RESPONSE OF ADIRONDACK ECOSYSTEMS TO ATMOSPHERIC POLLUTANTS AND CLIMATE CHANGE AT THE HUNTINGTON FOREST AND ARBUTUS WATERSHED: RESEARCH FINDINGS AND IMPLICATIONS FOR PUBLIC POLICY

FINAL REPORT 09-08
NOVEMBER 2009

NEW YORK STATE
ENERGY RESEARCH AND
DEVELOPMENT AUTHORITY

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Final Report

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NYSERDA
Report 09-08

NYSERDA 4917

November 2009

Notice

Abstract

Investigations at the Huntington Forest have done extensive evaluations of the effects of “acid rain” and climate change on terrestrial and aquatic ecosystems in the Adirondack Mountains of New York State. This is the only research site in the Adirondacks that includes a complete suite of field instruments for monitoring air quality, climatic effects and hydrological responses for both terrestrial and aquatic ecosystems. A combination of atmospheric deposition measurements from the National Atmospheric Deposition Program/National Trends Network (NADP/NTN), CASTNET (Clean Air Status and Trends Network) and MDN (Mercury Deposition Network) have been linked with hydrological, climatological and biogeochemical measurements. Deposition measurements have documented improvements in precipitation chemistry and watershed responses due to decreases in sulfur emission, but the contribution the atmospheric deposition of biologically available nitrogen continues to be elevated. The net retention or loss of this added nitrogen has been shown to be linked to climatic conditions as well as landscape features including topography, soil conditions and the composition of the forest vegetation. Results from intensive and extensive analyses within and among sites have been incorporated into modeling tools to provide information that is relevant to policy decisions with respect to the regulation of atmospheric emissions that influence air quality and climate in the United States.

Keywords:

Biogeochemistry; watershed; Adirondack; Atmospheric Pollutants; Ecosystem; Climate Change; Long-term monitoring; soils.

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EXECUTIVE SUMMARY

For the past 30 years, scientists associated with the Huntington Forest (HF) have investigated the effects of “acid rain” on forest ecosystems and their associated surface waters. The Adirondack Region of New York state has received considerable attention by scientists, policy makers and the general public due to its spatial extent of natural habitats, elevated inputs of atmospheric deposition and sensitivity to disturbances. The region has a large number of water bodies, many of which are highly sensitive to acidic inputs. Research in the Adirondacks has also documented concerns related to forest health in northern forests and linkages to acidic deposition.

In addition to initiating the “acid rain” research at the HF, NYSERDA funding has been used to support the base operation of deposition monitoring, water chemistry responses and hydrological measurements at the HF, including the Arbutus Watershed system. Substantial support of these research activities has also been provided by the National Science Foundation, U.S. Environmental Project Agency and the United States Department of Agriculture Forest Service. The HF has the only infrastructure within the Adirondacks that supports a complete array of measurements that facilitate quantitative evaluations of the effects of air pollutants on forest ecosystems and their interconnected surface waters. The analysis of acid rain was initiated with establishment at the HF of a National Atmospheric Deposition /National Trends Network (NADP/NTN) Site in 1978. After the initiation of the NADP/NTN station at the HF various studies have been conducted to evaluate the effects of atmospheric deposition.

There has recently been an increase in the interest on the role of climate change on global processes, as well as regional effects within the Northeast United States and the Adirondack Mountains of New York State. Meteorological data have been collected since 1940 at the HF, but annual mean temperatures, precipitation and snowfall have not shown any significant change through 2007. Although we have not been able to detect changes in the climate at the HF, there is a clear indication that the climate is being altered throughout the Northeast. These alterations include changes in temperature, precipitation quantity, the relative distribution of precipitation as rain and snow, and hydrology. Research efforts at the Huntington Forest and the Arbutus Watershed have included an integration of analyses of the effects of air pollutants and climatic effects including the role of changes in winter and summer conditions.

To decrease atmospheric deposition, the U.S. Congress passed amendments to the Clean Air Act in 1990 that required electric utility power plants to further control the emissions of sulfur dioxide. There have been significant changes in atmospheric deposition at the HF since the amendment passed. The most notable change has been a decrease in sulfate deposition, but other inputs have also decreased including nitrate and calcium. The effects of changes in atmospheric deposition in the Adirondacks with respect to the recovery of surface waters from acidification have been evaluated. Time-series analyses have shown that concentrations of sulfate, nitrate, ammonium and basic cations have decreased in precipitation, resulting in increases in pH. Only recently have these declines in sulfate concentrations of Adirondack lakes, including Arbutus Lake, resulted in substantial increases in pH and ANC in these surface waters. Our studies have shown that there is a substantial internal source of sulfur from the watershed that may play an important role in delaying the recovery of impacted surface waters from acidification.

Most recent measurements at the HF indicate that dry deposition is a relatively small part of total nitrogen and sulfur deposition. These and other data from the HF on deposition chemistry have been used in developing a predictive model of atmospheric deposition of major air pollutants for the entire Adirondack Park. This regional model of atmospheric deposition has been used in other studies that have evaluated the contribution of acidic deposition to ecosystem response in the Adirondacks, with particular focus on nitrogen dynamics.

The Arbutus Lake Watershed is part of the original Adirondack Long Term Monitoring (ALTM) project and is the only ALTM site with hydrological monitoring. Within the Arbutus Watershed, we have quantified changes of both the concentrations and the fluxes of major solutes. Decreases in concentrations and fluxes of sulfate and calcium are responses to changes in atmospheric deposition. We have also been able to evaluate the role of within lake processes in affecting biogeochemical responses showing that responses to atmospheric and climatic changes differ substantially across the landscape (i.e., uplands, wetlands, lakes). The Arbutus Watershed was upgraded in 2007 with a "state of the art" wireless communication system that includes near real-time data and digital images from the site. Both archived data and realtime data are available on our Web site. Realtime data are available at:
http://www.esf.edu/hss/em/huntington/data_map_click.html
Archived data are accessible at:
http://www.esf.edu/hss/em/huntington/archive.html

Although a linkage has been found between nitrogen atmospheric deposition and nitrate concentrations in the surface waters, the importance of other factors in affecting both the temporal and spatial patterns of nitrate concentrations has been emphasized in our investigations at the Arbutus Watershed and other sites in the northeast U.S. including other ALTM lakes. Second-growth western Adirondack sites have higher soil solution nitrate concentrations and fluxes than the HF. Differences in soil solution nitrate concentrations between old-growth sites are due to the relative dominance of sugar maple that produces higher concentrations of nitrate within the soil. Within the Adirondacks the presence of sugar maple is a function of calcium availability in the soil, but other factors including gap formation can affect nitrate concentrations in forest stands. Within the Arbutus Watershed, nitrate concentrations are also higher at those locations with nitrogen fixing alders.

As part of the Adirondack Manipulation and Modeling Project (AMMP), we did experimental additions of nitrogen and found that the patterns of nitrogen loss varied with site and form of nitrogen addition and most of the nitrogen input was retained. The complexities associated with evaluating the effects of nitrogen deposition on forest ecosystems and simulation modeling have suggested that marked nitrate losses will only be manifested over extended periods. Specific findings at the Arbutus watershed as well as Grass Pond and Constable Pond in the western Adirondacks have clearly demonstrated the importance of within lake processes in affecting the retention of nitrate and the generation of dissolved organic nitrogen. The heterogeneous topography in the Adirondacks results in diverse landscape features and patterns of hydrological connectivity that are especially important in regulating the temporal and spatial patterns of nitrate concentrations in surface waters. Analyses of nitrate generation patterns between subcatchments S14 and S15 in the Arbutus Watershed have amplified our findings on the importance of vegetation type (i.e., presence of sugar maple and basswood) and geology (i.e., elevated calcium concentrations) result in high nitrate concentrations in surface waters. Understanding the relative importance of both edaphic (e.g., soils and vegetation) and atmospheric (e.g., deposition) factors in affecting nitrate transport to surface waters is critical for evaluating the relative importance of nitrogen pollutant additions in affecting nitrate concentrations.

Hydrological and chemical observations from the outlet of Arbutus Lake and its major inlet (Archer Creek Watershed) have been used to analyze climatic impacts on ecosystem processing. Both climatic conditions and changes in atmospheric deposition have a major influence on dissolved organic carbon and the dynamics of nitrate and sulfate. These results suggest that climatic change in conjunction with atmospheric deposition of nitrogen may alter nitrate export, especially during snowmelt when episodes may result in deleterious surface water conditions.

We have studied the influence of climate change on watershed response by evaluating how storms affect hydrology and biogeochemistry. It is expected that both the intensity and frequency of storms will increase in the northeastern U.S., including the Adirondacks. Work within the Archer Creek watershed has demonstrated linkages between hydrological and biogeochemical responses including evaluations of how hydrological connectivity affects chemical responses to these storms. Following droughts, a substantial decrease in stream water pH was noted due to the mobilization of sulfur previously stored in wetlands, suggesting the importance of wetlands in affecting watershed responses to droughts.

Forest vegetation in the Adirondacks plays a critical role in the response of watersheds to atmospheric pollutants and climate change. Sugar maple presence and abundance have been clearly linked to nitrate concentrations in soils and surface waters of the Adirondacks as well as other regions in the northern forest. There has been considerable concern associated with the loss of calcium from forested ecosystems due to acidic deposition and the concomitant decline in sugar maple. A calcium rich subcatchment in Archer Creek has a greater proportion of sugar maple and basswood while a subcatchment with lower calcium concentrations has a higher proportion of American beech. A combination of these chemical and biological attributes result in the more calcium rich catchment having substantially higher nitrate concentrations in soils and surface waters. Analyses on the effects of calcium concentrations to determine vegetation relationships and soil nitrate levels have been done for a wide range of sites across the entire Adirondacks. Within the Adirondacks soil calcium availability has a major influence on vegetation type and the type of vegetation has a major effect on stream nitrate concentrations and fluxes. We have documented marked changes in vegetation at the HF due to beech bark disease. The influences of geology and vegetation need to be considered when evaluating the response of Adirondack ecosystems to changes in atmospheric deposition associated the emissions of nitrogen oxides associated with the combustion of fossil fuels.

We have employed a variety of approaches for integrating the results of the HF/Arbutus Watershed for larger regions including the Adirondacks, northeastern U.S. and southeastern Canada. The results of studies on the Arbutus Watershed have been considered in assessments of the effects of acidic deposition for the Adirondacks and New York State. More specifically as part of the ALTM project, the Arbutus Watershed has been part of the analyses on lake/watershed responses including analyses of nitrogen budgets and acid neutralizing capacity. The evaluation of Adirondack nitrogen budgets emphasized the importance of specific watershed features including the presence of lakes have an influence on the level of nitrogen retention. Using the detailed hydrological and biogeochemical information available for the Arbutus Watershed, we have also employed the forest watershed biogeochemical simulation model PnET-BGC to predict long-term changes in watershed chemistry including an analysis of how various scenarios associated with changes in atmospheric emission and resultant deposition will be reflected in future surface water chemistry conditions. Such simulation modeling has also been used to compare and contrast watershed responses of the Arbutus Watershed with other watersheds in the region.

The HF/Arbutus Watershed has also been associated with various regional projects that have synthesized results from the northeastern U.S. and southeast Canada. Many of these studies have been supported by the Northeast Ecosystem Research Cooperative (NERC). These regional syntheses have included the use of stable nitrogen isotopes to evaluate nitrogen saturation and a variety of studies that have evaluated watershed elemental budgets. The HF has also been part of a network of sites (GCTE) that have evaluated the effects of soil warming on ecosystem response.

Our research has provided information relevant to policymakers and resource managers on the effects of air pollution on forest and aquatic ecosystems. Our ongoing measurements of atmospheric deposition at the HF have revealed that sulfate deposition to the Adirondacks has decreased over the last 30 years. This decrease is consistent with decreases in emissions of sulfur dioxide. These observations are important because they indicate that the 1970 and 1990 Amendments of the Clean Air Act have helped reduce acidic deposition and inputs of sulfate, which is the major source of acidity to acid-sensitive lakes in the Adirondacks. Using mass balance calculations we have confirmed the contribution of internal sulfur sources that may delay the recovery of forested ecosystems following decreases in sulfur deposition. We have also shown that there has not been a concomitant substantial change in nitrogen deposition; hence the relative importance of nitrogen in contributing to acidic deposition is increasing. Long-term measurements have also shown a decrease in sulfate concentrations.

We have documented the importance of within lake processes in affecting chemistry. These within lake processes result in different chemical responses to changes in atmospheric deposition and climate than upland systems and their associated surface waters. Our studies have shown that these upland systems in the Adirondacks are much more responsive than lakes to climatic events including snowmelt and droughts. These upland systems need to be monitored for a full evaluation of atmospheric and climatic effects. Climatic events associated with snowmelt and drought effects have a major influence on watershed responses including the generation of acidic episodes. Climatic predictions for the region indicate that the period of snow cover will decrease, and drought frequency and duration will increase. Both in-lake biological processing of nitrogen as well as nitrogen inputs and transformations associated with nitrogen fixation and the cycling, storage and export of nitrogen in wetlands, add to the complexity of differential patterns of nitrate concentration across the Adirondack region. The reason for the long-term decline in lake nitrate is unclear. It is possible that this trend is due to changes in climate and/or hydrology. Our analysis showing the importance of geology (e.g., calcium concentrations) and vegetation type (e.g., sugar maple and basswood) indicate that these factors are an important influence affecting the response of Adirondack ecosystems to changes in atmospheric pollutants.

Biogeochemical model PnET-BGC calculations for the Arbutus watershed have clearly demonstrated that acidification of soil and water has resulted from inputs of acidic deposition over the last 150 years, and that chemical recovery has occurred over the last 30 years in response to the 1970 and 1990 Amendments to the Clean Air Act. Projections of potential future changes suggest that under current deposition patterns Adirondack lakes will either continue to acidify or recover at a very slow rate. Model predictions suggest that additional reductions in sulfur and nitrogen will help accelerate the rate of ANC increase but the period of chemical recovery will be decades.

Future research efforts at the HF and the Arbutus Watershed will include an integrated effort to analyze the effects of air pollutants and climatic change on ecosystem responses including changes in surface water chemistry. We anticipate evaluating various policy scenarios that affect the emissions of pollutants and their effects on ecosystem processes. We will continue ongoing, long-term measurements of atmospheric deposition and evaluate the response of the HF/Arbutus Lake Watershed system to these changes. Our approaches will use a combination of chemical mass balances, isotopic evaluations, statistical determinations and modeling to evaluate acid deposition on Adirondack ecosystems. Our studies are being done in the context of other intensive and extensive analyses of vegetation and soil components and processes in the region. These results are being made available as part of the historical data base of HF/Arbutus

Watershed that has been used for evaluating the influences of atmospheric deposition and climate on key biogeochemical processes. The integration of watershed measurements within the Arbutus Watershed is also being facilitated by the availability of near real time measurement system that provides results to the general community on the World Wide Web.

1. INTRODUCTION

The Huntington Forest (HF) has been the site of investigations on the effects of "acid rain" on forest ecosystems for the past 30 years. The HF is in the center of the Adirondacks, a region that has had considerable attention due to its sensitivity to "acidic deposition." The initiation of acid rain research as well as continuing support on the evaluation of "acidic deposition" effects to the Adirondack region at the HF has been aided by funding through New York State Energy Research Development Authority (NYSERDA). The analysis of acid rain was initiated with establishment at the HF of a National Atmospheric Deposition /National Trends Network (NADP/NTN) Site in 1978 (http://nadp.sws.uiuc.edu/sites/siteinfo.asp?id=NY20&net=NADP). After the initiation of the NADP/NTN station at the HF, various studies have evaluated the effects of acid rain on forested ecosystems and associated waters. Many of these studies have been done in conjunction as collaborative investigations including sites and scientists throughout the world, but with a particular focus on the northeast U.S. and the Adirondacks. The HF atmospheric monitoring (http://www.epa.gov/castnet/ **)** has also been expanded to include dry deposition and the monitoring of atmospheric mercury inputs in December 1999 (http://nadp.sws.uiuc.edu/mdn/).

Understanding the effects of acidic deposition, mercury inputs and climate has been facilitated by the development at the HF of the Arbutus Watershed system. Investigations at the Arbutus Lake watershed include the monitoring of the hydrology and chemistry at various locations including the outlet and the major inlet. Monitoring is a critical activity to assess environmental changes (Table 1) (Lovett et al., 2007).

Table 1. Attributes of highly effective monitoring programs (Adapted from Lovett et al., 2007)

(1) Design the program around clear and compelling scientific questions. *Questions are crucial because they determine the variables measured, spatial extent of sampling, intensity and duration of the measurements, and, ultimately, the usefulness of the data.*
(2) Include review, feedback, and adaptation in the design. *The guiding questions may change over time, and the measurements should be designed to accommodate such changes. The program leaders should continually ask,"Are our questions still relevant and are the data still providing an answer?" The program should have the capacity to adapt to changing questions and incorporate changing technology without losing the continuity of its core measurements.*
(3) Choose measurements carefully and with the future in mind. *Not every variable can be monitored, and the core measurements selected should be important as either basic measures of system function, indicators of change, or variables of particular human interest. If the question involves monitoring change in a statistical population, measurements should be carefully chosen to provide a statistically representative sample of that population. Measurements should be as inexpensive as possible because the cost of the program may determine its long-term sustainability.*
(4) Maintain quality and consistency of the data*. The best way to ensure that data will not be used is to compromise quality or to change measurement methods or collection sites repeatedly. The confidence of future users of the data will depend entirely on the quality assurance program implemented at the outset. Sample collections and measurements should be rigorous, repeatable, well documented, and employ accepted methods. Methods should be changed only with great caution, and any changes should be recorded and accompanied by an extended period in which both the new and the old methods are used in parallel, to establish comparability.*

***(5) Plan for long-term data accessibility and sample archiving**. Metadata should provide all the relevant details of collection, analysis, and data reduction. Raw data should be stored in an accessible form to allow new summaries or analyses if necessary. Raw data, metadata, and descriptions of procedures should be stored in multiple locations. Data collected with public funding should be made available promptly to the public. Policies of confidentiality, data ownership, and data hold-back times should be established at the outset. Archiving of soils, sediments, plant and animal material, and water and air samples provides an invaluable opportunity for re-analysis of these samples in the future.*

***(6) Continually examine, interpret, and present the monitoring data.** The best way to catch errors or notice trends is for scientists and other concerned individuals to use the data rigorously and often. Adequate resources should be committed to managing data and evaluating, interpreting, and publishing results. These are crucial components of successful monitoring programs, but planning for them often receives low priority compared to actual data collection.*

***(7) Include monitoring within an integrated research program**. An integrated program may include modeling, experimentation, and cross-site comparisons. This multi-faceted approach is the best way to ensure that the data are useful and, indeed, are used.*

The funding for the projects described in this report has supported: (1) the continuation of the monitoring efforts for the Huntington Forest NADP/NTN site; (2) the evaluation of results from Huntington Forest CASTNET site: (3) the operation of the Huntington MDN site; (4) the continuation of monitoring of the Arbutus Watershed and expansion of the monitoring of subcatchments in the Archer Creek Watershed to include the evaluation of the effects atmospheric inputs and climate change; (5) the evaluation of the role of nitrogen fixing alders in affecting nitrogen inputs to wetlands; and (6) the application of the PnET-BGC model for evaluating watershed responses to atmospheric deposition including the effects of “acid rain”.

This report also provides a synopsis of recent research findings related to the effects of acidic deposition and implications for public policy with particular attention to those investigations that have been centered at the HF and Arbutus Watershed. These results are placed in the context of the response of Adirondack ecosystems to atmospheric air pollutants and climate change.

2. IMPORTANCE OF THE ADIRONDACKS

The Adirondack Region of New York State has received considerable attention by scientists, policy makers and the general public due to its spatial extent of natural habitats, elevated inputs of atmospheric deposition and sensitivity to disturbance. This large (2,400,000 ha) region in northern New York is the largest park in the contiguous United States (Figure 1).

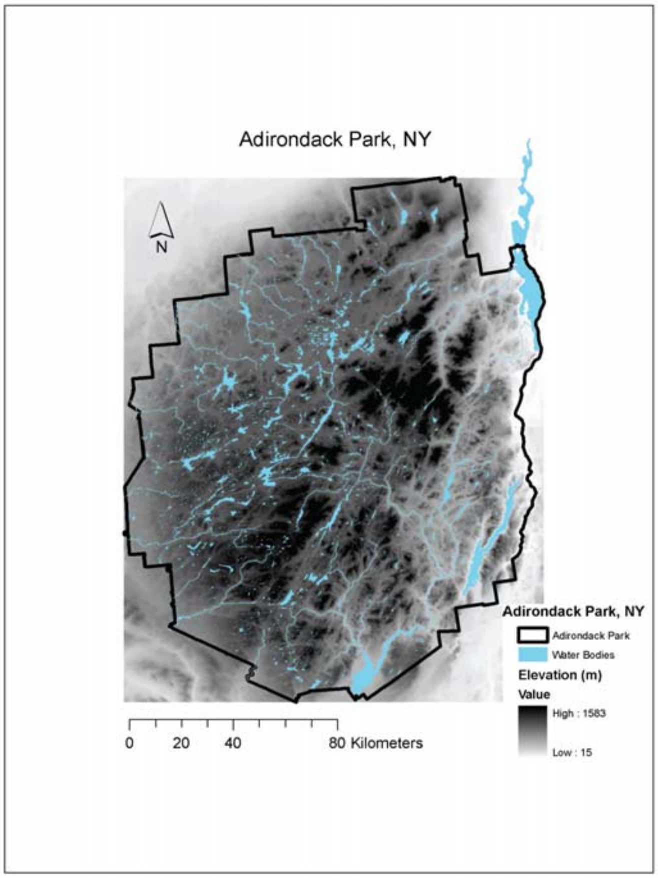


Figure 1.Elevation and water bodies in the Adirondacks.

The Adirondacks have a rich environmental history, including concerns over land usages that provided some of the motivation for the founding of the Adirondack Park. At the 1894 Constitutional Convention in New York State, a new covenant to achieve meaningful protection of the Forest Preserve was included in the new Constitution and from that time on, the Adirondack Forest Preserve was designated to be "forever wild." The Adirondack Park is a complex mixture of private and public lands. These lands have a wide range of protection ranging from complete protection for public wilderness areas to other areas that have considerable commercial development (Graham, 1984).

Beginning in the mid 1970s, considerable attention was focused on the Adirondacks due to the concerns related to “acid rain.” The focus on the Adirondacks was due to the region having high levels of atmospheric deposition and a large number of water bodies (1290 lakes >4 ha surface area; total surface area118,777 ha), many of which are highly sensitive to acidic inputs (Figure 1).

Later research in the Adirondacks also documented concerns related to forest health, including problems associated with winter freezing injury to trees and nutrient depletion from soil. Useful summaries of the impact of air pollutants on Adirondack ecosystems can be found in Driscoll (1991), Driscoll et al. (2003ab) and Jenkins et al. (2007).

3. THE HUNTINGTON FOREST AND ARBUTUS WATERSHED IN THE CENTRAL ADIRONDACKS

The Huntington Forest (HF) also known at the Huntington Wildlife Forest lies in the center (latitude 44º E 00" N, longitude 74º E 13" W) of the Adirondacks and is within the Hudson River drainage (Figure 2).

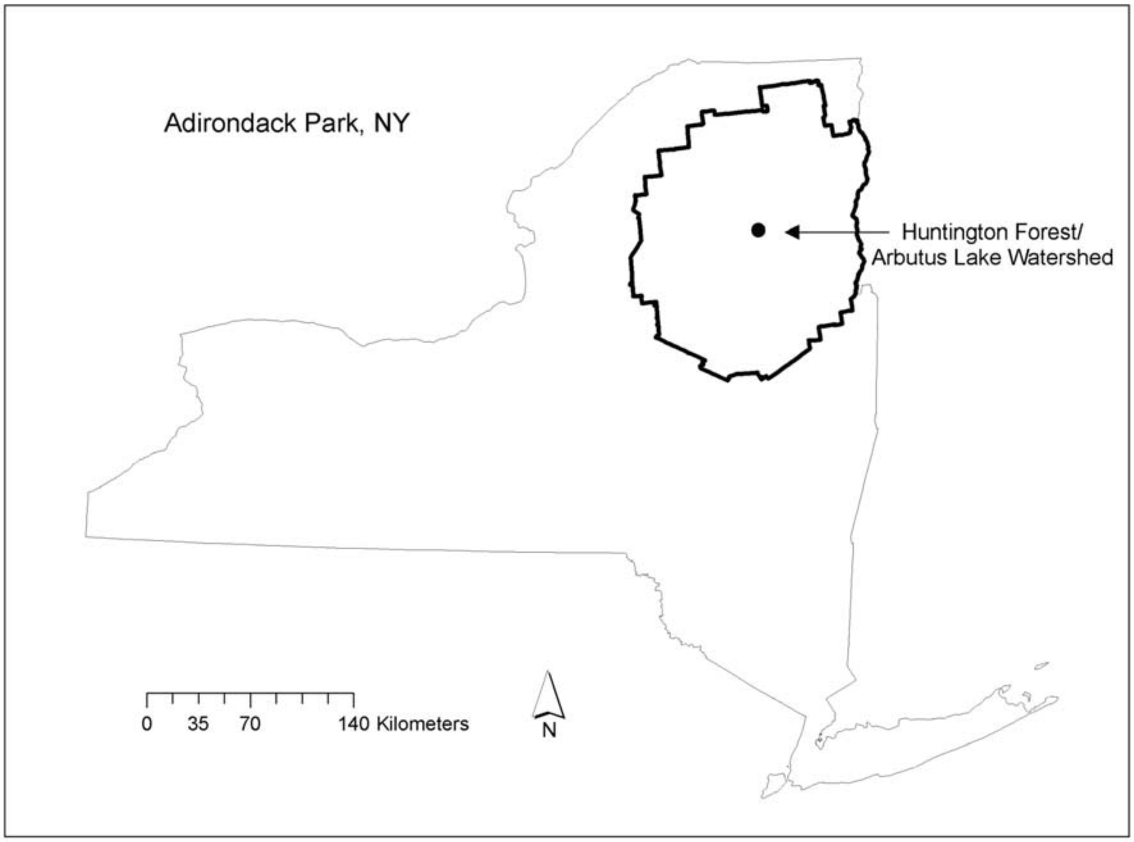


Figure 2. Location at Huntington Forest and the Adirondack Park in New York State

In 1932, the Huntington Wildlife Forest was donated by Archer and Anna Huntington to what is now the State University of New York, College of Environmental Science and Forestry (Masters, 1993). The 6,000 ha HF is located in the Town of Newcomb, western Essex County and in the Town of Long Lake, eastern Hamilton County, New York, (latitude 44 00° N, longitude 74 13° W). The HF is part of the Adirondack Ecological Center (AEC: http://www.esf.edu/aec/) and is a participant in the Northeast Ecosystem Research Cooperative (NERC: http://www.ecostudies.org/nerc/).

The topography of the HF is mountainous and elevations range from 457 m to 823 m. Vegetation consists of northern hardwoods (72%), mixed hardwood-conifers (18%), and conifers (10%). Wetlands constitute an important component of the landscape of the HF (Bischoff et al., 2001).

The property also contains five lakes: Catlin (area=217 ha; max. depth=17 m), Rich (160 ha; 18 m), Wolf (58 ha; 14 m), Arbutus (49 ha; 8 m) and Deer (38 ha; 3 m). Arbutus Lake and its associated watershed have been extensively studied. Further details on the Arbutus Watershed are provided in Chapter 7.

Upper slopes at the HF are dominated by *Fagus grandifolia* (American beech) and *Acer saccharum* (sugar maple). Overstory vegetation at lower elevations is characterized by *Tsuga canadensis* (hemlock), *Picea rubens* (red spruce) and scattered individuals of *Abies* *balsamea* (balsam fir). The changes in vegetation composition at the Huntington Forest are discussed later in this report. Upland watershed soils are generally <1 m in depth and include Becket-Mundal series sandy loams (coarse-loamy, mixed, frigid typic Haplorthods) while Greenwood Mucky peats are found in valley bottom wetlands. Groundwater occurs predominantly in deep near-stream peats (1-3 m depth), pockets of glacial till in valley-bottoms (0-2 m) and limited zones of glacial outwash deposits.

4. REALTIME AND ARCHIVED DATA WITHIN THE ARBUTUS WATERSHED

The Arbutus Watershed was upgraded in 2007 with a “state of the art” wireless communication system. In addition to continuous measurements at the Arbutus Lake inlet and outlet, we have added a meteorological tower, two upper watershed stream gauges and five groundwater wells to the monitoring network. These upper two subcatchments (S14 and S15) have distinct differences in Ca^{2+} concentrations and vegetation types (Christopher et al., 2006). The number and variety of study sites, coupled with near real-time data from the wireless network, now allows for more detailed and comprehensive examination of critical environmental parameters within a forested Adirondack watershed in response to atmospheric deposition and climate change. This system is also designed to allow for additional watershed measurements to be incorporated into the network. Both the realtime and archived data are available at the following Web sites as described below.

4.1 Realtime Data (http://www.esf.edu/hss/em/huntington/data_map_click.html)

4.1.1 Data System

The realtime data system includes the following :

1) the ***AEC*** (The Adirondack Ecological Center) is the main building at the HWF. This is the location of the Arbutus Hydrological Monitoring Network’s (AHMN) master radio. From here, data are transformed from Serial to IP type and transmitted to the SUNY-ESF campus, located in Syracuse, New York, USA ;

2) The ***Walkup*** site contains a 130-foot (38 m) tower that was first installed to monitor air quality and meteorological parameters, as part of the AIRMoN project

(through 2001). It currently serves as a secondary repeater site, relaying data from the Arbutus Lake Outlet site;

3) The ***Goodnow*** site contains a former USFS fire tower, measuring 60 feet (18.3 m), which was operational until 1979. It is now used for public access at the culmination of the Goodnow Mt. Trail. This site is used as the main repeater of the AHMN system, relaying data from all other sites to the AEC. Measurements: air temperature;

4) The ***Ackerman*** site contains a new 80-foot (24.4 m) tower, located in a sizeable clearing in the upper Arbutus Lake Watershed area. It serves as our meteorological station. Measurements: air temperature, solar energy, relative humidity, rainfall, snow depth, wind speed & direction;

5)The ***Inlet*** - 130 ha Archer Creek Catchment drains into Arbutus Lake. This catchment has been monitored since 1994 using an H-flume at the Arbutus Lake Inlet site. An 80-foot (24.4 m) tower was installed in the summer of 2006 for radio communications. Measurements: air temperature, water temperature, water level & discharge, and water pH];

6) The ***Outlet*** - Arbutus Lake Watershed is gauged by means of a v-notch weir at this site, installed in 1991 by the USGS. This station is now managed by our biogeochemistry lab and was updated with new equipment in March 2007. Measurements: water temperature, water level & discharge, precipitation, water pH, digital camera;

7) The ***Stream 14*** site drains a subcatchment in the upper Arbutus Watershed, close to the Ackerman Clearing site. A V-notch weir was installed at this site

during the summer of 2005. Measurements: water temperature, water level & discharge, and water pH;

8) The ***Stream 15*** site drains a subcatchment in the upper Arbutus Watershed, close to the Ackerman Clearing site. A V-notch weir was installed at this site during the summer of 2005. Measurements: water temperature, water level & discharge, water pH;

9) ***Well 12*** - measuring water temperature and water level;

10) **Well 33** - measuring water temperature and water level;

11) ***Well 34*** - measuring water temperature and water level;

12) ***Well 35*** - measuring water temperature and water level; and

13) ***Well 36*** - measuring water temperature, water level.

4.1.2 Additional instrumentation

There are also two realtime digital cameras:

Goodnow Mt. Camera http://www.esf.edu/hss/em/huntington/goodnowCam.html

Digital images are taken with a StarDot Technologies, NetCam XL with a Standard Varifocal Lens (4.5 ~ 12mm, 81°-38° wide, Manual Iris & Focus/Zoom). The camera is located on the front of the Adirondack Ecological Center and points southeast toward Goodnow Mountain. There is a fire tower, which is visible on top of the Goodnow Mountain, just to the right of the most prominent conifer in the foreground. The Goodnow Mountain image is updated every 30 minutes.

Arbutus Lake Camera http://www.esf.edu/hss/em/huntington/arbutusCam.html

Digital images are taken with a StarDot Technologies, model NetCam SC camera, with a Standard Varifocal Lens (4.5 ~ 12mm, 81°-38° wide, Manual Iris & Focus/Zoom). The camera is located on the top of the 130-foot Walkup Tower, near the outlet of Arbutus Lake, and points toward the northwest. A new photograph is taken every 15 minutes.

4.1.3 Phenocam Study http://phenocam.unh.edu

The Arbutus Lake and Goodnow Mountain cameras provide data (photographs) for the Phenocam Project. This study focus is to use a network of digital cameras, mounted on towers, buildings, etc., throughout the United States and Canada, to monitor phenological changes to forest canopy over time. It is hypothesized that these images can be used to study climate change, specifically, to quantify whether or not trees are "leafing out" earlier, compared to past years.

4.2 Archived Data http://www.esf.edu/hss/em/huntington/archive.html

4.2.1 Archived Chemistry Data

Archived data, including weekly stream samples, have been collected from the Arbutus Lake Inlet and Outlet since 1995. Previously, samples were collected from the Arbutus Lake Outlet only (1983-1994). When the weekly collection is made, two replicate samples are taken from each site. Following collection, samples are kept cold and mailed to the Biogeochemistry Laboratory at SUNY-ESF, where laboratory analyses are performed. Data produced from these analyses include: pH, DOC, NO_3^-, SO_4^{2-}, Cl^-, NH_4^+ total dissolved N, Na^+, K^+, Mg^{2+}, Ca^{2+}, total Al and Si.

4.2.2 Archived Hydrology Data

The stage height at the Arbutus Lake Inlet and Outlet has been continuously measured with a pressure transducer, and recorded by a Campbell Scientific, Inc. datalogger from 1999-2007. During this period, data were downloaded weekly, by AEC staff, and emailed to SUNY-ESF.

Since 2007 and the establishment of the wireless data network at the Huntington Wildlife Forest, data are downloaded from the Arbutus Inlet and Outlet sites automatically by a server at SUNY-ESF. In addition, data are also downloaded from many other sites at the HWF (Goodnow Mountain Fire Tower, Stream 14, Stream 15, Ackerman Clearing Tower, Groundwater Wells 12, 33, 34, 35 & 36).

4.2.3 Archived Meteorological Data

In 2007, we began measuring air temperature at the fire tower on Goodnow Mountain. A meteorological station was also established in the upper Arbutus Watershed, and at the Ackerman Clearing site.

A large number of individuals and projects have supported research on atmospheric air pollutants and climate change at the Huntington Forest (**Appendicies I and II**) .

5. HISTORICAL CHANGES OF CLIMATE AND INTERACTIONS WITH WATERSHED PROCESSES AT THE HUNTINGTON FOREST

5.1 Critical Issues:

- *Climate change is of critical importance on global, regional, and local scales including the Adirondacks of New York.*
- *Climatic changes both associated with effects during the winter and summer have a marked effect on watershed biogeochemical responses.*

5.2 General Relationships associated with Climate

Climate can be defined as the meteorological conditions, including temperature, precipitation, and wind that are characteristic for a specific region. There has been considerable interest by scientists and policy makers on climatic changes associated with the increases in atmospheric “greenhouse” gases. Various international (IPCC, 2007) and regional (NECIA,2006) reports have clearly documented recent changes and predictions of even more drastic alterations of the climate. Within the northeast United States it is predicted that there will be an increase in temperatures, rain on snow events and summer droughts and a decrease in the duration and extent of the snowpack (NECIA, 2006). The overall importance of these climatic changes in affecting biogeochemical changes of ecosystems in the northeast has recently been reviewed by Campbell et al. (2009). The general relationships between changes in temperature and precipitation in affecting biogeochemical processes in forests are given in Figure 3.

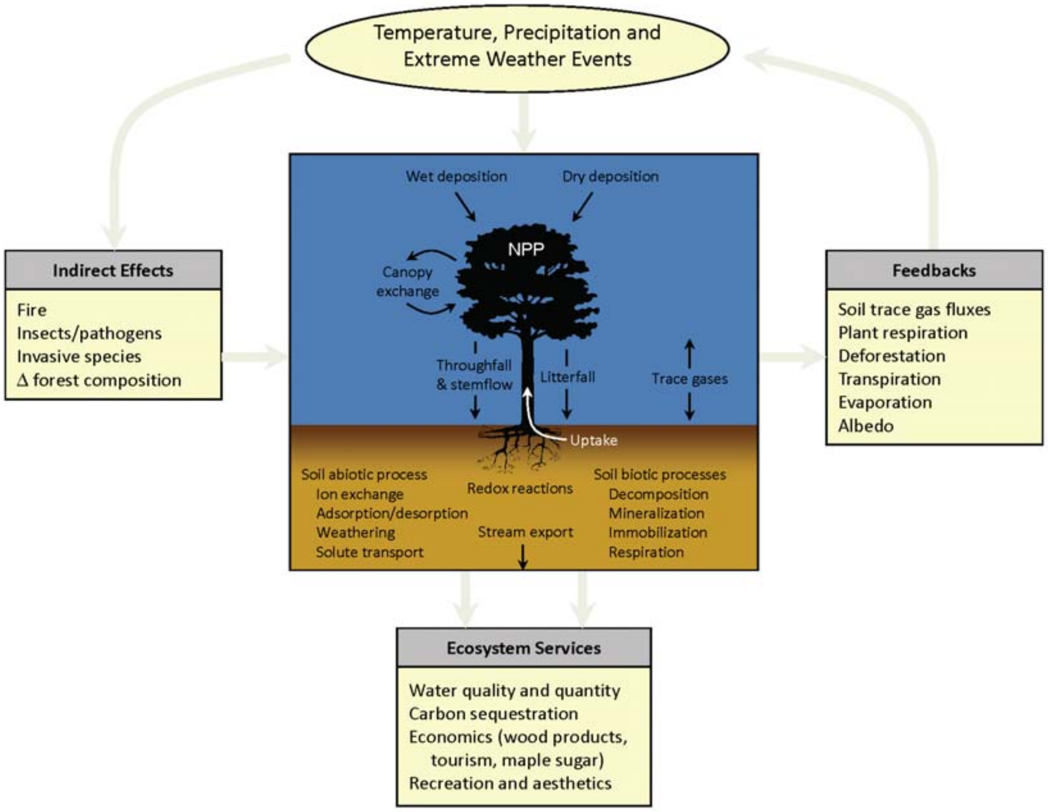
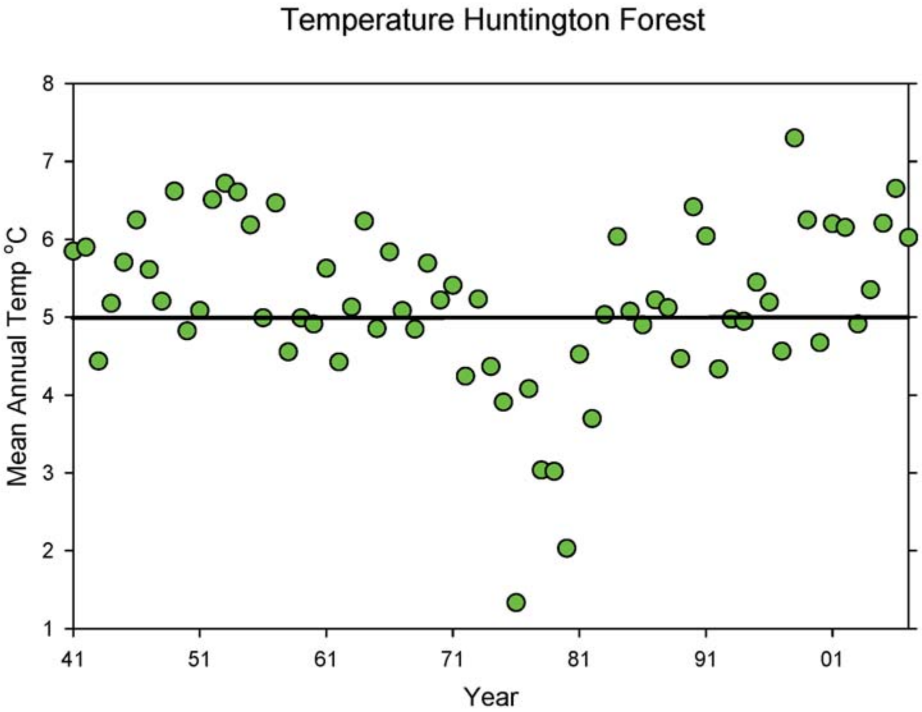


Figure 3. Conceptual diagram showing the direct and indirect effects of changes in temperature and precipitation on biogeochemical processes in forests and on the services forests provide. Also, shown are feedbacks that further influence climatological effects. Adapted from Campbell et al. (2009).

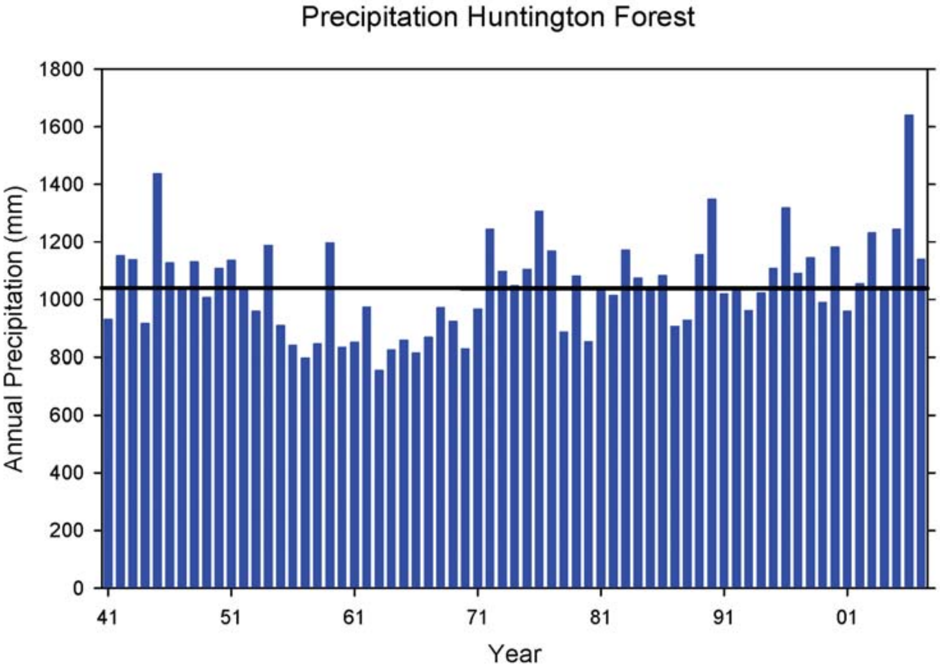
5.3 Historical Meteorology at the Huntington Forest

Meteorological data have been collected since 1940 at the HF. Annual mean temperatures, precipitation and snowfall have shown no significant change from 1940 through 2007 although from 1975 through 1981 the temperatures were generally cooler than average (Figure 4). The HF has a mean annual temperature of 5.0°C, mean annual precipitation is 1046 mm and mean annual snow fall of 303 cm.



Temperature Huntington Forest

Figure 4a. Mean annual temperature (Horizontal line is mean value for period.)



Precipitation Huntington Forest

Figure 4b. Mean annual precipitation (Horizontal line is mean value for period.)

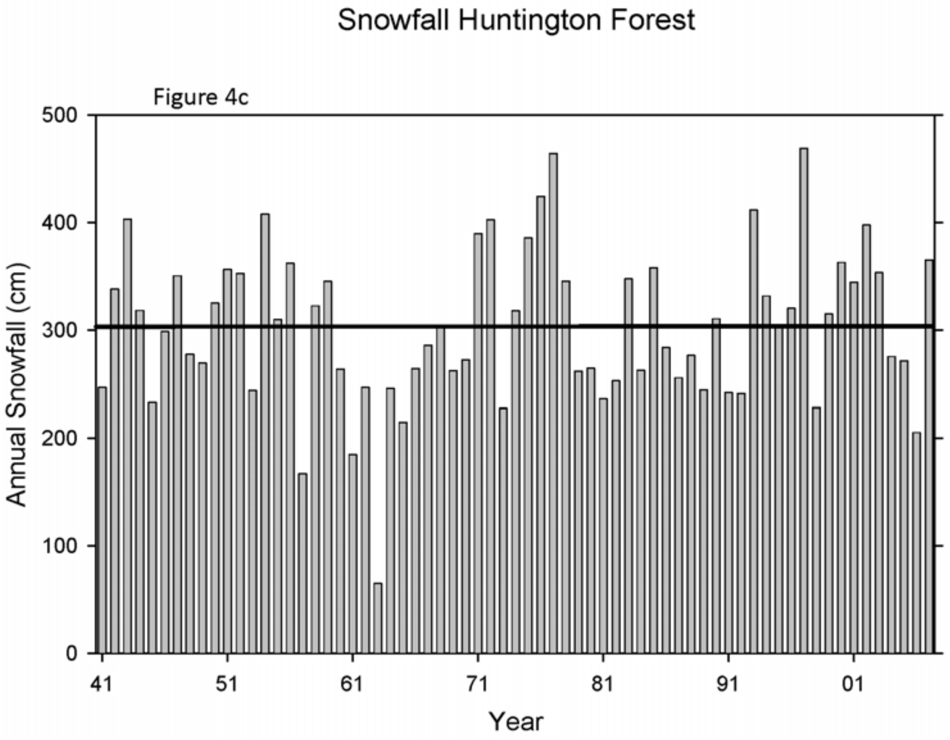


Figure 4c. Mean annual snowfall. (Horizontal lines are means for the period.)

These values are similar to values reported previously for the HF (mean annual temperature of 4.4°C and mean annual precipitation is 1010 mm) for years 1951 through 1980 by Shepard et al. (1989). Although we have not been able to detect changes in climate to date at the Huntington Forest, there is a clear indication that climate change is occurring in the Northeast United States and these changes are altering precipitation and temperature, both of which have substantial impacts on the hydrology of the Adirondacks (NECIA, 2006). Hence, our research efforts at the Huntington Forest and the Arbutus Watershed have included an integration of analyses of the effects of air pollutants (including acidic deposition) and climatic effects including the role of changes in winter conditions (e.g., timing, amount, and duration of the snow pack; changes in temperature regimes) and summer conditions (e.g., timing and duration of droughts; changes in the growing season for vegetation).

5.4 Climatic Influences on Watershed Biogeochemical Responses

Using both hydrological and chemical information from Arbutus Watershed chemistry data, climatic effects on biogeochemical response have been evaluated. Hydrological and chemical results from the outlet of Arbutus Lake as well as for its major inlet (Archer Creek Watershed) have been used to determine how biogeochemical processes are influenced by climatic conditions. Studies have shown that both climatic conditions and changes in atmospheric deposition have a major influence on DOC (Park et al., 2005) and the dynamics of NO_3^- and SO_4^{2-} (Park et al., 2003). We have also noted a strong linkage between winter temperature and NO_3^- export (Figure 5).

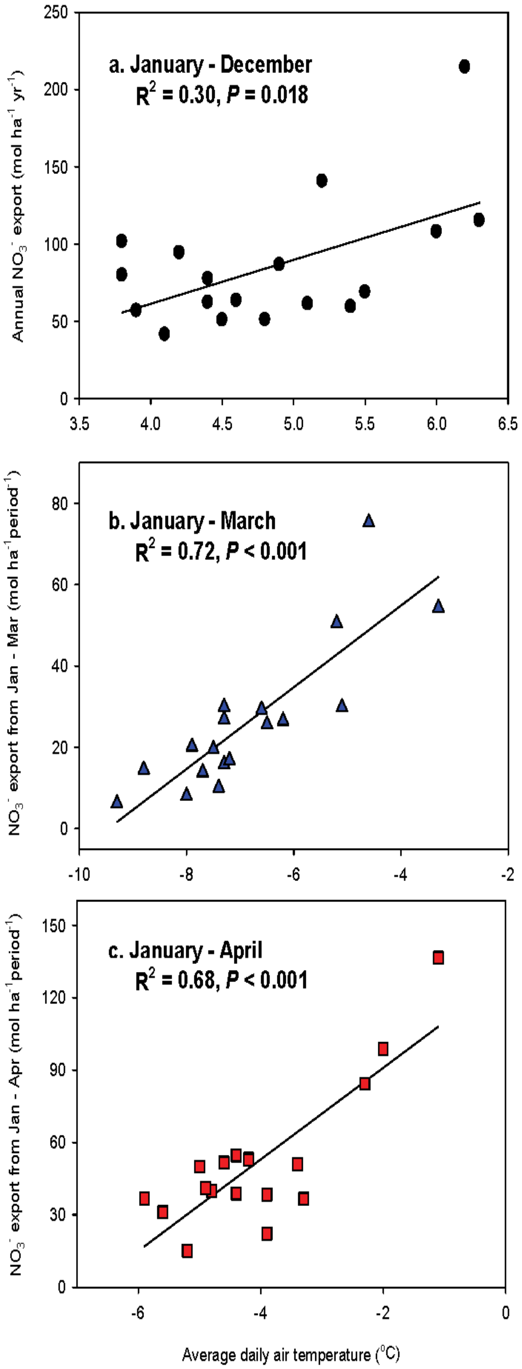


Figure 5. Relationships between average air temperatures and NO_3^- export in lake outlet either for the entire year (a) or for the months preceding spring snowmelt (b: January–March; c: January–April) from 1984 to 2001. The line through the plot is the best-fit regression line and statistical significance is indicated by R^2 followed by P values (Adapted from Park et al., 2003).

These results suggest that climatic change and conjunction with atmospheric deposition of nitrogen may alter NO_3^- export during snowmelt periods. These snowmelt episodes may substantially influence the quality of downstream surface waters. As part of our intensive study comparing biogeochemical and hydrological responses S14 and S15 (the two upper catchments with distinctive Ca^{2+} chemistry and vegetation types), we have been able to ascertain NO_3^- and SO_4^{2-} mobility in the winter and spring by evaluating the stable isotopic patterns of these solutes. Note that 50% or more of the annual watershed discharge can occur during snowmelt (Campbell et al., 2005). Our results have shown that direct atmospheric inputs of NO_3^- and SO_4^{2-} are not the only major sources of these solutes to drainage waters. Internal sources are also major contributors of both nitrogen and sulfur to these watersheds (Piatek et al., 2005; Campbell et al., 2006). There are distinct changes in the isotopic abundances (especially $\delta^{15}N$, $\delta^{34}S$ and $\delta^{18}O$) as NO_3^- and SO_4^{2-} are transported through the soil (Figure 6). These results illustrate the importance of evaluating internal nitrogen and sulfur sources when quantifying the effects of atmospheric deposition on surface waters.

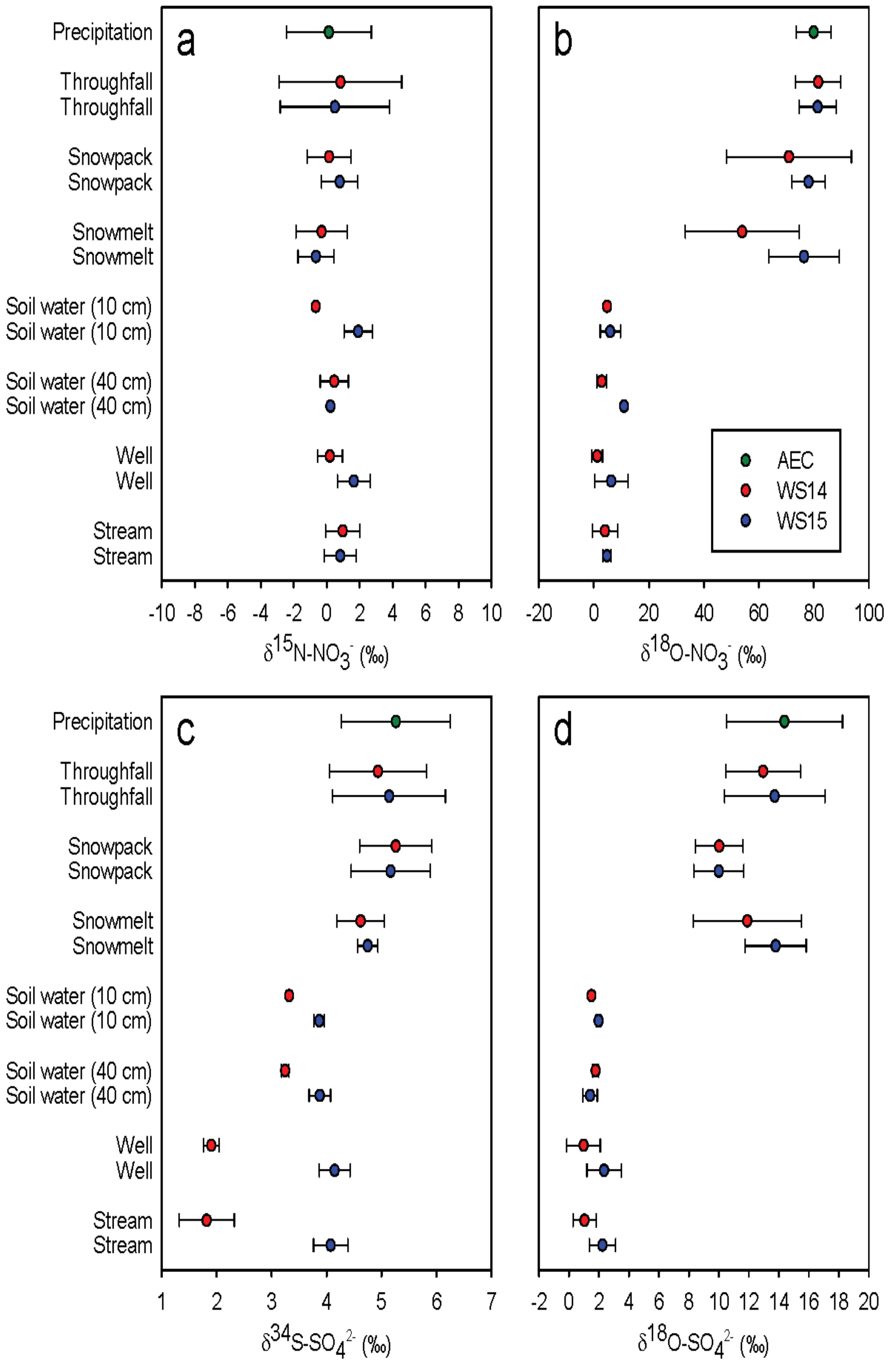


Figure 6. Mean isotopic values of NO_3^- and SO_4^{2-} (±1 SD) in WS14 and WS15 and at the Adirondack Ecological Center (precipitation only). Samples were collected during the snow-covered period (2 December to 10 April) of 2003–2004 (Adapted from Campbell et al., 2006).

In evaluating watershed responses to climate change, it is critical to understand how storms affect hydrology and biogeochemistry. It is expected that both the intensity and frequency of storms will increase in the northeastern U.S. (NECIA, 2006). Work within the Archer Creek watershed has demonstrated linkages between hydrological and biogeochemical responses including how hydrological connectivity affects chemical responses to storms (Inamdar et al., 2004; McHale et al., 2004) (Figure 7).

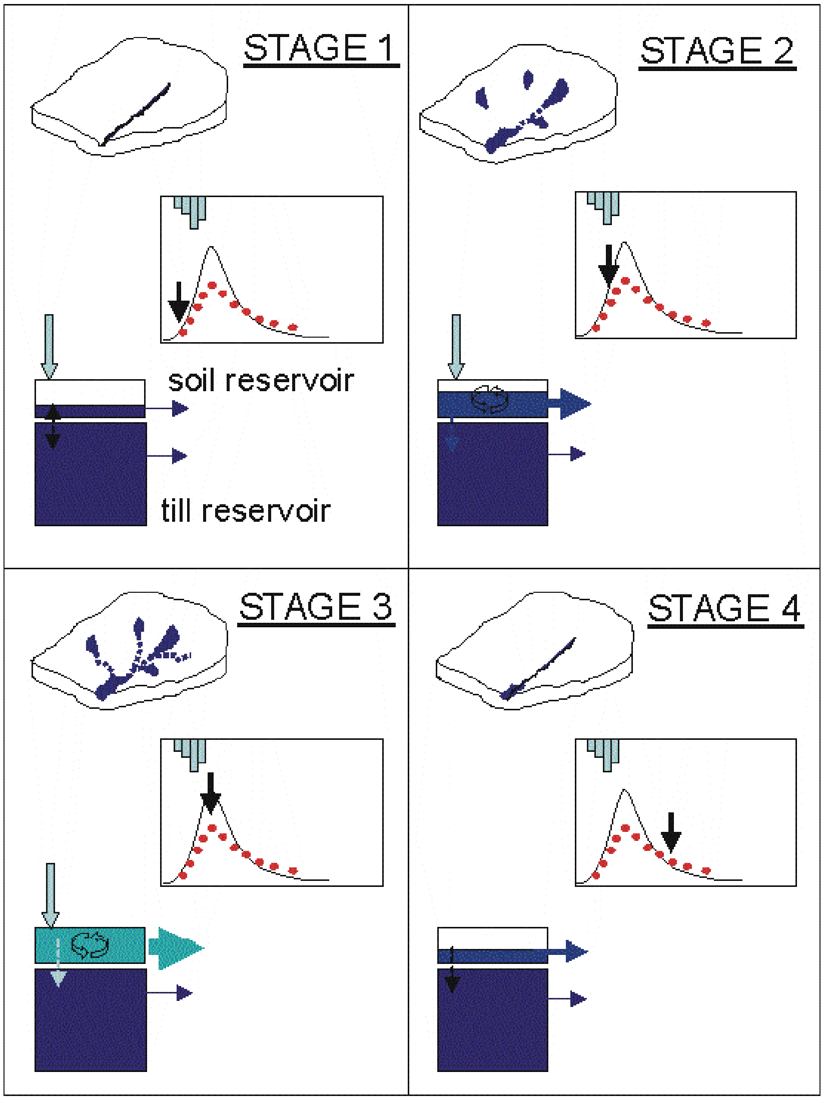


Figure 7. Conceptual model for NO_3^- and DOC evolution considering water and solute contributions from deep and near-surface flow paths and spatial connectedness of saturated areas. Note: arrow on the hydrograph (inset) indicates position of the stage during the event (Adapted from Inamdar et al., 2004).

There are marked differences in the hydrological responses of individual storms (Table 2, from Mitchell et al., 2006) and resultant surface water chemistry (Table 3, from Mitchell et al., 2006).

Table 2. Summer and fall storms at Archer Creek Watershed (From Mitchell et al., 2006)

Reference	**Storm #**	**Dates**	**Precipitation (mm)**	**Discharge (mm)**	**% Water Yield**
Mitchell et al. (2006)	1	Sept. 14-18, 2002	18.5	0.32	2
	2	Sept. 21-24, 2002	33.0	1.23	4
	3	Sept. 27-29, 2002	42.9	3.9	9
	4	Oct. 16-21, 2002	67.6	9.4	14
Inamdar et al. (2004)	Floyd Storm	Sept. 16-25, 1999	138	21	15
McHale et al. (2002)[1]	*1*	Oct. 14, 1995	34.3	8.9	26
	2	Oct. 21, 1995	70.9	34.7	49
	5	June 10, 1996	13.5	14.0	104
	6	July 4, 1996	13.0	11.8	91

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[1] Storms 3 and 4 were snow melt events and thus not included in this comparison

Table 3. Comparative chemistry of solutes in stream discharge in summer and fall storms at the Archer Creek Watershed. Mean values are weighted by discharge for each event (From Mitchell et al., 2006).

Solute Parameter	Storms								
mol$_c$ L^{-1} mol L^{-1}(DOC)	Mitchell et al. (2006)				Inamdar et al. (2004)	McHale et al. (2002)			
pH units	1	2	3	4		*1*	*2*	*5*	*6*
SO_4^{2-} Mean	180	270	303	249	248	158	122	121	117
Max.	208	389	363	287	261	171	156	129	129
Min.	160	152	251	215	164	148	106	114	107
NO_3^- Mean	10	25	14	17	13	7	6	4	6
Max.	16	28	17	20	17	10	8	5	8
Min.	7	4	5	1	10	5	5	3	4
DOC Mean	442	915	1255	1343	1300	NA	NA	NA	NA
Max.	513	990	1510	1930	1579	NA	NA	NA	NA
Min.	326	322	443	520	535	NA	NA	NA	NA
C_b Mean	467	549	494	457	379	345	261	229	277
Max.	490	567	560	519	432	378	330	241	294
Min.	460	487	421	425	313	322	243	222	260
pH Mean	5.6	5.8	5.1	5.3	5.8	6.1	5.4	6.3	NA
Max.	5.7	6.2	6.2	6.2	7.0	6.8	6.5	6.5	NA
Min.	5.4	5.2	4.8	5.0	5.4	5.8	5.0	6.2	NA

Following droughts, a substantial decrease in pH in stream water occurs in response to storm events. This decrease is caused by a release of SO_4^{2-} from the oxidation of sulfide based upon elevated $\delta^{34}S$ values (Figure 8).

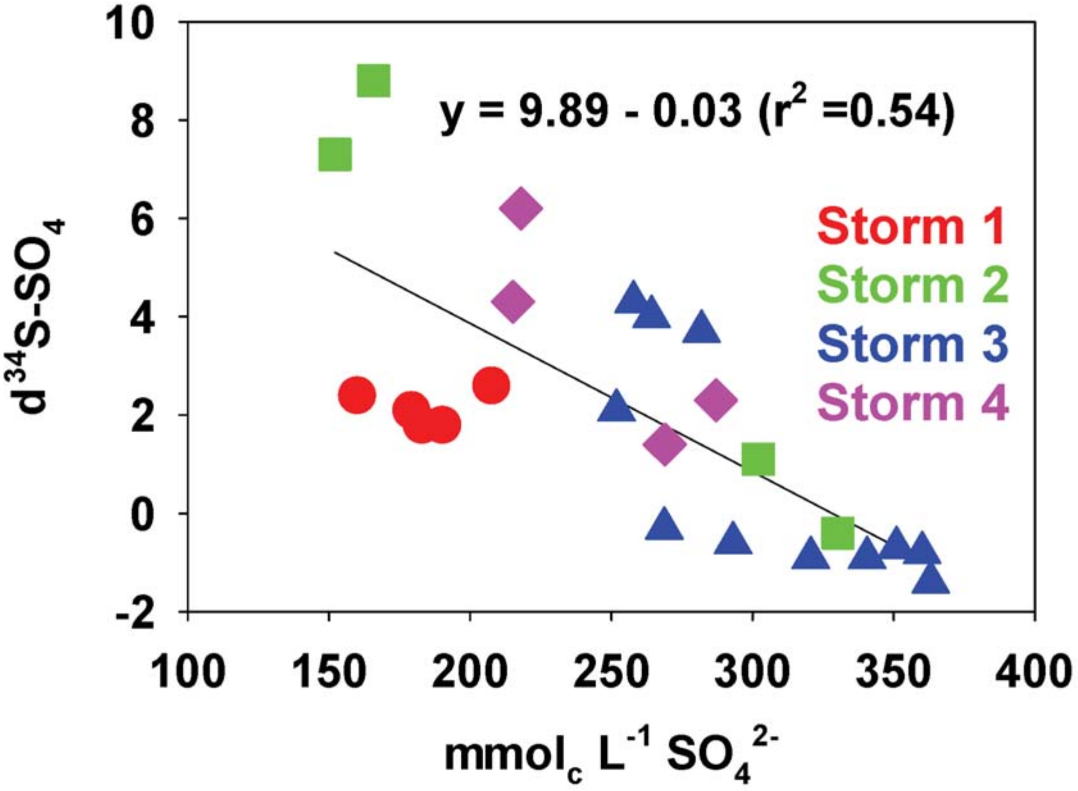


Figure 8. Relationship between $\delta^{34}S$-SO_4^{2-} values and SO_4^{2-} concentrations for four storms in 2002 (Adapted from Mitchell et al., 2006). [Storm 1: circle; Storm 2: square; Storm 3: triangle; Storm 4: diamond).

The use of $\delta^{34}S$ values for SO_4^{2-} can be used to evaluate sulfur sources. During dissimilatory sulfate reduction, there is discrimination for the lighter (S^{32}) isotope causing the resultant sulfide product to have a lower $\delta^{34}S$ value compared to the reactant (SO_4^{2-}). When this sulfide with a distinctively low $\delta^{34}S$ value is oxidized to SO_4^{2-} this solute has relatively low $\delta^{34}S$ value (Mitchell et al., 1998). Hence, the temporal changes in the $\delta^{34}S$

values in surface waters can be used to ascertain the contribution to oxidized sulfide to SO_4^{2-} fluxes in watersheds. Hydrological, chemical and isotopic responses to drought have also been compared with two other watersheds in the northeast U.S. Patterns in responses were attributed to differences in watershed attributes including mineral weathering and the presence of wetlands (Mitchell et al., 2008).

5.5 Key Findings:

- *Increased winter temperature is strongly coupled with the amount of nitrate released from the Arbutus Watershed suggesting the importance of climate change in affecting long-term nitrate loss.*
- *Summer droughts followed by watershed rewetting result in substantial amounts of the mobilization of sulfate and depression of pH in surface waters of the major inlet to Arbutus Lake (Archer Creek).*
- *Increased release of sulfate to surface waters is closely related to the oxidation and mobilization of previously stored sulfide formed under reducing conditions such as those associated with wetlands.*

6.ATMOSPHERIC DEPOSITION IN THE ADIRONDACKS WITH PARTICULAR FOCUS OF RESULTS FROM THE HUNTINGTON FOREST

6.1 Critical Issues

- *There has been considerable focus on evaluating the amount of atmospheric deposition of acidifying compounds of sulfur and nitrogen due to the sensitivity of some Adirondack ecosystems to acidification.*
- *Temporal changes in the deposition of atmospheric pollutants have important affects on ecosystem and watershed processes.*

The HF has participated in the National Atmospheric Deposition Program (NADP) and the National Trends Network (NTN) since Oct. 31, 1978 (http://nadp.sws.uiuc.edu/sites/siteinfo.asp?id=NY20&net=NADP). Mercury (Hg) deposition has been monitored at the HF as part of the Mercury Deposition Network since December 10, 1999 (http://nadp.sws.uiuc.edu/mdn). During the period of measurements, there have been significant changes in atmospheric deposition. This change in deposition is a direct function of changes in emissions including the reductions of SO_2 emissions from electrical power utilities (Figure 9).

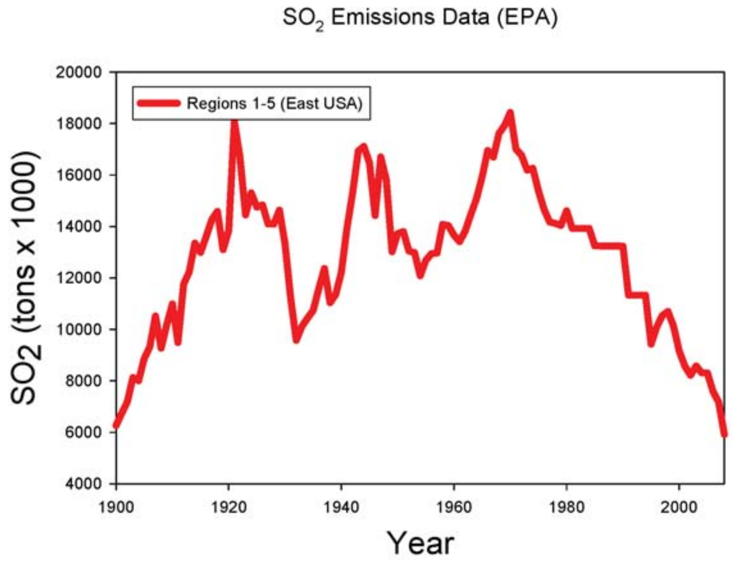


Figure 9. Sulfur dioxide emissions from eastern United States. US EPA Regions 1-5.

The most notable change has been a decrease in sulfate (SO_4^{2-}) deposition ($r^2 = 0.96$, $p < 0.001$), but other inputs such as nitrate (NO_3^-; $r^2 = 0.23$, $p = 0.01$) and calcium (Ca^{2+}; $r^2 = 0.28$, $p = 0.004$) have also decreased (Figure 10).

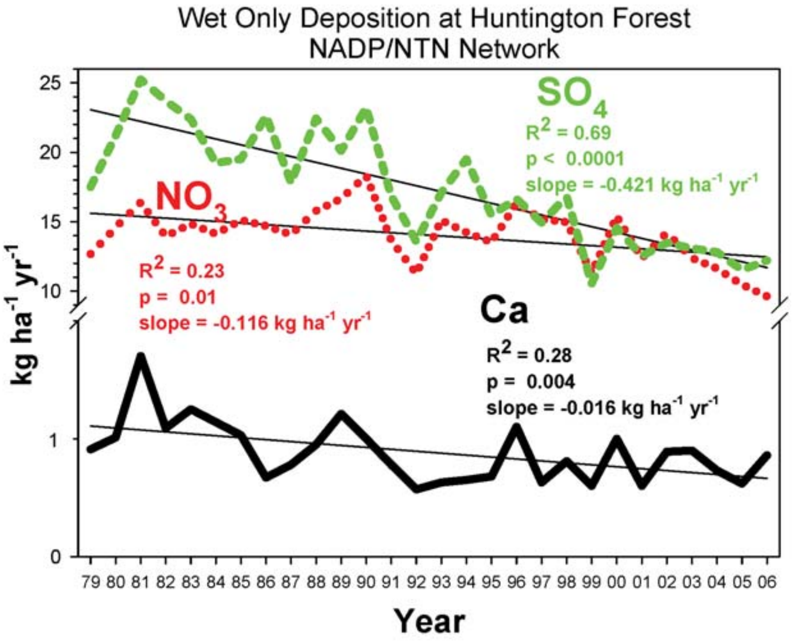


Figure 10. Changes in annual deposition of sulfate, nitrate, and calcium

Decreases have also been found for H^+ ($r^2 = 0.50$, $p < 0.001$), Mg^{2+} ($r^2 = 0.48$, $p < 0.0001$), Na^+ ($r^2 = 0.41$, $p = 0.003$) and Cl^- ($r^2 = 0.20$, $p = 0.02$). Due to these changes the relative contribution of NO_3^- in the acidity of precipitation has increased compared to the other

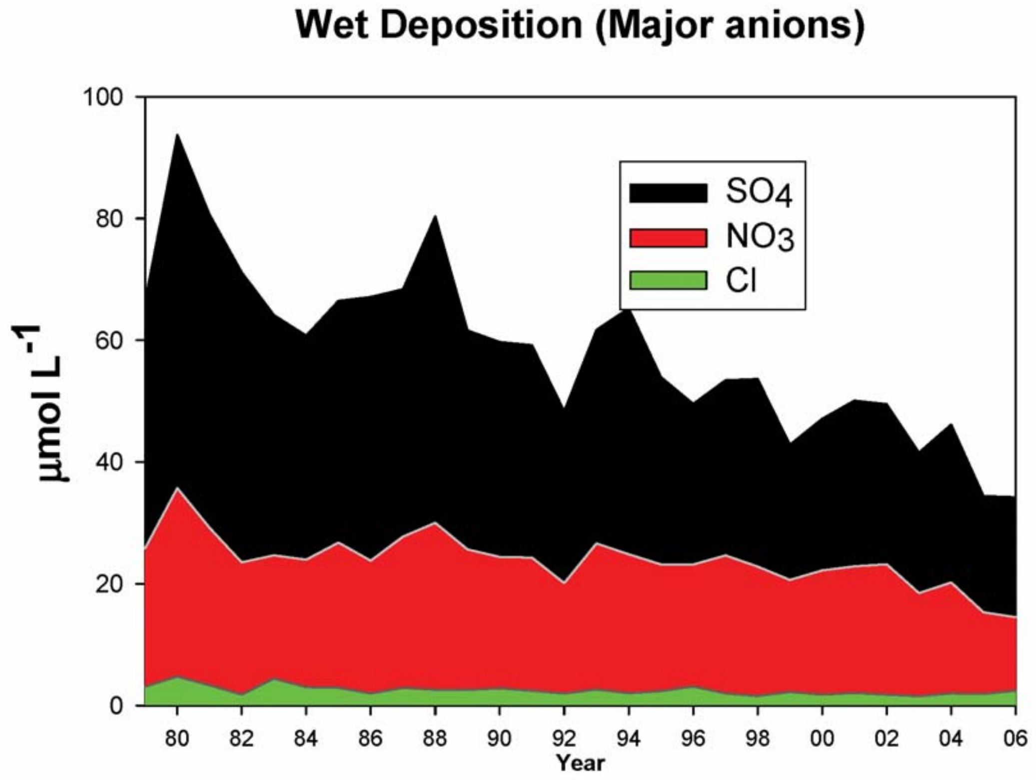
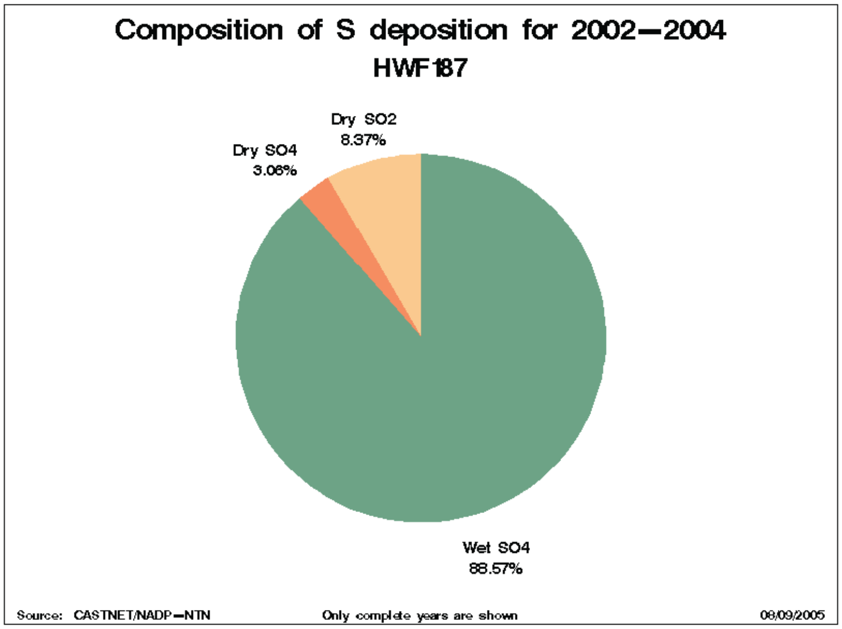


Figure 11. Changes in the relative proportion of the major anions in precipitation

These changes of the Huntington Forest precipitation chemistry have been placed in the context of both policy implementations and regional patterns. The results at the Huntington Forest are of particular importance since this is the only site in the entire Adirondack region that has an infrastructure that includes measurements of atmospheric deposition (NADP/NTN, CASTNET, MDN) as well as quantitative measurements of biogeochemical and hydrological responses of a watershed. To reduce atmospheric deposition, in 1990 Congress passed Amendments to the Clean Air Act that required electric utility power plants to decrease emissions of sulfur dioxide and nitrogen oxides. Tessier et al. (2002) analyzed precipitation volume, wet deposition, and the concentration of the sum of base cations measured at 12 NADP sites in Massachusetts, New Hampshire, Vermont and New York (including the Huntington Forest). Values were compared five-years prior and five-years after Phase I implementation. Continued deposition of base cations may help to reduce the detrimental effects of acidic deposition to acid sensitive soils. All sites, however, exhibited a decline in base cation concentrations. This decline is a contributing factor to the depletion of base cations in soils and surface waters of the region.

Adjacent to the Arbutus Watershed at the HF is a 38-m walk up tower equipped with meteorological instrumentation and filter packs for sampling air chemistry that was monitored by NOAA as part of the Atmospheric Integrated Research Monitoring Network (AIRMoN) through 2001. Eddy correlation measurements of ozone (O_3) and sulfur dioxide (SO_2) have been made using this tower (Meyers and Baldocchi, 1993). Dry deposition measurements were also made as part of the IFS project (Shepard et al., 1989; Johnson and Limburg, 1992). In May 2002, a Clean Air Status and Trends Network (CASTNET) site was installed at the HF. CASTNET is operated by the U.S. Environmental Protection Agency (EPA) and provides atmospheric data on the dry deposition component of total acidic deposition, ground-level ozone and other forms of atmospheric pollution. Most recent measurements indicate that dry deposition is a relativ



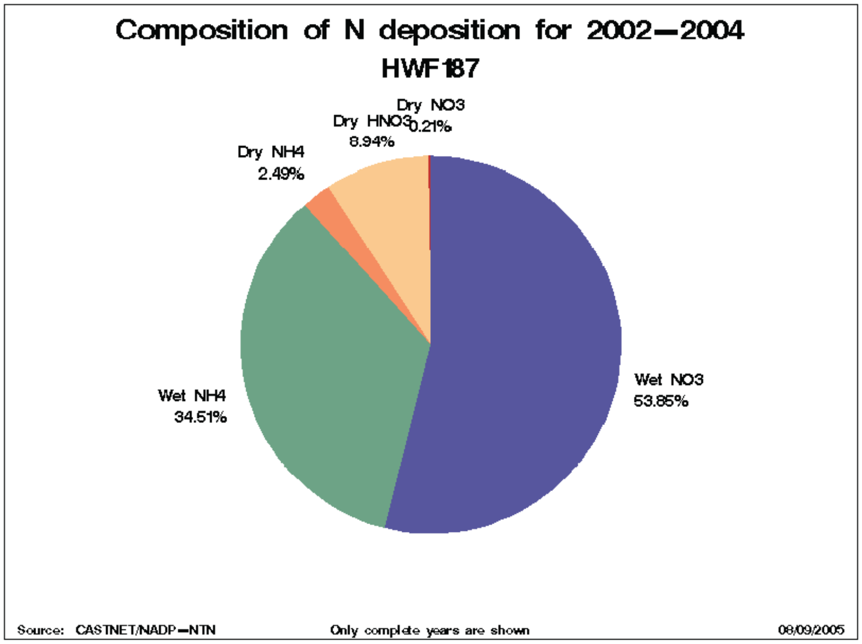


Figure 12b. Relative imoportance of wet and dry N deposition

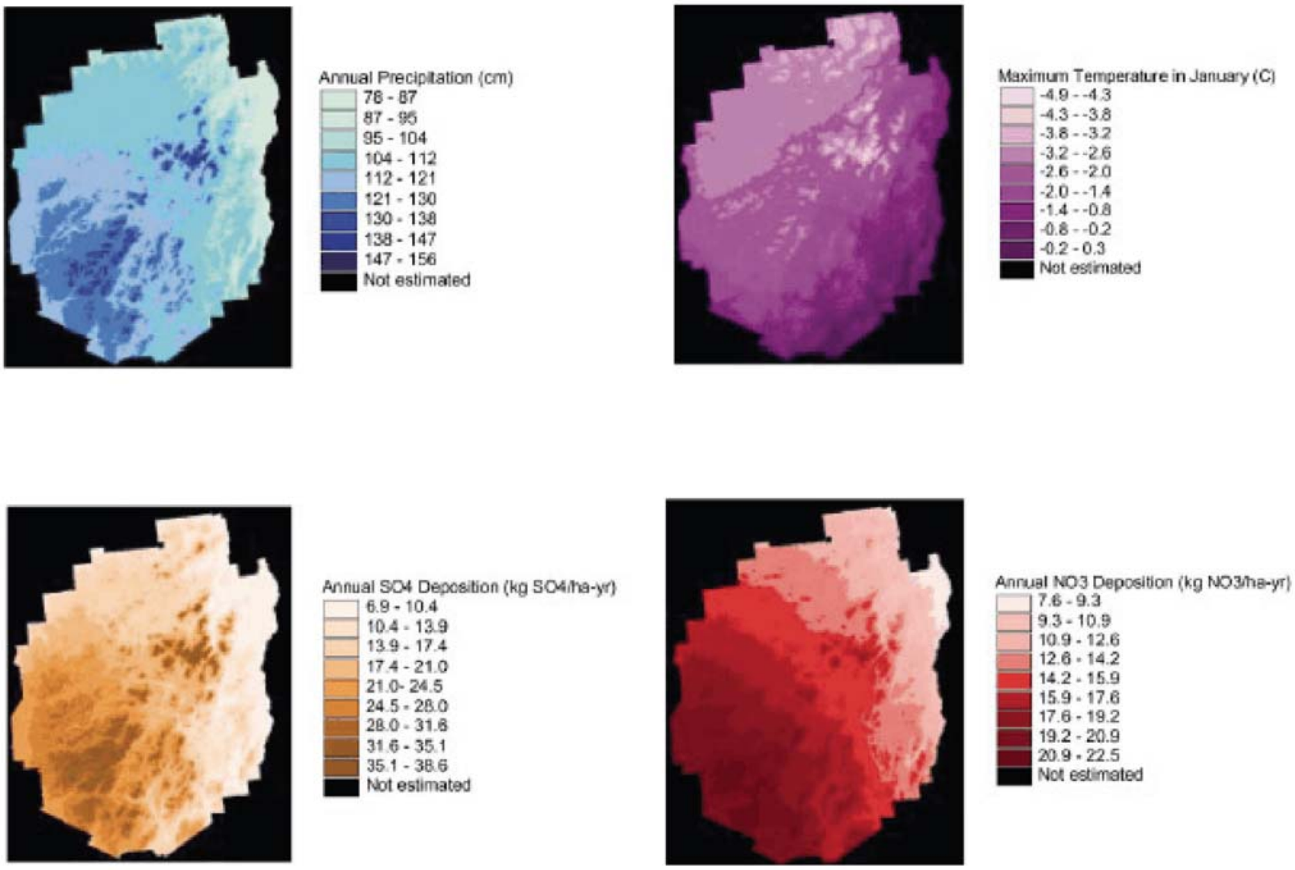


Figure 13. Predicted annual precipitation quantity (a), monthly mean maximum daily air temperature in January (b), annual SO_4^{2-} deposition in precipitation (c), and annual NO_3^- deposition in precipitation (d) over the Adirondack Park.. Reprinted from Atmospheric Environment, Spatial patterns of precipitation quantity and chemistry and air temperature in the Adirondack Region of New York, 36:1060, M. Ito, M.J. Mitchell and C.T. Driscoll (2002), with permission from Elsevier.

These results show that highest precipitation amounts and atmospheric deposition are found in the southwest portion of the Adirondacks and at higher elevations. This regional model of atmospheric deposition has been used in other studies that have evaluated the contribution of acidic deposition to ecosystem response in the Adirondacks with particular focus on nitrogen dynamics (Ito et al., 2005a; McGee et al., 2007ab).

The effects of changes in atmospheric deposition in the Adirondacks with respect to the recovery of surface waters from acidification have also been evaluated. Driscoll et al. (1998) used time-series analysis showing that concentrations of sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+) and basic cations have decreased in precipitation, resulting in increases in pH.

6.2 Key Findings:

- *There have been significant declines in the deposition of* SO_4^{2-}, NO_3^-, Cl^-, $Ca2^+$, Mg^2, *and* Na^+ *at the Huntington Forest. The decline of* SO_4^{2-} *has been particularly marked and this decline is directly a function of decreases of atmospheric emissions of sulfur which contribute to deposition to the region. Similar declines have been found at other deposition monitoring sites in the region.*
- *The relative contribution of* NO_3^- *to acidity has increased due to the proportionally greater reduction of* SO_4^{2-}.
- *Dry deposition of N and S compounds is a relatively small proportion (~11%) of total deposition.*
- *Deposition results from the Huntington Forest have been used for developing regional depositional models.*

7. TEMPORAL AND SPATIAL PATTERNS IN SURFACE WATER CHEMISTRY AND HYDROLOGY IN THE ARBUTUS WATERSHED

7.1 Critical Issues:

- *Analyses of temporal and spatial patterns of surface water chemistry and hydrology provides information on watershed responses to changes in climate and atmospheric inputs of atmospheric pollutants.*
- *The Huntington Forest is doing intensive hydrological and biogeochemical measurements at Arbutus Watershed (from 1991) and its subcatchments including the major inlet of Arbutus Lake (Archer Creek) (from 1991) and two small catchments (S14 and S15) (from 2002) in the upper elevations of the watershed.*
- *Arbutus Watershed is part of the Adirondack Long-Term Monitoring Project (composed of 52 lakes) and is the only lake/watershed that has direct hydrological measurements of discharge.*

A major focal point of research at the Huntington Forest and the Arbutus Watershed has been the evaluation of how atmospheric deposition and climatic factors as well as other watershed features affect the processing of atmospheric pollutants (Figure 14).

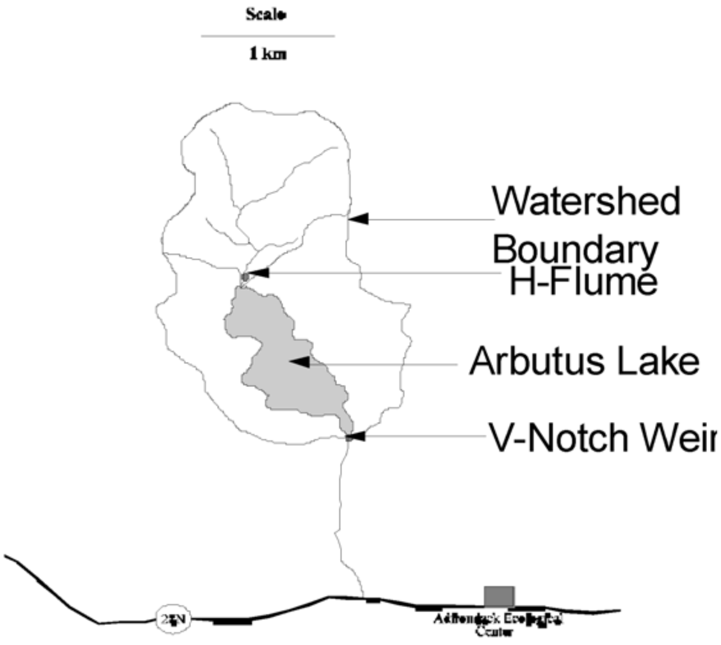


Figure 14. Arbutus Watershed at the Huntington Forest. The Archer Creek Catchment is the area above the H-flume and constitutes the major inlet to Arbutus Lake.

The Arbutus Lake Watershed has been gauged at the lake outlet since October 1991 with a V-notch weir. The data logger at the weir was originally connected to a telephone line permitting monitoring of water discharge from Arbutus Lake and now this system is part of a wireless network for data monitoring. The 130 ha “Archer Creek Catchment” is the major inlet to Arbutus Lake. This catchment has been monitored since 1994 using a H-flume equipped with automated discharge logging and sample collection system. Water chemistry samples are collected weekly except during storm events when more frequent sampling is done. In addition, transects of piezometers, water table wells, soil tension lysimeters, snow lysimeters and throughfall collectors, have been installed for characterizing solute chemistry. Various plots and subcatchments including both upland and wetland sites have been intensively instrumented since 1994 and are described in detail in Bischoff et al., 2001; McHale et al., 2000, 2002; Ohrui et al.,

1999. In addition, Geographical Information System (GIS) data layers have been developed for the site including a Digital Elevation Model (DEM) with 3-m resolution. Detailed stream and wetland maps have been produced and sampling points located, all of which are part of the GIS.

7.2 The Arbutus Watershed and the ALTM (Adirondack Long-Term Monitoring) Project

The Arbutus Lake Watershed is part of the original Adirondack Long Term Monitoring project that was established in June 1982 and 17 lakes with an additional 35 lakes added in 1992 (total 52 lakes) (Driscoll and Van Dreason, 1993; Driscoll et al., 2003a). The Arbutus Watershed is the only ALTM site with hydrological monitoring. In addition no other watershed in the Adirondacks has the broad spectrum of instrumentation, historical records and detailed analyses that have been developed at the HF and the Arbutus Watershed. We have been able to quantify changes in both concentrations and fluxes of major solutes (Mitchell et al., 1996, 2001b). Decreases in solute concentrations and fluxes of SO_4^{2-}, Ca^{2+} and other solutes occur in response to changes in atmospheric deposition (Figure 15).

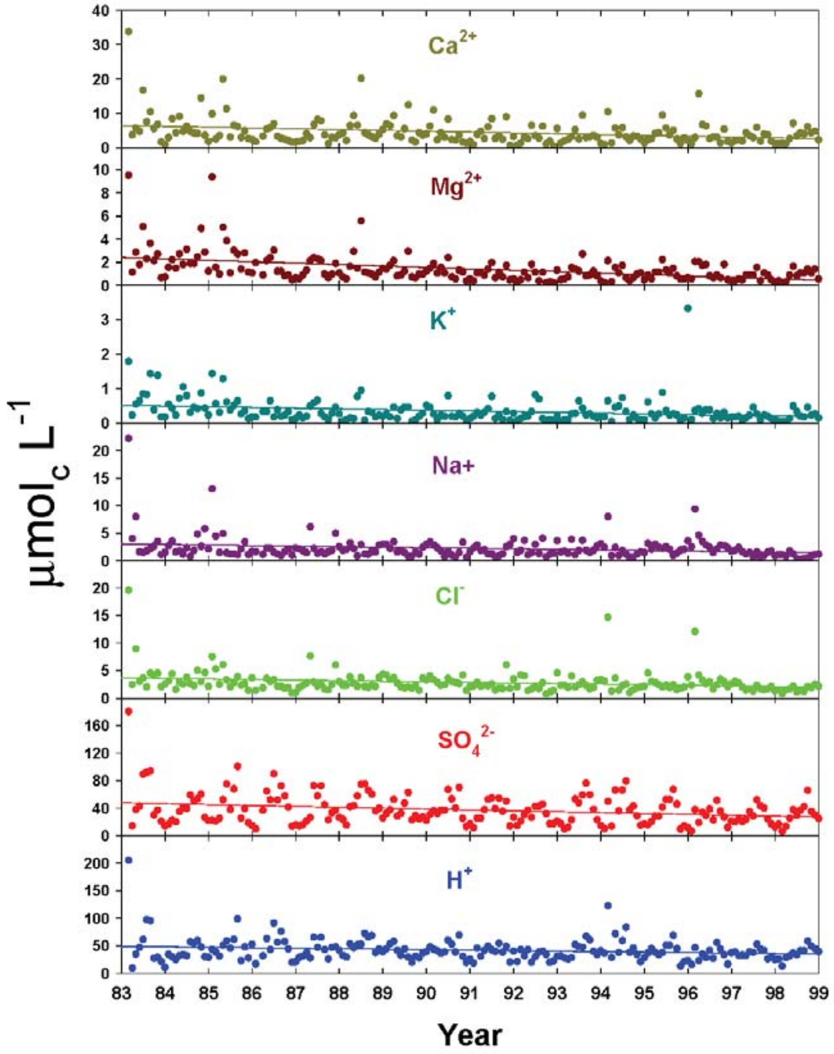


Figure 15. Significant ($p < 0.05$) temporal changes detected by the seasonal Kendall test in monthly solute concentrations at the outlet of the Arbutus Watershed at the HF. Line is the calculated regression line. Adapted from Mitchell et al. (2001b).

These decreases have been linked to changes in the atmospheric emissions of sulfur from the combustion of fossil fuels associated controls on electric utilities. We have also been able to use the NADP/NTN data to develop mass balances of the major solutes in the Arbutus Watershed (Table 4).

Table 4. Annual hydrological and biogeochemical solute fluxes at Arbutus watershed from January 1985 through December 1998 (From Mitchell et al., 2001b).

Flux	Water	Solute										
		Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	H^{+}	NH_4^{+}	NO_3^{-}	Cl^{-}	SO_4^{2-}	Al	DON
	mm yr^{-1}	mol_c ha^{-1} yr^{-1}									mol ha^{-1} yr^{-1}	
Wet Only Precip.	1149	42	11	3	22	430	128	266	28	355	na	na
Discharge to inlet	750	1384	324	38	271	6	9	181	78	990	35	85
Discharge from outlet	734	1033	307	51	232	4	15	87	73	834	24	91
Precip. - Discharge to inlet	399	-1342	-313	-35	-249	424	119	85	-50	-635	na	na
Precip. - discharge from outlet	415	-991	-296	-48	-210	426	113	179	-45	-479	na	na

Such results provide information on the relative importance of terrestrial and aquatic processes in regulating the transport and supply of solutes. We have also been able to evaluate the role of within lake processes in affecting solute transport. Our results have shown that changes in atmospheric deposition and climatic conditions are manifested differently across the landscape (uplands, wetlands, lakes) (Bushey et al., 2008; Ito et al., 2007; Mitchell et al., 2001, 2006). For example, our specific work at the Arbutus Watershed (e.g., Mitchell et al., 2001b), at Grass and Constable Ponds (Ito et al., 2007) as well as analyses using all of the ALTM lake/watersheds (Ito et al., 2005a) have shown the importance of within-lake processes in affecting nitrogen retention. We have also shown that changing climatic conditions that effect events may be most clearly manifested in wetlands where changing hydrological conditions result in differences in redox conditions. Periods of droughts result in the lowering of the water level and an increasing oxidative conditions. Such conditions result in the conversion of reduced to oxidized chemical species (e.g., sulfide converted to sulfate) and the concomitant generation of acidity. These oxidized chemical species and acidity are released to surface waters when droughts end and the wetlands are rewetted resulting in episodic acidification (Mitchell et al., 2006, 2008). Such changes in wetland hydrologic conditions are of specific importance to the Adirondacks due to the extensive distribution of wetlands in this region (Driscoll, 1991). Understanding how wetlands as well as other components of the landscape of the Adirondacks including lakes and uplands is needed for evaluating long-term changes in climate and atmospheric deposition to the region.

A relatively uniform rate of decline in SO_4^{2-} concentrations in lakes across the region (1.91±0.27 µeq/L/yr) suggests that this change was due to decreases in atmospheric emissions and deposition. Only recently have these declines in SO_4^{2-} concentrations of Adirondack lakes resulted in substantial increases in pH and ANC in these surface waters (Driscoll et al., 2009). We have also documented how these decreases in sulfur deposition have resulted in the decrease of SO_4^{2-} concentrations in the Arbutus Watershed (Mitchell 2001b). Moreover, some of our recent results using a combination of chemical, isotopic and hydrological approaches have suggested that there may be a substantial internal source of sulfur within the Arbutus watershed (Campbell et al., 2006). Such internal sulfur sources may play an important role in delaying the recovery of acid impacted surface waters from acidification (Mitchell et al., 2001).

7.3 Key Findings:

- *For Arbutus Lake and Archer Creek decreases in solute concentrations and fluxes of* SO_4^{2-}, Ca^{2+} *and other solutes have been documented. These decreases have been attributed to changes in atmospheric deposition.*
- *Using results from the Arbutus Watershed as well as other ALTM lake/watershed systems in the Adirondacks including Grass and Constable Ponds, the importance of within-lake processes in affecting nitrogen region has been documented.*
- *The importance of these within-lake processes has important implications in interpreting the long-term changes in lake water chemistry including recovery from acidification.*
- *Only recently have these declines in* SO_4^{2-} *concentrations of Adirondack lakes resulted in substantial increases in pH and ANC in these surface waters.*

- *Our results have suggested that there may be a substantial internal source of sulfur within the Arbutus watershed. These internal sulfur sources may play an important role in delaying the recovery of acid impacted surface waters from acidification.*

8. NITROGEN DYNAMICS

8.1 Critical Issues:

- *The relative importance of nitrogen deposition compared to sulfur deposition has increased due to the marked reductions in SO_2 emissions.*
- *The evaluation of the nitrogen dynamics of forest ecosystems and their associated watersheds is complicated by the broad range of biotic processes that affect the transf and transformation of nitrogen compounds.*
- *Analyses both within and among watersheds have shown a large range of temporal a spatial patterns of NO_3^- concentrations in surface waters.*
- *Understanding the causes driving these temporal and spatial patterns of NO_3^- concentrations is needed for evaluating the long-term effects of nitrogen atmospheric deposition on ecosystems.*

The relative importance of atmospheric inputs of nitrogen have decreased due to the marked reduction of atmospheric sulfur inputs as discussed previously in Chapter 5. Although there is a linkage between atmospheric nitrogen deposition and NO_3^- concentrations in the surface waters of the northeast United States (Aber et al., 2003), other factors such as climate, land disturbance, and types of vegetation affect both the temporal and spatial patterns in NO_3^- concentrations (Campbell et al., 2004). It has generally been assumed that as forest ecosystems mature their ability to retain nitrogen should decrease especially under conditions of elevated atmospheric nitrogen deposition. However, various studies have shown that the temporal patterns of nitrogen loss and retention including NO_3^- concentrations in surface waters within the northeastern United States have shown variable patterns including recent decreases in NO_3^- concentrations (Goodale et al., 2003). We analyzed the effect of stand maturity and differences in nitrogen atmospheric inputs, by evaluating the nitrogen dynamics of various sites in the Adirondacks. For example, in support of the importance of nitrogen atmospheric deposition in affecting nitrogen loss, we found that the second-growth western Adirondack sites (Woods Lake, Pancake Hall Creek) that have some of the highest amounts of nitrogen deposition in precipitation also had higher soil solution NO_3^- concentrations and fluxes than the HF site in the central Adirondacks with lower nitrogen deposition (Mitchell et al., 2001a).

However, further studies showed the importance of specific site conditions including soil chemistry and vegetation composition in affecting the nitrogen dynamics of forest ecosystems. In comparing two old-growth sites (Ampersand and Catlin Lake), Ampersand had substantially higher NO_3^- concentrations due to the relative dominance of sugar maple that produced litter with high nitrogen mineralization and nitrification rates (Mitchell et al., 2001a; McGee et al., 2007b). These analyses show that the nitrification rates are not only a function of stand age, but also nutrient concentrations (especially Ca) and the resultant influence on litter quality (lower lignin to nitrogen ratios) (Figure 16).

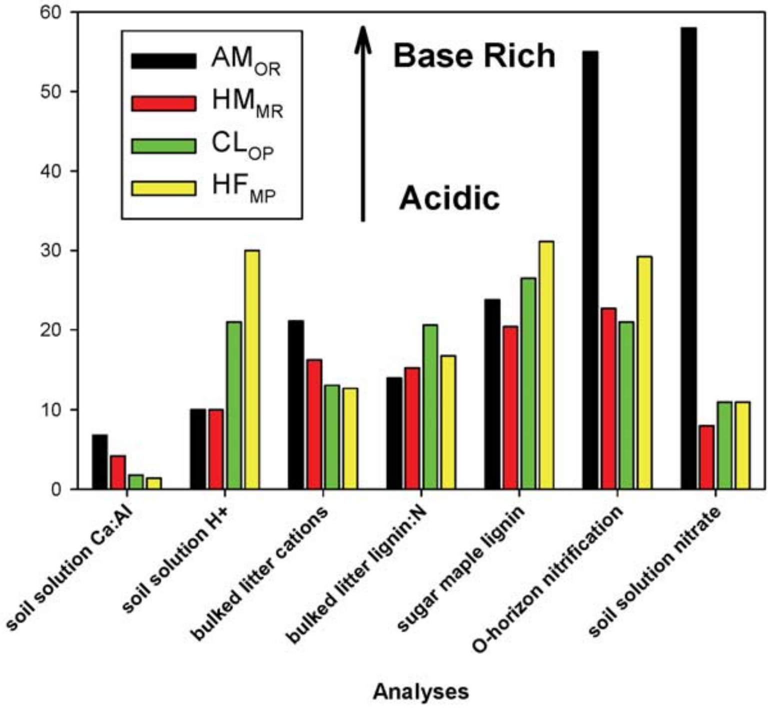


Figure 16. Summary of site conditions, litter quality, and nutrient cycling processes at four Adirondack northern hardwood forest sites. Study sites have been ordered in relation to site conditions. Response variables are: Ca:Al in shallow (15 cm) soil solution; H^+ concentration in shallow soil solution (μeq L^{-1}); bulked leaf litter total cation content (mg g^{-1} dry wt); bulked leaf litter lignin:N; sugar maple litter lignin content (percent); O-horizon net nitrification rates (μmol N g^{-1} dry wt soil yr^{-1}); NO_3^- concentration (μeq L^{-1}) in soil solution below rooting zone (50 cm). (AM=Ampersand Mountain; HF=Huntington Forest; HM=Hennessy Mountain; CL=Catlin Lake). Adapted from McGee et al. (2007a)

In addition, the effects of gap generation were examined to see if local vegetation disturbances can contribute to higher NO_3^- concentrations. (McGee et al., 2007a). Pit (location of marked soil disturbance) and proximate (directly adjacent to pit zones) associated with both recent and old tree-fall gaps accounted for 0.3 and 12% of the total stand area in the Ampersand site. These proximate zones contributed 24–27% of the total stand soil NO_3^- leaching. Although the majority of solutes leached from this system (~75%) were leached from undisturbed forest zones, discrete microenvironments within gaps have some influence on solute dynamics and the capacity of the forest matrix to retain nitrogen. It is expected that NO_3^- leaching will decrease over time in these disturbed microsites with the reestablishment of forest vegetation that will serve as nitrogen sink.

Also nitrogen-fixing alders in wetlands are important in the production of nitrogen (Kiernan et al., 2003; Hurd and Raynal, 2004; Hurd et al., 2005; Gokkaya et al. 2006). Within the Arbutus Watershed NO_3^- concentrations increased by ~16 μmol L^{-1} in stream reaches with alder, compared to those reaches in which alder was absent, with highest concentrations associated with periods of high flows (Figure 17).

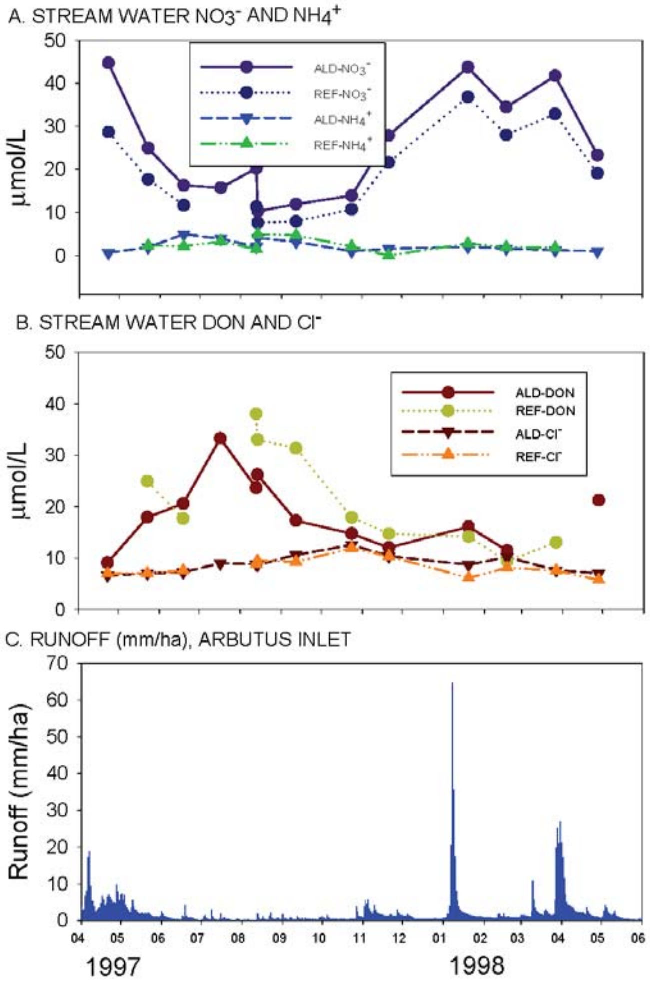


Figure 17. Nitrogen and chloride concentrations in channel water of alder and reference reaches. Values are means of duplicate samples: (a) NO_3 and NH_4; (b) DON and chloride; c) runoff, measured at the adjacent Arbutus Inlet catchment. Adapted from Hurd and Raynal (2004).

These results suggest that nitrification is enhanced in the presence of alders. This additional NO_3^- may be especially important during periods of high discharge that also coincide with episodic acidification of surface waters in the Adirondacks.

The Adirondack Manipulation and Modeling Project (AMMP) included separate experimental nitrogen additions of $(NH_4)_2SO_4$ at Woods Lake, Pancake Hall Creek and HF plus additions of HNO_3 at Woods Lake and HF (Mitchell et al., 2001a). Patterns of nitrogen loss varied with site and form of nitrogen addition, but most of the nitrogen input was retained (Hurd et al., 1998; Mitchell et al., 2001a).

For 16 ALTM lake/watersheds no consistent changes in NO_3^- concentrations were found from 1982 to 1997 (Driscoll et al., 1995, 1998). Simulations suggested that marked NO_3^- loss will only be manifested over extended periods (Driscoll et al., 1998). Specific findings at the Arbutus watershed have clearly demonstrated the importance of within-lake processes in affecting the retention of NO_3^- and the generation of dissolved organic nitrogen (DON) (McHale et al., 2000). An examination of two other lake/watersheds (Grass Pond and Constable Pond) in the Adirondacks also showed the importance of these within-lake processes in affecting nitrogen dynamics of these watersheds (Ito et al., 2007). The heterogeneous topography in the Adirondacks results in diverse landscape features and patterns of hydrologic connectivity that are especially important in regulating the temporal and spatial patterns of NO_3^- concentrations in surface waters. An example of the effect of the role of hydrological connectivity was shown by analyzing temporal patterns of DOC and NO_3^- in the Archer Creek Watershed where it was found that streamflow NO_3^- concentrations are derived from till groundwater and that DOC was is derived from the forest floor (Inamdar et al., 2004). A conceptual model of watershed connectivity was developed that shows how changing watershed wetness affects solute concentrations in stream waters (Figure 7).

Studies at the Archer Creek Catchment have also shown the importance of landscape position

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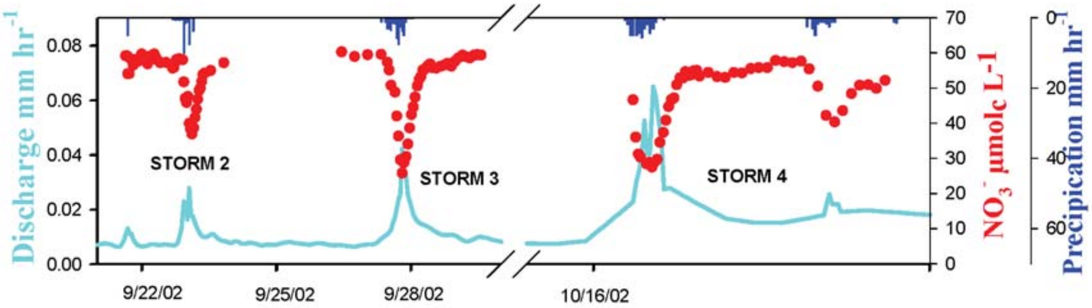

Figure 18. Changes in nitrate concentrations during storm events in subcatchment S14 in the Arbutus Watershed (Adapted from Christopher et al., 2008).

In marked contrast with subcatchment (S15) that has lower nitrification rates, these same storm events resulted in peaks of NO_3^- in surface waters (Figure 19).

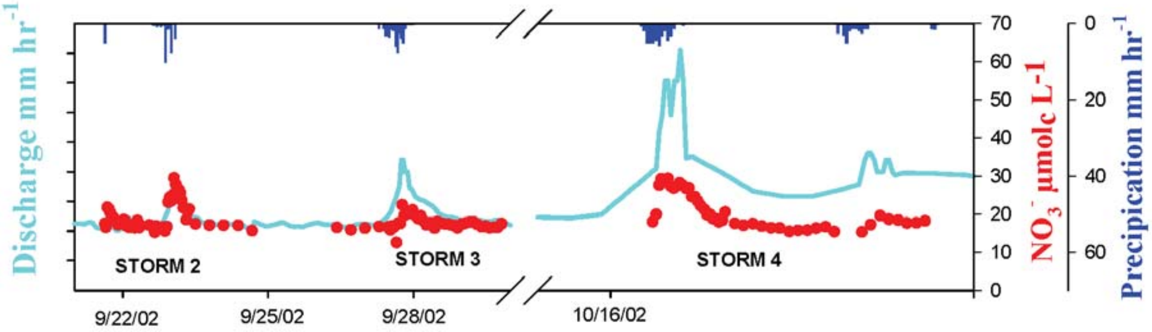

Figure 19. Changes in nitrate concentrations during storm events in subcatchment S15 in the Arbutus Watershed (Adapted from Christopher et al., 2008).

A conceptual model is provided that shows how the strength of NO_3^- contributions of water sources affects the temporal patterns of surface water NO_3^- concentrations (Figure 20). Understanding the relative importance of both edaphic (e.g., soils, vegetation) and atmospheric (e.g., deposition) factors is critical for evaluating how nitrogen inputs affect NO_3^- concentrations in surface waters.

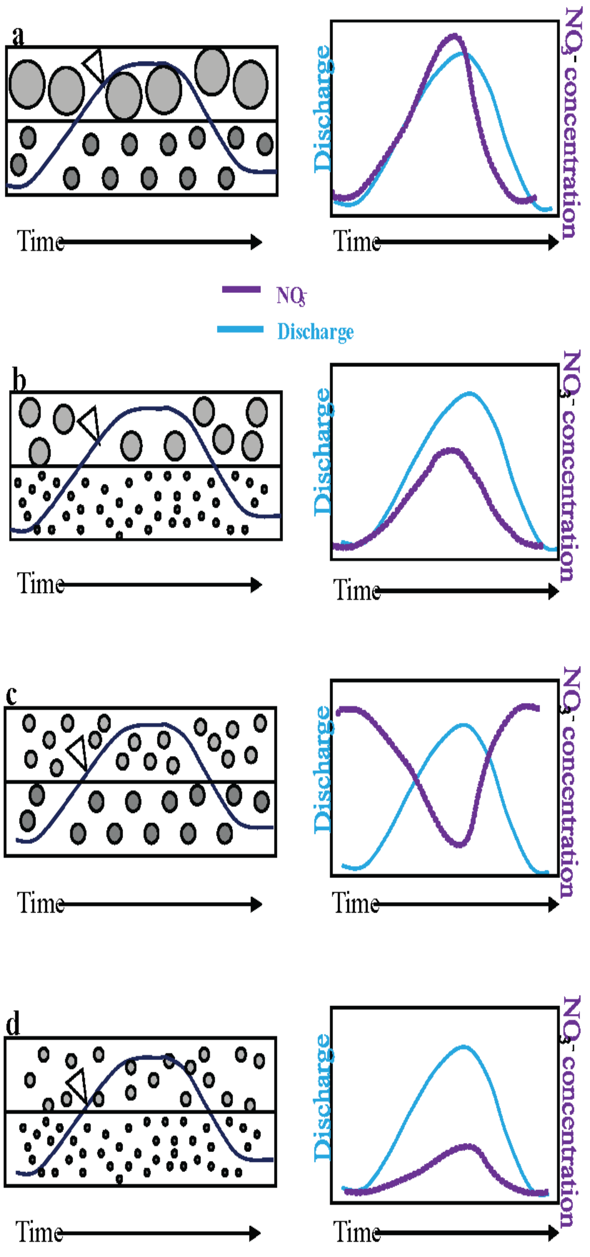

Figure 20. Conceptual model indicating the dominant factors controlling the concentration of stream water NO_3^- during snowmelt in S14 (a) and S15 (b) and late-summer/fall storms in S14 (c) and S15 (d). Size of the circles represents the relative concentration of NO 3 in the shallow versus deep water source. The triangle represents the position of the water table (From Christopher et al., 2008).

8.2 Key Findings:

- *Within forest ecosystems in the Adirondacks the amount of* NO_3^- *in the soil and surface waters is strongly influenced by vegetation type with tree species such as sugar maple and bass wood associated with high rates of* NO_3^- *generation.*
- *The vegetation composition is related to calcium availability with tree species such as sugar maple and basswood found in more calcium rich sites while other tree species such as American beech are more common on sites with lower calcium availability.*
- *Nitrate generation within a forest stand was affected by stand dynamics with highest* NO_3^- *soil concentrations found in those areas disturbed by tree windthrows.*
- *Nitrogen fixing alders can be substantial sources of fixed nitrogen in wetlands.*
- *Experimental N additions in Adirondack forests indicated that most added N was retained within the soil in agreement with similar studies in other regions. These results support the importance of biological processes in the retention of nitrogen.*
- *Intensive studies at the Arbutus Watershed and the ALTM lakes did not find any consistent long-term temporal pattern of* NO_3^- *concentrations.*
- *Analyses of landscape features in the Adirondacks suggests the heterogeneous topography in the Adirondacks results in diverse landscape features and patterns of hydrologic connectivity that are especially important in regulating the temporal and spatial patterns of* NO_3^- *concentrations in surface waters.*

9. GEOLOGY, SOILS AND VEGETATION LINKAGES TO BIOGEOCHEMISTRY AT THE HUNTINGTON FOREST (HF)

9.1 Critical Issues:

- *Forest vegetation influences soil and water chemistry*
- *Spatial and temporal changes in forest vegetation interact with the influences of atmospheric deposition and recovery of ecosystems from acidification*
- *Calcium availability is a key element in affecting the composition of forest vegetation and the resultant influences on soil and water chemistry*

9.2 General Biogeochemical Relationships

Forest vegetation plays a critical role in the biogeochemical relationships of watersheds in the Northeast. For example, sugar maple abundance has been clearly linked to NO_3^- concentrations in soils and surface

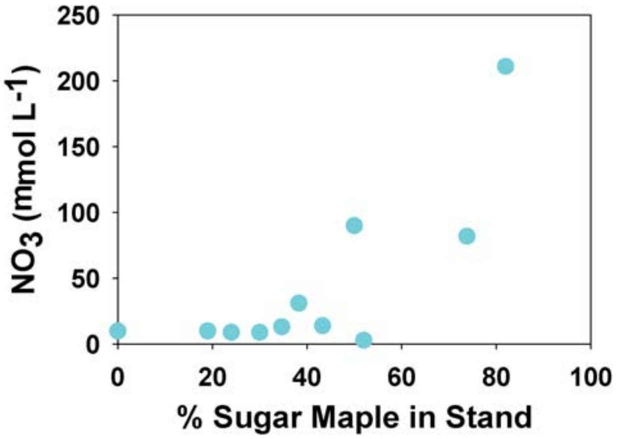

Figure 21. Concentration of NO_3^- in B-horizon soil solution in mixed-species stands in the Adirondack Mountains of New York State, plotted against the percentage of sugar maple in the stand (Mitchell et al. 2003). These soil solution samples are from a depth largely below the rooting depth of the trees, so the nitrate present in the water at this depth is considered an index of the amount of nitrate lost from the plot by leaching. These data indicate that increased nitrate leaching is observed in stands having more than about 50% sugar maple (Adapted from Lovett and Mitchell, 2004).

At the HF, as in other sites in the northeastern U.S., marked changes in the forest vegetation have occurred (Bailey et al., 2004; Lovett et al., 2004). Beech bark disease has resulted in the death of larger trees and the regeneration of small individuals from this coppicing tree species (Forrester et al., 2003; Table 5).

Table 5. Percent change from 1985 to 2000 in (a) total aboveground living (foliar+branch+bole wood+bole bark) and dead (bole wood+bole bark) biomass (Mg ha^{-1}) for stems > 5.0 cm dbh and (b) foliar biomass at the Huntington Forest IFS site. P-values indicate the degree of difference in biomass between the time periods. From Forrester et al. (2003)

a. Total aboveground	Living				Dead			
Species	**1985**	**2000**	% Change	p-value	**1985**	**2000**	% Change	p-value
Acer saccharum	94	85	-10	0.04	5	16	+235	0.001
Fagus grandifolia	59	58	-1	0.82	7	13	+99	0.03
Acer rubrum	25	27	+7	0.27	2	3	+59	0.40
Betula alleghaniensis	24	23	-5	0.43	4	4	+14	0.66
Populus grandidentata	4	0	-100	0.05	1	4	+270	0.07
TOTAL[a]	210	196	-7	0.03	18	41	+122	<0.0001

b. Foliar

Species	**1985**	**2000**	% Change	p-value
Acer saccharum	1.4	1.3	-11	0.02
Fagus grandifolia	1.2	1.2	+1	0.78
Acer rubrum	0.3	0.4	+6	0.42
Betula alleghaniensis	0.8	0.7	-8	0.21
TOTAL	4.1	3.9	-6	0.04

[a] Includes species that contributed <2.0 Mg ha^{-1} (*Populus tremuloides, Prunus serotina, Abies balsamea, Picea rubens, Acer pensylvanicum, Tsuga canadensis).*

There is a complex set of interactions among atmospheric deposition, climate, geology, soils and vegetation when evaluating the recovery of surface waters from acidification and watershed responses to changing climate.

9.3 Importance of Calcium

There is concern over the loss of available Ca^{2+} from forested ecosystems and the concomitant decline in sugar maple due to the effects of acidic deposition (Bailey et al., 2004). We have found that the linkages of geology, soils and vegetation are important in affecting watershed responses. In the Archer Creek watershed there are two small subcatchments (S14 and S15) located in the upper elevations. These two catchments have markedly different Ca^{2+} concentrations and other cations in the soil (Table 6).

Table 6 . Soil chemistry means (S.D.) for forest floor samples from Catchments 14 and 15. C cations (From Page and Mitchell, 2008a)

Variable	Catchment 14	Catchment 15	F-value	P-value
pH (units)	5.17 (0.62)	4.06 (0.32)	46.7	<0.001
Ca (mg g^{-1})	15.2 (6.2)	3.37 (1.5)	45.3	<0.001
Mg (mg g^{-1})	1.38 (0.72)	0.61 (0.15)	14.4	0.001
OM (%)	64.5 (17.7)	46.6 (20.8)	6.52	0.016
K (mg g^{-1})	0.67 (0.17)	0.55 (0.10)	5.50	0.026
Fe (mg g^{-1})	7.46 (4.1)	10.7 (4.5)	4.33	0.047
Na (mg g^{-1})	0.12 (0.08)	0.11 (0.02)	0.25	0.621
Moisture (%)	68.7 (7.7)	67.6 (8.9)	0.22	0.642
Al (mg g^{-1})	3.89 (2.6)	3.99 (3.0)	0.01	0.919

These concentration differences are also manifested in other components of the ecosystem including throughfall concentrations (Table 7).

Table 7. Volume weighted mean concentrations in throughfall of catchments (S.D.) 14 and 15 solutes (μeq L^{-1} for all anions and cations and μmol L^{-1} for Al, SI, DOC, DON, and total N; pH is in standard units) in subcatchments 14 and 15 (From Domser 2008).

Solute	Catchment		P-value
	14	15	
pH	6.2 (0.8)	5.8 (0.3)	
Si	6 (3)	3 (1)	0.02
Ca^{2+}	126 (162)	27 (8)	0.02
K^+	67 (25)	39 (20)	0.06
Mg^{2+}	49 (60)	12 (4)	0.09
DON	14 (3.6)	10.8 (4.2)	0.10
Cl^-	36 (52)	9 (3)	0.11
Na^+	25 (43)	5 (2)	0.14
DOC	836 (538)	604 (193)	0.16
SO_4^{2-}	45 (24)	31 (16)	0.18
H^+	4.0 (6.7)	2.6 (2.2)	0.39
Total N	28 (6.2)	24.9 (6.8)	0.41
NO_3^-	6 (4.2)	6.6 (4.8)	0.48
Al	0.3 (0.4)	0.2 (0.3)	0.59
NH_4^+	8 (5.3)	7.8 (5.2)	0.78

The Ca^{2+} rich subcatchment (S14) also has a greater proportion of sugar maple and basswood while the catchment with lower Ca^{2+} concentrations (S15) has a higher proportion of American beech. A combination of these chemical and biological attributes result in the more Ca rich catchment having substantially higher NO_3^- concentrations in soil and surface waters (Figure 22).

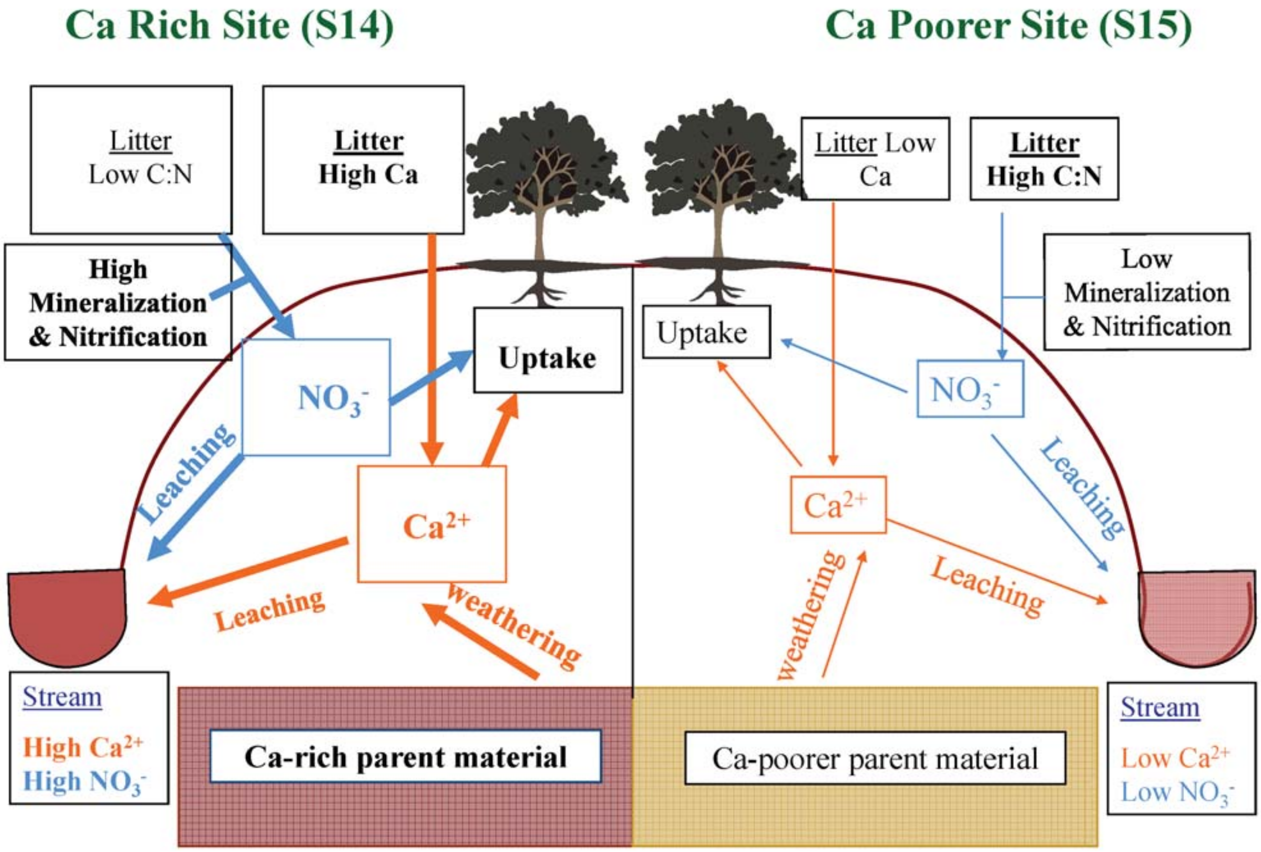

Figure 22. Conceptual model indicating the dominant factors controlling the variation in stream water chemistry across sites with similar hydrology, atmospheric deposition and land use but varying parent material, vegetation and soil processes. Thicker arrows indicate relatively greater fluxes and larger boxes indicate relatively larger pools (Adapted from Christopher et al., 2006).

The high NO_3^- concentrations have been directly attributed to "hotspots" of NO_3^- generation that are associated with the presence of basswood and sugar maple (Page and Mitchell 2008a). We have examined differences in the cycling of Ca^{2+} in each of these subcatchments using Ca^{2+} stable isotopes (Page et al., 2008). The relationship between Ca^{2+} concentrations, vegetation type and soil NO_3^- generation has also been established for a wide range of sites across the Adirondacks (Page and Mitchell, 2008b).

Inorganic nitrogen concentrations in the forest floor of Adirondack soils are a function of Ca^{2+} concentrations, moisture, temperature, and organic matter content (Figure 23).

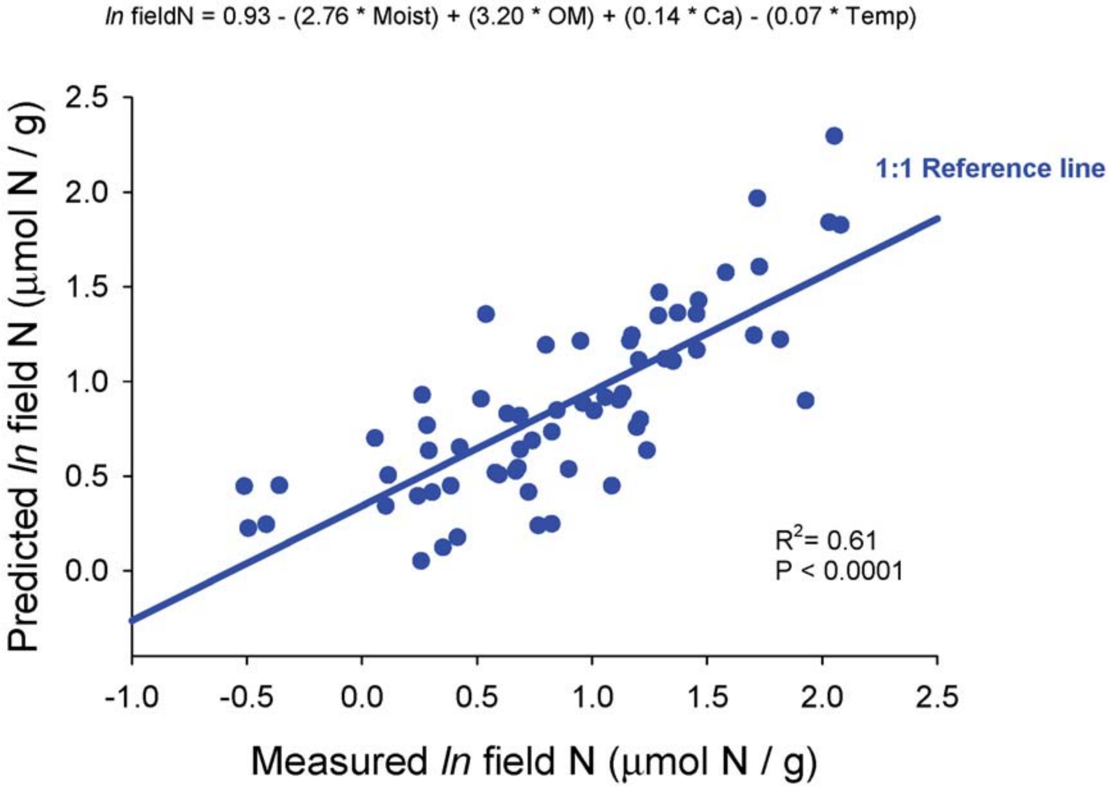

Figure 23. Regression plot showing actual vs. predicted field-extracted inorganic N from the forest floor for central Adirondack Mountains. Regression variables are: (1) field-extracted inorganic N from the forest floor expressed as a natural logarithm (ln [field N]); measured as µmol N/g), (2) forest floor moisture (Moist), (3) forest floor organic matter (OM), (4) upper mineral soil exchangeable Ca in mg/g (Ca), and (5) mean temperature from 20 days prior to sampling (Temp). The line is a 1:1 reference line to indicate R^2 = 1 and residual values. (Adapted from Page and Mitchell, 2008b).

Our studies have shown that within the Adirondacks Ca has a major influence on vegetation type. In turn, the type of vegetation is a major component in affecting the amount of NO_3^- generated within watersheds. The influences of geology and vegetation need to be considered when evaluating the response of Adirondack ecosystems to changes in atmospheric nitrogen deposition. This evaluation needs to include how vegetation type influences recovery of both soils and surface waters from acidification.

9.4 Key Findings:

- *The presence and health of sugar maple is closely linked to the availability of Ca in soil.*
- *There have been marked changes in the forest vegetation of the Adirondacks including the death of large American beech trees due to beech bark disease.*
- *Within the Adirondacks spatial patterns of the chemistry of watersheds are linked to soil chemistry (especially Ca availability) and forest vegetation.*
- *Those sites with sugar maple and other tree species that have high Ca requirements produce litter that has high N mineralization and nitrification rates resulting in elevated* NO_3^- *concentrations in soils, ground waters and surface waters.*
- *The interaction between vegetation type and atmospheric deposition needs to be considered in assessing long-term changes in soil and water chemistry including recovery from acidification.*

10. INTEGRATION OF RESULTS ACROSS THE ADIRONDACKS, NORTHEASTERN U.S. AND SOUTHEASTERN CANADA

We have employed a variety of approaches for integrating the results of the HF/Arbutus Watershed for larger regions including the Adirondacks, northeastern U.S. and southeastern Canada. Results from the HF have been considered in assessment associated with acidic deposition for the Adirondacks (e.g., Jenkins et al., 2007) and New York State (e.g., Driscoll et al., 2003b). More specifically as part of the ALTM project, the Arbutus Watershed has been part of the analyses on lake/watershed responses to atmospheric deposition including analyses of nitrogen budgets (Ito et al., 2005a) and acid neutralizing capacity (Ito et al., 2005b). The evaluation of Adirondack nitrogen budgets emphasized the importance of specific watershed features, including the presence of lakes, that have an influence on the level of nitrogen retention.

Using the detailed hydrological and biogeochemical information available for the Arbutus Watershed, we have also employed the PnET BGC simulation model to predict long-term changes in watershed chemistry including an analysis of how future scenarios associated (Chen et al., 2004). Such simulation modeling has also been used to compare and contrast watershed response of the Arbutus Watershed with other watersheds in the region (Figure 24).

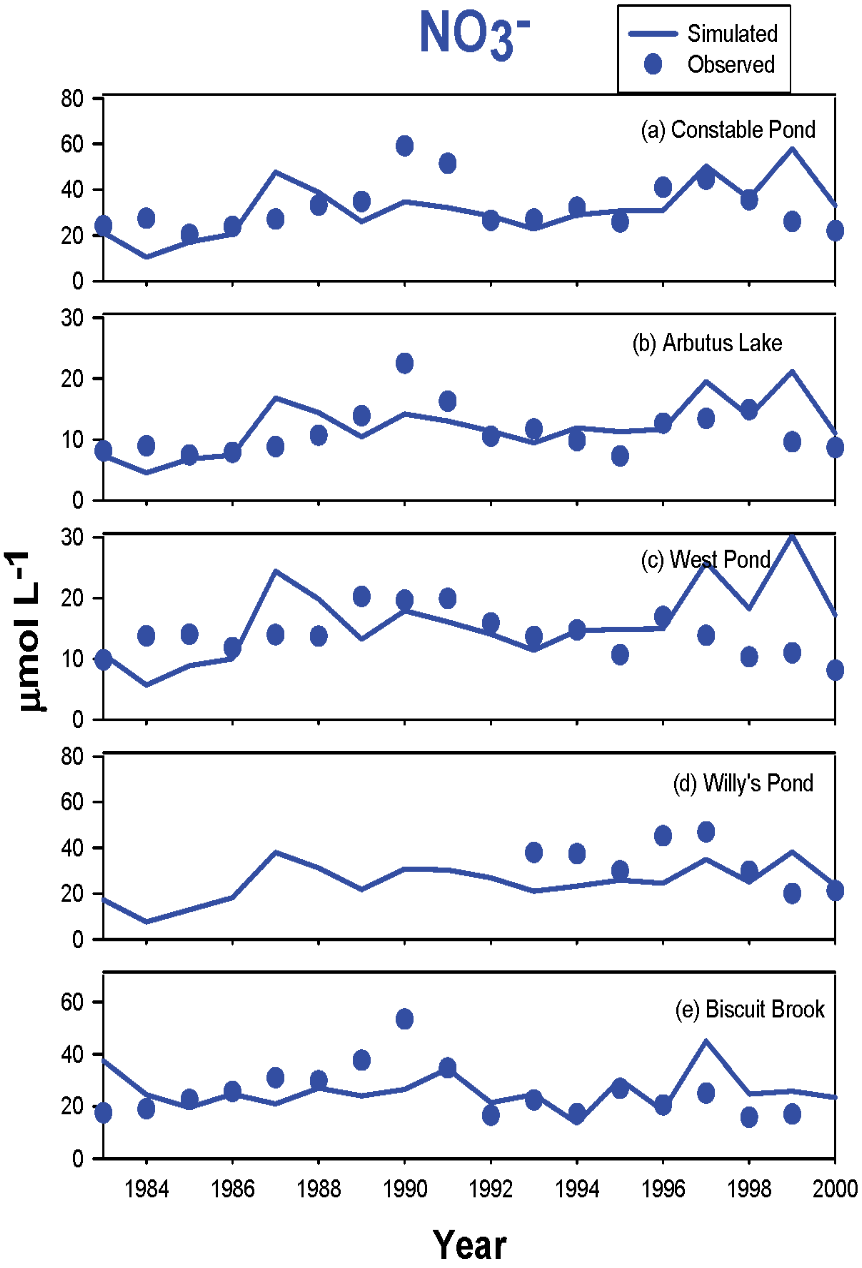

Figure 24. A comparison of measured and model-simulated values of annual volume-weighted concentrations of nitrate at (a) Constable Pond, (b) Arbutus watershed, (c) West Pond, (d) Willy’s Pond and (e) Biscuit Brook (Adapted from Chen et al., 2004).

In addition to Arbutus Lake, three other Adirondack watersheds (Constable Pond, Willy's Pond, and West Pond) and one in the Catskill Mountains (Biscuit Brook) were studied. These sites were selected based upon the availability of biogeochemical data and also represent a range of surficial geology (ranging from Sphagnum tin till to thick till) and acid neutralizing capacity (-10 to 67 μeq L^{-1}) across the region. Simulated internal fluxes of major elements at the Arbutus watershed compared well with previously published measured values. In addition, based on these simulated fluxes, element and acid neutralizing capacity (ANC) budgets were developed for each site. Sulfur budgets at each site indicated little retention of inputs of sulfur. The sites also showed considerable variability in retention of NO_3^-. Land-disturbance history and in-lake processes were found to be important in regulating the output of NO_3^- via surface waters. Deposition inputs of base cations were generally similar at these sites. Various rates of base cation outputs reflected differences in rates of base cation supply at these sites. Atmospheric deposition was found to be the largest source of acidity, while cation exchange, mineral weathering and in-lake processes generated ANC. For these same five watersheds, model simulations were conducted under three scenarios: 1) the Base Case (full implementation of 1990 CAAA in 2010); 2) the Moderate Control (additional ~20% reduction in NO_x emission and ~35% reduction in SO_2 emission beyond the 1990 CAAA in 2010); 3) the Aggressive Control (additional ~30% reduction in NOx emission and ~50% reduction in SO_2 emission beyond the 1990 CAAA in 2010) until year 2050 for each site (Figure 25).

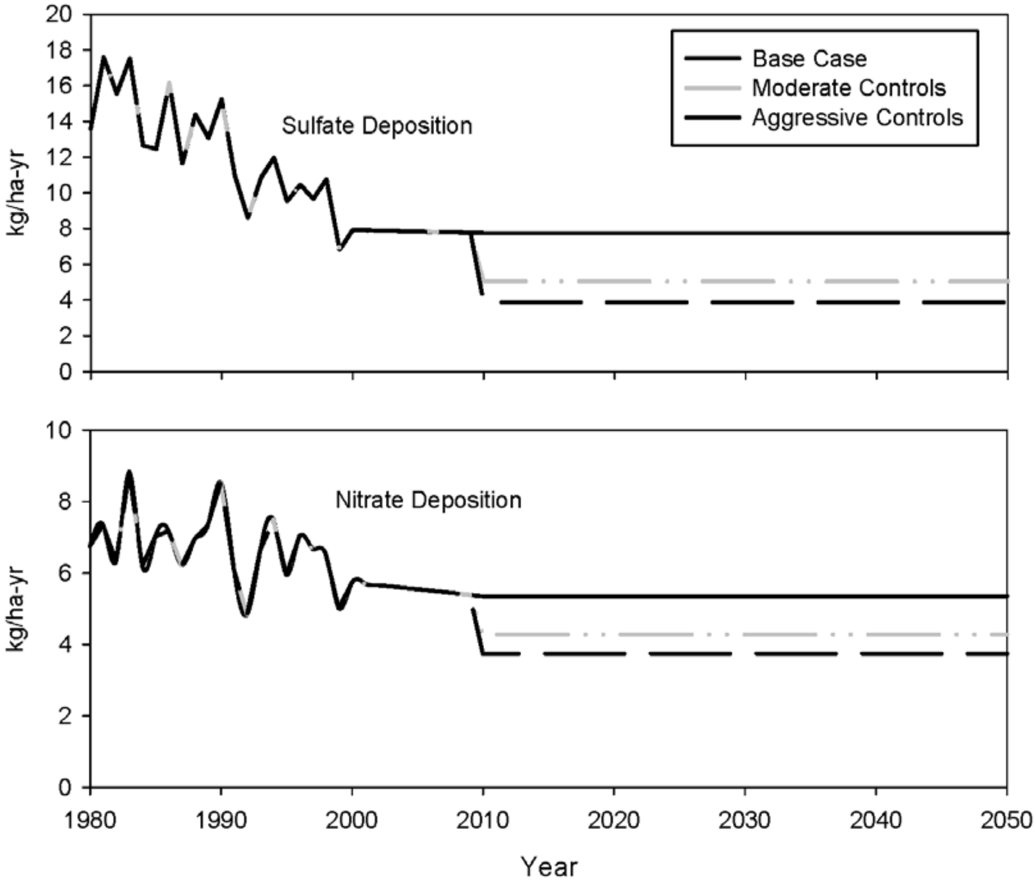

Figure 25. Scenarios of atmospheric deposition of sulfate (a) and nitrate (b) used to simulate the long-term response of soil and surface water chemistry at Huntington Forest (From Chen, 2001).

Model simulations showed these reductions resulted in lower surface water concentrations of SO_4^{2-}, NO_3^-, Ca^{2+} and inorganic aluminum and higher surface water pH and ANC for all the sites, including the Arbutus Watershed at the Huntington Forest (Figure 26).

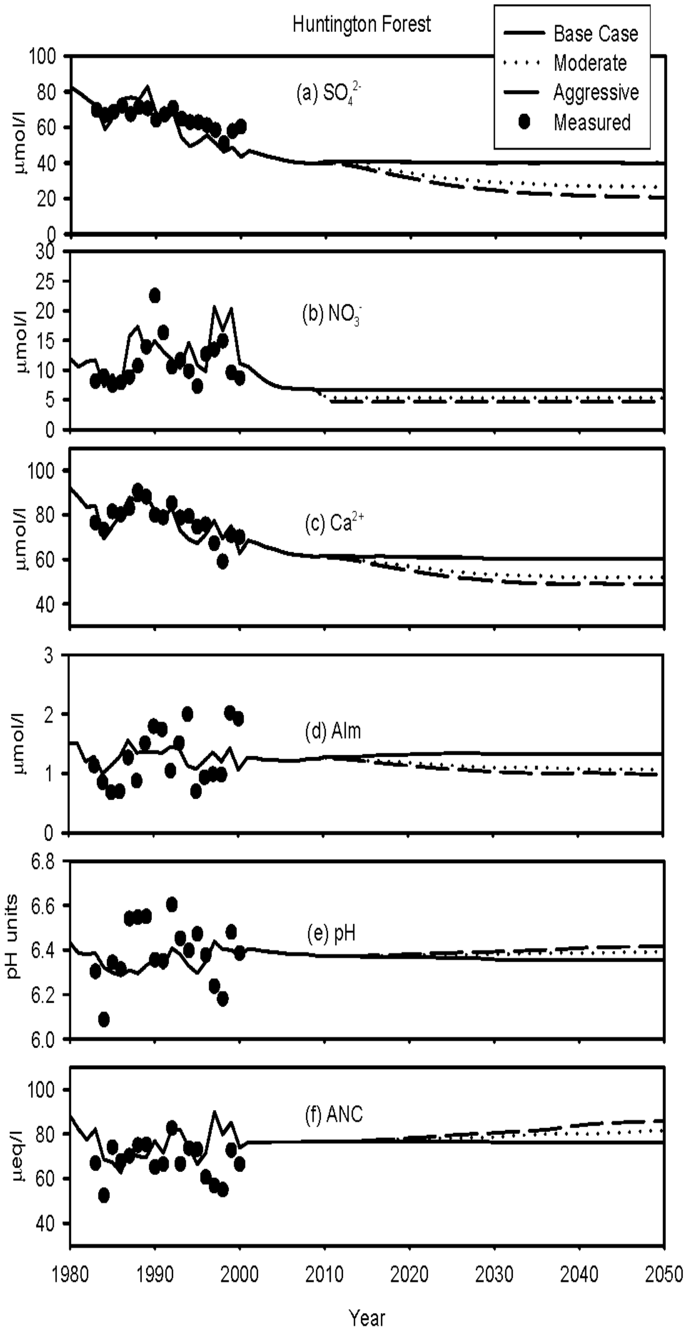

Figure 26. Simulated surface water concentrations sulfate (a), nitrate (b), calcium(c), monomeric aluminum (d), surface water pH (e) and ANC (f) at Huntington Forest (Arbutus Watershed) during 1980-2050 under the base case, moderate control and aggressive control scenarios. (From Chen, 2001).

Comparisons have also been done for a wide range of hardwood terrestrial ecosystems across the Adirondacks. Key findings have included the recognition of the role of forest maturity and interactions with site characteristics (particularly calcium availability) are key to understanding how forests are responding to air pollutants (McGee et al., 2007b; Page and Mitchell, 2008ab). These comparisons have also included evaluations of how experimental additions of sulfuric (Mitchell et al., 1998) and nitric acids (Mitchell et al., 2001a, 2003) vary among sites in the Adirondacks.

The HF/Arbutus Watershed has also been associated with various regional projects that have synthesized results from study sites in the northeastern U.S. and southeast Canada. Many of these projects have been supported by the Northeast Ecosystem Research Cooperative (For further information go to: http://www.ecostudies.org/nerc/). These regional syntheses have included the use of stable nitrogen isotopes to evaluate nitrogen saturation (Pardo et al., 2006) and a variety of studies that have evaluated watershed elemental budgets (e.g., Campbell et al., 2004, Watmough et al., 2005). The HF has also been part of a network of sites (GCTE) that have evaluated the effects of soil warming on ecosystem response (e.g., Rustad et al., 2001). Details on the soil warming experiment at the HF can be found in McHale et al. (1996) and McHale and Mitchell (1996).

11. PUBLIC POLICY IMPLICATIONS

Many aspects of this research have provided information that is relevant to policymakers and resource managers that are interested in the effects of air pollution and climate change on forest and aquatic ecosystems in the Adirondack region of New York. Our ongoing measurements of atmospheric deposition at the Huntington, using NADP/NTN and CASTNET measurements, indicate that deposition of SO_4^{2-} to the Adirondacks has decreased over the last 30 years. This decrease is consistent with decreases in emissions of SO_2 for the source area for the Adirondacks and has resulted in a decrease in the wet deposition of H^+ to the region. In contrast, there has been no large change in concentrations or deposition of NO_3^- or ammonia in precipitation over the monitoring period, which is consistent with limited changes in emissions of NO_x and ammonia for the source area of the region. Note that the decline in SO_4^{2-} coupled with the lack of change in concentrations and deposition of NO_3^- suggest that the relative role of NO_x emissions in regulating the acidity of precipitation in the Adirondacks and elsewhere in the eastern U.S. has increased over the past 30 years.

Starting in 1983, long-term measurements of water chemistry at Arbutus Lake through the ALTM (Adirondack Long Term Monitoring) Project has also shown a decrease in SO_4^{2-} concentrations. These long-term decreases agree with results from other ALTM lakes and are consistent with decreases in SO_2 emissions and wet SO_4^{2-} deposition (Driscoll et al., 2009). Because this is the only ALTM lake that includes hydrological monitoring, we have also been able to conduct mass balance calculations that confirm these decreases, and also have shown the potential importance of internal sulfur sources that may delay the recovery of forested ecosystems from decreases in sulfur deposition.

With data from both the upland watershed (Archer Creek) and the entire Arbutus Watershed, we have been able to document the importance of within-lake processes in regulating chemistry. This analysis shows that within-lake processes result in different chemical responses to changes in atmospheric deposition and climate than upland systems. Our studies have shown that these upland systems are much more responsive to climatic events including snowmelt and droughts than lakes. Hence the surface waters in these upland systems are more sensitive to the concomitant influences between atmospheric pollutants and climate change than lakes. Our results have shown that snowmelt and drought events in Archer Creek have markedly different chemistry including acidic episodes compared with the long-term averages. Climatic predictions for the region indicate that the period of snow cover will decrease and drought frequency and duration will increase. Such changes will amplify the importance of climatic events in affecting the surface water chemistry of the region. These observations are important because they indicate that although the 1970 and 1990 Amendments of the Clean Air Act resulted in decreases in acidic deposition and inputs of SO_4^{2-} which are the major source of acidity to acid-sensitive lakes in the Adirondacks, these climatic events may contribute to a deterioration of water quality.

Both in-lake biological processing of nitrogen as well as nitrogen inputs and transformations associated with nitrogen fixation and the cycling, storage, and export of nitrogen in wetlands add to the complexity of differential patterns of NO_3 concentration across the Adirondack region. The reason for the long-term decline in NO_3^- concentrations in Adirondack lakes is unclear (Driscoll et al., 2009). It is possible that this trend is due to changes in climate and/or hydrology. Our analyses showing the importance of geology (e.g., calcium concentrations) and vegetation type (e.g., sugar maple and basswood) indicate that these factors have an important influence in affecting the response of Adirondack ecosystems to changes in atmospheric pollutants.

As part of our study, calculations were conducted with the biogeochemical model PnET-BGC for four lake/watershed ecosystems including the Arbutus watershed. Results of this analysis clearly demonstrate that acidification of soil and water have resulted from inputs of acidic deposition over the last 150 years, and that chemical recovery has occurred over the last 30 years in response to the 1970 and 1990 Amendments to the Clean Air Act. Projections of potential future changes suggest that under current deposition patterns lakes will either continue to remain acidic or recover at a very slow rate. Model predictions suggest that additional reductions in SO_2 and NO_x emissions will help accelerate the rate of ANC increase but the period of chemical recovery will be decades.

An understanding of site-specific biogeochemical linkages among geology, vegetation and surface water is important in evaluating ecosystem responses to future reductions in atmospheric deposition. The composition of terrestrial and riparian wetland vegetation mediates changes in nitrogen concentration of soil and surface waters and contributes to a diversity of responses of ecosystems in the Adirondack region. Alder-dominated wetlands will be slower to recover than other wetland types because they serve as an additional source of nitrogen from fixation.

12. FUTURE DIRECTIONS

Current research efforts at the HF and the Arbutus Watershed include an integrated effort to analyze the effects of air pollutants and climatic change on ecosystem responses including changes in surface water chemistry. We anticipate evaluating how various policy scenarios that affect the emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x) and Hg will affect ecosystem response. We will continue ongoing, long-term measurements of wet deposition of major solutes (NADP/NTN) and mercury (MDN), dry deposition and ozone (CASTNET), and climate. The research will occur at the HF/Arbutus Lake Watershed system, which has long historical records and an extensive infrastructure that enables analyses of the effects of atmospheric deposition and climatic influences on ecosystem/watershed responses in the Adirondack Mountains. We will use a combination of chemical mass balances, isotopic evaluations, statistical analyses and modeling (PnET-BGC) to evaluate acid deposition and mercury policies on forest and aquatic ecosystems. We will use data from atmospheric deposition at the HF combined with hydrology, chemistry and isotopic measurements from Arbutus Lake outlet, Archer Creek Watershed (the major inlet of Arbutus Lake), and two small headwater subcatchments of Archer Creek that have distinct differences in Ca^{2+} availability. These differences make these subcatchments ideal for evaluating vegetation/soil/watershed relationships associated with exchangeable nutrient cation depletion. These results will be placed in the context of other intensive and extensive analyses of vegetation and soil components and processes. These analyses are being made available as part of the historical data base of HF/Arbutus Watershed that has been used for evaluating the influences of atmospheric deposition and climate on key biogeochemical processes at other forest and aquatic study sites. The integration of watershed measurements within the Arbutus Watershed is also being facilitated by the availability of a real time measurement system that provides results to the general community on the World Wide Web.

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APPENDIX I

Individuals involved with research on hydrology and biogeochemistry at the Huntington Forest/Arbutus Watershed since from 1998 through 2007

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APPENDIX II

Projects that supported research on hydrology and biogeochemistry at the Huntington Forest/Arbutus Watershed since from 1998 through 2007

NYSERDA Funded Projects in BOLD

Hydroclimatic effects on ecosystem response: A synthesis of long-term results from watersheds in the northeastern United States and southeastern Canada. NSRC/NERC U.S. Forest Service. 2007-2010.

The Impact of Changing Climate on Winter Nitrogen Export from a Forested Watershed of the Adirondack Mountains. McIntire-Stennis. 2007-2010

Integrated Major Research Instrumentation for Realtime Analyses within an Experimental Watershed. NSF-MRI. 2004-2007.

Regional Analysis of Snowmelt and Storm Events: Biogeochemical and Hydrological Responses. NERC-US Forest Service.2003-2006.

Baseline Monitoring of Huntington Forest/Arbutus Watershed. NYSERDA 2003-2005.

Evaluation of discrepancies in sulfur budgets of watersheds in the Northeast U.S. and Southeast Canada: a modeling and isotopic approach. U.S. Forest Service, Northeastern Ecosystem Cooperative. 2001-2006.

An Integrated Assessment of the Recovery of Surface Waters from Reduced Levels of Acid Precipitation in the Catskills and Adirondacks. NYSERDA. 2001-2003.

The impact of forest management on hydrology and biogeochemistry. McIntire-Stennis Cooperative Forestry Research Program. 2001-2004.

Topographical linkages between nitrogen and organic carbon solutes within a forested watershed. NSF-Ecosystems. 2000-2004.

Terrestrial-Aquatic linkages controlling nutrient dynamics in a forested catchment of the Adirondack Mountains. McIntire-Stennis Cooperative Forestry Research Program. 2000-2003.

Nitrogen transport dynamics through aquatic/terrestrial interfaces in a forested headwater watershed in Northeastern United States. USDA-NRICCP Water Resources and Assessment Program. 1999-2002.

Effects of atmospheric deposition of sulfur, nitrogen and mercury on Adirondack Ecosystems. NYSERDA. 1999-2001.

An evaluation of the recovery from acidification of surface waters in the Adirondacks: Role of watersheds and forest maturation. NYSERDA. 1999-2002.

Measurement of Precipitation Chemistry at the Huntington Wildlife Forest. US-EPA via RPI. 1998-2007.

Continuation of Adirondack Manipulation and Modeling Project. ESEERCO-NYSERDA. 1998.

Studies of nitrogen movement in Adirondack Mountain Wetland Ecosystems. NiMo. 1998.

Analysis of the Patterns of Nitrate Leaching in Response to Atmospheric Deposition of Nitrogen in the Northern U.S. U.S. E.P.A. 1994-1998.

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RESPONSE OF ADIRONDACK ECOSYSTEMS TO ATMOSPHERIC POLLUTANTS AND CLIMATE CHANGE AT THE HUNTINGTON FOREST AND ARBUTUS WATERSHED:RESEARCH FINDINGS AND IMPLICATIONS FOR PUBLIC POLICY

FINAL REPORT 09-08

STATE OF NEW YORK
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