HBR-LTER and HBES. The SCC and PMC establish an agenda to foster regular discussion of issues such as "new experiments," "synthesis," "gaps in coverage", "strategies to attract new scientists and enhance diversity" and "improvements in education and outreach."

Our governance structure, conceptual model (Groffman et al. 2004) and the LTER framework for Integrative Science for Society and Environment (LTER 2007) have been useful in the preparation of this renewal proposal, allowing researchers to articulate how their ideas fit into the HBR-LTER, the overall HBES, LTER Network initiatives, and organizational framework of the project in a public and transparent process. This process has helped the PIs make decisions about how to allocate LTER funds for in a scientifically sound, semi-democratic way that allows for the development and evolution of the HBR-LTER.

The governance structure has also facilitated our ability to increase and maintain the participation of new scientists and under-represented groups in the project, which has been identified as a priority in previous reviews of the HBR-LTER. In recent years we have been encouraged by a number of new scientists who are working in the HBES, including Pamela Templer (microbial and plant processes, Boston Univ.), Andrew Richardson (land-atmosphere dynamics, data fusion, Harvard Univ.), Lynne Christensen (moose, biogeochemistry, Vassar College), Kevin McGuire (hydrology, Virginia Tech), Mark Green (hydrology, Plymouth State Univ.), Christine Goodale (biogeochemistry, Cornell), Winsor Lowe (salamanders, Univ. of Montana), Beverly Wemple (forestry, University of Vermont), Michele Pruyn (plant ecology, Plymouth State) and Laura Schneider (geography, Rutgers). This influx of talented new scientist is expanding the scope of research and invigorating the HBR research community. Though the HBRF, the Hubbard Brook Consortium and the REU, we work aggressively to encourage and facilitate people from underrepresented groups working at the HBR.

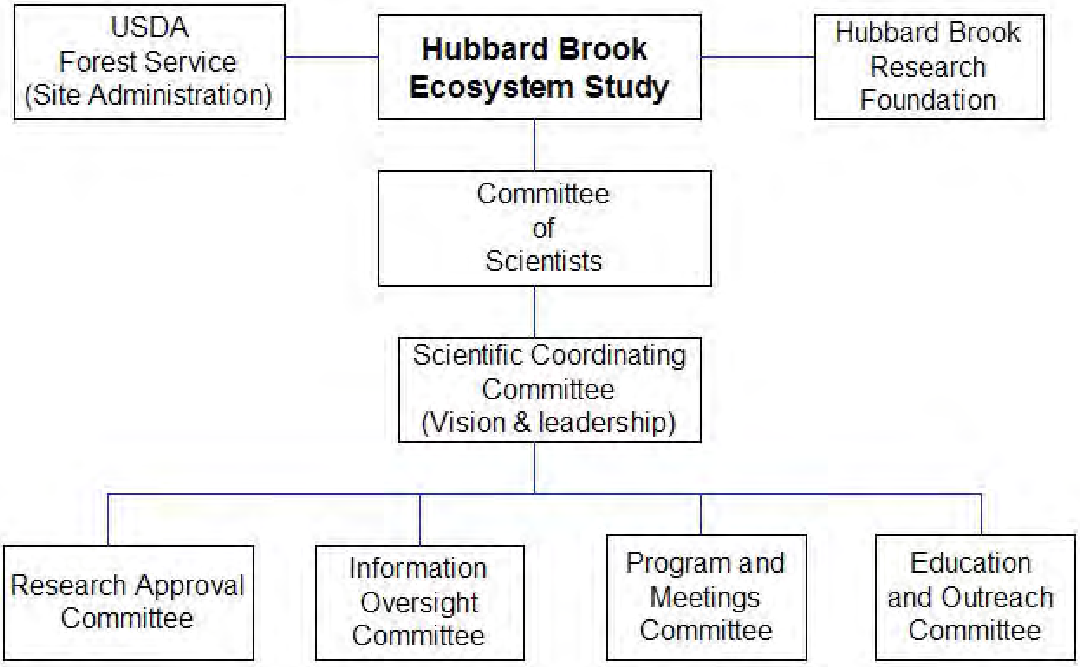



**Figure 3-1.** Governance structure of the Hubbard Brook Ecosystem Study.

## 4.0 INFORMATION MANAGEMENT AND TECHNOLOGY

### Governance

Information management (IM) and technology at HBR are supervised by an Information Oversight Committee (IOC) comprised of two Working Groups, Data and Website. The Data Working Group addresses topics such as data quality assurance and quality control (QA/QC), metadata, and the sample archive. The Website Working Group is responsible for developing, maintaining, and updating the content, structure, and appearance of the HBR website. The IOC meets twice each year and reports to the Scientific Coordinating Committee (governing body for HBR). The IOC is led by a founding member of the HBR (Likens) and includes a representative cross-section of HBR participants. The primary role of the HBR Information Manager is to support the HBR information management system and to provide expertise in IM for scientists conducting research projects and data syntheses. The Information Manager also contributes to LTER network IM activities and serves on network-level committees (IM Executive Committee, Databits Editor, and ad-hoc working groups). Three other people are involved in information management at HBR and the combined work of the IM group amounts to approximately 1.5 FTE.

### Data Acquisition and Management

Research at HBR is conducted by a geographically dispersed group of cooperating scientists from many institutions. The data collected by these scientists include core data sets that comprise the long-term monitoring program, as well as data from shorter-term studies. Scientists who wish to conduct new research at HBR need to first obtain permission from the Research Approval Committee. As part of this process, they submit an on-line proposal submission form (http://www.hubbardbrook.org/proposal_submission/subform3.htm) and agree to contribute the data obtained in the study and accompanying metadata to the HBR database. The information on the proposal submission form is appended to a database, and approved projects are tracked over time until completion. HBR scientists may operate independently; however the data they collect are ultimately stored in a centralized relational database management system (RDBMS) at the USDA FS office in Durham, NH.

Since the data are diverse and often highly specialized, individual researchers are responsible for developing their own database management protocols (e.g., database design, QA/QC) prior to submission to the centralized RDBMS. However the Information Manager provides guidance and assistance at the onset and through all phases of research to ensure the integrity and safety of the data and metadata. Backup guidelines were developed by the IOC for researchers to ensure that valuable data from HBR are not lost before they are entered into the centralized RDBMS (http://www.hubbardbrook.org/data/info_management.htm). Currently, data are typically submitted to the Information Manager by email; however an effort is underway to develop a more standardized approach that uses on-line forms to reduce entry errors and to facilitate updates at shorter intervals. At present, HBR data are typically updated in the centralized RDBMS on an annual basis. Data are copied and archived in their original, unmanipulated form in a fire resistant vault at the USDA FS in Durham, NH. Data formatting and comprehensive QA/QC checks are made with a series of manual inspections and automated computer programs. Data are stored in a MySQL database on a server managed by the USDS FS in Durham, NH. Duplicate tape backups of the entire HBR database are stored in the vault at the USDA FS in Durham, NH and at the HBR.

### Data dissemination

The HBR website is the primary means by which HBR information is disseminated, although non-digital data (charts, maps, photographs.) are made available upon request. The HBR website was redesigned in 2007 in compliance with the Guidelines for LTER Web Site Design and Content, a document that the HBR Information Manager helped develop. Recent modifications include a more prominent display of the LTER network identity and more accessible links to LTER network resources (e.g., ClimHydroDB, SiteDB, Metacat). Data from HBR are updated on the website at least annually and often more frequently. HBR adheres to the LTER Network Data Access Policy that was approved by the LTER Coordinating Committee in 2005. To date, all the data collected at HBR are considered Type I and are released to the general public within 2 years from the time of collection. A considerable amount of effort has been invested in providing high quality metadata to ensure the long-term usability of the data. All metadata are in the Ecological Metadata Language standard adopted by the LTER network and are at the highest level of completion (Level 5). Ecological Metadata Language files have been developed for both geospatial datasets (GIS) and non-geospatial data and are displayed on the website using stylesheets.

The HBR website resides on an LTER Network Office (LNO) server in New Mexico, taking advantage of the hardware, software, and support provided through the LNO. This close cooperation with the LNO enables us to easily integrate data and information from HBR with the broader scope and initiatives of the LTER Network. When new data sets are added to the website or when other significant changes to the website are proposed, they are first reviewed by the HBR Website Working Group to ensure the quality of the material posted. A few highlights of data and information posted on the HBR website are described below.

*Intranet* – A password protected intranet site was developed as a means of sharing ideas, information, and documents among the 48 geographically dispersed members of the Committee of Scientists. The site mostly contains internal communications such as meeting minutes, NSF reviews, email lists, presentations, and proposals.

*Personnel database* – A personnel database, including *curriculum vitas*, is maintained on the HBR website. Individuals update their own vitas via a password-protected web form. Updates can be made any time and reminders (and subsequent follow-ups) are sent out twice annually to ensure that the information is current.

*Current Research* – A description of current research activities is available through the HBR website to keep the public abreast of research initiatives and preliminary findings. Updates are made frequently to reflect changes in the development and scope of current research.

*Photo archive* – The website has a searchable archive of digital images that are frequently used in publications, presentations and textbooks. Most of the historical HBR photographs and slides have been scanned at high resolution to ensure that these irreplaceable images are preserved in perpetuity. Members of the HBR community can upload new images to the archive from remote locations using an on-line form.

*Publications* **-** A document archive including paper copies of HBR publications, theses, correspondence, and maps is maintained at the Cary Institute of Ecosystem Studies in Millbrook, NY. A digital database of the HBR publication list that dates back to 1955 and includes more than 2,100 publications is accessible in a searchable format on the HBR website.

In February 2007, we started tracking data use through the website to comply with the LTER Network Data Access Policy. When users view or download data, they are required to register by entering their name, affiliation, email address, and full contact information. This information is stored in a database and provides statistics on data use (Figure 4.1). On average, 3,705 HBR datasets are downloaded per year (approximately 10 per day) by users representing 29 countries, 156 degree granting institutions, 15 government agencies, and 17 identifiable K-12 schools or districts. In addition to data-use statistics such as these, we have also been tracking website activity with an analytical tool to help identify areas of need on the website. As an example of how this information is being used, we have found that nearly 50% of the data downloads are by students and that the education section of the website receives a high proportion of pageviews. Consequently, we are planning to place more emphasis on the student resources section of the website.

## Sample Archive

HBR is committed to the permanent storage of physical samples (e.g., streamwater, precipitation, vegetation, soil) so that they will be available for future research. After samples are collected and analyzed, they are stored in a physical sample archive building located at HBR. The building was constructed solely for this purpose and now houses approximately 40,000 samples. Samples are preserved, barcoded, and cataloged with accompanying metadata in the HBR centralized RDBMS. Requests for reanalysis of these samples (e.g. isotopic analyses, heavy metals) are received periodically, and have resulted in a number of publications. We have recently embarked on a major new initiative to reorganize the archive building and revamp the database and website interface.

**Scientific workflows and uncertainty analysis**

A major IM initiative at HBR is the development and formalization of scientific workflows. The answers to many of the pressing ecological questions at HBR and elsewhere require the fusion of data from many sources. However this kind of integrative, data-intensive research poses new information management challenges. We recognized the need for a more structured approach to workflows based on our efforts to quantify uncertainty in ecosystem nutrient budgets. Ecosystem ecologists have generally lagged behind hydrologists and atmospheric scientists in accounting for uncertainties in reported results. More often than not, ecosystem element budgets report elemental pools and fluxes without fully accounting for the uncertainty in these estimates, making it difficult to evaluate the significance of findings or to compare results across ecosystems. Some sources of uncertainty are well understood and commonly reported, such as the variability reflected in replicate plots. Other aspects of uncertainty are rarely reported. For example, forest element budgets require the use of regression equations to estimate the biomass of tree components. The uncertainty in these equations should be included in estimates of uncertainty in element budgets, along with the uncertainty in nutrient concentrations of tissues, measurement errors, and sampling error. We recently developed and demonstrated a Monte Carlo approach to propagating uncertainty in an ecosystem nitrogen budget (Yanai et al. in press); this model has already been used by researchers at other sites. One reason that sources of uncertainty are rarely comprehensively considered is that the sequence of operations involved in many ecosystem calculations is complex and typically not completely documented. The detail necessary to reproduce the results far exceeds the amount of information that can be published in journal articles. To resolve this issue we are planning to use scientific workflow software such as Kepler (https://kepler-project.org/) to record, execute and share workflows and derived datasets. We intend to organize workshops and working groups (e.g. through NERC and NCEAS) that will involve information managers and scientists beyond the HBR community, as this is an area of emerging interest in ecology (Hobbs 2009) in which we could provide leadership. This initiative provides a good example of how information managers and scientists are working together not only to improve the information infrastructure but also to strengthen scientific results and analyses.

**Assessment of Information Management System**

In summer 2009, a comprehensive evaluation of the HBR Information Management System was conducted. The study was led by a graduate student who was funded through a grant from NSF's Office of Cyberinfrastructure to the Center for Research on Collaboratories and Technology Enhanced Learning Communities, a social science research center in the School of Information Studies at Syracuse University. The final report (http://www.hubbardbrook.org/documents/2009_HB_IM_Assessment.pdf) is being used to strengthen the IM program at HBR by helping make decisions on how best to allocate time and resources.

**Future directions**

Since HBR became an LTER site in 1987, the Information Manager has been supported entirely by the USDA FS. In the coming year a change will occur and the Information Manager position will be funded through the LTER program, although the USDA FS will continue to provide office space in Durham, NH as well as expertise and oversight to ensure a smooth transition. This change will be beneficial to HBR because the IM will be focused entirely on LTER-related projects without any other institutional responsibilities. Future goals of information management at HBR will include better tracking projects with the newly developed network-level LTER project database, identifying and incorporating legacy and new datasets in the RDBMS, and continuing to expand and enhance the streaming sensor network at HBR.

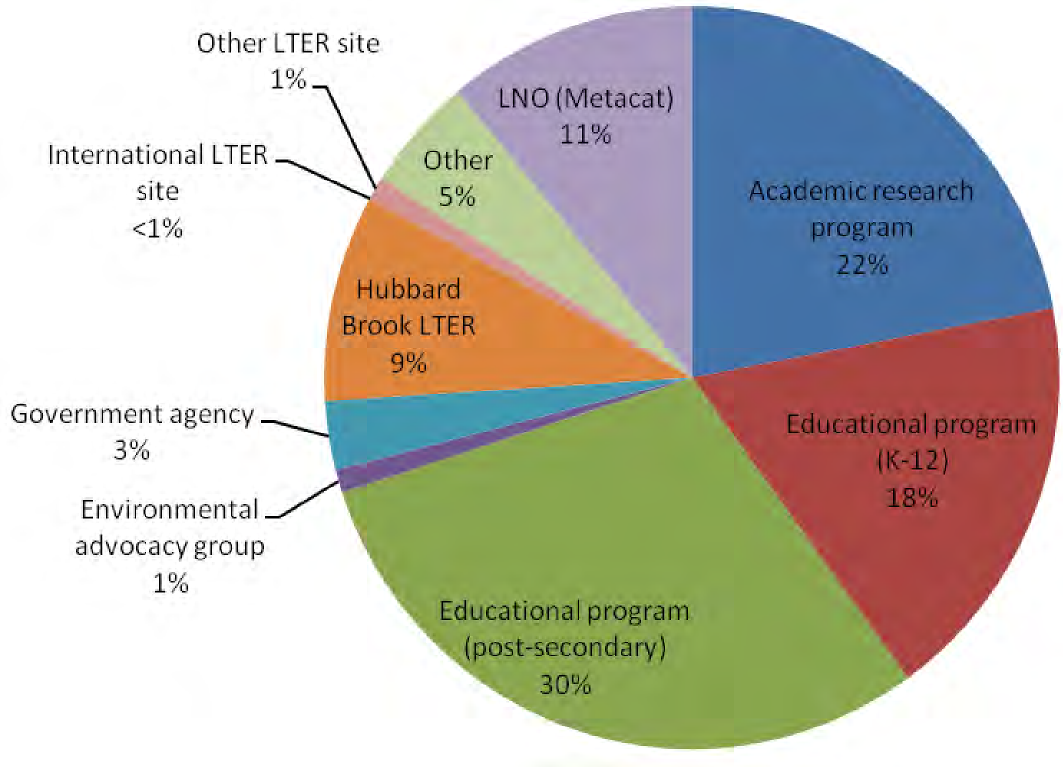



**Figure 4-1.** Percentage of datasets downloaded from the HBR website by category of data user since February 2007.

## 5.0 OUTREACH/EDUCATION

**<u>Outreach</u>:** Outreach and Education programs in the HBR LTER are coordinated by the Hubbard Brook Research Foundation (HBRF), a private-funded "friends" group that manages facilities and outreach activities. The *Science Links* program of the HBRF was developed to facilitate information exchange among scientists, policy makers, natural resource managers and the public. *Science Links* is a series of scientific synthesis projects on issues in ecosystem science relevant to the expertise and long-term research of the HBR. The program is built on three premises: 1) environmental policy is more effective when it is grounded in environmental science; 2) ecosystem science can be enriched by an awareness of current public policy issues and social concerns; and 3) science serves the public best when it does not advocate specific policies, but instead provides scientific information about the likely outcomes of alternative policy choices.

*Science Links* projects have been completed on ecosystem effects of atmospheric emissions of S (Driscoll et al. 2001), N (Whitall et al. 2003), and Hg (Driscoll et al. 2007c), and on long-term monitoring (Lovett et al. 2007). Each project produces a peer-reviewed scientific paper and a policy publication. The findings are disseminated through a communication strategy to educators, policy makers, the general public, and the media. Outreach activities include press conferences, Congressional briefings, workshops, mailings, and presentations by *Science Links* team members. We are currently working on projects on local-scale C management and migratory birds, and we plan a review of the program to guide future activities.

**Local-Scale Carbon Management:** There is a critical need to quantify C emissions and to guide C management, but little attention has been given to local-scale C management. We have developed detailed C budgets for 9 counties in the Northeast with contrasting land-use characteristics, including four LTER sites (HBR, PIE, BES, HVF). We are also evaluating management strategies to decrease net C emissions. The C project will be completed in 2010.

**Migratory Birds**: We have initiated a *Science Links* project that builds on long-term research at HBR on the factors and processes that regulate bird populations. We plan to provide a quantitative assessment of the relative risks of the multiple threats to forest birds in the Northeast, which include climate change, insect pests, forest management activities, atmospheric deposition, diseases and pathogens, and suburban and exurban development. Such an analysis is essential to understand and project the potential effects of environmental change on birds and to make informed and efficacious policy and management decisions. The project was started in 2009 and will be completed in 2011.

***Science Links* Review**: With the C project, five *Science Links* projects will have been completed over a 10-yr period. We are conducting a critical review of the program, which began with a presentation on *Science Links* at the 2009 Cary Conference on Science Communication and continued with an AIBS webinar. These activities will result in a journal article summarizing the *Science Links* program. Further assessment will include facilitated roundtables of stakeholders leading to recommendations for the near- and long-term future of *Science Links*, including a possible regional partnership involving interested research institutions and LTER sites.

**<u>Education</u>:** Schoolyard efforts of the HBR-LTER are focused on two major audiences: secondary schools and undergraduates, with multiple programs in each.

**Secondary schools**: With support from Schoolyard LTER supplements and the USDA FS, our Environmental Literacy Program targets middle and high schools through a three-faceted approach including curriculum development, teacher training events, and school partnerships.

*Curriculum development:* We use *Science Links* as a platform for developing teaching guides and user-friendly data sets aimed at the needs of high school biology, chemistry, and environmental science classes. Using the summary work of the *Science Links* team, the HBRF education staff identifies and develops classroom-applicable lessons, activities, and support resources for teachers. We are working with partner schools (described below) to develop science inquiry activities using data from our long-term records. These activities have been requested by teachers to help prepare students for the region-wide New England Common Assessment Program science exams.

*Teacher training:* We present our curriculum to interested teachers at training events, such as the New Hampshire Science Teachers Association meetings, and at our own events. In 2009 over 100 teachers attended presentations of our curricula on acid rain and migratory birds.

*School Partnerships*: We are involved with six schools in the region, representing the four school districts closest to HBR. HBRF education staff work with teachers at these schools and facilitate the use of HBR created curricula. Teachers at the schools also work with our education staff to guide the development of teaching resources. For example, we are developing preparation materials for New England Common Assessment Program exams, which are given in all public schools in NH, VT, and RI. This effort was initiated by teachers at a partner school and we expect the products to have wide appeal in the region.

**Undergraduate students:** The HBR-LTER conducts undergraduate training year-round. The centerpiece program is a 10-week Research Experience for Undergraduates (REU) site program in the summer months. Additional efforts include partnerships with visiting undergraduate classes and a pilot of a new winter ecosystems course held in January, 2010. In addition to these group efforts, described below, the scientists in the HBR individually support approximately 20 additional undergraduates per year either as summer field assistants or lab assistants during the academic year.

*Research Experience for Undergraduates:* During the summers of 2008 and 2009 an NSF-funded REU program was conducted with Plymouth State University. The program is supplemented by the HBRF, which adds 3-4 students and crucial staff support. Each student is mentored by HBR scientists. The program is unique in that it emphasizes science communication to broader audiences; in addition to conducting research projects, each student develops a science communication project with a non-profit or management agency engaged with the public.

*Undergraduate faculty partnerships:* Faculty who bring at least one undergraduate class per year to HBR are asked to provide the HBR staff with a syllabus and written statement describing how the site visit is incorporated into the course curriculum. This has grown from our on-site tour efforts as a way to ensure that HBR staff are meeting the needs of each visiting class and that the visiting instructors are supporting our efforts with classroom instruction.

*Winter field course:* We completed a pilot Winter Ecosystems course in January, 2010. Seven HBR scientists and staff presented a 4-day Winter Ecosystems module as a major part of a winter ecology course offered at neighboring Plymouth State University. We expect to build on this effort and offer some form of a winter course each year, possibly targeting teachers and undergraduates in alternating years.

**Other Outreach and Education efforts:** We conduct many tours and provide interpretation for visiting audiences. For example, in 2009 these included: The New Hampshire Fisheries Council, The New England Forestry Foundation, The New England-St. Lawrence Valley Geography meeting, and a group of silviculturists from the region. We also maintain educational resources on our website, including virtual tours of the watersheds and Mirror Lake. These are currently underutilized, and we plan to revamp the site and begin using them more heavily with our partner faculty and schools in the coming years.

**Proposed new work**: We will complete our self-study of the *Science Links* program and review and revise the program based on this assessment. We will complete the local-scale C management project and the planned project on migratory birds. We will likely conduct another *Science Links* project on a topic to be determined later in this LTER cycle. Many aspects of our education efforts are new, but have been well received, so we expect they will continue to grow. For example, we are organizing for the renewal request for our REU program and brainstorming the potential directions to take our new winter field course program. We expect our curricula connecting the Long-term Monitoring efforts with inquiry tasks as defined by the New England Common Assessment Program exams to generate interest among teachers region-wide and become a major avenue of school outreach for the site.

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