

# NYSERDA Environmental Research Program Plan Research Area 1: Ecological Effects of Climate Change and the Deposition of Sulfur, Nitrogen, and Mercury

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## **NYSERDA's Promise to New Yorkers:**

NYSERDA provides resources, expertise, and objective information so New Yorkers can make confident, informed energy decisions.

### **Mission Statement:**

Advance innovative energy solutions in ways that improve New York's economy and environment.

### **Vision Statement:**

Serve as a catalyst – advancing energy innovation, technology, and investment; transforming New York's economy; and empowering people to choose clean and efficient energy as part of their everyday lives.

# **NYSERDA Environmental Research Program Plan Research Area 1: Ecological Effects of Climate Change and the Deposition of Sulfur, Nitrogen, and Mercury**

Final Report

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# 1 Introduction

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## 1.1 Environmental Research Program

The New York State Energy Research and Development Authority's (NYSERDA) Environmental Research Program (Program) is in the midst of its fourth comprehensive planning effort for the years 2018 to 2022. The Program is charged with increasing understanding and awareness of the environmental and health impacts of energy choices and emerging energy options and providing a scientific foundation for creating effective and equitable energy-related environmental policies and resource management practices. The Program's major strategic objectives include:

- Conducting research that enhances the understanding of the sources, fate, and transport of environmental pollution related to energy development and use in New York State under a changing climate.
- Supporting the advancement of fundamental understanding of the ecological effects and responses to changes in energy-related emissions under concurrent environmental change.
- Examining the health, environmental, and ecological benefits, as well as potential impacts, of alternative energy and technology solutions.
- Ensuring accountability in energy and environmental decision-making by quantifying and analyzing the impacts of energy-related decisions through long-term environmental monitoring, experiments, and modeling.
- Developing and adapting environmental research capability to address emerging issues facing New York State and the broader region and create opportunities for leadership and innovation.

More information on the Environmental Research Program can be found at [nyserda.ny.gov/All-Programs/Programs/Environmental-Research/](https://nyserda.ny.gov/All-Programs/Programs/Environmental-Research/)

The new five-year research plan (research plan) builds on previous research plans, which were released in 2007 and 2013 under the Environmental Monitoring, Evaluation, and Protection (EMEP) program. To create the 2018 research plan, a cross-section of researchers from State and federal agencies, universities, and non-governmental organizations (NGOs), reviewed the 2013 research plan and recommended changes. In addition, science and policy experts met for a workshop in May 2018 to identify information gaps and emerging research needs in New York State. The reviews of the 2013 research plan and the notes and presentations from the workshop formed the basis of the 2018 research plan.

The research plan is broad in scope and envisions that ensuing work may be supported directly by NYSERDA as well as by other State and federal agencies, NGOs, and by funds leveraged from several sources. The users of the research plan will include NYSERDA, the New York State Department of Environmental Conservation (DEC), Office of the Attorney General (OAG) and other State agencies;

regional and national research funding and environmental organizations; and the scientific community, resource managers, and policymakers. The focus areas in the research plan will help maximize the use of limited resources to serve the needs of decision-makers and residents in New York State.

## 1.2 Overview of the Research Plan

The research plan investigates the environmental and economic effects associated with energy use and development, including the effects of shifting energy generation and curbing energy-related emissions. This update highlights the interactive effects of climate change and atmospheric deposition on terrestrial and aquatic ecosystems and identifies several emerging issues and expanded research needs. The research NYSERDA supports through the research plan can enhance government accountability and support decision-making in New York State.

While emissions reductions over the past several decades have yielded important benefits for some ecosystems, the impacts of electricity generation continue to affect the State's sensitive ecosystems and vulnerable populations. On-going measurements, mechanistic studies, synthesis, and modeling will continue to advance understanding of these effects. In addition, ecosystems recovering from previous higher levels of sulfur, nitrogen, and mercury deposition are characterized by on-going legacy effects (e.g., smaller pools of soil base cations) and are experiencing the direct effects of climate change together with other concurrent environmental changes influenced by climate, such as invasive species, lake browning, and harmful algal blooms. These interacting drivers of environmental change strongly influence the magnitude, timing, and extent of ecosystem recovery and ecosystem services provided to society. This research plan increases the Program emphasis on climate change and its interactions with atmospheric deposition; policy and management assessments for decision-making; and emerging issues expanded research that have heightened significance in the context of climate change. As such, the research plan is guided by the following sets of questions:

1. How is the climate of New York State changing (e.g., temperature, precipitation)? What are the effects of climate change on the variability of climate-driven processes (e.g., hydrology, nutrient cycling, and phenology)? What are the ecological effects of this climate variability? And, what management or policy actions can help mitigate these effects? (Sections 2.0, 7.0)
2. How are sulfur, nitrogen, and mercury deposition in New York State changing in response to international, national, regional, and State policies related to energy-related atmospheric emissions? How is ecosystem recovery influenced by legacy effects, management actions (e.g., liming), and policy decisions? (Sections 3.0, 4.0, 5.0, 6.0, 7.0)



3. What are the interactive effects of changing atmospheric emissions and deposition of multiple pollutants in the context of climate change? (Section 5.0)
4. How are emerging issues such as lake browning, harmful algal blooms, and invasive species altering ecosystems? To what extent are these issues exacerbated by climate change? What are the best management options for reversing or mitigating the impacts of these issues? (Section 6.0)
5. How can synthesis, critical loads and scenario modeling, and ecosystem service analysis help support energy-related decision-making in New York State and beyond? (Section 7.0)

To address these questions, the research plan is divided into six major parts: Climate Variability and Effects (Section 2.0), Climate Change and Acidic Deposition (Section 3.0), Climate Change and Mercury Deposition (Section 4.0), Multi-Pollutant Interactions and Concurrent Environmental Change (Section 5.0), Emerging Issues and Expanding Research Needs (Section 6.0), and Decision-Support Research (Section 7.0). A new seventh part on science translation and outreach (Section 8.0) was added to this research plan to support the uptake and use of this Program's research by decision-makers and the public. An appendix is included to provide details on research related to these themes that should be consulted when new related research is proposed.

Several research projects that have been supported by NYSERDA over the last five years are still in progress. As such, this research plan represents a work in progress. Final results and conclusions from on-going NYSERDA-supported projects, in addition to new research findings and policies, will be considered when revisiting, revising, and reconsidering priorities within this research plan to ensure it effectively addresses current and future environmental concerns.

## 2 Climate Variability and Effects

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Greenhouse gas emissions from energy generation and use are the primary driver of global climate change and its effects. Climate change alters many processes such as precipitation regimes, snowmelt processes, plant and animal distribution and abundance, and the magnitude, frequency, and duration of flood and drought events. These climatic changes are likely to affect New York State ecosystems by driving phenological change, species shifts, localized species extinctions, invasive species spread, increased algal blooms, water quality degradation, habitat deterioration and loss, biodiversity, and the supply of critical ecosystem services. Understanding these impacts to ecosystems requires long-term climate and ecosystem monitoring together with process-level research.

While NYSERDA's 2011 report *ClimAID: Responding to Climate Change in New York State* continues to serve as NYSERDA's keystone study on climate change, much has changed since that report was published, and recent research points to areas in need of further study. Therefore, this 2018 research plan has an expanded focus on climate change, its interaction with atmospheric deposition, and its direct and indirect effect on New York State ecosystems.

### 2.1 Climate Trends

Climate change in New York State is increasing temperature, the length of growing seasons, and the frequency of extreme precipitation events, as well as changing winter snow pack, soil frost dynamics, and surface water hydrology. For example, New York and surrounding states have experienced, and are expected to continue to experience, a substantial increase in the frequency and severity of intense rainfall events. The magnitude and intensity of precipitation events are closely linked to river discharge, which is a strong driver of nutrient (nitrogen and phosphorus), dissolved organic carbon (DOC), and sediment loading to receiving waters. Increased precipitation has also led to higher nutrient loading in lakes.<sup>1</sup> Precipitation-driven export of DOC has cascading impacts on ecosystems, in addition to adverse effects on drinking water supplies. Changes in hydrology and nutrient cycling can alter the flux of cations and contaminants from soils to aquatic ecosystems, and thus change how ecosystems respond to deposition impacts. Warmer waters associated with climate change can hold less oxygen, adding an important stress to aquatic ecosystems. Monitoring can help quantify the impacts of sediment loading on lakes. Research has suggested that detrimental effects on the structure and health of fish communities and biodiversity can occur and may be further exacerbated by harmful algal blooms.

## 2.2 Phenological Change

There is abundant and growing evidence of changes in the phenological characteristics of plants and animals, such as leaf-out, blooming, breeding, hibernation, and migration in New York State. For example, studies have shown that wildflowers and woody perennials are blooming earlier compared to historical records (e.g., using lilac as an indicator species), and climate change has also altered the arrival time of migratory birds. The timing of springtime bird migrations is important as earlier onset of plant leaf-out and blooming can cause some migratory birds to arrive after the time of peak spring food resources. Some studies across the United States have suggested that a timing mismatch between plants and microbes driven by rising temperatures and changing seasonal patterns could alter nutrient cycling by plants.<sup>2</sup> A longer growing season driven by earlier spring and later fall could impact plant phenology driven by day length, resulting in leaching of nutrients from soil rather than uptake into vegetation. These same dynamics occur in waterbodies where the timing of phytoplankton blooms and zooplankton growth are becoming uncoupled. Tracking species assemblages and distribution, and the effects of phenological timing mismatches in terrestrial and aquatic ecosystems, would advance the understanding of the impacts of climate change and identify important management needs. Enhanced understanding of phenological changes and their ecological effects in New York State is needed to support climate adaptation and mitigation strategies.

## 2.3 Ecological Effects

Evidence suggests that the inhabitable ranges of some bird, plant/tree, fish, and invertebrate/insect species are shifting, and non-native species are expanding into new regions. Regional studies in the Northeast have investigated the potential impact of climate change on species distributions and assemblages. In Vermont, for example, researchers identified a shift in the boundary between northern hardwoods and the boreal forest in the Green Mountains of 299 to 390 feet upslope between 1964 and 2004.<sup>3</sup> At the community scale, climate change can alter food chains and trophic niches of current communities as well as create ecological communities with no prior analog. New York State forest ecosystems are changing due to climate change and other drivers. More information is needed to understand changes in forest growth, health, composition, regeneration, and competition to guide forest management and policy.

Climate change is also affecting the distribution and abundance of native and non-native pests (e.g., hemlock woolly adelgid) and disease-transmitting organisms (e.g., ticks and mosquitos). For example, several studies in the Northeast have found links between tick activity and climate, specifically an increase in late spring and early summer moisture.<sup>4</sup> Changes in tick activity could have profound impacts on the health of animal species in New York State. Ticks have the potential to greatly affect the population of large mammal species including moose, and both ticks and mosquitos can also pose a public health threat. Warmer winters with less snow cover have also recently promoted an increase in deer populations in the region and associated degradation of understory vegetation.

Although carbon cycling in New York will not have a big effect on global atmospheric carbon dioxide levels, the effects of climate change on carbon dynamics has high relevance to forest ecosystems and water quality. Lake browning is driven by forest soil carbon dynamics, and there is a large potential for interaction between acid rain legacy effects and emerging climate change effects in controlling movement of carbon from soil to water. Carbon is also a critical control of cation exchange in Adirondack soils, which in turn controls calcium nutrition of the forest, among other things.

The following research priorities advance questions and needs to increase the understanding of climate trends and variability in New York State and their impacts on ecosystems. Climate impacts specific to acidic deposition, mercury deposition, and multi-pollutant interactions are discussed in Sections 3.0 and 4.0 of the research plan.

## 2.4 Research Focus

- Support integration of existing monitoring networks and data with NYS Mesonet and other meteorological networks (e.g., mountain cloud water monitoring), including the physical co-location of higher-end weather stations at monitoring sites.
- Investigate how fluctuations in snow cover will affect forest floor biogeochemistry, and how extreme weather events can affect forest plant and animal communities.
- Expand monitoring of surface waters on an on-going basis and during extreme weather events, such as storms and droughts, and deploy a network of stream temperature monitors to estimate and track changes in stream temperature over time to enhance understanding of the impacts of changing climate and physical stream conditions on aquatic biota and to inform stream restoration, fish stocking, and other management decisions.
- Evaluate interactions between acidity stress and temperature stress in New York streams.
- Conduct additional stream monitoring and data collection to better understand links between discharge and nutrient/sediment export in the context of projected increases in precipitation and the frequency of intense rainfall in New York State.

- Draw on Adirondack lake monitoring programs to track the potential impacts of climate change on physical, chemical, and biological characteristics of lakes and streams, such as water levels and the re-suspension of bottom sediment; ice cover dynamics; duration of summer stratification period; alteration of the distribution of cold, cool, and warm-water fish species; changes in algal biomass and grazing (including the potential for harmful algal blooms); and change in diversity and growth rates across trophic levels.
- Expand monitoring of phenological changes and investigate the effects of phenological changes caused by climate change. Incorporate such monitoring data into the U.S. Phenology Network. Specific questions that require additional monitoring and data collection include:
  - How is climate change affecting critical phenological characteristics of plant and animal species such as leaf-out, blooming, hibernation, and migration?
  - What is the potential for phenological timing mismatches between plants, animals, and the ecosystems they rely on?
  - How are phenological changes affecting productivity?
- Enhance monitoring of habitat characteristics and community level climate effects in sensitive ecosystems, especially at the transition between biomes or climate zones, to inform predictions of species transition due to a warming climate.
- Assess the impacts of increasing temperature and changing precipitation patterns on plant and animal species distributions, assemblages, and communities in New York State.
- Research the impact of warming and changes in precipitation patterns on the ranges of native and non-native, with a focus on invasive plant species and pests, such as the hemlock wooly adelgid.
- Research the consequences of changes in abundance and ranges of native and non-native species on ecologically important conditions in aquatic ecosystems such as streamflow, ice cover, and water temperatures.
- Study the effects and interactions between climate and air pollution on plant and animal distribution, abundance, and diversity. Model these interacting effects and their cumulative impacts on New York State ecosystems.

## 2.5 Relevance to Other Research in the Region and the Nation

Many ecosystems in New York State, and the biodiversity they support, are undergoing major changes from climate change, invasive species, continued acidic and mercury deposition, and other stressors.

The Millennium Ecosystem Assessment detailed the global issues that ecosystems are facing.<sup>5</sup> The U.S. Phenology Network offers a database of phenological observations by citizen scientists, government agencies, non-profit groups, other researchers to monitor the impacts of climate change on plants and animals in the United States. Evaluating how these rapid environmental changes may alter ecosystem

function and services will be critical for understanding the extent of human impacts and for identifying strategies to mitigate those impacts. While many studies have assessed the effects of individual stressors and how they affect natural systems, few studies have considered their combined or cumulative effects. In New York State, *ClimAID: Responding to Climate Change in New York State*<sup>6</sup> (2011) explores multiple stressors that could be reduced to ease ecosystem effects associated with climate change.

The NYS Mesonet, a network of 126 weather stations across the State, provides valuable information on air temperature, humidity, wind speed and direction, pressure, solar radiation, snow depth, and soil temperature and moisture; with vertical profiles of atmospheric data, energy flux, and snow water content for a subset of the sites. These data are collected, archived, and processed in real time by the University of Albany and can be used to feed weather prediction models and decision support tools across New York State along with gridded climate data available through models such as the Parameter-elevation Regression on Independent Slopes Model (PRISM).

NYSERDA has supported research to study the climate impacts on ecosystems in the past, but this work has been limited. One of these projects (contract 31846) examined the effects of flooding from Tropical Storm Irene on biota in Esopus Creek in the Catskill Mountains, aiming to identify features that strengthen resiliency or promote recovery of stream biomass and biodiversity. This work provided information on the resilience of these ecosystems to disturbance and the timescale on which recovery occurs. The DEC conducted fishery surveys in 2013 and 2014, which provided data that complemented the macroinvertebrate surveys completed at five of the same study sites as in contract 31846<sup>7</sup>. Aiming to support resource managers in selecting adaptation options, another project (contract 28260) developed spatial tools and other products to help protect and restore ecosystems degraded by climate change. Changes in habitat structure (e.g., decreased cold water habitats for brook trout and increased warm water habitat for bass) are affecting ecosystems, but it is unclear what species will move or adapt as climate zones and habitats change, and what barriers organisms face to movements or adaptations.

Beyond New York State, the Hubbard Brook Ecosystem Study in New Hampshire is one of several sites that conducts climate-related research. Detailed climate and streamflow records at this site have been recorded for more than 60 years. This information is useful for informing New York-based studies of climate change and ecosystem impacts. The changes in climate at Hubbard Brook, including increased temperature, a reduction in snow pack, and warming of the soils during the plant growing season, have consequences for its ecosystems, in addition to ecosystem services, such as maple syrup production, tourism, and recreation.

## 3 Climate Change and Acidic Deposition

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With support from NYSERDA and others, scientists in New York State have initiated and led groundbreaking studies on acidic deposition that played a central role in the passage of the 1990 Clean Air Act Amendments to curb emissions of sulfur and nitrogen oxides. Since that time, on-going monitoring of acidic deposition has tracked the response to changing emissions, and research on soils, surface waters, trees, fish, and other organisms have quantified both the direct impacts of acid rain and corresponding indirect effects (e.g., loss of soil base cations) that now influence the extent and timing of ecosystem recovery as emissions decline.

Rollbacks of federal policies to control emissions from the power sector have recently been proposed and may affect future deposition patterns. In addition, current changes in climate influence the effects and recovery of ecosystems from atmospheric deposition in ways that are not fully understood. Continued deposition monitoring and modeling can help evaluate the impact of policy decisions; research on the interactive effects of climate change and atmospheric deposition will support a multi-pollutant look at changing ecosystems; and studies on the chemical and biological recovery of terrestrial and aquatic ecosystems in the context of climate change will likely reveal new insights into the unprecedented processes of deacidification as well as inform policy and management decisions aimed at accelerating recovery and restoring ecosystems and the benefits they provide to the economy and citizens of New York State.

### 3.1 Acidic Deposition Monitoring and Modeling to Assess Policy Decisions

Emissions of sulfur and nitrogen compounds from combustion sources, including fossil-fuel power plants, are precursors to acidic deposition.<sup>8</sup> Atmospheric deposition monitoring programs provide high-quality, reliable data that inform current scientific and policy questions and issues. With changing policies and advances in scientific understanding, these monitoring networks and the data they generate should be reassessed periodically to optimize their value and effectiveness.

There is a need to support and expand assessment capabilities to fill geographic gaps in response to shifting emissions sources and to address ecosystem gaps to characterize deposition status and trends in sensitive ecosystems. There may also be a need to add ancillary measurements to existing monitoring programs and to compare measurements and model estimates for specific locations to improve estimates of dry and total deposition in locations where measurements do not exist. Finally, if acidic deposition

continues to decline, it may be appropriate to reevaluate these monitoring networks to determine whether the number and location of sites needed is changing over time; and assess technologies and protocols for monitoring. These considerations may best be addressed in concert with other atmospheric deposition and ecological monitoring components through a focused analysis of network needs, design, technologies, quality assurance protocols, and sharing of data and monitoring (see Section 6.5).

### **3.1.1 Research Focus**

- Continue to support ongoing long-term wet and dry acidic deposition monitoring for sulfur and nitrogen in New York State, including the Catskills and Adirondacks, and include base cation monitoring where possible to understand the influence of policy changes and influence of climate on recovery. Fill data gaps, including measurements of acidic deposition in other regions, such as urban areas, and in sensitive and unique ecosystems in New York, such as peatland bogs, alpine systems, and tributary watersheds.
- Enhance or expand existing long-term atmospheric deposition monitoring networks to better understand climate and other influences through the addition of low-cost ancillary measurements; including selected biological measurements, using high-frequency autonomous sensors, and continuous temperature measurements.
- Continue research into cloud water chemistry and its effects on high-elevation ecosystems to better understand the levels of emissions and deposition that protect sensitive montane ecosystems that will experience stress from climate change. Cloud water exhibits higher concentrations of major ions than precipitation and is believed to have played a major role in the acidification of sensitive, high-elevation ecosystems.
- Improve model estimates of deposition by comparing the measurements and predictions derived from various monitoring and modeling efforts, which may include the National Atmospheric Deposition Program's (NADP) National Trends Network (NTN), the Clean Air Status and Trends Network (CASTNet), the Total Deposition Program (TDEP), and the Community Multi-scale Air Quality (CMAQ) model. Evaluate whether dry deposition can be sufficiently estimated using other characteristics that are more easily measured than dry deposition (e.g., wind, solar radiation, vegetative characteristics, and wet deposition).

### **3.1.2 Relevance to Other Research in the Region and the Nation**

NYSERDA, New York State agencies, and federal agencies have supported acid rain research for decades. NADP is a member-supported deposition network in which program participants fund its operating costs. By applying and following the program's Quality Assurance Plan, any organization can participate. Many regulatory and environmental entities (e.g., DEC, United States Environmental Protection Agency [EPA], Environmental Defense Fund, United States Department of Agriculture [USDA] U.S. Forest Service, United States National Park Service [NPS]) use the resulting information on temporal trends and spatial patterns of atmospheric deposition of pollutants for basic and applied scientific analyses, land management and planning, and to provide accountability for policy changes.



NADP is comprised of five separate monitoring networks plus an additional network that is operating as a NADP transition program. Three of these monitoring networks collect data that directly supports atmospheric deposition research. Each fulfills a different role:

1. The NTN determines the chemical concentrations and deposition of precipitation in weekly samples. There are 18 active NTN sites located throughout New York State (three sites – Western, four sites – Central, one site – Northern, six sites – Adirondacks, two sites – Catskills, one site – New York City, and one site – Long Island).
2. The Atmospheric Integrated Research Monitoring Network (AIRMoN) collects daily single-event deposition chemistry. There is one active AIRMoN site in New York State located near Ithaca in Central New York.
3. The Ammonia Monitoring Network (AMoN) continuously monitors ambient ammonia concentrations. There are five active AMoN sites in New York State (Huntington Wildlife Forest, Whiteface Mountain, and Nick’s Lake – Adirondacks, Claryville – Catskills, Cedar Beach –Southold – Long Island, and Cary Institute – Millbrook).

NADP also has science committees that inform the overall program, one of which is the TDEP Science Committee. There is a modeling effort through TDEP that provides estimates of sulfur and nitrogen wet and dry deposition in a consistent fashion across the United States for use in critical loads and other ecological assessments. The dry deposition component is based on both measured values (e.g., atmospheric concentrations from CASTNet) and modeled estimates from CMAQ, similar to the wet deposition component which incorporates measured values from NTN and modeled estimates from the PRISM.

In addition, EPA’s Clean Air Markets Division administers and operates the CASTNet, which is a national long-term environmental monitoring program. CASTNet was established in 1991 under the Clean Air Act Amendments to assess trends in acidic deposition as a response to emission reduction regulations such as the Acid Rain Program and NO<sub>x</sub> Budget Trading Program. CASTNet has since evolved to measure concentrations of wet and modeled (based on atmospheric concentrations and estimated deposition velocities) dry air pollutants that affect regional ecosystems and rural ambient ozone levels. CASTNet data can be used in conjunction with data from other NADP networks to formulate a more comprehensive understanding of nitrogen and sulfur deposition in the more acid-sensitive regions of NYS. Today, five CASTNet sites operate in New York State (Whiteface Mountain [base and summit], Huntington Wildlife Forest, and Nick’s Lake in the Adirondacks; Connecticut Hill near Ithaca in central New York; and Claryville near Biscuit Brook in the Catskills).

The DEC has supported cloud water collection that has occurred from June to September at Whiteface Mountain for decades. The monitoring network includes two high-elevation atmospheric monitoring

stations, including the only mountain cloud monitoring station still operating in the United States at the Whiteface Mountain summit which facilitates cloud water collection to evaluate occult atmospheric deposition in high-elevation forests<sup>9</sup>. The stations were managed under CASTNet from 1994 through 2000, by the Adirondack Lakes Survey Corporation (ALSC) from 2001–2017,<sup>10</sup> and then by the Atmospheric Sciences Research Center (ASRC) – University at Albany starting in 2018. Additionally, DEC operates 18 continuous sulfur dioxide (SO<sub>2</sub>) and four continuous nitrogen dioxide (NO<sub>2</sub>) air monitors across New York State.

EMEP has traditionally supported several deposition monitoring activities, either directly (e.g., contracts 30682, 30882, and 31250), or as components of a more focused research project, such as contract 53968. Through this contract, high-resolution trends in cloud water chemistry, specifically the presence of sulfur- and nitrogen-containing organic compounds and the aqueous-phase reactions taking place were examined to understand the role of cloud water in the acidification of sensitive, high-elevation ecosystems. Beginning in 2018, NYSERDA entered into monitoring contracts with multiple organizations to continue long-term deposition monitoring of acidic and mercury deposition in New York State and to observe the effects on the forest environment (contracts 122529 [streams], 122530 [lakes], 122681 [NADP, streams, and soils], 122813 [NADP], 124461 [clouds], and 127704 [NADP]).

### **3.2 Effects of Acidic Deposition and Climate Change on Watershed Biogeochemistry**

Decades of acidic deposition has altered the biogeochemistry of soils and surface waters across large areas of New York State and the Northeast by depleting soil calcium and other nutrients, increasing sulfur and nitrogen accumulation, and mobilizing dissolved inorganic aluminum into surface waters. Ecosystem recovery from acidification can be divided into chemical recovery, which is broadly defined as a return of soil and surface water chemistry (e.g., base saturation of soils, acid-neutralizing capacity of surface waters) to unimpaired levels, and biological recovery, which is the degree of re-establishment of key biotic components and their functions. This section of the research plan addresses how the effects of acidification on watershed biogeochemistry has changed under declining emissions, resulting status of chemical recovery, and how these biogeochemical processes are influenced by changing climate. Research connecting chemical recovery, which has been observed in areas such as the Adirondacks and Catskills, to biological recovery, which has lagged in comparison, is examined in Section 3.3. Projections of future recovery under climate change and other concurrent environmental changes are examined in Section 5.0, Multi-Pollutant Interactions and Concurrent Environmental Change, and Section 7.0, Decision-Support Research.

Recent studies suggest that calcium depletion in soils may have slowed or stopped at some locations in response to decreasing sulfur deposition levels. Research suggests that soil remains calcium depleted even as they are becoming less acidic, yet several recent studies provide early indications of soil recovery from acidic deposition. One recent study of 27 sites in eastern Canada and the northeastern United States suggests that effects of acidic deposition on North American soils may have begun to reverse.<sup>11</sup> Processes involved with the replenishment of calcium in soils are not fully understood but have significant implications for the health and productivity of aquatic and terrestrial ecosystems. Furthermore, there is uncertainty regarding whether these observations represent short-term or long-term change. This is particularly important because the extent to which acid-sensitive lakes and streams will continue to recover is tightly coupled with soil processes, and the lack of reversal in calcium availability may continue contributing to adverse impacts on vegetation and aquatic organisms.

Research and sampling efforts have bridged important information gaps regarding relationships between soil conditions and surface water chemistry; however, some critical questions remain. Specifically, the anticipated interactions with climate change are not well understood. In addition, ecosystems in New York State have already been rendered susceptible to stress as they respond to the low deposition levels, and therefore will be vulnerable to climate change effects in ways that are becoming apparent, such as ongoing increases in movement of organic carbon from soils to surface waters, as well as in ways that cannot be anticipated.

After several decades of acidic deposition, many surface waters in New York and the Northeast became more acidic, less productive, and higher in toxic metals such as dissolved inorganic aluminum and mercury—resulting in observed impairments to the water quality and productivity of lakes and streams. Some aspects of lake chemistry (e.g., pH) have improved, while others have not. For example, recent studies suggest that calcium concentrations remain low in many lakes because of the depleted soil pool, and calcium concentrations in streams, which tend to be lower than in lakes, have continued to decrease. It is expected, however, that calcium concentrations in surface water would decrease to some extent as sulfate and nitrate concentrations decrease and less base cation leaching from soils occurs. Additional research is needed to ascertain how changes in soil conditions over extended periods affect the long-term chemical recovery of lakes, streams, wetlands, forests, and other ecosystem components, and the associated ecological impacts of depleted chemical conditions.

### 3.2.1 Research Focus

- Expand soil monitoring at coordinated ecosystem monitoring sites, especially at sites where stream chemistry is also monitored, to allow for a better understanding of belowground biogeochemical dynamics. Soil chemistry (e.g., carbon), temperature, and moisture records are needed, and ideally should be collected upstream and close to existing biological monitoring locations for streams.
- Evaluate the extent to which soils in acidified regions of New York State show signs of recovery from past acidification. Research the recovery capacity of calcium-depleted ecosystems and the interaction of calcium with other elements. Although calcium depletion is relatively well-established, additional information on the degree to which ecosystems are recovering, and the impact of climate change in weathering rates and base cation availability, would be beneficial.
- Conduct research to merge the watershed level estimates of base cation weathering and thus recovery (e.g., from MAGIC) with point-based process models (e.g., PROFILE) to better understand how weathering is affected and how that plays out in the watershed outlet.
- Continue to research and document observed delays in chemical recovery given the decreases in emissions and acidic deposition over the past several decades. Use this information to update existing biogeochemical models to incorporate what has been learned from monitoring of waters and soils, advance how these models are linked to biological responses, inform projections of ecosystem function under alternative future deposition scenarios, and describe possible ecosystem recovery goals.
- Develop stream and lake chemistry indicators of soil and forest health conditions that can aid in the development of empirical, steady-state or dynamic models describing, among other things, the loading and unloading of sulfur and nitrogen in soils.
- Expand stream sampling in the Adirondacks and Catskills for long-term monitoring of both hydrology and chemistry. Focus stream sampling on headwater streams that are not necessarily monitored through other networks and consider nested gages. This enhanced monitoring will help to better characterize hydrologic changes associated with altered snowpack, snowmelt, and precipitation patterns associated with climate change.
- Continue sampling the chemistry of Adirondack lakes. Consider reducing the number of lakes and focusing on those representative of broader types, as well as those that may be more indicative of climate effects or climate resiliency, such as cold-water lakes.
- Evaluate the need for reinstating sampling for total phosphorus and chlorophyll *a*; sample for carbon quality (including finding better measures of it) and mercury; and characterize the temperature and dissolved oxygen profiles of the lakes for observing biogeochemical changes and the response to lower atmospheric emissions and climate impacts.
- Determine whether current models of acidification (e.g., MAGIC, PnET-BGC) have adequately predicted current trends in nitrogen, sulfur, and base cations in soils and surface waters, and plant responses to those trends. If not, support model development, including improvement of existing models and development of new models.

### 3.2.2 Relevance to Other Research in the Region and the Nation

Several recent and ongoing EMEP projects are related to ecosystem response and recovery. For example, one project (contract 57630) is using existing data to examine patterns in total phosphorus and chlorophyll and to understand the impact of atmospheric deposition on nutrient limitation in freshwater ecosystems as acidity decreases. Another project (contract 25928) will expand the use of long-term monitoring of Adirondack Lakes to better understand the processes involved in lake and stream acidification recovery.

EMEP funded projects also support development and updates of existing biogeochemical models. As part of one project (contract 50771), researchers are providing estimates of weathering rates of basic cations for 25 watersheds in the Catskills, which may help improve the predictive power of general biogeochemical models. Another EMEP project (contract 31250) is collecting atmospheric deposition, climatological, and hydrologic data at Huntington Wildlife Forest to better understand the influence of atmospheric deposition and climate on key biogeochemical processes.

EMEP has also supported monitoring and trend analysis for soils (contracts 50771 and 50773), streams (contracts 40509, 73402, 16295), and lakes (contracts 25928, 40512, and 57630). Soils are a key part of the biogeochemical makeup of these ecosystems and continuing a program that links soil monitoring to stream chemistry provides an efficient way to evaluate effects such as acid rain legacies and trending climate. Overall surface water surveys (contracts 34356A) will continue to monitor the shifts in chemistry in Adirondack surface waters in response to changes in atmospheric deposition of acid rain precursors. Stream surveys in the Adirondacks (contract 16295), which were coupled with soil sampling, have helped find missing links between soil and stream chemistry. Due to the close coupling of shallow groundwater flow paths with the chemistry of small streams, soil conditions, and belowground vegetation systems, stream chemistry can help provide a sensitive indicator of ecosystem response to decreases in deposition and recovery from acidification.

The NPS, the EPA, the U.S. Forest Service (in Shenandoah National Park, Virginia), and the U.S. Forest Service at sites in West Virginia, North Carolina, Tennessee, and South Carolina have supported several model-based assessments of ecosystem response to changing levels of sulfur and nitrogen deposition, in the context of changing climate and land management. For example, MAGIC, a process model was applied to address questions related to soil base cation status for a group of 65 streams and their watersheds in the southern Blue Ridge physiographic province of the southern Appalachian Mountains.

EPA's 2018 *Integrated Science Assessment for Oxides of Nitrogen, Oxides of Sulfur, and Particulate Matter-Ecological Criteria* (second external draft) includes a detailed discussion on how deposition of nitrogen oxides (NO<sub>x</sub>) and sulfur oxides (SO<sub>x</sub>) alter soil and aquatic biogeochemistry.<sup>12</sup>

In cooperation with the DEC and EPA, the ALSC monitored Adirondack lakes as part of the Adirondack Long-Term Monitoring program (ALTM). Fisheries have been resurveyed in this program's 52 lakes and limited episodic stream sampling during high-flow events has been conducted. Annual sampling of many of the ALTM lakes has been conducted in cooperation with EPA's Temporally Integrated Monitoring of Ecosystems (TIME) program; however, TIME ceased sampling at the end of 2016. Beginning in 2014, several changes were made to the ALTM lake monitoring efforts. For example, monitoring for total phosphorus and chlorophyll *a* was discontinued, and sampling schedules were changed for several lakes. Fifteen lake sites were reduced to annual sampling during the summer, and 43 lake sites were reduced to seasonal sampling or six times per year. The changes in sampling regime were dependent on several criteria (e.g., capturing a range of DOC, acid-neutralizing capacity [ANC], and nitrate [NO<sub>3</sub>]; involvement in ongoing intensive research projects), and was determined following a statistically robust evaluation of the long-term dataset, which revealed the ability to continue to observe trends with a reduction in sampling at each of the sampling locations.

The Adirondack Effects Assessment Program's (AEAP) long-term biological monitoring of 28 Adirondack lakes was initiated in 1994 but was subsequently reduced to 14 lakes, monitored two times per year, before ending in 2012. The program made data, which included zooplankton and phytoplankton sample results, from the 18 years available via publications and reports. A project recently completed by Rensselaer Polytechnic Institute (contract 115876) combined the physical, chemical, and biological data collected at lakes in the Adirondacks that overlapped with both AEAP and the ALTM program over an 18-year period and published a cleaned up and complete dataset that is publicly available.<sup>13</sup>

In the Catskill Mountains, the United States Geological Survey (USGS) continues to monitor five streams for continuous flow and conducts biweekly and periodic event sampling as part of EPA's long-term monitoring. The steering committee for the biennial Catskill Environmental Research and Monitoring Conference has been working to develop a web-based bibliography and data catalog for Catskills-based research. Additionally, the Catskill Science Collaborative is moving forward with developing plans for a Catskill Research Forest and better coordination of research and monitoring efforts. At a broader scale, the EPA conducts National Aquatic Resource Surveys. These are a useful analogue to what has been done in the Adirondacks, but with a contiguous-U.S. perspective.

### 3.3 Ecological Effects Under Climate Change and Implications for Recovery

Acidic deposition can affect both aquatic and terrestrial ecosystems through acidification of soil and drainage water. The processes of acidification and recovery take place over long-time scales and involve various ecosystem compartments. Recovery is influenced by potential policy rollbacks, as well as changing temperature and precipitation patterns associated with climate change. Reductions in deposition are often decoupled from biological recovery, whereas chemical recovery in some watersheds appears to correlate with deposition much more closely. New York State would benefit from more research to evaluate how aquatic and terrestrial systems are responding to decreased deposition at plot and whole landscape scales under a changing climate and whether changing policy has a large enough effect on deposition to alter this process. This information is also critical for assessing policy decisions and understanding where management efforts to accelerate biological recovery should occur.

In past decades, acidic deposition has decreased the availability of cations such as calcium and magnesium in soils with low acid-buffering capacity, which are common throughout much of the Adirondack region and found in many other upland forested areas of the eastern United States. Acidic deposition altered the chemistry of soils across large areas of New York and the Northeast by causing the depletion of calcium and other nutrients, increasing the accumulation of sulfur and nitrogen, and mobilizing inorganic aluminum, which enters soil pore waters and ultimately surface waters.

Some forest plant species were unable to tolerate the high acidity, high aluminum, and low base cation supply. As a result, calcium loss from terrestrial systems may be causing changes in plant growth and health, especially for some tree species and geographies, such as sugar maple in northern New York State. Researchers need a better understanding of how soil changes are affecting tree species composition and health, building on the work of Horn et al. (2018) that examined the sensitivity of 71 tree species to nitrogen and sulfur deposition.<sup>14</sup> This information is critical to determining how forests, including forest overstory and understory vegetation, will respond to the offsetting effects of varying degrees of declining

acidic inputs and continuing base cation depletion, as well as to interacting factors such as climate change and non-native pests. Soil calcium in terrestrial ecosystems may also influence the population of fauna (i.e., microorganisms, isopods, snails, caterpillars) and the organisms that feed on them, namely songbirds. Understanding these food web effects is important for evaluating the need for, and the potential benefits of, management actions to accelerate recovery.

The acidification of surface waters can lead to declines in fish populations. Acidic water also affects aquatic plants and insects eaten by fish. As a result of these effects, the entire aquatic food chain can be depauperate, leaving a lake or stream less healthy, resilient, and productive. In addition, lakes and streams across sensitive areas of New York State exhibit chronic and episodic acidity with related negative impacts on water quality and aquatic life. Under changing climate conditions, more extreme weather events are anticipated, raising concerns about changes in the magnitude and frequency of episodic acidification and its potential to undermine recovery.

As emissions of sulfur have declined, the acid-base chemistry of surface waters is beginning to show signs of chemical improvement. Data from Adirondack lakes show widespread improvement in surface-water sulfate, varied improvement in surface-water nitrate, improved ANC, and reduced levels of inorganic aluminum. Recovery from the effects of acidification, however, will take years or decades. Recovery entails improvements in water and soil chemistry necessary to support a more diverse and abundant aquatic community and productive forests. Recovery from acidic deposition is a process closely linked to reductions in emissions of  $\text{SO}_2$  and  $\text{NO}_x$ , and there no longer appears to be a debate about the direct connection between reduction in acid rain precursors and reduction in the level of acidic deposition. The record of evidence suggests that in the Adirondacks and elsewhere, changes have been observed in lake and stream water chemistry with sulfur levels declining nearly everywhere but decreases in nitrogen levels not seen in some areas. However, lake biology appears to lag chemical recovery in stream waters and biological recovery in streams and lakes are generally lagging.

Using a variety of ecosystem management options (e.g., watershed/in-stream liming, restoration of lake/stream ecosystem resilience through stocking of native fishes), resource managers may be able to accelerate ecological recovery. Policymakers and resource managers tasked with protecting and restoring impaired aquatic and terrestrial ecosystems need a better understanding of current biological impacts, the potential for recovery, as well as important management options, costs, benefits, and application procedures.



### 3.3.1 Research Focus

#### 3.3.1.1 Terrestrial Ecosystems

- Conduct research to examine how calcium loss from terrestrial systems affects plant growth and health, especially in sugar maples and other sensitive or base-cation accumulating species, and how these effects are moderated or exacerbated by changing climatic conditions.
- Model the responses of Adirondack understory plant communities to future changes in acidic deposition and climate change.
- Conduct research on the effect of declining soil calcium levels on terrestrial food webs in the Adirondacks' and Catskills' ecosystems, including songbird populations, and put these effects in the context of additional stressors associated with climate change.
- Support studies to better understand the percent base saturation at which sensitive understory and overstory vegetation is adversely affected. For example, a base saturation of 17% seems to be an important threshold for sugar maple regeneration. This research can support the development of models that are sensitive to soil percent base saturation for key vegetation types in upland forested areas throughout the Northeast.
- Evaluate the implications of research on soil base saturation for forest management and forestry practices under changing chemical and climatic conditions.
- Support research on the legacy effects of excess nitrogen accumulation on terrestrial ecosystems.
- Support investigations of how soil carbon, nitrogen, and sulfur are changing in response to recovery from decreasing acidic deposition under a changing climate and increasing levels of carbon dioxide (CO<sub>2</sub>) in the atmosphere as well as research on the implications for forest ecosystem carbon dynamics (e.g., carbon sequestration and storage).

#### 3.3.1.2 Aquatic Ecosystems

- Research and monitor the status, extent, and severity of impacts from both chronic and episodic acidification, and the potential for recovery of resident fish assemblages in acid-sensitive streams of New York State under changing climate. Due to their complexity and high variability, stream ecosystems are some of the least understood and studied but remain some of the most severely acidified aquatic systems in parts of the State.
- Conduct research to understand the extent to which acidification and water warming constrain the extent of suitable stream habitat for cool-water species such as brook trout in the Adirondack and Catskill regions. This could help determine the interacting effects of acidification recovery and stream warming caused by climate change.
- Continue toxicity tests that link aluminum chemistry to mortality data in previously assessed streams to provide some measure of potential recovery of Adirondack and Catskill streams from toxic aluminum effects. While sampling for this information should not be intensive, it would be helpful to target sampling at the time of year when aluminum concentrations are high (i.e., springtime, due to snow melt) and to the most sensitive systems (streams and a few of the most sensitive lakes).

- Conduct research to monitor lake biological recovery. As part of this effort, return to lakes that have been previously sampled and remeasure at least some of the many species assemblages (e.g., bacterioplankton, phytoplankton, zooplankton, benthic macroinvertebrates, and fish communities) to help understand trends in species richness, community composition, and the appearance and disappearance of important indicator (and/or invasive) species in connection with changes in water chemistry, such as recovery from acidification or change in climate. Not all species assemblages need annual data collection, so surveys at most target lakes could be done on a rotating basis.
- Use monitoring data to assess biological recovery across trophic levels (e.g., species interactions within or across aquatic and terrestrial food webs). Rarely have there been regular measurements of physical and chemical characteristics alongside phytoplankton, zooplankton, and fish, as well as benthic invertebrate assemblages. Yet the underlying food web (e.g., zooplankton and benthic invertebrates) can modulate the way top trophic levels (e.g., fish) respond to changes in acidic deposition and climate.

### **3.3.1.3 Accelerating Recovery**

- Assess past research on lake and watershed liming projects and interpret results relative to what is already known. Evaluate and synthesize past efforts to reintroduce fish or other species in restoration efforts to inform future accelerated recovery activities.
- Investigate how the application of lime to watersheds influences mercury mobilization and bioaccumulation in aquatic and terrestrial organisms.
- Compile and evaluate information on the relative cost-effectiveness of liming and other restoration efforts such as forest thinning, burning, and carbon additions for achieving management goals in variable ecological conditions. Reexamine past efforts and previously collected data to elicit new ideas and opportunities.
- Conduct experiments and demonstrations of management practices to accelerate recovery of terrestrial and aquatic ecosystems and organisms that explore both soil and seed dispersal limitations. Expand the investigation of restoration strategies to include forest management practices in addition to the application of lime or other calcium-rich materials. Evaluate the consequences for terrestrial and aquatic ecosystem components including soils, forests, wetlands, fish, plants, and other biota, and consider the impact of climate change on these efforts.

### **3.3.2 Relevance to Other Research in the Region and the Nation**

Several liming projects have taken place in the Northeast over the past 20 to 30 years, including the Adirondack Lake Acidification Mitigation Project, Living Lakes Project, Woods Lake investigations, Honnedaga Lake Watershed Liming projects, and the DEC Lake Liming program. An EMEP project recently completed evaluated regeneration and crown condition of northern hardwood tree species in the Adirondack Mountains, which provided information for the management of terrestrial ecosystems in New York State that are thought to be highly responsive to changes in acidic deposition (contract 41874). Another project evaluated the extent to which implementation of the 1990 Clean Air Act Amendments

has improved fish assemblages from acidic lakes in the Adirondack region (contract 41878). As part of this work, researchers developed fish-chemistry response models and determined how different fish management practices (e.g., liming, reclamation, stocking) may have affected recovery. As part of a separate project, researchers assessed the mechanisms (e.g., litter decomposition) by which organic matter accumulated in limed soils at the Woods Lake catchment; this provides information on how liming may affect carbon storage in forest ecosystems for consideration in land management strategies (contract 33076).

Until recently, limited watershed and in-stream liming has taken place in New York State, but with the Honnedaga Lake Watershed Liming projects (contracts 27329, 33074, 33075A, and 50775), researchers can now compare the ecological effects of liming applications on aquatic and terrestrial systems. Additionally, projects in this area afford an opportunity to assess the transport, transformation, and trophic transfer of mercury in forest and surface water ecosystems in response to tributary and watershed liming, providing a better understanding of mercury-acidification interactions and identifying any potentially unintended consequences of liming (contract 33075A). One recent study reported that while in-stream and watershed liming accelerated chemical recovery in limed streams, it did not successfully accelerate biological recovery (contract 50775).<sup>15</sup>

At the Hubbard Brook Experimental Forest in New Hampshire, researchers added a calcium silicate mineral (wollastonite) to a paired watershed in 1999 to evaluate ecosystem response over a 15-year period. Calcium restoration in this study resulted in higher net primary productivity and recovery of tree biomass relative to an untreated reference watershed.<sup>16</sup>

While these studies have advanced the state of the science on liming and ecosystem recovery, the costs, benefits, and long-term impacts of these projects have not yet been fully analyzed and documented so they can serve as useful resource management tools.

## 4 Climate Change and Mercury Deposition

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Coal-fired power plants are the largest source of mercury emissions in the United States. Once deposited, mercury can be transformed to methylmercury as it moves through watersheds. This more toxic form of mercury bioaccumulates in food webs, exposing people and wildlife to elevated methylmercury via fish consumption. Approximately 85% of the methylmercury exposure to the United States population is from consuming estuarine and marine fish that often exceed human health consumption guidelines, which points to the need for increased research in estuarine and coastal regions affected in New York State (e.g., NY/NJ Harbor, Long Island Sound, Hudson River wetlands).

NYSERDA-funded research led the way to understanding the magnitude and effects of mercury deposition in New York State and the region. The resulting research played an important role in informing State and federal decisions to control mercury emissions from coal-fired power plants. As a result, fossil-fuel-fired power plants have taken measures to reduce mercury emissions under the EPA's Mercury and Air Toxics Standards (MATS) as well as State-based legislation. The percentage of electricity generated from coal in the United States has decreased from more than 50% in 2000 to approximately 27% in 2018 due to decreasing cost and abundance of natural gas and environmental regulations, such as the MATS.<sup>17</sup> However, proposals have been advanced by the current EPA to rollback MATS, while at the same time global mercury emissions may continue to increase, raising important questions about how human and wildlife methylmercury exposure from fish consumption may change in the future. Moreover, even if mercury deposition continues to follow a downward trend, climate change may further increase precipitation, thereby increasing mercury loading to aquatic ecosystems. These changing policy and climate conditions underscore the need to continue and expand mercury monitoring and research on deposition, watershed cycling, bioaccumulation and magnification, and effects.

### 4.1 Mercury Deposition Monitoring and Modeling to Assess Policy Decisions

Mercury emissions policies in New York, across the country, and around the world influence deposition in the State. As global mercury policies and emissions change, the species and sources of mercury deposited in New York State will likely shift. It is important to understand how those policy changes may affect the magnitude and spatial pattern of mercury deposition, mercury methylation and cycling of methylmercury, mercury concentrations in fish and other organisms, and methylmercury exposure pathways for people and wildlife in New York State.

To understand the ecosystem response to changing United States and global mercury emissions under changing policies, it is important to understand how much mercury is being deposited, the geographic distribution of the sources of mercury (local vs. regional vs. global), how much is being re-emitted, to what extent the legacy mercury load in soils and watersheds will drive mercury bioaccumulation in terrestrial and aquatic food chains, and how climate and land use change will influence these mercury processes at local and global scales. Understanding this complex mercury cycle starts with mercury deposition monitoring.

#### **4.1.1 Research Focus**

- Continue on-going monitoring and measurements of speciated ambient air concentrations of mercury, wet and dry mercury, and mercury in litterfall. Consider expanding mercury monitoring in New York State and adding other locations and types of environments (e.g., estuarine/coastal regions of the Hudson River, New York/New Jersey (NY/NJ) Harbor, Long Island Sound, and the Great Lakes, and streams and rivers in mercury-sensitive regions).
- Apply recent method developments for the quantification of natural abundance mercury isotope ratios in air and deposition; these recent method developments now allow for cost-effective measurements of mercury sources using these tracers. These mercury isotope ratios can be used to help estimate contributions of local, regional, and global background pools of atmospheric mercury in New York State, which will help evaluate the impacts of national and international mercury policy decisions.
- Conduct research to develop a model of dry-only deposition for mercury based on litterfall mercury for both long-term monitoring and short-term research. Mercury in litterfall may serve as a proxy for dry mercury deposition because some mercury deposited in particulate and gaseous forms adheres to leaves; however, elemental mercury enters the stomates of leaves as well.
- Evaluate the use of stable isotopes of mercury for source attribution for both upland watersheds and estuarine and coastal ecosystems in New York State.
- Evaluate the utility of existing models to estimate mercury chemistry under various emissions and deposition scenarios to improve representation of mercury fate and transport processes.

#### **4.1.2 Relevance to Other Research in the Region and the Nation**

Through EMEP, NYSERDA and the DEC support the three Atmospheric Mercury Network (AMNet) sites in New York State, which are located in Rochester, Bronx, and Huntington Wildlife Forest (contracts 31250, 122681). Up until 2018, the AMNet sites in the State had provided measurements of atmospheric mercury concentrations of gaseous oxidized, particulate-bound, and elemental mercury.

In 2018, it was decided to discontinue the measurements of two of the three atmospheric mercury concentrations and only collect and analyze for elemental mercury. As part of another project (contract 50462), researchers evaluated the controlling factors of long-term trends in mercury wet deposition at Huntington Wildlife Forest.

NADP conducted a pilot program and is currently operating the Mercury Litterfall (Litterfall) Monitoring Network as a NADP transition program to complement the existing MDN and AMNet monitoring programs.

1. The Mercury Deposition Network (MDN) provides mercury concentrations in precipitation and deposition from weekly samples. There are five active MDN sites in New York State (Bronx – New York City, Biscuit Brook – Catskills, Huntington Wildlife Forest – Adirondacks, Rochester – Central, and Cedar Beach-Southold – Long Island).
2. The AMNet provides continuous collection of dry and gaseous atmospheric mercury in conjunction with MDN wet mercury deposition. There are three active AMNet sites in New York State (Bronx – New York City, Huntington Wildlife Forest – Adirondacks, and Rochester – Central).
3. The Litterfall Monitoring Network (NADP transition program) provides mercury concentrations in composite litterfall (dry deposition) samples collected during autumn. There are two active Litterfall Monitoring Network sites in New York State (Huntington Wildlife Forest – Adirondacks and Biscuit Brook – Catskills). This program provides a way to collect measurements to approximate a large part of the mercury dry deposition in a forest landscape in a consistent manner across the country.

EMEP and the Environmental Research Program support the AMNet, MDN, and Litterfall Monitoring Network of the NADP at Huntington Wildlife Forest in the Adirondacks (contracts 31250, 122681); MDN and Litterfall Monitoring Network at Biscuit Brook in the Catskills (contracts 30682, 122813); and the MDN at Cedar Beach-Southold on Long Island. Syracuse University (contract 10659) developed estimates of mercury deposition to the Adirondacks based on models (e.g., the Big Leaf model<sup>18</sup>) and experimental and monitoring deposition data. Together, these provide the best data underpinning estimates of mercury deposition.

Various entities, including the EPA and NADP, are working to standardize methods for speciated mercury monitoring (e.g., for Tekran). These entities are establishing protocols on data collection and standardizing measurement procedures so the same methodology can be used across these networks to facilitate data sharing and data comparisons.

## 4.2 Effects of Mercury Deposition and Climate Change on Watershed Biogeochemistry

The transformation of mercury to methylmercury is the key process controlling the bioavailability of the toxic form of mercury in food webs. New data, models, and analytical techniques have informed the scientific community's understanding of the biogeochemical processes driving mercury methylation in freshwater systems. Research has suggested that observed decreases in atmospheric mercury deposition may be driving decreased total and methylmercury concentrations in surface water,<sup>19</sup> but sparse observations and substantial temporal variability have prevented meaningful analysis of trends. Recent research efforts, for example, have correlated mercury methylation with sulfur, anoxic conditions, DOC, acidic environments, and other factors.

In addition to monitoring and studying freshwater systems, research is needed to advance the understanding of mercury methylation in wetlands, forest soils, coastal systems (e.g., estuaries, bays, sounds), and how confounding factors, such as climate change, nutrient enrichment, increasing dissolved organic carbon, and declining acidic deposition influence mercury cycling (especially the production and transport of methylmercury) and bioaccumulation in fish and wildlife.

Better understanding of the factors influencing methylation in various settings, and of the types of locations where methylation occurs in different ecosystems and regions can help decision-makers assess what levels of deposition need to be achieved to reduce fish mercury concentrations in different settings throughout New York State, where fish advisories and monitoring efforts should be targeted, what management strategies might help reduce methylation rates, and characterize the expected response time of various types and locations of aquatic systems to changes in mercury deposition. Additionally, given the vast amount of legacy mercury in some aquatic systems, in situ mitigation efforts to constrain mercury methylation could be an important management tool for some systems going forward.

### 4.2.1 Research Focus

- Continue to monitor and track stores, sources, and movement of mercury in soil to better understand controls on mercury sequestration and mobilization under changing deposition and climate.
- Research, monitor, and synthesize data to better understand how increases in precipitation and amplification of the hydrologic cycle under climate change are influencing the fate and transport of methylmercury in the environment, as well as processes and ecosystems that regulate production of methylmercury (e.g., wetlands or anoxic sediments).

- Conduct research on how forest cover affects surface water mercury concentrations of mercury to understand how land use and land cover change, specifically the difference between deciduous and coniferous forests, affect mercury flux in soils. Identify whether small-scale differences in forest cover can help reconcile the differences in mercury flux observed among nearby watersheds. Streams in forested watersheds may be especially responsive to differences in forest cover and methylmercury production in forest soils.
- Conduct research on the mercury methylation process and sources, and its relationship to DOC availability in different environments, especially estuaries and coastal areas, wetlands, lakes, and streams. Methylation processes may vary among these locations, given diversity in organic matter availability and other variables. Research the relationship between the character of dissolved organic matter and the transport and bioavailability of mercury to better understand the interactions between mercury and DOC, which has been changing in recent years with changing climate and (in some parts of the State) changes in the amount of acidic deposition.
- Apply mercury stable isotope ratios at an ecosystem scale to assess the origin of mercury, and to help estimate the relative contributions, bioavailability, and residence time of atmospherically deposited pools in comparison to legacy sources.
- Support the development of models (e.g., models similar to MERcury Geo-spatial Assessment for the New England Region [MERGANSER]) to predict better methylation and bioaccumulation of mercury in lakes, reservoirs, streams, rivers, estuaries, and near-shore marine environments to support the development of fish consumption advisories and the prediction of impacts to piscivorous wildlife under changing emissions and deposition.
- Support the expansion and testing of chemical metrics as a screening approach for mercury-sensitivity of brook trout and other fish developed for the Adirondacks to a larger part of the Adirondacks as well as to streams in other parts of the State.<sup>20</sup>

#### 4.2.2 Relevance to Other Research in the Region and the Nation

These process-level research recommendations represent an important step in advancing knowledge concerning the biogeochemical cycling of mercury and methylmercury in lakes, streams, wetlands, terrestrial systems, and coastal waters; the links to nutrient inputs and eutrophication; the connections to atmospheric mercury deposition and cycling of legacy mercury; the influence of climate on mercury retention, methylation, and transport within the watershed; and the bioaccumulation of methylmercury in freshwater and marine biota, including those consumed by humans and by wildlife.

Such mechanistically focused studies will not only benefit the State, but also complement efforts in selected coastal regions of the United States (e.g., the Coastal and Marine Mercury Ecosystem Research Collaborative [C-MERC]). This information will be especially useful in developing and improving models for the behavior and fate of mercury under a changing climate and provide substantial value to local and federal public health and environmental agencies that issue human health advisories for commercial and sport fish consumption.



### 4.3 Ecological Effects Under Climate Change and Implications for Recovery

Current information is insufficient to understand how mercury and methylmercury exposure in biota, as well as methylmercury bioaccumulation and biomagnification, relate to changes in emissions and deposition together with changing climate and reductions in acidic deposition. In addition, research on the extent to which legacy mercury in soils will move into the food web, factors influencing rates of methylation and methylmercury transport in different settings, and the influence of food web structure and function, will help policymakers understand how quickly changes in mercury emissions affect fish and wildlife in different settings.

These efforts are especially important given the potential interactions with climate change as well as changing national and international policies such as MATS and the Minamata Mercury Convention. It has become increasingly evident that recently deposited mercury is more reactive (i.e., methylation with subsequent bioaccumulation) than older mercury. On-going mercury monitoring and data analysis is critical to informing policymakers of the benefits of potential regional, national, and international mercury emissions reductions.

Terrestrial food webs have the potential to biomagnify methylmercury to a great extent. Mercury concentrations in terrestrial animals increase as mercury moves through the food chain, but the transfer mechanisms are not well understood, and spatial patterns of mercury bioaccumulation in terrestrial systems have only recently been studied in detail. For example, there may be an aquatic subsidy of mercury to terrestrial ecosystems. Recent studies have also shown that lichen can bioaccumulate mercury and then pass it on to wildlife once consumed (e.g., deer eating lichen). Additional research in this area is needed. Currently, there is no long-term monitoring of terrestrial invertebrates, though some collections have been included in other food web studies.

Mercury persists in the environment long after emissions and deposition decline. Consequently, songbirds, bats, and other insectivores, especially those in wetland habitats, are likely to continue to be affected even after emissions are reduced. Recent evidence of mercury concentrations in bats indicates widespread potential impacts to a variety of species across many habitats in New York State. Expanded mechanistic studies using biomonitoring data could provide insight into the effect levels for mercury in avian populations.

Trends of mercury in inland lake fish generally show declines over time, but the results are mixed, with some inland lakes increasing while others are decreasing. This inconsistency is likely due to the variety of factors that affect mercury bioaccumulation in individual organisms and concentrations in different ecosystems (including widely varying food chain lengths and fish growth rates among lakes) and limited time-series observations. Previous fish and surface water survey efforts provide considerable information on fish mercury status in individual waterbodies, but few waterbodies have repeated measurements. Similarly, mercury data for fish in New York State's streams and rivers has been collected since the 1970s, but there have been few repeated samplings over time, so information with which to assess trends in these habitats is limited.

There are several drivers of observed variation in fish mercury concentrations in fresh waters across New York State. Some factors associated with higher fish mercury concentrations are abundant wetlands and forest cover, low nutrient status, and waterbody acidity. These factors may explain high levels of observed mercury bioaccumulation in lakes of the Adirondacks and Catskills.<sup>21</sup> The MERGANSER model and the National Descriptive Model of Mercury in Fish (NDMMF) have been used to predict mercury concentrations in fish and freshwater piscivorous birds (e.g., common loons) from estimates of mercury deposition and lake or watershed features.<sup>22</sup> These models have not yet been applied to New York State waters, but could be considered. A simple chemical metric approach has been developed to identify Adirondack streams in which relatively high mercury concentrations are likely to occur in brook trout and other native fishes,<sup>23</sup> but this has not been fully tested across the Adirondack region or applied to streams in other mercury-sensitive regions of the State.

Mercury data from loon recaptures over time have shown that some individuals had declining mercury levels, while others had increased mercury body burdens. Several short-term monitoring studies have reported that the concentration of total mercury in loons decreased by up to 50% over five years as sources of mercury pollution were significantly reduced. Interpretation of these trends must account for seasonal habitat changes. Better methods and longer-term data are needed to detect and evaluate trends in biotic mercury levels as emissions, deposition, land cover, and climate continue to change.

## 4.3.1 Research Focus

### 4.3.1.1 Terrestrial Ecosystems

- Conduct research to better understand interactions between mercury cycling and changing anthropogenic emissions together with climate change and other large-scale environmental changes (e.g., land cover and land use). This will help better anticipate impacts of human and natural disturbances on mercury cycling in terrestrial and aquatic ecosystems.
- Continue to monitor mercury in terrestrial invertebrates to inform studies of a variety of other ecosystem components. Researchers can use tissue concentrations of mercury and methylmercury in terrestrial invertebrates as an indicator for mercury concentrations in the substrate in which the organisms live, as well as for studies of the dynamics of mercury in food webs.
- Support focused effects research on songbirds, raptors (e.g., bald eagles), and bats in areas with historically high exposure based on past monitoring efforts in New York State to understand biological effect thresholds and inform wildlife management efforts.
- Support research on whether changes in biodiversity could alter assumptions about mercury bioaccumulation rates in food chains. Biodiversity changes in plants or animals may be affecting mercury bioaccumulation in wildlife.

### 4.3.1.2 Aquatic Ecosystems

- Continue to support biological monitoring for both total mercury and methylmercury in freshwater systems (both lotic and lentic) to better understand how emissions policies affect fish and wildlife within the State, with a focus on recreationally caught and consumable species. Such a program should include a network of routine fish mercury monitoring waters that builds upon the 2003–2005 fish mercury survey,<sup>24</sup> 2005–2009 stream fish and macroinvertebrate mercury work in the Adirondacks,<sup>25</sup> and other available long-term data; as well as stream and river biotic mercury surveys conducted previously across the State, and should include all regions of the State (i.e., beyond the Adirondacks and the Catskills). Where feasible, include diverse groups of organisms, their prey species, and their environments to characterize spatial patterns and temporal trends in mercury bioaccumulation and biomagnification, and to advance understanding of the environmental factors that influence mercury methylation and bioaccumulation.
- Expand monitoring efforts to include measures of mercury and methylmercury in fish and other organisms in coastal waters (e.g., the Hudson River Estuary, the New York Bight, Long Island Sound). Assess mercury's impact and trends in fish in these systems, both spatially and temporally.

- Continue to monitor and track the long-term trends of mercury concentration levels in loons, and other piscivorous birds in areas where breeding loons are not present (e.g., bald eagles in the Catskills and Finger Lakes, belted kingfishers statewide), to provide insight on how changing mercury emissions, with climate change (e.g., increase in temperature, flooding events), affect behavior and population dynamics. These studies should account for variability in mercury uptake due to the seasonal migratory behavior of individual bird species (e.g., blood from loons indicate mercury exposure over a month timescale, whereas feathers from loons indicate mercury exposure over a lifetime).
- Initiate studies to further investigate the levels at which mercury has adverse behavioral and reproductive effects on wildlife and how these levels may be influenced by environmental factors associated with climate change, including on piscivorous species that occupy habitats with high mercury deposition and methylation rates.
- Continue monitoring and research to identify the best use of aquatic invertebrates and small or young of year “prey” fish species in surveys of mercury in game fish, in aquatic settings that are fishless (e.g., small streams), and in systems with relatively short food chains (e.g., streams throughout the Adirondacks). Measurements of mercury and methylmercury tissue concentrations of aquatic invertebrates and prey fish are often used as indicators of mercury concentrations in the substrate and local environment in which the organisms live, and for studies of dynamics of mercury in food webs.
- Support research to compile measurements of fish mercury collected through monitoring programs and evaluate changes in both fish and surface water mercury concentrations in the context of changing aquatic food webs (e.g., decreasing zooplankton populations). Use the results to help refine current models of fish mercury concentrations and assess the influence of changing mercury deposition on aquatic ecosystems.

#### **4.3.2 Relevance to Other Research in the Region and the Nation**

The DEC has been collecting mercury concentration data in fish in New York State for decades. These data inform the New York State Department of Health (DOH) fish consumption advisories and aid in the description of trends in mercury bioaccumulation in aquatic systems, which can be related back to emissions reduction policies.

EMEP has supported the monitoring of mercury in common loons and songbirds under various contracts. Researchers working under contracts 113882 and 34358 used the common loon and songbirds as indicator species of the synergistic effect of acidic deposition and mercury contamination on aquatic and terrestrial Adirondack ecosystems. These efforts built on previous long-term mercury monitoring and provide valuable data on temporal trends in biotic mercury exposure and adverse effects to wildlife. As part of this work, researchers also conducted a detailed study of food web linkages and mercury in

songbirds (contract 34358). Another project statistically analyzed previously collected loon survey and mercury data to develop sampling guidance for the ongoing Adirondack Loon Monitoring Program (contract 108229). Results indicate a need for sampling approaches that are tailored to lakes of varying pH class as well as more sampling in lakes with lower pH.

Several other EMEP projects have focused on aquatic ecosystems. For example, researchers at Syracuse University evaluated spatial and temporal trends in mercury concentrations among fish within New York State's freshwater and marine ecosystems (contract 34357), and researchers at USGS are evaluating spatial patterns and temporal trends in fish mercury concentrations of streams and rivers across the State using existing data compiled from various sources (contract 37346). As part of this EMEP project, researchers conducted fish surveys for mercury, as well as stream water chemical sampling in 36 small Adirondack streams (contract 37346). Results from these projects will improve our understanding of mercury bioaccumulation in fish and help characterize the magnitude of impacts to fish assemblages. In the Finger Lakes, researchers are investigating mercury across multiple trophic levels (two species of forage fish, two to three species of game fish, macroinvertebrates, periphyton, and suspended particulate matter) in five different lakes and their watersheds (contract 50778). The USGS is evaluating methylmercury and total mercury (MeHg:THg) ratios for a wide variety of aquatic invertebrate taxa in New York State streams to develop a tool that will allow for the effective use of total mercury monitoring in macroinvertebrate tissue (contract 40515).

A broad regional survey of stream fish mercury concentrations, conducted by the USGS in 2016, included 47 stream sites in New York State. This Northeast Regional Stream Quality Assessment generated mercury concentration data for small ("prey") fish and game fish from streams in forested, agricultural, residential, and dense urban settings across the more-developed portions of the State. The study also provided data on mercury in stream water and bed sediment, and data on various other mercury-relevant parameters. In addition, mercury isotopes were measured in small fish, game fish, and bed sediments of 23 of the 92 streams overall, including 12 streams in New York; the mercury isotope analyses of State sites were partially supported by EMEP (contract 37346). The mercury isotope data clearly distinguish sites with strong urban-industrial influences from those receiving mercury from atmospheric deposition to the landscape.

Recent evaluations of breeding bald eagles in the Penobscot River watershed of Maine, affected by both atmospheric deposition and legacy mercury from a chlor-alkali plant in the State, indicate mercury concentrations at levels high enough to potentially cause reproductive harm. It is possible that other breeding populations in New York State also have elevated levels.

As in aquatic systems, mercury concentrations in terrestrial animals increase as mercury moves through the food web, but the transfer mechanisms are not well understood, and spatial patterns of mercury bioaccumulation in terrestrial systems have recently only been realized. A pilot study showed that stable isotopes of mercury in bird blood samples can be used to identify the sources of the mercury (contract 30388). Despite not defining a clear causal mechanism, the study showed that species, habitat, and location explain significant portions of the mercury isotope signatures in songbirds and that mercury stable isotopes are an effective tool for a priori categorization. However, it was found that source partitioning can be challenging using stable isotopes and further studies are required to make accurate mixing models that can predict sources.

In coastal systems, the C-MERC led by the Dartmouth College Superfund Research Program published a series of 11 synthesis papers along with a summary report linking global mercury emissions to mercury in seafood, and to human health impacts from methylmercury exposure.<sup>26,27,28</sup>

## 5 Multi-Pollutant Interactions and Concurrent Environmental Change

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Many ecosystems in New York State are undergoing change as a result of the combined and interactive effects of the deposition of multiple pollutants, climate change, invasive pests, land use, and other anthropogenic influences. Integrating the effects of multiple interacting drivers of change on the ecosystems of New York State is critical for making long-term projections of ecosystem health and recovery, evaluating the impacts of policy decisions related to the power sector, and informing management decisions to adapt to a changing climate.

The basic organizing question for this section is as follows: How is ecosystem recovery from atmospheric deposition of sulfur, nitrogen, and mercury being influenced by other concurrent environmental changes, such as invasive species and climate change; and how are New York State terrestrial and aquatic ecosystems expected to change in the future in response to these stressors?

While many studies look at the effects of individual stressors and how they affect natural systems, few studies have considered their combined or cumulative effects. Climate change is expected to affect biogeochemical cycles of nitrogen, phosphorus, dissolved organic carbon, and mercury. For example, the close relationship between river discharge and sediment loading and the delivery of nutrients and toxins to surface waters suggests that increases in the frequency or severity of intense precipitation events is likely to affect the water quality of receiving waters. These conditions are compounded by land-use changes, such as the historical degradation and loss of riparian and floodplain wetlands that reduces the natural capacity of these ecosystems to process and remove pollutants from the water. Likewise, other factors such as invasive plant species introductions and subsequent native plant species extinctions, will continue to alter biological communities and the rates of key processes such as decomposition and nutrient cycling. Research to understand these multi-pollutant interactions and their relationships to concurrent environmental change is a new area to be discussed in this research plan.

New York State and the Northeast in general are considerably more forested than 100 years ago. The structure, composition, health, and function of these forests is altered by the pollution interactions and concurrent environmental changes outlined in this section. Understanding how different plant species and forest communities are changing and will change forests in the future is critical to protecting and restoring ecosystems and ecosystem services of public value, as well as conserving the climate mitigation and adaptation values that forests provide.

In addition, it is widely appreciated that the spread of invasive forest pests is changing the forested landscape in ways that add a major stressor to ecosystems also facing climate change and responding to changes in atmospheric deposition. There is a need for increased research on the distribution of forest pests and their effects under climate change. Baseline data are key to understanding the effects of pests on the landscape, including the impacts to biodiversity and to keystone species such as sugar maple.

## 5.1 Research Focus

- Improve models to simulate the effects of climate change, extreme events, and hydrologic variability on the recovery of ecosystems from sulfur, nitrogen, and/or mercury deposition.
- Support research on the interactive and cumulative effects of climate change, atmospheric deposition, and invasive species on biogeochemical cycling and eutrophication. For example, how do the impacts of invasive species together with climate change and atmospheric deposition alter the flux of cations and contaminants from soils to aquatic ecosystems.
- Support research and monitoring to evaluate the relationship between mercury concentrations in terrestrial and aquatic ecosystems and changes in acidic deposition and climate; including the effect of sulfate and nitrate inputs on methylmercury production, and the role of decreased pH in methylmercury bioaccumulation.
- Evaluate the role of dissolved organic matter (DOM) in mercury and methylmercury bioavailability, transport, and bioaccumulation in freshwater and coastal ecosystems, including during extreme precipitation events. DOC mobility is increasing across the State due to recovery from acidic deposition, in part to increased precipitation and warmer temperatures. Even if mercury deposition further decreases, increasing DOC in aquatic ecosystems could increase mercury levels in fish tissues.
- Conduct a review of existing programs and articulate critical research gaps and needs at the intersection of invasive pests, atmospheric deposition, and climate.
- Conduct research and modeling to understand how nitrogen fertilization and climate change affect the distribution and abundance of invasive plant and insect species in terrestrial and aquatic ecosystems.
- Evaluate the impacts of invasive plant and insects on biogeochemical processes and on forest, stream, and lake ecology.
- Continue studying the relationship between nitrogen and mercury bioaccumulation in coastal systems. Research suggests that anthropogenic nitrogen loading and methylmercury bioaccumulation in fish are inversely related in estuarine systems. Study of an estuarine system that has low nitrogen loading may be particularly useful.



## 5.2 Relevance to Other Research in the Region and the Nation

Several recent EMEP and ongoing Environmental Research Program projects have considered the effects of multiple stressors on aquatic and terrestrial ecosystems. In one project (contracts 31250, 122681) atmospheric deposition, climatological, and hydrologic data are being collected at Huntington Wildlife Forest to better understand the links between deposition and ecological effects and evaluate the influences of atmospheric deposition and climate on ecosystems. In another project (contract 50462), investigators examined the climatic, terrestrial, and anthropogenic factors that have influenced the decadal pattern of mercury wet deposition in upstate New York using the CMAQ model. This research found that meteorological conditions and atmospheric photochemistry affected mercury deposition more than in-State anthropogenic sources during summer months, and the effect of emissions reductions varied for wet and dry deposition during the spring and fall.

As part of other EMEP projects, researchers have investigated the links between climatic variation and surface water chemistry (i.e., nitrate, DOC, and inorganic monomeric aluminum) among 29 acid-sensitive lakes in the Adirondacks (contract 40512) and analyzed the role of changing atmospheric deposition and climate on water quality (contract 44376). Other projects evaluated the combined effect of acidic deposition and beech bark disease on northern hardwood tree species (contract 41874) and the effects of soil acidification, base cation depletion, and nitrogen enrichment on forest understory plant species in northern hardwood forests of the Adirondack Mountains (contract 50773).

## 6 Emerging Issues and Expanded Research Needs

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This 2018 research plan incorporates emerging issues identified through the consultative process, including the causes and dynamics of harmful algal blooms and the effects of surface water browning (increases in the mobilization of dissolved organic matter) on the structure and function of aquatic ecosystems. This section also incorporates research needs for existing issues with increasing significance to New York State such as the impacts of changing nitrogen deposition and the potential for oligotrophication of some surface waters under climate change. Data syntheses that bring together datasets across program areas to gain new understanding are also encouraged. Finally, added attention on priorities, design, and technology for long-term monitoring programs represents a fourth area of research in this section.

### 6.1 Surface Water Browning

DOC is increasing in many lakes and streams throughout the Adirondacks. Recent research has highlighted the role of DOC as a major factor regulating aquatic ecosystem function, including light availability, respiration and dissolved oxygen, metals speciation, pH, and contaminant concentrations such as mercury. DOC is also sensitive to climate change and may, therefore, modulate how aquatic ecosystems respond to climate warming.<sup>29</sup> DOC is a critical factor regulating many aspects of ecosystem structure and function and has responded strongly to reduced acidification. Inorganic monomeric aluminum concentrations are strongly and inversely related to DOC concentrations in Adirondack streams; thus toxicity, even at unchanged pH and total aluminum levels, may be declining substantially in Adirondack streams as the ratio of inorganic to organic aluminum concentrations declines. This relationship likely has implications for mercury methylation and bioaccumulation. Scientists need more information on DOC to disentangle complex mechanisms driving long-term environmental change in New York State ecosystems, including both biological response and recovery and to understand if and how browning affects lake responses to climate warming, algal blooms, nutrient increases and eutrophication, and dissolved oxygen.

### 6.1.1 Research Focus

- Increase chemical and biological monitoring of browning of lakes, rivers, and streams.
- Investigate the causes of browning, identify the processes and sources of lake browning, including the potential for soil changes to play a role.
- Conduct research on the effects of browning on the food web structure and function of lentic and lotic ecosystems to better understand ecosystem effects of increased mobilization of DOC, implications for mercury methylation and bioaccumulation, the bioavailability of toxic inorganic aluminum, and the role of acidic deposition legacy effects on changes in soil carbon dynamics.
- Expand wetland monitoring and assessment (e.g., spatial and temporal patterns in recovery from acidification) and evaluate the role of wetlands within watersheds on different responses (e.g., DOC protection from inorganic monomeric aluminum, the supply of mercury, and conversion of ionic mercury to methylmercury) in both lotic and lentic systems. This effort is especially important in the Adirondacks where wetlands are a central component of many watersheds, and in the Catskills where contrasting conditions can help identify and isolate important drivers and processes in DOC cycling.

### 6.1.2 Relevance to Other Research in the Region and the Nation

Lake survey work has shown that 29 out of 48 lakes in the ALTM program showed significant increases in concentrations of DOC since 1992, two lakes exhibited decreases, and 17 showed no trend.<sup>30</sup> The authors report that elevated DOC is changing the acid-base status of Adirondack lakes largely due to increases in DOM with strongly acidic functional groups. A subset of ALTM lakes also appear to be experiencing changes in their physical characteristics during the summer stratification period, consistent with increases in DOM.

A survey of DOC and fish mercury in 36 Adirondack streams (contract 37346) showed that a DOC threshold (> 6.9 mg/L during summer) was reliably associated with relatively high mercury concentrations in brook trout and other native fishes.<sup>31</sup> These more mercury-sensitive streams were also closely associated with higher ultra violet absorbance (i.e. UVA at 254nm), which suggests a simple screening approach for DOC-related changes associated with mercury bioaccumulation.

Related work showed that seepage lakes in the Adirondacks may become nitrogen-limited, while drainage lakes may become less phosphorus-limited, both resulting in increased productivity. Long-term measurements of total phosphorus and chlorophyll *a* in lakes from the Adirondacks are needed to inform how future decreases in atmospheric nitrogen and sulfur deposition will influence the trophic status of lake ecosystems throughout the region and elsewhere.<sup>32</sup>

Other researchers have looked at the question of whether and how fast boreal lakes in Sweden may brown in the future under climate change. They found that lakes that drain watersheds where there is a water retention time of one to three years are particularly vulnerable to browning induced by climate change.<sup>33</sup> The authors go on to suggest that vulnerable lakes include those used for drinking water supplies, and therefore, understanding lake browning is important to climate change preparedness.

## **6.2 Harmful Algal Blooms (HABs)**

The occurrence of harmful algal blooms (HABs) in freshwater lakes is on the rise in New York State. HABs can impair waterbodies for recreation and pose challenges for municipal drinking water supplies that draw on surface waters. Climate, phosphorous, and other drivers of HABs, especially in minimally disturbed waters, are not well understood. The DEC recently received funding for significant HAB work. NYSERDA may wish to consider focusing on HABs in less disturbed systems, which may not be the focus of the DEC, but may assist the DEC in gaining a better understanding of why HABs occur and where. By focusing on minimally disturbed waters, NYSERDA could examine the influence of climate change or browning on the prevalence of HABs.

### **6.2.1 Research Focus**

- Integrate baseline monitoring and additional research to locate possible harmful algal blooms in minimally disturbed waters.
- Initiate research to understand the drivers of HABs (especially temperature and precipitation) with a focus on minimally disturbed waters across the State to inform management strategies to mitigate HABs.
- Evaluate fishery challenges related to warming lake water and changes in thermal dynamics and trophic ecology of lakes, changes in basal resource availability or quality, and signs of changing plankton communities in increasing algal blooms.

### **6.2.2 Relevance to Other Research in the Region and the Nation**

New York State DEC has a HAB surveillance, research, and management program. The program focuses on waterbodies that have public access, serve as drinking water supplies, or have regulated bathing beaches. Given that the widespread occurrence of HABs in freshwater lakes is relatively recent, it represents an emerging area of research in the region and the nation. Additional information for less developed lakes that do not receive excessive nutrients, such as phosphorus and nitrogen from agriculture and/or wastewater treatment plants, which is believed to be the primary cause of HABs, will help advance understanding of the potential role of climate change and other factors in this phenomenon.

## 6.3 Nitrogen Deposition and Cycling

Deposition of nitrogen-containing air pollutants has been declining in recent years, largely due to the reduction of nitrogen oxide emissions from the energy sector. While the decline in total nitrogen deposition and the increased relative importance of reduced nitrogen compounds (ammonia and ammonium) compared to nitrogen oxides has occurred throughout the Northeast, the responses of ecosystems to these changes have been highly variable. Some ecosystems, such as the Hubbard Brook forest in New Hampshire, have shown declining nitrate in stream water, while in other places, such as Biscuit Brook in the Catskills, there has been no consistent trend in stream water nitrate.

The likely cause of this variability is that nitrogen is very sensitive to other biological changes occurring simultaneously in watersheds. For example, the cycling and export of nitrogen from a forest can be strongly influenced by changes in tree species composition (such those caused by invasive forest pests and pathogens), by climatic effects on soil biological processes, and by effects of elevated CO<sub>2</sub> on tree growth. In addition, recent research has shown that deacidification of forest ecosystems due to declining sulfur deposition can accelerate nitrogen cycling processes and lead to greater nitrogen export to surface waters.

Nitrogen is also fundamentally different from sulfur because it contributes to both acidification and eutrophication of ecosystems. Excess nitrogen supply can increase the growth of some plants at the expense of others and can therefore cause changes in species composition.

Thus, predictions of the response of ecosystems to changing nitrogen deposition must consider the many other biological changes occurring in the ecosystem. While nitrogen has been a focus of ecosystem studies for decades, the issues of interactions between nitrogen deposition and other stressors, and the eutrophication effects of nitrogen on ecosystems are emerging issues for which effective policy development will require accelerated research.

### 6.3.1 Research Focus

- Determine how changes in plant species composition caused by invasive pests or invasive plants will alter nitrogen cycling response to declining N deposition in forests.
- Study the effects of nitrogen on the eutrophication of forest ecosystems and the impacts of elevated nitrogen supply on plant species composition.
- Investigate the impacts of changing climate and atmospheric CO<sub>2</sub> concentrations on the forest nitrogen cycle, with particular focus on how climate change will affect nitrogen availability for plants and export to surface waters.

- Study and model the dynamics of nitrogen de-saturation of forest ecosystems that will occur as nitrogen deposition declines, with the goal of predicting the future productivity, nitrogen retention, and nitrogen export from forested watersheds. Include the responses of the nitrogen cycle to ecosystem deacidification from declining sulfur emissions.
- Develop and test models that can simulate the responses of forest ecosystems to the interacting effects of changes in nitrogen deposition, climate, CO<sub>2</sub>, and plant species composition.
- Investigate the impacts of nitrogen deposition dominated by reduced nitrogen compounds (ammonia and ammonium) compared to the nitrogen-oxide-dominated deposition of the past.

## 6.4 Data Synthesis and Integration

Synthesizing large datasets from on-going monitoring programs and existing research findings can point to novel research approaches that can reveal observations not seen within single-focused individual research projects. This approach can support the mining of previously collected data, and thus add value through recovery of valuable information from prior investments. In addition, it is desirable to link results from various projects with long-term monitoring data (e.g., collected through the State University of New York College of Environmental Science and Forestry [SUNY ESF] at the Huntington Wildlife Forest) and climate change projections (e.g., using data associated with the Intergovernmental Panel on Climate Change [IPCC] reports and information from the U.S. National Climate Assessment) to provide insights that are more informative in the long term. Syntheses intended to directly support management and policy decision-making are covered in Section 7.0.

### 6.4.1 Research Focus

- Support synthesis studies to assess biological recovery, links between acidification processes and effects of nutrients, browning effects on thermal stratification, and changes in the chemistry or biology of New York State ecosystems due to changes in climate. Long-term programs that monitor lake water chemistry and biota (e.g., ALTM, AEAP) in New York do not generally synthesize information they generate. Similar to recent work integrating physical, chemical, and biological data integrating ALTM and AEAP data,<sup>34</sup> it would be valuable to evaluate the various existing datasets in terms of their spatial and temporal resolutions, along with their data collection goals and objectives, to identify opportunities to integrate these datasets for exploratory data analyses. These synthesis studies can improve the understanding of how acidic deposition has influenced water chemistry effects and how this has ultimately affected the biology of these waters.
- Support research that links soil, wetland, stream, groundwater, and/or lake chemistry to the health and recovery of the biota in that environment. Links between forest structure and the chemistry of wetlands, soils, and surface waters could be further explored in relation to the U.S. Forest Service's Forest Inventory and Analysis and Forest Health Monitoring programs.

- Conduct synthesis studies on the impacts of climate change on resident and migrating fish, birds, and wildlife in New York State. For example, leveraging analyses already conducted by the Cornell University Lab of Ornithology, the Audubon Society, and others, a synthesis study could examine data related to the effect of climate change, such as warming temperatures on the presence of resident and migrating bird populations. Supplement existing analyses with additional community science data (e.g., ebird, the Christmas Bird Count, the Breeding Bird Survey), as necessary to build species distributions, and use these, as well as climate and land use projections, to address research questions.

#### **6.4.2 Relevance to Other Research in the Region and the Nation**

Several recent EMEP projects as well as some ongoing Environmental Research Program projects have reevaluated or combined existing data sets in an effort to advance science and inform policy. For example, researchers from Rensselaer Polytechnic Institute recently compiled Adirondack lake data collected through the AEAP and the ALTM program into a single formatted data set (contract 115876). These data were cleaned and made publicly available in a scientific data repository, allowing other researchers to analyze how recovery from acidification and warming may be altering biological communities in complex ways. Researchers at USGS evaluated changes in soil and stream water chemistry in response to acidic deposition in the Catskills using data from various sources (contract 40509). Under this contract, surface water chemistry from five stations in the Catskills was compared to changes in atmospheric deposition from three nearby NADP stations and to soil chemistry at two nearby locations. These results are being further compared to data collected at certain locations in Pennsylvania and in the White Mountains of Maine and New Hampshire (e.g., using data from EPA's LTM network and the USGS Hydrologic Benchmark network). For a separate project (contract 40508-1), researchers re-analyzed data from three field research studies and used the results to develop and test a new forest ecosystem model that simulates responses (i.e., forest productivity, carbon storage, and nitrogen cycling and retention) to environmental changes (e.g., nitrogen deposition, climate change, and shifts in tree species composition). Under another project, researchers reevaluated results from loon sampling surveys conducted between 1998 and 2016 to develop guidance on the location, frequency, and duration of future sampling efforts to best show spatial and temporal trends (contract 108229).

Since 2016, researchers from the USGS have collaborated with Syracuse University and the DEC to assess long-term data from the ALTM program to determine if chemical and biological recovery has occurred in Adirondack lakes (contract 41878) that have been monitored by the ALSC between 1984 and 2012; and with Syracuse University and E&S Environmental Chemistry Inc., to develop biological models needed to predict how fish assemblages in streams of the western Adirondacks (quantified in prior study under contract 37346) have reacted to decreases in acidic deposition since

the 1990 Clean Air Act Amendments (contract 41878) and should respond in the future to different total loads of sulfur and nitrogen deposition (contract 73402A). In an analogous study, the USGS assessed long-term chemistry and fish-survey data collected by the National Park Service and University of Tennessee between 1993 and 2015 to develop biological models needed to predict how fish assemblages in streams of the Great Smoky Mountain National Park could respond to different total loads of sulfur and nitrogen deposition.

In 2009, EMEP developed a synthesis of acidic-deposition-related impacts titled “Actions and Response.” This synthesis focused on emissions policies and environmental responses. In 2015, EMEP completed a multi-disciplinary synthesis of published research findings on effects of acidic and mercury deposition on sensitive ecosystems in New York State (Adirondack and Catskill Mountains, Great Lakes, estuaries, and coastal ecosystems).<sup>35,36</sup> This project built on a wealth of EMEP-sponsored research and other research projects that previously categorized, quantified, and advanced understanding of ecosystem processes related to atmospheric deposition of strong acids and mercury, nutrient and mercury cycling, element interactions and leaching, response of watershed ecosystems to changes in atmospheric deposition, and associated biological effects in aquatic, wetland, and terrestrial environments. In addition, a number of recent studies address the relationship between critical sulfur loads and aquatic ecosystem protection, watershed cation weathering rates, stream acid neutralization capacity, forest understory biodiversity and soil acidification, and impacts to ecosystem services from aquatic acidification.<sup>37,38,39,40</sup> For example, there is evidence that red spruce in the northeastern United States are recovering because of decreased acidic deposition and elevated temperature after decades of growth declines and increased mortality.<sup>41</sup>

## **6.5 Review of Long-Term Monitoring Programs**

In the face of financial resource constraints, NYSERDA is interested in understanding how to maintain an appropriate multimedia monitoring program that is sufficiently and statistically robust to identify impacts on and recovery of fish, wildlife, and the ecosystems they depend on in response to air quality management. Additional research and evaluation are needed to answer this question.

### **6.5.1 Research Focus**

- Conduct a review of long-term monitoring programs in New York State (e.g., deposition, lakes, streams, wildlife) to evaluate opportunities to reduce the cost or pivot in the face of changing deposition, changing climate, and emerging technologies.
- Evaluate technologies and methods for surveying biological assemblages in lakes and streams. For example, hydroacoustic devices have found fish in deep lakes that were previously thought to be fishless. Similarly, a new monitoring approach using environmental DNA shows promise



as an inexpensive method to determine presence or absence, as well as the relative abundance of species of concern in aquatic systems.

- Test and deploy new environmental sensor technology and wireless communication tools to aid in the understanding of real-time ecological processes and extreme events such as severe storms that cannot be easily manually sampled. Advances in these tools present an opportunity to deploy sensor networks to monitor key environmental conditions over a broad landscape. Such sensors may be especially important for understanding the effects of short-term events, or to measure subtle changes in conditions across a landscape that would be too costly with traditional methods. Also, it would be helpful to have work focused on micrometeorology and related sensors to measure ecosystem functions, such as ecosystem metabolism or greenhouse gas fluxes, in response to multiple drivers of change.
- Assess emerging monitoring technologies (e.g., remote sensing, automated monitoring, in situ environmental monitoring) that can be used to provide data to show trends in the chemistry and biology of lakes, streams, wetlands, soils, and forests as they recover from the effects of acidic and mercury deposition and react to changes in climate and develop quality assurance protocols for these technologies.
- Evaluate and publish findings that document success stories that clearly indicate in a quantitative fashion the various improvements that have been realized in response to recent decreases in emissions and deposition of sulfur, nitrogen, mercury, and other air pollutants.<sup>42</sup>

### **6.5.2 Relevance to Research in Other Regions and the Nation**

The review of long-term monitoring and research programs could build on multiple studies of the approach, design, and cost of long-term ecological monitoring programs as well as information on emerging technologies. For example, work by Lindenmayer and Likens suggests the need for a new paradigm in environmental monitoring that is adaptive and problem-driven.<sup>43</sup> Havstad and Herrick argue for integrated monitoring programs that combine soil, hydrology, and biota, and are designed to detect long-term trends with a focus on indicators that are early responders to environmental change and reflect the potential for larger, more significant changes to occur.<sup>44</sup> Caughlan and Oakley suggest using a cost-benefit approach to prioritize monitoring activities while also accounting for the importance of replication and statistic power, when funding is constrained.<sup>45</sup> Finally, Trevathan and Johnstone outline ways that new technologies for monitoring of remote aquatic ecosystems can help contain costs, engage communities, and provide near real-time data.<sup>46</sup>

Past research funded by NYSERDA helped demonstrate the intrinsic value of novel or emerging techniques and technology in ecological assessments and monitoring programs. For example, under contract 50776, the USGS collaborated with Paul Smiths College to show that environmental DNA (eDNA) could effectively characterize the presence or absence, as well as the relative abundance of brook trout populations in 40 headwater streams from across the western Adirondacks.<sup>47</sup>

## 7 Decision-Support Research

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While individual studies often include policy implications in their findings, they do not necessarily provide the kind of analysis, modeling, and synthesis needed to directly support policy and management decisions related to the mitigation of atmospheric deposition and climate change associated with energy generation and use. Currently, ecosystem benefits and services are not fully accounted in the cost-benefit calculations used in setting federal environmental regulations.<sup>48</sup> There is a need for focused decision-supported research to shed light on the relative environmental consequences, costs, and benefits of management and policy options that account for legacy effects, lag times, pollutant interactions, and climate change.

In this five-year research plan, decision-support research is a central focus, and includes defining and modeling policy and management scenarios; reassessing the state of the science in the context of specific decision making through synthesis activities; using critical loads modeling to evaluate how projected deposition under policy scenarios compare with target and critical loads; conducting experiments and reviewing literature, data, and case studies on management activities to accelerate ecosystem recovery; defining and estimating ecosystem services and how the quantity, distribution, and economic value of services that benefit people and nature change under relevant policy and management options; and improving estimates of the economic value of ecosystem services and ecological benefits to improve cost-benefit analysis in decision-making.

Atmospheric deposition and climate change continue to affect a range of resources, processes, and activities, including wood and water resources, recreation, fish and wildlife, carbon sequestration, and air purification. The health of New York State's ecosystems and their benefits to people are increasingly vulnerable. For policymakers to make informed decisions and for the general public to understand how research and policies to protect and restore ecosystems benefit them, it is helpful to quantify and communicate the benefits of ecosystem improvements to human health, recreation, and the local economy. Improving understanding of the comprehensive social, environmental, and economic benefits of U.S. and international policies, management actions, and investments in alternative energy solutions will help garner support from a wide range of stakeholders.

## 7.1 Policy-Relevant Synthesis and Modeling

Emissions and deposition trends for energy-related pollutants in New York State reflect a combination of federal policy, regional carbon markets, and State policies and greenhouse gas reduction plans. The consequences of these policy decisions and the potential for ecosystem recovery is influenced by pollutant interactions and climate change. Decision-makers need information about the potential impact of current and future energy generation choices and the implementation or rollback of emissions policies on New York State's ecosystems.

Publicly available biogeochemical models such as PnET-BGC,<sup>49</sup> DayCent,<sup>50</sup> VSD-PROPS,<sup>51,52</sup> Spe-CN,<sup>53</sup> and other models commonly referenced in peer-reviewed literature (e.g., MAGIC, ForSAFE-VEG) predict and evaluate ecosystem responses to historical changes and future scenarios of atmospheric deposition, climate, and land use. These models can also be used to examine the time scales of ecosystem recovery; however, there is limited information on whether currently observable trends are likely to persist, and whether and at what chemical condition biological components will likely respond.

To promote transdisciplinary policy-relevant synthesis, it would also be useful to bring together researchers from various disciplines with stakeholder and policy professionals to exchange ideas at workshops and symposia to facilitate the generation of ideas, methodologies, and approaches to conduct cross-disciplinary syntheses that yields new insights for policy development.

### 7.1.1 Research Focus

- Forecast future projections of ecosystem recovery under changing deposition and climate. This work needs to account for the effects of future precipitation (i.e., the full range of predictions for intensity and frequency of extreme precipitation events due to climate change) on ecosystem recovery. Explicitly include model evaluation and sensitivity analysis in such forecasts.
- Use biogeochemical and ecosystem models to evaluate the effects of changing atmospheric deposition, land disturbance, and climatic conditions on changes on soils, surface waters, and forest ecosystems.<sup>54</sup> Policy scenarios and models can be used to project future ecological responses to changing sulfur, nitrogen, and mercury emissions, together with changes in invasive pests and plants, forest management, and species composition, with and without climate change and under different concentrations of atmospheric CO<sub>2</sub>.
- Develop or leverage existing models to predict mercury deposition, cycling, and chemistry under future policy and emission scenarios. Such modeling efforts should include dynamic models and consider the role of climate change. Sensitivity analyses on hydrology or rates of nitrogen cycling and related processes would provide additional insights.

- Couple policy scenarios and models of future emissions, deposition, and biogeochemistry with biological response models to assess how emissions policies affect fish and wildlife, with the overarching goal of sharing these results with policymakers. For example, researchers found a correlation between increased methylmercury levels in fish tissue and increases in DOC in the water. Similar correlations have been found with common loon bioaccumulation and the pH of their nesting lake. As a result, changes in deposition do not necessarily translate to similar changes in the biotic mercury at all locations due to various confounding factors.
- Conduct a synthesis study on coastal marshes to assess the consequences of sea level rise on biota in New York State. Using species distributions, climate change projections, and land-use projections already available, habitats can be prioritized that both are critical for current populations and can be expected to be critical under future land-use and climate scenarios.

### 7.1.2 Relevance to Other Research in the Region and the Nation

Over the past decade, NYSERDA and other funding agencies supported several policy-relevant synthesis initiatives that informed policies related to acidic deposition, nitrogen loading to estuaries, mercury inputs and management, the design of carbon emission standards for power plants, and trade practices to reduce the arrival of non-native forest pests. Most of the examples highlighted further in the Report are based on the work of a team of researchers working with boundary spanners and policy advisors to define relevant questions that can be addressed with existing data and models to help ensure resulting research would be relevant and actionable by decision-makers. As shown in the following examples, the impact of these projects can be boosted through the production of companion reports for non-technical audiences and outreach activities.

From 2001 to 2011, the Science Links program of the Hubbard Brook Research Foundation produced a series of synthesis papers and accompanying reports, supported in part by EMEP funds, on acid rain (*Acid Rain Revisited*), nitrogen in northeast watersheds (*Nitrogen: From the Sources to the Sea*), the potential for local mercury sources to have local impacts (*Mercury Matters*), and an analysis of local carbon emission reductions options (*Carbon and Communities*).<sup>55</sup> Each project addressed a set of three to five policy-relevant questions and together, they have established a strong track record for informing policy and management decisions.

Similarly, a series of synthetic policy-relevant papers have been developed on mercury. In 2005 and 2011 the Biodiversity Research Institute convened teams to produce large data syntheses for northeastern North America and the Great Lakes region. These “Mercury Connections” initiatives produced numerous papers that were relevant to the development of MATS and a National Mercury Monitoring Act, which was reintroduced in 2018.<sup>56</sup> Relatedly, the C-MERC released a series of papers and a summary report outlining the issues associated with marine mercury in 2012. C-MERC also issued *Sources to Seafood*,<sup>57</sup>

a report on mercury pollution in the marine environment. In 2013, the Biodiversity Research Institute and the International Persistent Organic Pollutants Elimination Network released *Global Mercury Hotspots*,<sup>58</sup> a report that discussed how fish around the world are consumed despite advisories warning against doing so because of elevated levels of mercury in fish tissue.

With respect to climate change and CO<sub>2</sub> emissions, a project on the co-benefits of different types of power plant carbon standards convened by Driscoll et al. with the Science Policy Exchange began in 2014 and has resulted in four major policy-relevant papers and continues to inform policy decisions related to the Clean Power Plan and its proposed replacement and the Affordable Clean Energy (ACE) Act, by quantifying the full benefits for options similar to these standards.

Finally, a recent synthesis effort led by Lovett et al. with the Science Policy Exchange produced a paper in *Ecological Applications* focused on the impacts and policy options for non-native invasive forest pests and pathogens and accompanying policy brief with a set of Tree-Smart Trade policy recommendations. The paper was an editor's pick by *Science* magazine, and the results have been widely covered in the media and serve as a resource to policymakers working on the reauthorization of the U.S. Farm Bill.

## 7.2 Critical Loads Modeling

Connecting the output from policy-relevant scenarios to critical loads maps and expanding critical modeling to support the evaluation of policy options against a broader range of ecological endpoints will enhance the value of the research for resource managers and policy makers. Research on the effectiveness of emission reductions often stops short of determining whether the targeted reductions allow ecosystems to recover. Critical loads research estimates an exposure to one or more pollutants, below which specified sensitive elements of the environment are not expected to experience significant harm. This research offers a way to evaluate the potential for ecosystem recovery (depending on the definition of significant harmful effects) and determine whether further additional emission reductions may be needed for full or partial recovery.

### 7.2.1 Research Focus

- Establish and apply dynamic models for aquatic and terrestrial critical and target loads to restore and protect sensitive lakes, streams, vegetation, and watersheds (e.g., soils) from acidic deposition. Such loads will reflect the point at which significant harmful effects occur and promote recovery in aquatic and terrestrial ecosystems.

- Conduct research and monitoring to improve the current models that predict ecosystem changes with depositional changes. Improvements may include refining specific model parameters, adding new formulations, and developing and testing new models.
- Evaluate how research on critical loads can better inform policy. Such research might include integrating climate analyses into critical loads analyses. In addition, critical loads could be used to evaluate how deposition levels achieved under attainment of the National Ambient Air Quality Standards (NAAQS) compare to target and critical loads for specific ecosystem indicators for soils, surface waters, forests, understory vegetation, wetlands, and estuaries. The results of such analyses could be useful to evaluating the need for stronger secondary standards under the NAAQS to protect ecosystem health. Currently, the secondary standards for SO<sub>x</sub> and NO<sub>x</sub> are the same as the primary standards that are based on protecting human health.
- Conduct research to determine specific ecological endpoints (chemical and biological) for the array of aquatic and terrestrial ecosystems/communities in the New York State Forest Preserve. These ecological endpoints are necessary in determining the loading standards and monitoring long-term ecological changes. Evaluate the extent to which ecological endpoints identified in national assessments are sufficient for application in the State.
- Conduct more research and monitoring to improve the models on tree species, forest understory composition, and net forest productivity in order to better understand critical loads for forests. Tree species such as sugar maple and red spruce are sensitive to soil acidification and do not respond well to spring frost events. They might be expected to be adversely affected by a changing climate.

## 7.2.2 Relevance to Other Research in the Region and the Nation

Two ongoing EMEP projects are evaluating critical loads related to acidic deposition. One project (contract 50771) is estimating the rate of release of calcium, magnesium, potassium, and sodium via chemical weathering in soils across 25 headwater catchments in the Catskills. This project is using a combination of geochemical modeling, cation depletion in soil profiles, and watershed balance calculations to estimate weathering release of basic cations and establish credible critical loads for the region. Results will inform biogeochemical models that require weathering rates as input. As part of another project (contract 73402), researchers are conducting model simulations of past acidification and developing future projections of stream recovery in the Adirondacks for several emissions scenarios, all within the context of critical loads. A third ongoing project (contract 41878) has developed biological models needed to predict how fish assemblages in streams of the western Adirondacks (quantified in prior study under contract 37346) will respond to various total loads of sulfur and nitrogen deposition scenarios (generated under contract 73402). Results from all three projects will help inform stakeholders on anticipated ecosystem responses in streams to ongoing and planned emissions reductions, as well as identify portions of the Adirondacks where acidified soils, forests, lakes, and streams can recover and estimate the emissions reductions required for that recovery.

There have also been ongoing efforts to conduct total maximum daily load (TMDL) analyses for specific New York lakes identified as impaired on the basis of measured water pH, as required by the Clean Water Act. Critical load models have been shown to be useful in developing TMDLs in the Adirondacks and Southern Appalachian Mountains (SAM). Specifically, work conducted in the SAM links statistical predictions of acid neutralizing capacity and base cation weathering for streams and watersheds of the SAM region with a steady-state model to estimate critical loads and exceedances.<sup>59</sup> In spite of the recent marked decreases in atmospheric sulfur and nitrate deposition, results suggest that stream recovery has been limited and delayed due to the high sulfate adsorption capacity of soils in the SAM resulting in a long lag time for recovery of soil chemistry to occur.<sup>60</sup> Additional coordination of critical and target load and TMDL efforts will be beneficial.

In 2010, NADP formed the Critical Loads of Atmospheric Deposition Science Committee (CLAD), a national platform to discuss current and emerging issues regarding the science and use of critical loads for effects of atmospheric deposition on ecosystems in the United States. CLAD members developed a collection of critical load maps for the United States in 2017 using critical load data that are publicly available as part of the NADP CLAD National Critical Load Database v3.0 (NLCD).<sup>61</sup> These maps help to identify spatial gaps in information, as well as additional research needs.

The EPA Clean Air Scientific Advisory Committee (CASAC) produced a report “Review of the Secondary National Ambient Air Quality Standards for Oxides of Nitrogen and Oxides of Sulfur” (2008–2012), which considered using a critical load approach for protection of aquatic ecosystems through dose-response of fish to acid neutralizing capacity by introducing the concept of aquatic acidity index. However, the U.S. EPA Administrator did not feel the scientific understanding was adequate to implement the aquatic acidity index as an approach to establish a secondary standard to protect aquatic ecosystems from emissions of nitrogen oxides and sulfur dioxide. The work of the current committee (2015–present) is still in progress.

### **7.3 Ecosystem Services and Economic Valuation**

Natural ecosystems provide fundamental services upon which humans depend. These ecosystem services are the processes by which the environment produces resources and services that humans often take for granted, such as filtering of air and water, flood control, timber, and habitat for fisheries and wildlife. A better understanding of human/ecosystem interactions will aid in protecting natural ecosystems and



the critical services they provide to humans. The impacts of acidic and mercury deposition, together with climate change, on various aspects of ecosystem services should be explicitly identified and quantified to the extent possible to move toward a triple bottom line (economic, social, and environmental) analytical framework that can account for externalities previously not considered.

Changes in ecosystem services and cultural landscapes resulting from multiple drivers of environmental and societal change need to be better understood as ecosystem services can be used to set policy objectives or target conditions. Continued research on how mercury pollution and the acidification of ecosystems affect ecosystem services (e.g., provisioning, regulating, supporting, or cultural services) and thereby, New York State's economy, would aid in a better appreciation and more comprehensive understanding of the benefits resulting from emissions regulations and other policies. The EPA's Final Ecosystem Goods and Services Classification System (FEGS-CS)<sup>62</sup> and the Integrated Valuation of Ecosystem Services and Tradeoffs model (InVEST)<sup>63</sup> offer frameworks for measuring, quantifying, mapping, and valuing these services. Other novel approaches to couple socio- and ecological models would be beneficial to develop for New York State.

Finally, in order to fully account for the ecosystem service benefits of policy actions, progress must be made on estimating the economic value of these services and incorporating these values into cost-benefit analyses. One such example identified and documented the sensitive aquatic ecosystem services valued by humans and the environmental pathways through which these ecological services may decrease in response to acidification. Beneficiary groups were identified for each sensitive ecological endpoint to clarify relationships between humans and the effects of aquatic acidification and lay the foundation for future research and analysis to define the value of the ecological services.<sup>64</sup> The U.S. Fish and Wildlife Service uses a regulatory Natural Resources Damage Assessment and Restoration program, providing another example of the economic valuation that could inform economic valuation studies.

### **7.3.1 Research Focus**

- Collect and synthesize information to quantify and map current ecosystem services in New York State and how such uses and values respond to changes in ecosystem quality related to climate change, acidic and mercury deposition, and nutrient enrichment.
- Support studies to estimate how ecosystem services under baseline conditions have changed over time and may change going forward under changing climate and deposition scenarios. This may include using critical loads models and other models to evaluate how ecosystem services are affected by various climate and atmospheric deposition scenarios.
- Develop social science approaches for translating ecological impacts and measures of chemical and biological recovery into social, economic, and cultural values.



- Conduct studies to improve the economic valuation of ecosystem services in New York State and support research to estimate the value of currently non-monetized benefits associated with management and policy actions (e.g., wildlife health). Apply expanded economic valuation techniques and estimates to scenarios of policy and management actions for reducing atmospheric deposition and mitigating climate change to generate comprehensive cost-benefit analyses for decision-making.

### 7.3.2 Relevance to Other Research in the Region and the Nation

Environmental policies that account for both the well-being of humans and nature will likely garner support by a wide range of stakeholders. However, information about the links between the natural and social sciences is weak in some areas. This weakness undermines efforts to perform social or economic valuation of ecosystems or to evaluate environmental changes in terms of cost-benefit analysis. When ecosystem services provided by healthy natural systems are not accounted for, a substantial portion of the benefits of environmental regulations remain outside of the cost-benefit calculation. For example, the EPA's 2012 *Retrospective Study of the Costs of EPA Regulations: An Interim Report of Five Case Studies*<sup>65</sup> developed costs associated with EPA regulations but did not include the environmental benefits associated.

Research on how mercury pollution and the acidification of ecosystems affect ecosystem services (e.g., provisioning, regulating, supporting, or cultural services) and thereby, New York State's economy, would aid in a better appreciation and more comprehensive understanding of the benefits resulting from emissions regulations and other policies. One such example identified and documented the sensitive aquatic ecosystem services valued by humans, and the environmental pathways through which these ecological services may decrease in response to acidification. Beneficiary groups were identified for each sensitive ecological endpoint to clarify relationships between humans and the effects of aquatic acidification, and to lay the foundation for future research and analysis to define the value of the ecological services.<sup>66</sup>

The U.S. Fish and Wildlife Service uses a regulatory approach called Natural Resources Damage Assessment and Restoration to quantify the impacts of contaminants, such as methylmercury, to determine the extent of injury using metrics such as bird-years-lost. The recovery of affected populations using the number of bird-years-gained to offset losses can be monetized. Future opportunities may exist to apply settlement funds from environmental enforcement cases related to air pollution and greenhouse gas emissions to supplement environmental projects aimed at conserving natural ecosystems for the air quality and climate regulation services they provide.

A recent EMEP study assessed the social and economic impacts of Adirondack ecosystem acidification and potential recovery using an ecosystem services framework and the Ecosystem Services (ES) model “Forest Ecosystem Service Toolkit” (FEST) (contract 33072). Results indicate that Adirondack hardwood forests have roughly half the monetary value of forests where acidic deposition had little or no impact on soil chemistry, and acidification of these forests limits options for sustainable management and reduces their potential economic and cultural value for current and future generations. As for lakes and streams, results demonstrate that Adirondack lakes with lower pH are less likely to contain desirable game fish, but stocking fish and liming might speed up the restoration of sport fisheries and their economic and cultural value. Another EMEP project evaluated property values in about 26 counties, including in the Adirondacks and Finger Lakes regions, as a metric of economic impact from changes in water quality due to acidic and mercury deposition (contract 33073). This project incorporated published data on fish tissue concentrations of mercury, water quality measures, and other measures of ecosystem integrity to estimate the impacts of water quality on property values. It was found that lower pH values, which are typically associated with improved lake clarity, added a small premium to property values, but when fish mercury concentrations in the nearest large lake were at least two times higher than the EPA standards, the property values were 2-4% lower. Under another contract (contract 28260), researchers developed spatial tools (e.g., synthesis maps for where adaptation strategies could be best implemented) to prioritize conservation investments. The Natural Resource Navigator site contains these tools that are publicly available and created to help natural resource managers protect and restore ecosystem services expected to be jeopardized by climate change.

## 8 Science Translation and Outreach

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Investigators supported by NYSERDA Environmental Research Program funds are encouraged to include plans for how the data from their research will be made available to the public and to outline plans for the translation and dissemination of their results. In this 2018 research plan, investigators are encouraged to pair-up with science communication and outreach specialists to develop broader impact sections in their proposals. In addition, NYSERDA will welcome proposals from science communicators and outreach specialists interested in convening workshops to support stakeholder engagement, societally relevant synthesis, and the development of communication products and strategies to increase their impact.

- Support the development of shared public data and meta-data from studies supported by NYSERDA funds to provide information on patterns and trends from multiple research programs to stakeholders.
- Support the development of science translation products for NYSERDA's Environmental Research Program, including websites and information kits, maps and data visualization products, fact sheets, policy briefs, slide decks, and translational reports.
- Support communication and outreach activities to disseminate the results of NYSERDA research to decision-makers and the general public, including public and workshop presentations, webinars, and educational briefings.
- Support stakeholder engagement processes and empirical research to better understand science questions and needs of diverse publics, to inform effective communication formats and strategies for specific stakeholder groups, and to assess how the public perceives ongoing and completed NYSERDA research.

## Appendix A

### NYSDERDA Contracts Cited in the Environmental Research Program Plan Research Area 1: Ecological Effects of Climate Change and the Deposition of Sulfur, Nitrogen, and Mercury

Contract	Project Title	Entity	Project Completed
10659	Land-Atmosphere Dynamics of Mercury and Ecological Implications for Adirondack Forest Ecosystems	Syracuse University	Ongoing
16295	Assessment of Acidic Deposition Effects on the Chemistry and Benthos of Streams of the East-Central Adirondack Region	U.S. Geological Survey	2018
25928	Research Using Adirondack Lakes Survey Corporation Data	Syracuse University	Ongoing
26578	Ambient Mercury Speciation Measurements for Tracking the Progress of Emission Reduction Strategies in the Adirondack Mountains of New York	Clarkson University	2014
27239	The Effects of Watershed and Stream Liming on Mercury in Surface Waters	U.S. Geological Survey	2016
28260	Spatially Prioritizing Conservation Investments in New York State: A Decision Support Toolkit for Climate Adaptation	The Nature Conservancy and the New York Natural Heritage Program	2017
30388	Songbirds as Indicators of Major Source Types of Mercury for New York Ecosystems	Biodiversity Research Institute and University of Michigan	2015
30682, 122813	Mercury Deposition Network (MDN) and Leaf Hg at Frost Valley YMCA	Frost Valley YMCA	Ongoing
30882, 127704	National Atmospheric Deposition Program (NADP)	National Atmospheric Deposition Program	Ongoing
31250, 122681	Huntington Wildlife Forest Monitoring	SUNY College of Environmental Science and Forestry	Ongoing
31846	Impact, Recovery, and Resiliency of Stream Ecosystems to Extreme Floods in the Upper Esopus Creek	U.S. Geological Survey	2015
33072	Social and Economic Impacts of the Acidification and Potential Recovery of Adirondack Ecosystems	SUNY College of Environmental Science and Forestry	2017
33073	Measuring the Value of Hg and Acid Pollution in New York State through Property Values	Clarkson University	2017

<b>Contract</b>	<b>Project Title</b>	<b>Entity</b>	<b>Project Completed</b>
33074, 33074B, 33074C	Accelerated Recovery Through Liming of Honnedaga Watershed and Streams – Assessment of Recovery from Acidification	U.S. Geological Survey, SUNY College of Environmental Science and Forestry, and Cornell University	Ongoing
33075, 33075A	Accelerated Recovery Through Liming of Honnedaga Watershed and Streams – Assessment of Liming on Hg	Syracuse University and U.S. Geological Survey	Ongoing
34356, 122529	Monitoring of New York State Streams	U.S. Geological Survey	Ongoing
34356A	Monitoring of New York Lakes and Streams in the Adirondacks	Adirondack Lakes Survey Corporation, U.S. Environmental Protection Agency, and NYS Dept. of Environmental Conservation	2017
34357	Monitoring of New York State Fish for Hg	Syracuse University	Ongoing
34358	Monitoring of New York State Birds for Hg	Biodiversity Research Institute	2018
37346	Fish Assemblage and Hg in New York State Streams	U.S. Geological Survey	Ongoing
38803	Adirondack Long Term Monitoring Program Evaluation	E&S Environmental Chemistry	2015
40508-1	Using Field Data to Parameterize and Test a New Forest Ecosystem Model	Cary Institute	2017
40509	Changes in Soil and Stream Water Chemistry in Response to Reductions in Acid Deposition in the Catskill Mountains of New York	U.S. Geological Survey	2018
40512	Influence of Climate on Adirondack Lake Recovery from Acidification	E&S Environmental Chemistry	2016
40515	Ratios of Methylmercury to Total Mercury in Aquatic Macroinvertebrates	U.S. Geological Survey	Ongoing
41874	Effects of Acidic Deposition on Adirondack Northern Hardwood Forests	E&S Environmental Chemistry	2017
41878	Response of Fish Assemblages to Changing Acid-Base Chemistry in ALTM Lakes, 1984-2012	U.S. Geological Survey	Ongoing
44376	Analysis of the Role of Changing Atmospheric Deposition and Climate on Water Quality in the Adirondack Mountains of New York State	SUNY College of Environmental Science and Forestry	Ongoing
50462	Controlling Factors of Long-Term Trends in Mercury Wet Deposition and Precipitation Concentrations at Huntington Wildlife Forest	SUNY College of Environmental Science and Forestry	2016
50771	Estimating Soil Weathering Rates in the Catskills Watersheds	Syracuse University	Ongoing

<b>Contract</b>	<b>Project Title</b>	<b>Entity</b>	<b>Project Completed</b>
50773	Effects of Acidic Deposition and Soil Acidification on Forest Understory Plant Biodiversity in the Adirondack Mountains	E&S Environmental Chemistry	2017
50775	Effects of Watershed and In-stream Liming on Accelerated Recovery of Macroinvertebrate Assemblages in Tributaries to Honnedaga Lake	U.S. Geological Survey	2018
50776	Environmental DNA: Emerging Methods for Detection and their Potential for Inventorying Brook Trout Populations in Streams of the Western Adirondacks	U.S. Geological Survey and Paul Smith's Adirondack Watershed Institute	2017
50777	Long-term Effects of the Clean Air Act on Brook Trout Survival and Toxicity in Acidified Streams of the Western Adirondacks, 1984-2017	U.S. Geological Survey	Ongoing
50778	Mercury Dynamics in Finger Lakes Fish and Invertebrates	Hobart and William Smith Colleges	Ongoing
53968	Investigating Sulfur- and Nitrogen-Containing Compounds in Cloud Water at Whiteface Mountain	University of Michigan	2018
57630	ALTM Nutrient Dynamics – Nitrogen, Phosphorus, and Chloride	Syracuse University	Ongoing
73402, 73402A, 73402B	Critical Loads in the Adirondacks	Syracuse University, U.S. Geological Survey, and E&S Environmental Chemistry	Ongoing
83743	Acid-Base Chemistry and Biota in Streams	U.S. Geological Survey	Ongoing
104107	Stream Regional Monitoring Network (RMN) Invertebrate Analysis	Watershed Assessment Associates	Ongoing
108229	Statistical Analysis of the Loon Monitoring Program	SUNY College of Environmental Science and Forestry	2017
113882	Monitoring of New York State Loons	Adirondack Center for Loon Conservation	Ongoing
115876	Compilation, Analysis, and Publication of Adirondack Effects Assessment Program (AEAP) Data and Associated Data Sets	Rensselaer Polytechnic Institute	2018
122530	Monitoring of New York Lakes in the Adirondacks	Adirondack Lakes Survey Corporation, U.S. Environmental Protection Agency, and NYS Dept. of Environmental Conservation	Ongoing
124461	Whiteface Mountain Cloud Monitoring	Atmospheric Sciences Research Center – University at Albany	Ongoing
124842	Synthesis of Environmental Mercury Loads in New York State	Biodiversity Research Institute	Ongoing

# Endnotes

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- 3 The Fourth National Climate Assessment: [nca2018.globalchange.gov](https://nca2018.globalchange.gov).
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- 5 Millennium Ecosystem Assessment: <https://www.millenniumassessment.org/en/index.html>
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- 8 Emissions from transportation sources are also important precursors to nitrogen deposition, and agricultural activities are an important source of ammonia in the environment.
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